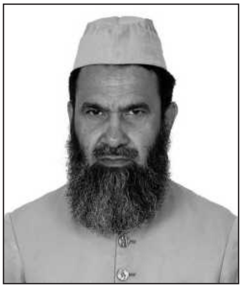
Non-Conventional Energy Resources

Third Edition

About the Author



B H Khan received his BSc Engineering degree from Aligarh Muslim University (AMU), Aligarh (first rank, 1976), ME from IISc Bangalore (1978) and PhD from IIT Kanpur (1989). Since 1978, he is a faculty of the Electrical Engineering Department, AMU, Aligarh, where he is currently working as professor.

Professor Khan is a recipient of the President of India Medal of Institution of Engineers (India), 2002, for his work on *Simultaneous ac–dc Transmission*. He also received the Railway Board's First Prize of the year 1986–87. He is senior member of IEEE (USA), Life Fellow of IE (India), a life member of the Indian Society for Technical Education and a life member of the System Society of India. Professor Khan has over 31 years of experience in teaching and research at the undergraduate and postgraduate levels in electrical engineering in India as well as abroad, and has worked on several sponsored research projects. His current areas of interest include Non-conventional and Renewable Energy Sources, Power Electronics and Microprocessor Applications.

Non-Conventional Energy Resources

Third Edition

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Published by McGraw Hill Education (India) Private Limited
444/1, Sri Ekambara Naicker Industrial Estate, Alapakkam, Porur, Chennai-600 116

Non-Conventional Energy Resources, 3e

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Print Edition
ISBN 13: 978-93-5260-188-2
ISBN 10: 93-5260-188-2

EBook Edition
ISBN 13: 978-93-5260-189-9
ISBN 10: 93-5260-189-0

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Typeset at Text-o-Graphics, B-1/56, Aravali Apartment, Sector-34, Noida 201 301, and printed at

Cover Printer:

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Contents

Preface

Energy has become an important and one of the basic infrastructures for economic development of a country. Energy security is, therefore, imperative for sustained growth of economy. The oil crisis of 1973 and concern for environment due to excessive use of fossil fuels have led to remarkable global efforts in harnessing alternative energy resources. The renewable energy resources such as the sun, wind, biomass and geothermal heat are environment friendly and perennial in nature. These resources are also referred as non-conventional energy resources as, at present, their large-scale use is not common. Harnessing energy through these resources using efficient technologies is expected to play an important role in serving as clean energy sources for mankind. Thus, processes to harness these are steadily gaining technical and economic importance worldwide. Most governments have substantial plans directed towards encouraging these technologies in order to develop them commercially. As we had hoped and wished initially, the development of these technologies have not been dramatic. They have yet to achieve the cost-benefit ratio possible with conventional fuels and are not likely to replace fossil fuels in the near future. Nevertheless, they have come to play a very important supportive role in addition to conventional sources. Therefore, it is necessary for energy planners/users to know the virtues as well as limitations of these technologies. The present book is an effort to explore these technologies in a balanced perspective.

Being a relatively recent field, the subject matter is scattered in specialized research journals and a few books of advanced levels are devoted exclusively to a particular technology. There is, however, scarcity of publications that introduce all these technologies in a single volume to a beginner. Therefore, a natural consequence of the current volume will be a much-needed and relatively inexpensive textbook at an undergraduate level. While teaching a course on non-conventional energy to undergraduate engineering students, the author himself felt this need, which encouraged him to write the present book.

Human resource development in the area of energy, in general, and in new and renewable sources of energy, in particular, has been neglected all over the world, and more so in developing countries. Therefore, the book is primarily intended to serve as textbook for undergraduate-level courses for engineering and science students.

It stresses scientific understanding, analysis and applications of non-conventional energy technologies. Many practicing engineers and scientists may not have a formal exposure to this area and may be interested to have a general training of these technologies. Therefore, the book is oriented to cover both basic study and its widespread applications. It describes the fundamental physical processes governing various non-conventional energy technologies and their applications. The book may also serve to create awareness among energy planners, policy makers and users about these technologies in general. Because of the spread of disciplines involved, it is not possible to discuss each of them exhaustively in a single book. Therefore, only relevant background up to a depth essential to understand the basic principles has been included.

In recent years, the harmful effects of global warming due to heavy dependence on fossil fuels are becoming more and more visible. The manifestations of global warming are appearing much earlier and much more widespread than initially expected. This has forced the global community to initiate corrective steps to check this trend. The need of developing clean, sustainable and secure energy resources is being increasingly realized. Also, the cost of fossil fuels, especially oil, is ever increasing. This has become evident that the era of low priced and secure availability of oil is over. The economic growth cannot be sustained until reliable energy is made available at a reasonable cost.

Due to the above-mentioned developments, attention is being focused to develop and utilize renewable and non-conventional energy sources which have been largely neglected so far due to unhindered and low-cast availability of oil. As a result, extensive R & D efforts are going on towards the development of these resources and related technologies. Consequently, the knowledge related to developments in these technologies needs frequent updating. Therefore, a need was felt to bring a thoroughly revised, expanded and updated third edition of the present book.

The contents are covered in fourteen chapters.

A brief review of both conventional and non-conventional energy sources highlighting the importance of non-conventional energy sources is included in Chapter 1. The concepts of energy storage and energy conservation are introduced early in the text in chapters 2 and 3 respectively. The general background of these concepts is helpful to understand these technologies and to integrate them in energy systems. The topic of solar energy is divided into three subsequent chapters. Chapter 4 covers the basics of solar energy while chapters 5 and 6 respectively cover solar thermal and solar PV systems. Chapter 7 covers wind-energy technology. The required background of fluid mechanics is also included in this chapter.

Biomass energy, again, requires knowledge of organic chemistry and biology of the senior secondary level. The required background is also included in Chapter 8, related to biomass energy. Chapter 9 is devoted to geothermal energy, which is important only in fairly limited geographical areas. Energy resources available in the ocean, i.e., tidal, wave and ocean thermal are covered in Chapter 10. Small hydro resources are explained in Chapter 11. Emerging technologies such as fuel cell, hydrogen energy and micro hydro resources are covered in Chapter 12. Some miscellaneous technologies such as MHD, thermoelectric and thermionic are covered in Chapter 13. Finally, financial and economic calculations are explained in Chapter 14.

Useful review questions including numerical problems, wherever feasible, are also included at the end of each chapter. The answers to numerical problems are also provided. Some important units and their interrelations are given in the appendices. Useful websites covering information on supplementary material, ongoing major projects and recent updated data on the subject are also listed.

For each of the technologies covered, the following salient features are included:

- Historical background
- Preliminary estimate and its geographical variation
- Basic principle of energy conversion
- System of conversion
- Current status
- Environmental impacts

The book covers basic principles, energy conservation and storage, system of conversion, emerging technologies, current status and environmental effects besides two complete chapters on Small Hydro Resources (Chapter 11) and Financial and Economic Evolution (Chapter 14). Some new topics have been included by modifying/updating the existing material, based on feedbacks received from the readers.

Some of the modifications made in the third edition are as follows:

- All chapters are thoroughly revised, at places new topics are added and all data are updated to current level of development.
- New review questions from different universities are added (updated total 267 questions).
- A number of new solved examples (updated total 75) and unsolved numerical problems are added.
- New Multiple Choice Questions (MCQs) are also added (updated total 285 MCQs).
- Major chapter-wise revisions and additions are listed as follows:
    - ◆ *Chapter 2:* New sections on energy audit and energy conservation opportunities in industry are added.
    - ◆ *Chapter 3:* A section on flow batteries is added.
    - ◆ *Chapter 4:* The section on empirical equations for estimating solar radiation is revised.
    - ◆ *Chapter 5:* A new section on thermal analysis of liquid flat plate collector is added.
    - ◆ *Chapter 6:* Sections on p-n junction theory, solar cell classifications, BOS components are revised while new sections on solar cell technologies and some typical design examples of solar system are included in the new edition.
    - ◆ *Chapter 7:* A new section on wind turbine siting is added.
    - ◆ *Chapter 8:* A new section on 'variations of basic biogas models' is added.
    - ◆ *Chapter 12:* Section on 'hydrogen as energy carrier' is revised.
    - ◆ *Chapter 13:* A new section on 'Peltier cooling' is added.

The book deliberately contains more material than could be covered in a one-semester course. This enables the instructor to design a one-semester course including topics of his choice depending on the particular energy supplies, which are more important in this situation. Alternatively, two courses, each of one-semester duration, may be planned with broad divisions such as chapters 1–5 and Chapter 7 in the first course, and Chapter 6 and chapters 8–14 in the second course with minor adjustments.

The contents of the book have been class tested for a two-semester (one year) course offered to final-year BTech students at AMU, Aligarh. In fact the book, in its present form, is the outcome of teaching of a course 'Non-Conventional Energy Sources' for many years by the author. As a result, it has undergone extensive screening and has been revised wherever found necessary.

The web supplements for this book can be accessed at *http://www.mhhe.com/khan/ncer3e* and contain Solutions Manual for instructors.

The author had useful discussions with many individuals from different areas of specialization during the course of preparation of this book. Their cooperation is gratefully acknowledged. The author would also like to thank the following reviewers for taking out time to review the book.

Ashwani Mathur	*JIET Jodhpur*
Tarun Gupta	*IIT Kanpur*
Sandeep Goyal	*RTU*
MD. S. Khan	*North Eastern Regional Institute of Science and Technology, Arunachal Pradesh*
Krishna Hazra	*Future Institute of Engineering and Management, Kolkata*
Subhas Chandra Haldar	*Haldia Institute of Technology, Haldia, West Bengal*
Subimal Ghosh	*IIT Bombay*

Thanks are due to my students who used the early versions of the manuscript in their course and provided valuable feedback. I also thank my family members for their cooperation, understanding and patience.

It is highly gratifying that the second edition of the book has been well received and appreciated. I hope the readers will welcome the third edition too and get benefit from the changes made. Any suggestions/feedbacks in the direction of further improvement in the book will be highly appreciated. In spite of best efforts, some errors might have still remained in the text. I welcome the suggestions and comments, if any, from all readers for further improvement of the book.

B H Khan

Publisher's Note

Constructive suggestions and criticism always go a long way in enhancing and endeavour. We request all readers to email us their valuable comments/views/feedback for the betterment of the book at **info.india@mheducation.com**, mentioning the title and author name in the subject line.

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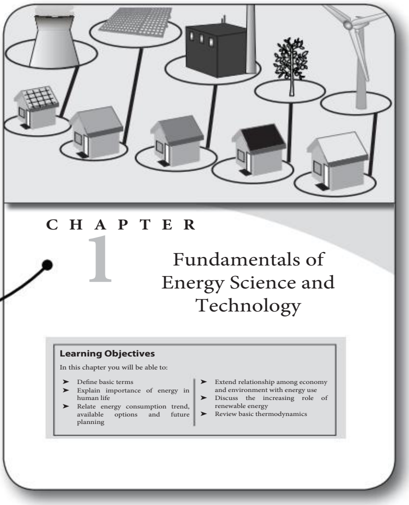
Visual Walkthrough

INTRODUCTION

Each chapter begins with an introduction that includes a brief write up about the significance, historical background and content of the chapter.



CHAPTER

1

Fundamentals of Energy Science and Technology

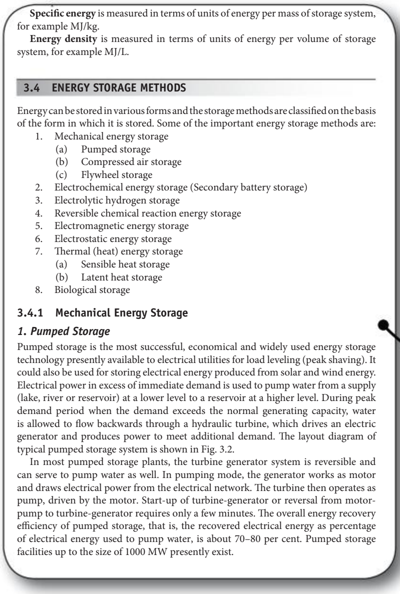
Learning Objectives

In this chapter you will be able to:

- Define basic terms
- Explain importance of energy in human life
- Relate energy consumption trend, available options and future planning
- Extend relationship among economy and environment with energy use
- Discuss the increasing role of renewable energy
- Review basic thermodynamics

SECTIONS AND SUBSECTIONS

Each chapter has been neatly divided into sections and subsections so that the subject matter is studied in a logical progression of ideas and concepts.



Specific energy is measured in terms of units of energy per mass of storage system, for example MJ/kg.

Energy density is measured in terms of units of energy per volume of storage system, for example MJ/L.

3.4 ENERGY STORAGE METHODS

Energy can be stored in various forms and the storage methods are classified on the basis of the form in which it is stored. Some of the important energy storage methods are:

1. Mechanical energy storage
   (a) Pumped storage
   (b) Compressed air storage
   (c) Flywheel storage
2. Electrochemical energy storage (Secondary battery storage)
3. Electrolytic hydrogen storage
4. Reversible chemical reaction energy storage
5. Electromagnetic energy storage
6. Electrostatic energy storage
7. Thermal (heat) energy storage
   (a) Sensible heat storage
   (b) Latent heat storage
8. Biological storage

3.4.1 Mechanical Energy Storage

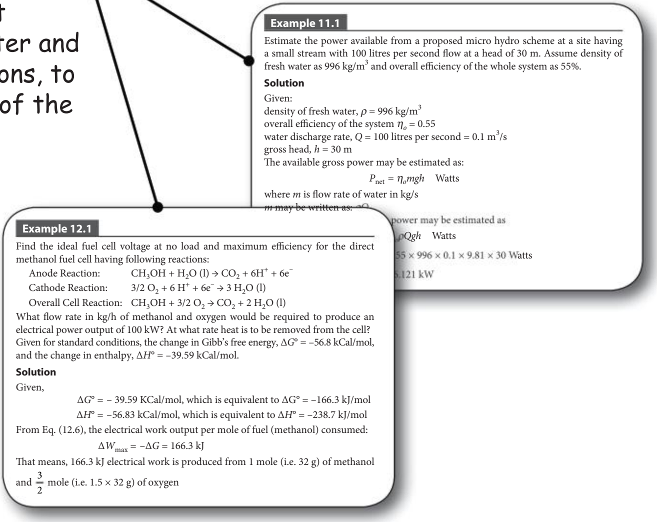
1. Pumped Storage

Pumped storage is the most successful, economical and widely used energy storage technology presently available to electrical utilities for load leveling (peak shaving). It could also be used for storing electrical energy produced from solar and wind energy. Electrical power in excess of immediate demand is used to pump water from a supply (lake, river or reservoir) at a lower level to a reservoir at a higher level. During peak demand period when the demand exceeds the normal generating capacity, water is allowed to flow backwards through a hydraulic turbine, which drives an electric generator and produces power to meet additional demand. The layout diagram of typical pumped storage system is shown in Fig. 3.2.

In most pumped storage plants, the turbine generator system is reversible and can serve to pump water as well. In pumping mode, the generator works as motor and draws electrical power from the electrical network. The turbine then operates as pump, driven by the motor. Start-up of turbine-generator or reversal from motor-pump to turbine-generator requires only a few minutes. The overall energy recovery efficiency of pumped storage, that is, the recovered electrical energy as percentage of electrical energy used to pump water, is about 70–80 per cent. Pumped storage facilities up to the size of 1000 MW presently exist.

WORKED EXAMPLES

Worked examples are provided in sufficient number in each chapter and at appropriate locations, to aid in understanding of the text material.



Example 11.1

Estimate the power available from a proposed micro hydro scheme at a site having a small stream with 100 litres per second flow at a head of 30 m. Assume density of fresh water as 996 kg/m^3 and overall efficiency of the whole system as 55%.

Solution

Given:

density of fresh water, $\rho = 996$ kg/m^3

overall efficiency of the system $\eta_o = 0.55$

water discharge rate, $Q = 100$ litres per second $= 0.1$ m^3/s

gross head, $h = 30$ m

The available gross power may be estimated as:

$$P_{net} = \eta_o mgh \quad \text{Watts}$$

where m is flow rate of water in kg/s

m may be written as: ρQ

power may be estimated as

ρQgh Watts

$55 \times 996 \times 0.1 \times 9.81 \times 30$ Watts

.121 kW

Example 12.1

Find the ideal fuel cell voltage at no load and maximum efficiency for the direct methanol fuel cell having following reactions:

Anode Reaction: $CH_3OH + H_2O\ (l) \rightarrow CO_2 + 6H^+ + 6e^-$

Cathode Reaction: $3/2\ O_2 + 6\ H^+ + 6e^- \rightarrow 3\ H_2O\ (l)$

Overall Cell Reaction: $CH_3OH + 3/2\ O_2 \rightarrow CO_2 + 2\ H_2O\ (l)$

What flow rate in kg/h of methanol and oxygen would be required to produce an electrical power output of 100 kW? At what rate heat is to be removed from the cell? Given for standard conditions, the change in Gibb's free energy, $\Delta G° = -56.8$ kCal/mol, and the change in enthalpy, $\Delta H° = -39.59$ kCal/mol.

Solution

Given,

$$\Delta G° = -39.59 \text{ KCal/mol, which is equivalent to } \Delta G° = -166.3 \text{ kJ/mol}$$

$$\Delta H° = -56.83 \text{ kCal/mol, which is equivalent to } \Delta H° = -238.7 \text{ kJ/mol}$$

From Eq. (12.6), the electrical work output per mole of fuel (methanol) consumed:

$$\Delta W_{max} = -\Delta G = 166.3 \text{ kJ}$$

That means, 166.3 kJ electrical work is produced from 1 mole (i.e. 32 g) of methanol and $\frac{3}{2}$ mole (i.e. 1.5 × 32 g) of oxygen

PHOTOGRAPHS

Photographs of important commercial systems are presented at appropriate locations.

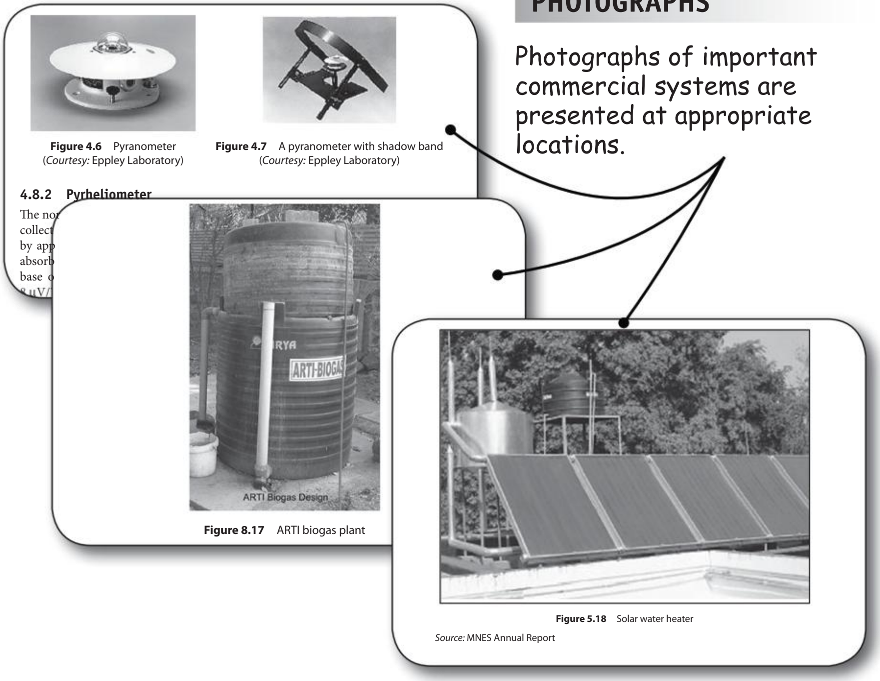


Figure 4.6 Pyranometer
(*Courtesy:* Eppley Laboratory)

Figure 4.7 A pyranometer with shadow band
(*Courtesy:* Eppley Laboratory)

4.8.2 Pyrheliometer

The nor
collect
by app
absorb
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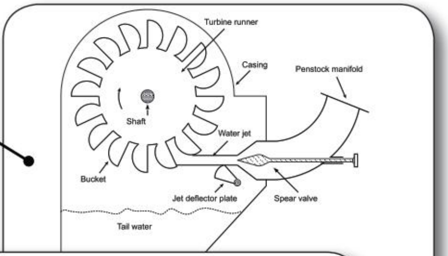
Figure 8.17 ARTI biogas plant

Figure 5.18 Solar water heater

Source: MNES Annual Report

ILLUSTRATIONS

Illustrations are essential tools in a book of engineering. Ample illustrations are provided in each chapter to demonstrate the concept, functional relationships and definition sketches for mathematical models.



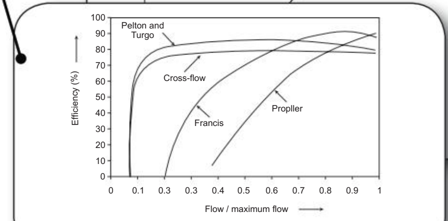
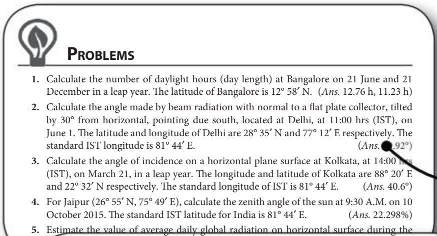
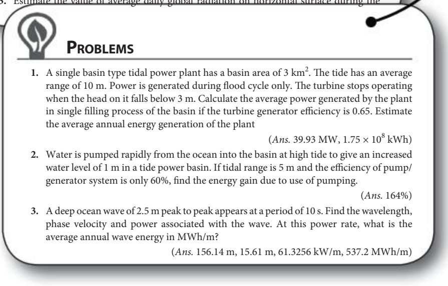


Figure 11.9 Part flow efficiencies of various turbines



Problems

1. Calculate the number of daylight hours (day length) at Bangalore on 21 June and 21 December in a leap year. The latitude of Bangalore is 12° 58′ N. (*Ans.* 12.76 h, 11.23 h)
2. Calculate the angle made by beam radiation with normal to a flat plate collector, tilted by 30° from horizontal, pointing due south, located at Delhi, at 11:00 hrs (IST), on June 1. The latitude and longitude of Delhi are 28° 35′ N and 77° 12′ E respectively. The standard IST longitude is 81° 44′ E. (*Ans.* [illegible].92°)
3. Calculate the angle of incidence on a horizontal plane surface at Kolkata, at 14:00 hrs (IST), on March 21, in a leap year. The longitude and latitude of Kolkata are 88° 20′ E and 22° 32′ N respectively. The standard longitude of IST is 81° 44′ E. (*Ans.* 40.6°)
4. For Jaipur (26° 55′ N, 75° 49′ E), calculate the zenith angle of the sun at 9:30 A.M. on 10 October 2015. The standard IST latitude for India is 81° 44′ E. (*Ans.* 22.298%)
5. Estimate the value of average daily global radiation on horizontal surface during the



Problems

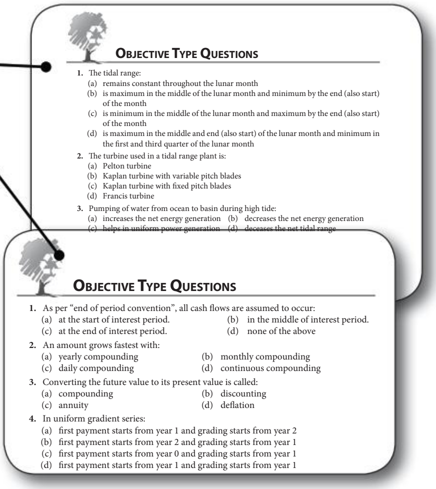
1. A single basin type tidal power plant has a basin area of 3 km^2. The tide has an average range of 10 m. Power is generated during flood cycle only. The turbine stops operating when the head on it falls below 3 m. Calculate the average power generated by the plant in single filling process of the basin if the turbine generator efficiency is 0.65. Estimate the average annual energy generation of the plant (*Ans.* 39.93 MW, 1.75×10^8 kWh)
2. Water is pumped rapidly from the ocean into the basin at high tide to give an increased water level of 1 m in a tide power basin. If tidal range is 5 m and the efficiency of pump/generator system is only 60%, find the energy gain due to use of pumping. (*Ans.* 164%)
3. A deep ocean wave of 2.5 m peak to peak appears at a period of 10 s. Find the wavelength, phase velocity and power associated with the wave. At this power rate, what is the average annual wave energy in MWh/m? (*Ans.* 156.14 m, 15.61 m, 61.3256 kW/m, 537.2 MWh/m)

PRACTICE PROBLEMS AND ANSWERS

Each chapter contains a set of practice problems. Solutions to these problems require not only the application of the material covered in the book but also enable the students to strive towards good comprehension of the subject matter. Answers are provided at the end of each problem.

OBJECTIVE-TYPE QUESTIONS

Each chapter contains a set of objective-type questions, which enables the user to obtain a clear comprehension of the subject matter and helps to prepare for competitive examinations. Answers to all these questions are provided in Appendix D at the end of the book.



OBJECTIVE TYPE QUESTIONS

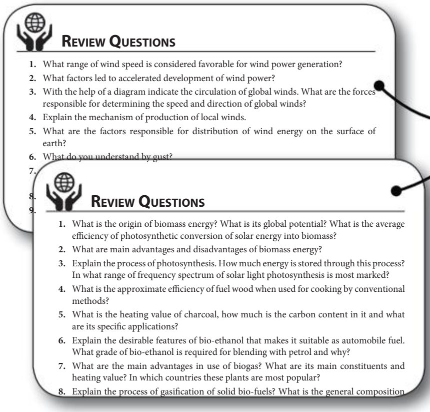
1. The tidal range:
   (a) remains constant throughout the lunar month
   (b) is maximum in the middle of the lunar month and minimum by the end (also start) of the month
   (c) is minimum in the middle of the lunar month and maximum by the end (also start) of the month
   (d) is maximum in the middle and end (also start) of the lunar month and minimum in the first and third quarter of the lunar month
2. The turbine used in a tidal range plant is:
   (a) Pelton turbine
   (b) Kaplan turbine with variable pitch blades
   (c) Kaplan turbine with fixed pitch blades
   (d) Francis turbine
3. Pumping of water from ocean to basin during high tide:
   (a) increases the net energy generation (b) decreases the net energy generation
   (c) helps in uniform power generation (d) deceases the net tidal range

OBJECTIVE TYPE QUESTIONS

1. As per "end of period convention", all cash flows are assumed to occur:
   (a) at the start of interest period. (b) in the middle of interest period.
   (c) at the end of interest period. (d) none of the above
2. An amount grows fastest with:
   (a) yearly compounding (b) monthly compounding
   (c) daily compounding (d) continuous compounding
3. Converting the future value to its present value is called:
   (a) compounding (b) discounting
   (c) annuity (d) deflation
4. In uniform gradient series:
   (a) first payment starts from year 1 and grading starts from year 2
   (b) first payment starts from year 2 and grading starts from year 1
   (c) first payment starts from year 0 and grading starts from year 1
   (d) first payment starts from year 1 and grading starts from year 1

REVIEW QUESTIONS

Each chapter contains a set of review questions including many from examinations of selected universities. This enables the user to have an idea about university examinations. The answers are embedded in the content within the chapters.

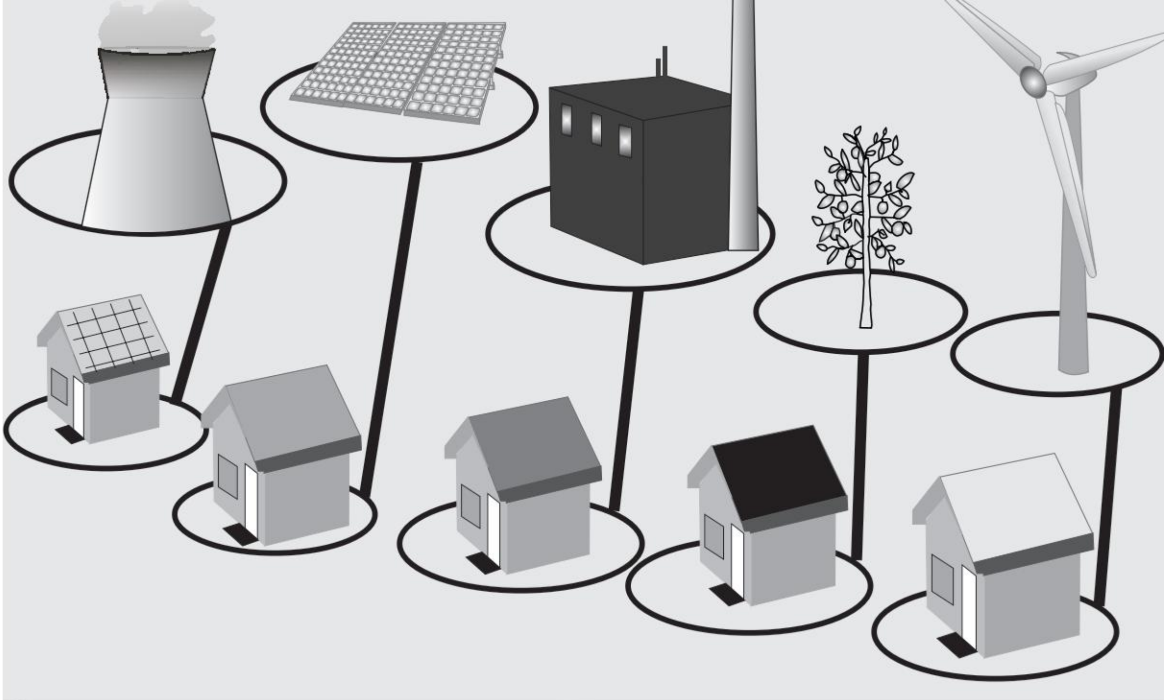


REVIEW QUESTIONS

1. What range of wind speed is considered favorable for wind power generation?
2. What factors led to accelerated development of wind power?
3. With the help of a diagram indicate the circulation of global winds. What are the forces responsible for determining the speed and direction of global winds?
4. Explain the mechanism of production of local winds.
5. What are the factors responsible for distribution of wind energy on the surface of earth?
6. What do you understand by gust?
7.
8.
9.

REVIEW QUESTIONS

1. What is the origin of biomass energy? What is its global potential? What is the average efficiency of photosynthetic conversion of solar energy into biomass?
2. What are main advantages and disadvantages of biomass energy?
3. Explain the process of photosynthesis. How much energy is stored through this process? In what range of frequency spectrum of solar light photosynthesis is most marked?
4. What is the approximate efficiency of fuel wood when used for cooking by conventional methods?
5. What is the heating value of charcoal, how much is the carbon content in it and what are its specific applications?
6. Explain the desirable features of bio-ethanol that makes it suitable as automobile fuel. What grade of bio-ethanol is required for blending with petrol and why?
7. What are the main advantages in use of biogas? What are its main constituents and heating value? In which countries these plants are most popular?
8. Explain the process of gasification of solid bio-fuels? What is the general composition



CHAPTER 1

Fundamentals of Energy Science and Technology

Learning Objectives

In this chapter you will be able to:

- Define basic terms
- Explain importance of energy in human life
- Relate energy consumption trend, available options and future planning
- Extend relationship among economy and environment with energy use
- Discuss the increasing role of renewable energy
- Review basic thermodynamics

1.1 INTRODUCTION

Any physical activity in this world whether by human beings or by nature, is caused due to flow of energy in one form or the other. Energy is required to do any kind of work. The word 'energy' itself is derived from Greek word 'en – ergon', which means 'in – work' or 'work content'. The work output depends on the energy input and the capability to do work depends on the amount of energy one can control and utilize.

Man has been using energy at an increasing pace for his sustenance and well-being ever since he came on earth. Primitive man depended on manual work. Since his work output was limited, his energy requirements were met through food intake. Life was simple and with limited demands, and the environment was relatively clean. Later on, he started using animal power to supplement manual energy to enhance his work output. Gradually, he learnt harnessing energy from wind and falling water to further enhance the work output. Much later in 1785, the invention of steam engine by James Watt of Scotland brought industrial revolution. It was the beginning of mechanical age or age of machines. Though increase in energy consumption had been gradual throughout the history, however, post industrialization the rate of consumption showed dramatic increase over a period of just a few generations. The advent of internal combustion engine in the late nineteenth century gave further momentum to the trend. Gradually, industrial revolution spread to the whole world. In 1888, Nickola Tesla invented commercial induction motor. The introduction of electrical machines along with commercial availability of electrical power started the new electrical age. All this led to increase of energy requirement by leaps and bounds. Energy has been the life-blood for continual progress of human civilization. Thus, with progress of human civilization the energy consumption also accelerated.

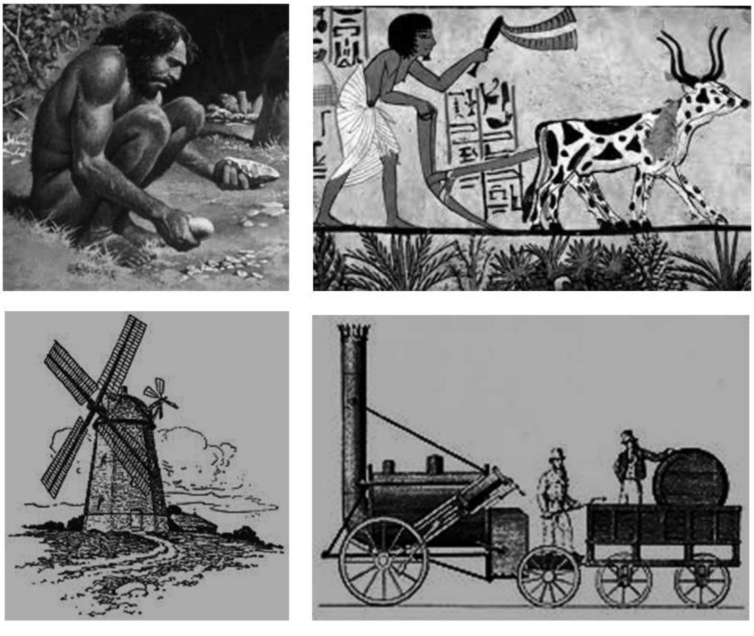


Figure 1.1 Energy use with progress of human civilization

1.2 ENERGY, ECONOMY AND SOCIAL DEVELOPMENT

Energy is universally recognized as one of the most important input for economic growth and human development. Access to modern energy services is fundamental to fulfilling basic social needs, driving economic growth and fueling human development. This is because energy services have an effect on productivity, health, education, safe and potable water and communication services. Modern services such as electricity, natural gas, modern cooking fuel and mechanical power are necessary for improved health and education, better access to information and industrial as well as agricultural productivity. Thus, secure, reliable, affordable, clean and equitable energy supply is fundamental to global economic growth and human development. One of the major challenges facing the world at present is that approximately 1.2 billion people live without any access to modern energy services. Access to energy is a fundamental pre-requisite for modern life and a key tool in eradicating extreme poverty across the globe.

Broadly, there are four major energy end use sectors:

- Commercial
- Industrial
- Residential
- Transportation

As energy is main driving force in all the sectors, consumption of large amount of energy in a country indicates more activities in these sectors. That implies better comfort at home due to use of various appliances of comfort, better transport facilities and more agricultural and industrial production. All this amounts to better quality of life. Therefore, the per capita energy consumption of a country is an index of standard of living or prosperity of the people of the country. In Table 1.1, the comparative data of annual primary energy consumption and GDP of some countries are given to emphasize this point.

Table 1.1 Annual Primary Energy Consumption and GDP of selected countries [1]

S.N.	Country	Per Capita Primary Energy Consumption in KGOE (kg of oil equivalent) (year 2013)	Per Capita GDP in USD (year 2014)
1.	USA	6,909	54,629
2.	Germany	3,874	47,624
3.	UK	2,967	45,603
4.	Japan	3,560	36,194
5.	China	2,143	7,593
6.	India	637	1630
7.	Global Average	1,919 (year 2012)	13,100 (year 2013)

As per International Energy Agency (IEA) data, the 2012 total annual energy consumption of the world was estimated as 375.9 Exajoules (or 8,978 MTOE) [2], out of which 16% energy was consumed by USA, which has about 4.4 per cent of world's population, while 17 per cent of world's population of India consumes only 5.9 per cent of total world energy. This mismatch reflects in the negative differential in the quality of life of the people in these countries. Electricity is considered a necessary requirement for economic and social development. In 2012 annual per capita electrical energy consumption in USA was 12,954 kWh and that in China and India was 3,488 kWh 760 kWh respectively. The average global per capita electrical energy consumption was 2,972 kWh.

Example 1.1

A poor rural family of five persons consumes 1 kg per person per day of firewood for cooking needs and 2 kg of kerosene oil per month for lighting. Calculate the annual primary energy consumption per person in KGOE. Assume heating value of wood as 4000 kcal per kg and that of kerosene oil as 45 MJ per kg.

Solution

Annual firewood consumption of the family for cooking = 5 × 1 kg × 365 = 1825 kg

Annual primary energy required for cooking = 1824 × 4000 kcal = 73,00,000 kcal

= 730 KGOE (refer Appendix A)

Annual kerosene requirement of the family for lighting = 12 × 2 kg = 24 kg

Annual primary energy required for lighting = 24 × 45 = 1080 MJ

$= 1080 \times 23.884 \times 10^{-3}$ KGOE

= 25.795 KGOE (refer Appendix A)

Total annual primary energy consumption of the family = 730 + 25.795

= 755.8 KGOE

Total annual primary energy consumption per person = 755.8 / 5 = 151.2 KGOE

1.3 OIL CRISIS OF 1973

In October 1973 OAPEC (Organization of Arab Petroleum Exporting countries and Egypt, Syria and Tunisia) proclaimed an embargo on oil production and started oil pricing control strategy, in response to support of USA to Israel in its war against Egypt. Oil prices shot up four folds (from 3 USD per barrel) causing severe energy crisis the world over. This resulted in spiraling price rise of various commercial energy sources leading to global inflation. The world financial system, which was already under pressure from the Bretton Woods breakdown, was set on a path of recession and inflation that persisted until the early 1980s, with oil prices continuing to rise until 1986. The world took this shock very seriously and for the first time a need for developing alternative sources of energy was felt. Alternate energy sources were given serious consideration and huge funds were allocated for development of these resources as well as for framing policies for energy conservation. Thus the year 1973 is considered as the year of first 'oil shock'. In the same decade one more 'oil shock' jolted the world in 1979 caused by interruptions in exports from the Middle East, due to the Iranian Revolution. By the end of 1980 the price of crude oil stood at 12 times (over 37 USD per barrel) what it had been just ten years earlier.

1.4 CLASSIFICATION OF ENERGY SOURCES

Energy resources can be classified on the basis of following criteria:

1. Based on Usability of Energy

(a) Primary resources These include resources embodied in nature prior to undergoing any human-made conversions or transformations. This only involves extraction or capture. Examples of primary energy resources are coal, crude oil, sunlight, wind, running rivers, vegetation and radioactive material like uranium etc. These resources are generally available in raw forms and are therefore, known as raw energy resources. Generally, this form of energy cannot be used as such. These are located, explored, extracted, processed and are converted to a form as required by the consumer. Thus some energy is spent in making the resource available to the user in a usable form. The energy yield ratio of an energy extraction process is defined as follows:

$$\text{Energy Yield Ratio} = \frac{\text{Energy received from raw energy source}}{\text{Energy spent to obtain raw energy source}}$$

Only resource for which the energy yield ratio is fairly high, are considered worth exploration.

(b) Secondary Resources The energy resources supplied directly to consumer for utilization after one or more steps of transformation are known as secondary or usable energy, e.g. electrical energy, thermal energy (in the form of steam or hot water), refined fuels or synthetic fuels such as hydrogen fuels, etc.

2. Based on Traditional Use

(a) Conventional Energy resources, which are being traditionally used, for many decades and were in common use around oil crisis of 1973, are called conventional energy resources, e.g. fossil fuels, nuclear and hydro resources.

(b) Non-conventional Energy resources, which are considered for large-scale use after the oil crisis of 1973, are called non-conventional energy sources, e.g. solar, wind, biomass, etc.

3. Based on Long-Term Availability

(a) Non-renewable Resources, which are finite and do not get replenished after their consumption, are called non-renewable e.g. fossil fuels, uranium, etc. They are likely to deplete with time.

(b) Renewable Renewable energy is energy obtained from sources that are essentially inexhaustible. Examples of renewable resources include wind power, solar power, geothermal energy, tidal power and hydroelectric power. The most important feature of renewable energy is that it can be harnessed without the release of harmful pollutants.

4. Based on Commercial Application

(a) Commercial Energy Resource The energy sources that are available in the market for a definite price are known as commercial energy. By far the most important forms of commercial energy are electricity, coal and refined petroleum products. Commercial energy forms the basis of industrial, agricultural, transport and commercial development in the modern world. In the industrialized countries, commercialized fuels are predominant sources not only for economic production, but also for many household tasks of general population.

(b) Non-commercial Energy The energy sources that are not available in the commercial market for a price are classified as non-commercial energy. Non-commercial energy sources include fuels such as firewood, cattle dung and agricultural wastes, which are traditionally gathered, and not bought at a price, used especially in rural households. Non-commercial energy is often ignored in energy accounting. Examples of non-commercial energy are: firewood, agro waste in rural areas, solar energy for water heating, animal power for transport, irrigation and crushing of sugarcane, etc.

5. Based on origin

(a) Fossil fuels energy
(b) Nuclear energy
(c) Hydro energy
(d) Solar energy
(e) Wind energy
(f) Biomass energy
(g) Geothermal energy
(h) Tidal energy
(i) Ocean thermal energy
(j) Ocean wave energy

1.5 CONSUMPTION TREND OF PRIMARY ENERGY RESOURCES

The global average consumption trend of various primary energy resources of the world is indicated in Fig. 1.2, though the trend differs from one country to another [9].

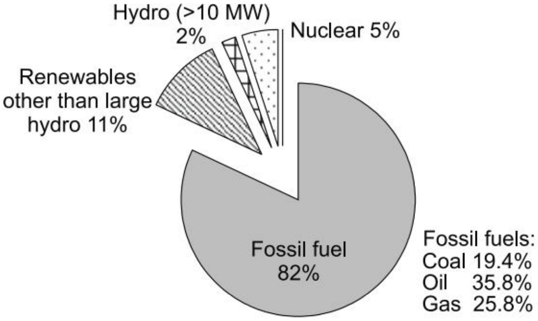


Figure 1.2 Percentage consumption of various primary energy resources

Looking at this figure, the heavy dependence on fossil fuels stands out clearly. About 82 per cent of the world's energy supply comes mainly from fossil fuels.

1.6 IMPORTANCE OF NON-CONVENTIONAL ENERGY SOURCES

The concern for environment due to ever-increasing use of fossil fuels and rapid depletion of these resources has led to development of alternative sources of energy, which are renewable and environment friendly. Following points may be mentioned in this connection:

1. Conventional sources (except hydro) are non-renewable and finite assets. With present rate of consumption their availability is rapidly declining.
2. The demand of energy is increasing exponentially due to rapid industrialization and population growth, the conventional sources of energy alone will not be sufficient in the long run, to meet the growing demand.
3. Conventional sources (fossil fuels, nuclear) also cause pollution leading to degradation of the environment. Ultimately, their use has to be restricted within acceptable limits.
4. Large hydro resources affect wild life, cause deforestation and pose various social problems.
5. In addition to supplying energy, fossil fuels are also used extensively as feedstock for the manufacture of organic chemicals. As reserves deplete, the need for using fossil fuels exclusively for such purposes may become greater.

Due to these reasons it has become important to explore and develop non-conventional energy resources to reduce too much dependence on conventional resources. However, the present trend of developments of non-conventional sources indicate that these will serve as supplement rather than substitute for conventional sources for some more time to come.

Realizing the importance of non-conventional energy sources, in March 1981 the government of India established a Commission for Additional Sources of Energy (CASE) in the Department of Science and Technology, on the lines of the Space and Atomic Energy Commissions. In 1982, CASE was incorporated in the newly created Department of Non-Conventional Energy Sources (DNES) under Ministry of Energy. Also IREDA (Indian Renewable Energy Development Agency Ltd.) a Non-Banking Financial Institution, under the administrative control of ministry was established in 1987 to promote, develop and extend financial assistance for renewable energy and energy efficiency /conservation projects. The DNES was later converted to MNES (Ministry of Non-conventional Energy Sources) in 1992. India was the first country in the world to set up a full-fledged ministry of non-conventional energy resources. In October 2006 the ministry was re-christened as the "Ministry of New and Renewable Energy".

1.7 ENERGY CHAIN

Generally, we cannot use the energy available from primary energy sources directly. For example we cannot drive an electric motor from uranium or coal. The energy available from primary energy source is known as raw energy. This energy undergoes one or more transformation stages before supplying to consumer. The sequence of energy transformations between primary and secondary energy (usable energy) is known as energy chain or energy route.

$$\text{Primary energy} \xrightarrow[\text{Transformation stages}]{} \text{Electrical energy} \xrightarrow[\text{Transmission Line}]{} \text{Consumer}$$

$$\text{Primary energy} \xrightarrow[\text{Transformation stages}]{} \text{Usable fuel} \xrightarrow[\text{Transported by rail/road/ocean/pipeline}]{} \text{Consumer}$$

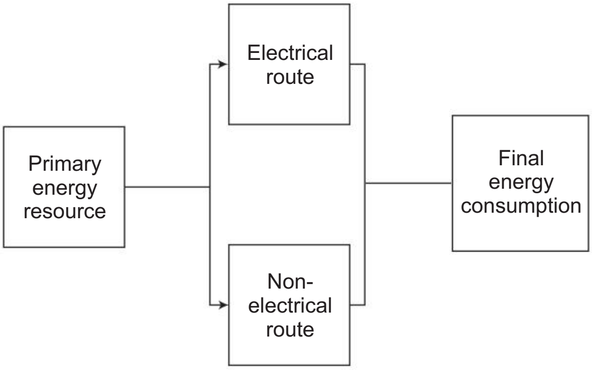


Figure 1.3 Energy routes

1.8 COMMON FORMS OF ENERGY

1. Electrical Energy

Electrical energy is considered to be the top grade energy. It is used universally as vehicle of energy. About 30–40 per cent energy distribution in the world is met through electrical supply system at present. It can be very conveniently and efficiently converted to other forms of energy.

2. Mechanical Energy

Mechanical energy is required for movement of objects, changing the shape of the objects, etc. It is used in transportation, agriculture, handling, processing, and other industrial processes.

3. Thermal Energy

Thermal energy is considered to be of lower grade as compared to electrical and mechanical energy. It is used to raise the temperature of an object during industrial processes. It can also be converted to mechanical energy with the help of heat engines. There are three grades of thermal energy depending on the temperature at which it available:

(a) *High grade* (500–1000 °C and higher): It can be converted efficiently into mechanical energy.

(b) *Medium grade* (150–500 °C): It can be converted into mechanical energy with difficulty and with lower efficiency.

(c) *Low grade* (80-50 °C): It cannot be ordinarily converted into mechanical energy and used mostly for the purpose of heating only.

4. Chemical Energy

Fuels and organic matter contain chemical energy. Exothermic chemical reactions release heat energy. Also chemical energy is directly converted into electrical energy in fuel cells, storage batteries, etc. and into thermal energy by combustion.

1.9 ADVANTAGES AND DISADVANTAGES OF CONVENTIONAL ENERGY SOURCES

Fossil fuels, nuclear and hydro resources are considered as conventional sources. There use has following advantages and disadvantages.

Advantages

1. *Cost* : At present these are cheaper than non-conventional sources.
2. *Security* : As storage is easy and convenient, by storing certain quantity, the energy availability can be ensured for certain period.
3. *Convenience*: These sources are very convenient to use as technology for their conversion and use is universally available.

Disadvantages

1. Fossil fuels generate pollutants. Main pollutants generated in the use of these sources are CO, CO_2, NO_x, SO_x, particulate matter and heat. These pollutants degrade the environment, pose health hazards and cause various other problems. CO_2 is mainly responsible for global warming also.
2. Coal is also a valuable petro-chemical and is used as raw material for various chemical, pharmaceuticals and paints, etc. industries. From long-term point of view it is desirable to conserve coal for future needs.
3. There are safety and technical issues with nuclear energy. Major problems associated with nuclear energy are as follows:
    (a) The waste material generated in nuclear plants has radioactivity of dangerous level; it remains above safe limit for a long period of time and thus is a health hazard. Its safe disposal, which is essential to prevent radioactive pollution, is a challenging task. Also the disposed radioactive waste is required to be guarded for a long period (till its radioactivity level comes down to a safe limit) in order to prevent against going in wrong hands.
    (b) Possibility of accidental leakage of radioactive material from reactor (as happened in Chernobyl, former USSR in April 1986)
    (c) Uranium resource, for which the technology presently exists, has limited availability.
    (d) Sophisticated technology is required for using nuclear resources. Only few countries possess the required expertise to use nuclear energy.

Due to these serious disadvantages Sweden has banned new nuclear plants since 1984 and planned to dismantle the existing plants in a phased manner. Germany is pressing ahead with its long-held policy of phasing out all reactors by 2022. Belgium is following its neighbour's lead, while Spain has no plans to add to its fleet of seven plants. Even France, the poster child for nuclear power, has announced plans to reduce drastically its dependency on atomic energy.

4. Hydroelectric plants are cleanest but large hydro-reservoirs cause following problems:
   (a) As large land area submerges into water, it leads to deforestation
   (b) Causes ecological disturbances such as earthquakes
   (c) Affects wild life
   (d) Causes dislocation of large population and their rehabilitation problems

1.10 SALIENT FEATURES OF NON-CONVENTIONAL ENERGY SOURCES

Merits

1. Non-conventional sources are available in nature free of cost.
2. They produce no or very little pollution. Thus by and large they are environment friendly.
3. They are inexhaustible.
4. They have low gestation period.

Demerits

1. In general the energy is available in dilute form from these sources.
2. Though available freely in nature the cost of harnessing energy from non-conventional sources is generally high.
3. Uncertainty of availability: the energy flow depends on various natural phenomena beyond human control.
4. Difficulty in transporting this form of energy.
5. Difficulty in storage.

1.11 ENERGY DENSITIES (HEATING VALUES) OF VARIOUS FUELS

Table 1.2 Energy densities of various fuels

Primary resource		Energy density
Coal:	Anthracite	32–34 MJ/kg
	Bituminous	26–30 MJ/kg
	Coke	29 MJ/kg
Brown coal:	Lignite (old)	16–24 MJ/kg
	Lignite (new)	10–14 MJ/kg
	Peat	8–9 MJ/kg

Crude petroleum	45 MJ/kg
Petrol	51–52 MJ/kg
Diesel	45–46 MJ/kg
Natural gas	50 MJ/kg, (42 MJ / m^3)
Methane (85% CH_4)	45 MJ/kg, (38 MJ / m^3)
Propane	50 MJ/kg, (45 MJ / m^3)
Hydrogen	142 MJ/kg, (12 M J / m^3)
Wood	10–11 MJ/kg
Natural Uranium	$0.26–0.3 \times 10^6$ MJ/kg
Enriched Uranium	$2.6–3.0 \times 10^6$ MJ/kg
U^{233}	83×10^6 MJ/kg
U^{235}	82×10^6 MJ/kg
Pu^{239}	81×10^6 MJ/kg

1.12 ENVIRONMENTAL ASPECTS OF ENERGY

1.12.1 Trade-off between Energy and Environment

Environment literally means surroundings. Air, soil and water are the main constituents of environment. Nature has originally provided them to human beings in clean form. However, with the passage of time, their quality is continuously being degraded due to various manmade reasons. Chief among them are a number of activities involving energy generation and its utilization. During any energy conversion process some energy is expelled by the energy conversion system into surroundings in the form of heat. Also some pollutants may be produced as a by-product of this process. Both of these cause certain degradation of environment. Every step must be taken to conserve the environment. Therefore, while supplying the increased energy demand, efforts should be made to adopt measures to minimize the degradation of environment. The present trend is to have a trade-off between the two. Future seems to be in favour of developing renewable and environment friendly energy resources. To create public awareness about environment conservation, 5th June is observed as 'World Environment Day'.

1.12.2 Ecology

Ecology deals with the relationship existing between living organisms (man, animals, plants and vegetation) and the environment. Normally, nature has self-cleaning capability and recycles (renews) its resources through various processes thus maintaining a state of equilibrium. Water cycle, nitrogen cycle and carbon cycle are the well-known examples of this. However, when human interference exceeds the limits, the ecological balance is disturbed.

1.12.3 Greenhouse Effect

A green house is an enclosure having transparent glass panes or sheets as shown in Fig. 1.4. It behaves differently for incoming visible (short wave) radiation and outgoing infrared (long wave) radiation. It appears as transparent for incoming solar radiation, allowing entry of sunlight and becomes largely opaque for reflected infrared radiation from earth surface, preventing exit of heat. Thus it maintains a controlled warmer environment inside for growth of plants, in places where the climate is very cold.

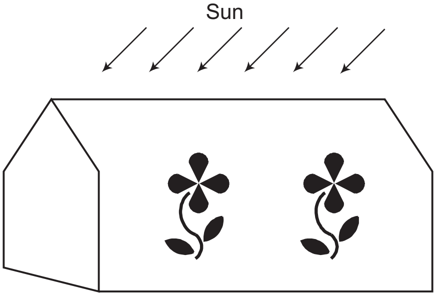


Figure 1.4 A Greenhouse

Carbon dioxide (CO_2) envelope present around the globe in the atmosphere behaves similar to a glass pane and forms a big global green house. This tends to prevent the escape of heat from earth, which leads to global warming. This phenomenon is known as *greenhouse effect*. Apart from CO_2, other gases behaving similar to CO_2 include methane, nitrous oxide (N_2O), hydrofluorocarbons (HFCs), chlorofluorocarbons (CFCs), hydro chlorofluorocarbons (HCFC), sulphur hexafluoride, ozone and water vapor. These gases are known as *greenhouse gases* (GHG). Their average concentrations in atmosphere along with Global Warming Potentials (GWPs) relative to CO_2 and atmospheric lifetimes are listed in Table 1.3.

Table 1.3 Average concentration of various GHGs in atmosphere [4]

S. N.	Name of the Gas	Concentration in ppm	GWP (100 yr time horizon)	Atmospheric lifetime (yrs)
1.	Carbon dioxide (CO_2)	400	1	100-300
2.	Methane (CH_4)	1.893	28	12
3.	Nitrous oxide (N_2O), commonly known as laughing gas	0.326	265	121
4.	Ozone (O_3)	0.337	N.A.*	hours-days
5.	CFC-11 (dichlorofluoromethane) (CCl_3F)	0.000236	4,660	45
6.	CFC-12 (dichlorofluoromethane) (CCl_2F_2)	0.000527	10,200	100
7.	HCFC-22 (hydrochlorodifluoromethane) ($CHClF_2$)	0.000231	1,760	11.9
8.	Carbon tetrachloride (CCl_4)	0.000085	1,730	26
9.	Sulfur hexafluoride (SF_6)	negligible	23,500	3,200
10.	Water vapour	5000 approx. (Horizontal and vertical average)	N. A. #	

* because of short atmospheric lifetime meaningful calculation is not possible.

\# It is not given a GWP because its concentration depends on air temperature and it does not decay in the environment. Although the greenhouse effect of water vapour is higher than CO_2, it is not a cause of climate change like CO_2.

Example 1.2

A chemical industry produces 5 Tg (teragrams) of N_2O per day. How much pollution is added into the atmosphere per day in terms of carbon equivalent?

Solution

The Global Warming Potential (GWP) of N_2O is 265.
The daily pollution of N_2O = 5 Tg
The daily pollution in terms of equivalent CO_2 (ref. Table 1.3)
= 5 × 265 = 1,325 Tg = 1,325 Million Tons of CO_2
As (12/44) is the carbon to CO_2 molecular weight ratio, the pollution in terms of Million Metric Tons of Carbon Equivalent (MMTCE) = 1,325 × (12/44) = 361.36 MMTCE

1.12.4 Global Warming

The presence of CO_2 in the atmosphere is not undesirable altogether. It is required for the growth of vegetation. Also it is due to its presence the earth maintains an average surface temperature of 15 °C that is hospitable to life. In absence of this layer the earth would be a frozen planet at about –18 °C (the temperature of outer atmosphere) [5]. However, any further increase in the concentration of CO_2 from present level will upset the temperature balance and would cause further warming of globe, which may have disastrous consequences. Mauna Loa Observatory (MLO), Hawaii is a premier atmospheric research facility that has been continuously monitoring and collecting data related to atmospheric changes including CO_2 concentration. *'Global warming is the continuing rise in the average temperature of the earth's atmosphere and ocean's surface due to greenhouse effect'.*

Global warming is being caused mainly due to ever-increasing emission of CO_2 because of burning of fossil fuels for energy in industry. Other sources have comparatively lesser contribution. CH_4 and N_2O are produced due to agricultural practices such as application of fertilizer, management of livestock and their manure. Cultivation of rice also produce smaller amount of CH_4. Chlorofluorocarbons (CFCs) are used as refrigerants but they are slowly being phased out. SF_6 are used in certain industries, for example, they are used as insulator and arc-quenching medium in SF_6 circuit breakers in electrical power system industry.

The concentration of CO_2 which was 280 ppm in 1850 has increased to 400 ppm in 2015 with relatively steep rise after 1950. During this period of 150 years the average earth temperature has increased by 0.5–0.8 °C. Historically, CO_2 concentration has varied cyclically a number of times in the past several hundred thousand years but has never crossed 300 ppm. Air bubbles trapped in Antarctic ice preserve an 800,000-year record of atmospheric carbon dioxide levels, which naturally varied cyclically a number of times from about 180 to about 280 ppm.

1.12.5 Consequences of Global Warming: [6, 7, 8]

Global warming is expected to have far-reaching, long-lasting and, in many cases, devastating consequences for planet Earth. The amount of global emission of CO_2 during 2012 is estimated as 31,734 million tons [2].

The effects of global warming are listed below:

- The average global temperature has increased by about 1.4 degrees Fahrenheit (0.8 degrees Celsius) over the past 100 years, according to the National Oceanic and Atmospheric Administration (NOAA).
- Scientists project that extreme weather events, such as heat waves, droughts, blizzards and rainstorms will continue to occur more often and with greater intensity due to global warming. These changes will likely include major shifts in wind patterns, annual precipitation and seasonal temperatures variations.
- One of the most dramatic effects of global warming is melting of polar ice caps. Most analyses project that, within a matter of years, the Arctic Sea will be completely ice-free during the summer months. Mountain Glacial retreat, too, is an obvious effect of global warming. The area of snow cover on land is also decreasing.
- Rise of sea level is another effect of global warming. There are two major processes by which global warming directly affects sea level. The first is thermal expansion of sea water due to temperature rise. Second, as ice melts, the ocean levels rise. Melting polar ice in the Arctic and Antarctic region, coupled with melting ice sheets and glaciers across Greenland, North America, South America, Europe and Asia, are expected to raise sea levels significantly. In 2014, the World Meteorological Organization reported that sea level rise accelerated 0.12 inches (3 millimeters) per year on average worldwide. This is around double the average annual rise of 0.07 in (1.6 mm) in the twentieth century. Global sea levels have risen about 8 inches since 1870. If current trends continue, many coastal areas where roughly half of the Earth's human population lives will be inundated.
- As levels of CO_2 increase, the oceans absorb some of that gas, which increases the acidity of seawater. Since the industrial revolution began in the early 1700s, the acidity of the oceans has increased about 25 per cent. Many marine organisms make shells out of calcium carbonate (corals, oysters), and their shells dissolve in acid solution. Thus as more and more CO_2 gets added to the ocean, it gets more and more acidic, dissolving more and more shells of sea creatures, which is not good for their health. If current ocean acidification trends continue, coral reefs are expected to become increasingly rare in areas where they are now common.
- The effects of global warming on the earth's ecosystems are expected to be profound and widespread. Migratory birds and insects are now arriving in their summer feeding and nesting grounds several days or weeks earlier than they did in the twentieth century. Warmer temperatures will also expand the range of many disease-causing pathogens that were once confined to tropical and subtropical areas, killing off plant and animal species that formerly were protected from disease.
- In addition to less nutritious food, the effect of global warming on human health is also expected to be serious. The American Medical Association has reported an increase in mosquito-borne diseases like malaria and dengue fever, as well as a rise in cases of chronic conditions like asthma, is already occurring, most likely as a direct result of global warming.

- Agricultural systems are likely to have a crippling blow. Though growing seasons in some areas will expand, the combined impacts of drought, severe weather, lack of snowmelt, greater number and diversity of pests, lower groundwater tables and a loss of arable land could cause severe crop failures and livestock shortages worldwide.

1.12.6 Pollution

1. Indoor Pollution

Indoor pollution is mainly caused due to use of conventional *Chulhas* in rural areas. About 5,00,000 children and women die from diseases caused due to indoor air pollution each year. This requires the need of improved household stove (*Chulhas*) to reduce indoor pollution.

2. Outdoor Pollution

Outdoor pollution is mainly caused due to use of fossil fuels. Emissions from fossil fuel based plants degrade the environment and cause various other problems. Coal and oil are more pollutant than gas.

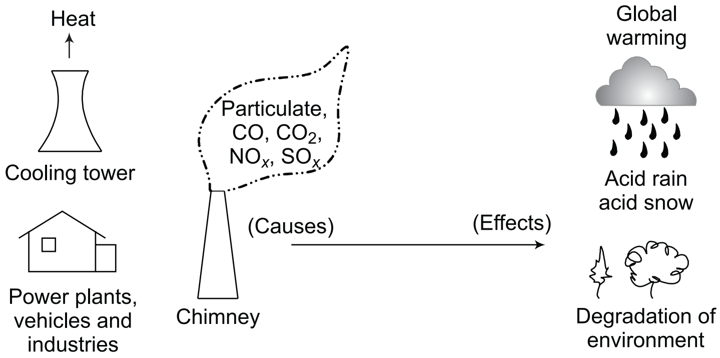


Figure 1.5 Causes and effects of pollution

Remedy

1. Use of fossil fuels should be slowly curtailed and focus should be shifted towards renewable energy sources.
2. Less polluting technologies should be employed for use of fossil fuels, i.e. gasified coal, which is less polluting, should be used instead of solid coal, in power plants.
3. Clean alternative fuels such as hydrogen should be used. Hydrogen is the cleanest fuel and does not cause pollution during power conversion.
4. Electric vehicles or battery-operated vehicles should be used in place of oil fed IC engine based vehicles.

Various Pollutants and Their Harmful Effects

(a) Particulate matter The presence of particulate matter–

- Reduces sunlight
- Reduces visibility

- A level above 100 μg/m^3 (yearly average) results in respiratory problems
- A level above 300 μg/m^3 (yearly average) results in bronchitis[*]

The annual average permissible limit is 75 μg/m^3

(b) Carbon Dioxide (CO_2) Carbon dioxide is ordinarily not considered a toxic gas. It is essential for photosynthesis and production of essential oxygen and organic matter in nature. But increased concentration of CO_2 adversely affects the global climate. Excess emission of CO_2 in the atmosphere causes global warming due to greenhouse effect.

The increasing CO_2 level in the atmosphere is mainly attributed to the following:

(i) Large-scale combustion of fossil fuels in coal fired thermal power plants all over the world.

(ii) Felling of trees on large scale (deforestation) for urbanization, agriculture, industrialization etc. resulting in reduced photosynthesis process.

(c) Carbon Monoxide (CO) CO is formed due to incomplete burning of carbon in inadequate air. It seriously impairs the oxygen dependent tissues in the body particularly, brain, heart and skeleton muscles. CO concentration of 100 ppm causes headache, 500 ppm causes collapse and 1000 ppm is fatal. Smokers inhale CO concentration of 400 to 450 ppm.

(d) Sulphur Oxides (SO_x) SO_x refers to all sulphur oxides, the two major ones being sulphur dioxide (SO_2) and sulphur trioxide (SO_3). The lifespan of sulphur oxides in the atmosphere is from 4 to 10 days. The presence of SO_2 in air is mainly due to manmade reasons involving combustion of fuels containing sulphur. The contribution from various sources is as follows:

(i)	Power plants	70%
(ii)	Industry	15%
(iii)	Motor Vehicles	8%
(iv)	Solid waste disposal	5%
(v)	Others	2%

Sulphur dioxide (SO_2) can further oxidize to form sulphur trioxide (SO_3), which in turn forms sulphuric acid (H_2SO_4) when absorbed in water.

Harmful Effects

(i) Causes respiratory deceases including asthma, irritates eyes and respiratory track

(ii) Causes acid rains, which is harmful to agriculture, forest, vegetation, soil and stones (and thus to buildings)

(iii) Causes corrosion of metals, deterioration of electrical contacts, paper, textile, building stones, etc.

Safe limit is 80 μg/m^3 (annual average).

(e) Nitrogen Oxides (NO_x) NO_x is a generic term for the mono-nitrogen oxides: NO and NO_2 (nitric oxide and nitrogen dioxide). They are produced from the reaction of nitrogen and oxygen gases in the air during combustion, especially at

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[*] *Bronchitis*: inflammation of mucus membrane inside the bronchial tubes, branches of wind pipe).

high temperatures. About 80 per cent of nitrogen oxides in atmosphere are produced due to natural causes (biological reactions) and about 20 per cent due to manmade causes: mostly due to combustion process in air at high temperature. Manmade causes include:

(i)	Motor vehicles	7%
(ii)	Industry	7%
(iii)	Power Plants	4%
(iv)	Solid waste	2%

Harmful effects

(i) Causes respiratory and cardiovascular illness
(ii) Deprives body tissues of oxygen
(iii) Forms acid in lungs and, therefore, more toxic than CO
(Safe limit is 100 $\mu g/m^3$)

1.12.7 Green Power

The term “green power” is used to describe sources of energy which are considered environment friendly, non-polluting; and therefore may provide a remedy to the systemic effects of certain forms of pollution, and global warming. This is in fact the renewable energy sourced from the sun, the wind, water, biomass and waste, etc.

Green energy is commonly thought of in the context of electricity, heating, and cogeneration, and is becoming increasingly available. Consumers, businesses, and organizations may purchase green energy in order to support further development, help reduce the environmental impacts associated with conventional electricity generation, and increase their nation’s energy independence. Renewable energy certificates (green certificates, or green tags) have been one of the ways for consumers and businesses to support green energy.

1.12.8 Amount of Pollutants from Fuel-based Power Plants

Table 1.4 lists the types and amount of pollutants from various fuel-based power plants.

Table 1.4 Amount of pollutants from various fuel-based power plants

Pollutant	Hard coal	Brown coal	Fuel oil	Other oil	Gas
CO_2 (g/GJ)	94,600	101,000	77,400	74,100	56,100
SO_2 (g/GJ)	765	1,361	1,350	228	0.68
NO_x (g/GJ)	292	183	195	129	93.3
CO (g/GJ)	89.1	89.1	15.7	15.7	14.5
Non methane organic compounds (g/GJ)	4.92	7.78	3.70	3.24	1.58
Particulate matter (g/GJ)	1,203	3,254	16	1.91	0.1
Flue gas volume, total (m^3/GJ)	360	444	279	276	272

1.13 THE UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE (UNFCCC)

Global environmental degradation is one of the most serious threats facing mankind as a result of the expansion of its activities around the globe. One of the international responses to global environmental problems is the United Nations Framework Convention on Climate Change (UNFCCC). This is an international environmental treaty (currently the only international climate policy venue with broad legitimacy, due in part to its virtually universal membership) negotiated at the United Nations Conference on Environment and Development (UNCED), informally known as the *Earth Summit*, held in Rio de Janeiro from 3 to 14 June 1992. The objective of the treaty is to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". The treaty itself set no binding limits on greenhouse gas emissions for individual countries and contains no enforcement mechanisms. In that sense, the treaty is considered legally non-binding. Instead, the treaty provides a framework for negotiating specific international treaties (called "protocols") that may set binding limits on greenhouse gases. The UNFCCC was adopted on 9 May 1992. It entered into force on 21 March 1994. As of March 2014, UNFCCC has 196 parties.

The parties to the convention have met annually from 1995 in Conferences of the Parties (COP) to assess progress in dealing with climate change. In 1997, the Kyoto Protocol was concluded and established legally binding obligations for developed countries to reduce their greenhouse gas emissions. The 2010 Cancun agreements state that future global warming should be limited to below 2.0°C (3.6°F) relative to the pre-industrial level. The 20th COP took place in Peru in 2014.

Example 1.3

(i) Determine the amount of CO_2 produced in burning of one kg of Brown Coal (lignite) and the amount of carbon added in atmosphere. (ii) Also calculate the amount of CO_2 and carbon added in atmosphere while producing 1 kWh (1 unit) of electricity from Brown Coal fed thermal plant. The efficiency of the plant (turbine + generator) may be assumed as 25%.

Solution

(i) From Table 1.2, the heating value of Brown Coal (lignite) is 16 MJ/kg
i.e. heat available from burning of 1 kg of Brown Coal = 16 MJ
From Table 1.4, the CO_2 produced in burning of Brown Coal
= 101,000 g/GJ (which is 0.101 kg/MJ)
i.e. 1 MJ of energy from Brown Coal produces 0.101 kg of CO_2
16 MJ of energy from Brown Coal produces 16 × 0.101 = 1.616 kg of CO_2
Therefore, burning of 1 kg of Brown Coal adds 1.616 kg of CO_2 in the atmosphere
As (12/44) is the carbon to CO_2 molecular weight ratio, the amount of carbon added in the atmosphere = 1.616 kg × (12/44) = 0.4407 kg

(ii) One Unit of electricity output = 1 kWh = 3.6 MJ
Efficiency of the thermal plant = 25%

To produce 1 kWh of electricity, the required input energy of the thermal plant = 3.6/0.25 = 14.4 MJ
The required Brown Coal = 14.4 / 16 = 0.9 kg
The amount of CO_2 added into atmosphere in producing 1 kWh of electricity = 0.9 × 1.6.6 = 1.45 kg
The amount of carbon added into the atmosphere = 1.45 kg × (12/44)
= 0.3966 kg

1.14 ENERGY-ENVIRONMENT-ECONOMY

Environmental degradation cannot be singled out as an independent matter among various global issues. Also important are the interactions among economic development, stable energy supplies, and global environmental conservation. In the next few decades fossil fuels will continue to be the principal source of energy driving economic development. The source of fossil fuels is stable and their extraction is affordable. Attempts to restrict the use of fossil fuels for environmental reasons are likely to have a negative impact on economic development and the overall availability of energy. Thus the "three Es" - environment, energy, and economic development are closely interrelated in a complex manner.

The strategy for mitigating "three Es" issues is a strategy for environmentally sustainable economic development. Herman Daly, a famous ecological economist laid down three conditions for sustainability:

1. The consumption rate of renewable resources is not higher than its recovery rate.
2. The consumption rate of non-renewable resources is not higher than the rate of increase in renewable resource supply.
3. The emission of pollutants is within the absorption capacity of the environment.

Unfortunately these conditions have been violated for years. Examples of respective violations typically include deforestation, the depletion of fossil fuels, and the increase in CO_2 concentration in the air. Such violations may be hard to reverse in the short term but, unless long-term remedial actions are taken, present global development trends will not be sustainable. In particular, a substantial reduction in resource consumption and emissions of pollutants is essential for the development of a sustainable human society on this planet.

As evident from the above discussions, the Economy, Environment and Energy are closely interrelated and an overall policy is required to deal with them.

1.15 WORLD ENERGY STATUS

1.15.1 Present Situation

The world annual primary energy supply and consumption along with electricity generation are given in Table 1.5. The primary energy supply differs from the final energy consumption because much of the energy that is acquired by humans is lost as other forms of energy during the process of its refinement into usable forms of energy and its transport from its initial place of supply to consumers. In 2012, the world annual primary energy consumption was 8,979 MTOE. Fossil fuels roughly provide about 82 per cent of this energy and will continue to provide more than 80 per cent of the total energy demand well into the future. Approximately 28 per cent of this energy is consumed in transportation sector and remaining 72 per cent by industries, domestic, agriculture and social consumers.

The energy demand has grown astronomically in recent years – with primary energy demand increasing by more than 50 per cent since 1973. This growth is forecast to continue at an annual average rate of 2.2 per cent during 2004–2030. Over 70 per cent of this growth will come from developing countries.

Table 1.5 The world primary energy supply, consumption and electricity generation [2]

Year	Primary energy supply (TPES) (MTOE)	Final energy consumption (MTOE)	Electricity generation (TWh)
1973	6,106	4,672	6,129
2012	13,371	8,979	22,668

1.15.2 Availability of Resources and Future Trend

1. Conventional Sources

(a) Fossil Fuels Fossil fuels include coal, oil and gas. These fuels are major source of energy since about 1850, the start of industrial era. Fossil fuels are so called because these are in fact the fossils of old biological life that once existed on the surface of earth. It is formed in several parts of earth at varying depths, during several million years by slow decomposition and chemical actions of buried organic matter under favourable pressure, heat and bacterial marine environment.

Coal Despite its poor environmental credentials, coal remains a crucial contributor to energy supply in many countries. Coal's dominant position in the global energy mix is largely due to the fact that it is abundant, widely distributed across the globe and affordable. Coal is the most widespread fossil fuel around the world, found in about 75 countries and actively mined in 50 countries. The future of coal depends primarily on the advance of clean coal technologies to mitigate environmental risk factors, CO_2 emissions, in particular. It is the world's largest source of electricity, accounting for around 40 per cent of global electricity production. World present (year 2013) proved reserves of coal is estimated as 8, 91,530 MT, which based on current production rates should last for around 115 years. The annual production and proved reserves of few top coal producing countries is given in Table 1.6.

Oil Oil is a premier energy source with a wide range of possible applications. Its main use however, will be shifting towards transport and the petrochemical sector. The annual production and proven reserves of few top oil producing countries are given in Table 1.7.

Table 1.6 Status of few top coal producing countries (year 2013 data) [2]

S.N.	Country	Proved Reserve in Million Tons (MT)	Annual Production	
			(MT)	(%age of world total)
1.	China	1,14,500	3,561	45.5
2.	USA	2,37,295	904	11.6
3.	India	60,600	613	7.8
4.	Indonesia	28,017	489	6.3
5.	Australia	76,400	459	5.9
6.	Russian federation	1,57,010	347	4.4
7.	World	8,91,530	7,823	100

Table 1.7 Status of few top oil producing countries (year 2013 data) [2]

S.N.	Country	Proven Recoverable Reserve in Million Tons (MT)	Annual Production	
			(MT)	(%age of world total)
	Saudi Arabia	36,500	540	13.1
	Russian federation	8,184	525	12.8
	USA	4,215	440	10.7
	China	2,783	208	5.1
	Canada	23,598	193	4.7
	Kuwait	13,845	165	4.0
	Venezuela	40,450	155	3.8
	UAE	40,450	153	3.7
	Iraq	19,300	153	3.7
	Iran	21,359	151	3.7
	World	2,23,454	4,177	100

Apart from the above-mentioned conventional oil resource other possible future unconventional oil resources are "Oil shale" and "Tar sands". These are cross-linked chain of hydrocarbons. (A **cross-link** is a bond that links one polymer chain to another. They can be covalent bonds or ionic bonds).

Oil shale refers to "Kerogen" a solid form of petroleum. When oil shale is heated, the kerogen decomposes and gives crude oil. The distillation of crude oil from oil shale is not economical so far. The world's estimate of crude oil from oil shale is about (2800 to 3300) × 10^9 barrels with largest reserves in USA.

Tar sands (oil sands or bituminous sands) are loose sand or partially consolidated sandstone containing naturally occurring mixtures of sand, clay, and water, saturated with a dense and extremely viscous form of petroleum referred to as bitumen or tar due to its similar appearance, odour and colour. Synthetic crude oil can be obtained from tar sand. The world's total estimated reserve of crude oil from tar sand is about 249.67×10^9 barrels, out of which 70.0 per cent are located in Canada. Recently, new technology has enabled profitable extraction of petroleum from tar sands.

If the unconventional oil resources, including oil shale and oil sands, etc. are taken into account, the global oil reserves will be four times larger than the current conventional reserves.

Gas The cleanest of all fossil-based fuels, natural gas is plentiful and flexible. It is increasingly used in the most efficient power generation technologies, such as, Combined Cycle Gas Turbine (CCGT) with conversion efficiencies of about 60 per cent. The reserves of conventional natural gas have grown by 36 per cent over the past two decades and its production by 61 per cent. The exploration, development and transport of gas usually require significant upfront investment. Close coordination between investment in the gas and power infrastructure is necessary. The annual production and proved reserves of few top gas producing countries is given in Table 1.8.

Table 1.8 Status of few top gas producing countries (year 2013 data) [2]

S.N.	Country	Proven Recoverable Reserve in Billion Cubic Meters (bcm)	Annual Production	
			(bcm)	(%age of world total)
1.	USA	7,716	689	19.8
2.	Russian federation	47,750	671	19.3
3.	Qatar	25,200	161	4.6
4.	Iran	33,790	159	4.6
5.	Canada	1,982	155	4.5
6.	China	3,030	115	3.3
7.	Norway	2,007	109	3.1
8.	Netherland	1,303	86	2.5
9.	Saudi Arabia	8,028	84	2.4
10.	Algeria	4,502	80	2.3
11.	Turkmenistan	25,213	75	2.1
12.	World	2,09,741	3,479	100

There are four main categories of unconventional natural gas: shale gas, coalbed methane, gas from tight sandstones ('tight gas') and the least well-known methane hydrates.

Shale gas refers to natural gas that is trapped within shale formations. Shales are fine-grained sedimentary rocks that can be rich resources of petroleum and natural gas. Shale gas is not a "new" energy resource. The first commercial gas well in the USA, drilled in New York State in 1821 was in fact a shale gas well. Over the years, limited amounts of gas were produced from shale formations, until the recent "Shale Gas Revolution" changed the natural gas scene, first in the United States and subsequently in other countries around the globe. It is believed that the total shale gas resource base is both large and wide-spread around the world. However, this potential resource has not yet been quantified on a national level in the majority of countries. The most credible studies put the global shale gas resource endowment at about 16,110 tcf (456 tcm). It is assumed that nearly 40 per cent of this endowment would be eventually recoverable. The United States and the CIS (Commonwealth of Independent States) countries together account for over 60 per cent of the total estimate.

Coalbed methane (also known as colliery gas or coal seam gas) is present in some coal seams. It can be found in absorbed form within the coal matrix or unabsorbed in gaseous pockets. The gas generally lacks hydrogen sulphide but has a potentially higher level of carbon dioxide than natural gas. This resource is usually found at depths of 300–2000 metres below ground.

Tight gas refers to natural gas deposits which are particularly difficult to access from a geological viewpoint. Contained in rocks with very low permeability in deep formation, and is typically deeper than 4500m. Extraction of this gas would require a combination of extraction processes such as the hydraulic fracturing and horizontal drilling.

Methane Hydrate is a solid clathrate compound in which a large amount of methane is trapped within a crystal structure of water, forming a solid similar to ice. Methane hydrate is found in extensive seams under deep water in various parts of the world. A recent academic assessment of gas hydrates calculates the amount of gas hydrates in resource-grade deposits to be at least one third more than 2010 estimates of global natural gas reserves.

(b) Hydro Resources Among all renewables, hydropower is the most advanced and flexible source of power. It is a well-developed and established source of electric power. The early generation of electricity from about 1880 often derived from hydro turbines. A number of large and medium sized hydro schemes have been developed. Due to requirement of huge capital investment and strong environmental concerns about large plants, only about one third of the realistic potential has been taped so far. Hydro installations and plants are long lasting (turbine life is about 50 years). This is due to continuous steady operation without high temperature or other stresses. Therefore, it often produces electricity at low cost with consequent economic benefits.

The global installed (2012 data) generating capacity of hydro power is about 1,025 GW, which produces about 16.5 per cent of the world's total electrical energy.[2] Eight countries make up more than two third of the world's hydropower production. These are listed in Table 1.9 along with their installed capacities. Biggest Hydro plant is located at "Three Gorges" in China with capacity of 22.5 GW. Norway derives 96.7 per cent of its required electric power from hydro resources.

Table 1.9 Status of few top hydroelectricity producing countries (year 2012 data) [2]

S.N.	Country	Installed generating capacity (GW)	Annual Production	
			(TWh)	(%age of world total)
1.	China	194	872	23.2
2.	Brazil	84	415	11.1
3.	Canada	76	381	10.1
4.	USA	101	298	7.9
5.	Russian federation	49	167	4.5
6.	Norway	30	143	3.8
7.	India	40	126	3.4
8.	Japan	49	84	2.2
9.	World	1,025	3756	100

(c) Nuclear Resources U^{235}, U^{233} (isotopes of uranium) and Pu^{239} (plutonium) are used as nuclear fuels in nuclear reactors (thermal reactors) and are known as fissile (or fissionable) materials. Out of these, only U^{235} occurs in nature. U^{233} and Pu^{239} are produced from Th^{232} (thorium) and U^{238} respectively in fast breeder reactors (FBRs). Th^{232} and U^{238} are known as fertile materials. Natural Uranium contains 0.71 per cent of U^{235} and 99.29 per cent of U^{238}.

Uranium reserves in the world are small and its recovery is expensive. Concentrated deposits of Uranium are not available. The content of natural Uranium in Uranium ore is about 0.1–0.5 per cent. Major available sources of Uranium are in Australia, Canada, and Kazakhstan and to a lesser extent the USA. There are also a large number of smaller low grade sites. Thorium reserves are expected to be more than those of uranium.

Nuclear power is the least-cost, low-emission technology that can provide base-load power. The nuclear industry has a relatively short history. The first nuclear reactor in the world was commissioned in the Former Soviet Union's Obninsk in 1954. As in year 2012 there are around 427 nuclear power plants in the world, operating in 31 countries producing 10.9 per cent world's electricity. France produces 76.1 per cent of its total electrical power by nuclear means. Nuclear energy policy differs between European Union and some other countries, such as Austria and Ireland, which have no active nuclear power stations. The annual production and installed generating capacity of few top nuclear power producing countries is given in Table 1.10.

Presently, most commercial reactors are thermal reactors. Fast Breeder Reactors (FBRs) utilize fast neutrons and generate more fissile material than they consume. They generate energy as well as convert fertile material (U^{238}, Th^{232}) into fissile material (Pu^{239} and U^{233} respectively). The breeder technology is not yet commercially developed. Main problem being their slow breeding rate and therefore long doubling time (the time required by an FBR to produce sufficient fissile material, to fuel a second, identical reactor) of around 25 years. With continuing R & D efforts in this direction, it is hoped that by 2050, FBRs will be the main source of power after overcoming the present difficulties.

Table 1.10 Status of few top nuclear power producing countries (year 2012 data) [2]

S.N.	Country	Installed generating capacity (GW)	Annual Production	
			(TWh)	(%age of world total)
1.	USA	102	801	32.5
2.	France	63	425	17.3
3.	Russian federation	24	178	7.2
4.	Korea	21	150	6.1
5.	Germany	12	99	4
6.	China	13	97	3.9
7.	Canada	14	95	3.9
8.	Ukraine	13	90	3.7
9.	U. K.	9.3	70	2.8
10.	Sweden	9	64	2.4
11.	World	373	2461	100

Nuclear fusion reaction has a lot more potential and vast resources are available. However, controlled fusion reaction has not been achieved yet. It is predicted that by year 2500 some breakthrough will take place in fusion technology and once this happens, nuclear fusion reaction will be the main source of energy on earth.

2. Non-conventional Sources

Non-conventional technologies are presently under development stage. At present its share is very small.

(a) Solar Energy Solar energy can be major source of power and can be harnessed by using thermal and photovoltaic conversion systems. Maximum solar radiation received on the surface of earth, normal to it, on bright sunny day, at noon is approximately 1 kW/m^2, at sea level. The earth continuously intercepts solar power of 178 billion MW, which is about 10,000 times the world's demand. But so far it could not be developed on a large scale. According to one estimate, if all the buildings of the world are covered with solar PV panel, it can fulfill electrical power requirements of the world.

Solar PV power is considered as an expensive source of power. However, the prices are decreasing steadily. The price of SPV system has dropped from USD 10 per W in year 2000 to USD 3 per W in year 2013 [10] The use of solar energy is growing strongly around the world, in part due to the rapidly declining solar panel manufacturing costs. The Installed SPV generating capacity of top few countries is given in Table 1.11.

Table 1.11 Status (year 2014 end) of few top solar PV installed capacity countries [11]

S.N.	Country	Installed generating capacity (GW)
1.	Germany	38.2
2.	China	28.1
3.	Japan	23.3
4.	Italy	18.5
5.	USA	18.3
6.	France	5.7
7.	Spain	5.4
8.	UK	5.1
9.	Australia	4.1
10.	Belgium	3.1
11.	India	2.9
12.	World	198.3

(b) Wind Energy The power available in the winds over the earth surface is estimated to be 1.6×10^7 MW, which is more than the present energy requirement of the world. Wind power has emerged as the most economical of all renewable energy sources. The installation cost of wind power is ₹ 4 crore / MW (which is comparable to that of conventional thermal plants). There has been remarkable growth of wind power installation in the world. Wind power generation is the fastest growing energy source. The installed wind power and annual electricity generation of top few countries is given in Table 1.12. China, with about 114.6 GW, has the highest installed capacity while Denmark, with over 4.8 GW, has the highest level per capita. Wind accounts for about 39 per cent of Denmark's electricity production.

Table 1.12 Status of few top wind power producing countries (year 2014 end data) [12]

S.N.	Country	Installed generating capacity (GW)
1.	China	114.6
2.	USA	65.9
3.	Germany	39.2
4.	Spain	23
5.	India	22.5
6.	U. K.	12.8
7.	Canada	9.7
8.	France	9.3
9.	Italy	8.7
10.	Brazil	5.9
11.	World	371

(c) Biomass Energy Energy resources available from animal and vegetation are called biomass energy resources. Historically, humans have harnessed biomass-derived energy since the time when people began burning wood to make fire. Even today, biomass is the only source of fuel for domestic use in many developing countries. This is an important resource for developing countries, especially in rural areas. The principal biomass resources are:

- Trees (wood, leaves and forest industry waste)
- Cultivated plants grown for energy
- Algae and other vegetation from ocean and lake
- Urban waste (municipal and industrial waste)
- Rural waste (agricultural and animal waste, crop residue, etc.)

Solar energy absorbed by plants (through photosynthesis process) is estimated to be 2×10^{21} J / Year. Biomass material may be transformed by chemical or biological processes to other usable intermediate bio-fuels such as biogas (methane), producer gas, ethanol, biodiesel and charcoal etc. At present there are millions of biogas plants, in the world, most of them are located in China.

(d) Geothermal Energy Geothermal energy comes from the natural heat of the Earth primarily due to the decay of the naturally radioactive isotopes of uranium, thorium and potassium. Geothermal energy is derived from huge amount of stored thermal energy in the interior of earth. However, its economic recovery on the surface of the earth is not feasible everywhere. Its overall contribution in total energy requirement is negligible. However, it is a very important resource locally. Of the countries utilising their geothermal resource, almost all use it directly but only 24 use it for electricity generation. At end-2012, approximately 1,1490 MWe of geothermal electricity generating capacity was installed, producing over 68,630 GWh/yr. Installed capacity for direct heat utilisation amounted to about 50,000 MWt, with an annual output of around 4,30,000 TJ (equivalent to about 1,20,000 GWh). The annual growth in energy output over the past five years has been 3.8 per cent for electricity production and around 10 per cent for direct use (including geothermal heat pumps). The countries with the largest installed capacity were the USA, China, Sweden and Germany, accounting for about 63 per cent of the installed capacity and the five countries with the largest annual energy use were: China, USA, Sweden, Turkey and Japan, accounting for 55% of the world use. The oldest geothermal power generator is located at Lordarello in Italy, commissioned in 1904. The installed capacity and annual outputs in respect of electricity generation and direct use, respectively for top few countries is given in Table 1.13.

Table 1.13 The Installed capacity and annual outputs in respect of electricity and direct use for top few countries from geothermal resource (year 2011) [9]

S.N.	Country	Electricity Generation		Direct Use	
		Installed capacity, MW	Annual output, GWh	Installed capacity, MW	Annual output, TJ
1.	USA	3,101	15,009	12,611	56,551
2.	China	242	125	8,898	75,348
3.	Sweden	-	-	4,460	45,301
4.	Norway	-	-	1,000	-
5.	Germany	7.3	18.8	3,485	12,764
6.	Japan	537.7	2,632	2,099	25,697
7.	Turkey	114.2	616.7	2,084	36,885.9
8.	Italy	772	5,754	1,000	12,599.5

(e) Ocean Tidal Energy Tidal energy is a form of hydropower that converts energy of tides into electricity or other useful forms of power. Although not yet widely used, tidal power has potential for future electricity generation. Tides are more predictable than wind energy and solar power. It is in developing stage. There are at present only few operational tidal power plants. The first and the biggest 240 MW tidal plant was built in 1966 in France at the mouth of La Rance river, near St. Malo on the Brittany coast. A 20 MW tidal plant is located at Nova Scotia, Canada and a 400 kW capacity plant is located at Kislaya Guba, near Murmansk, Russia on the Barents Sea. Many sites have been identified in USA, Argentina, Europe, India and China for development of tidal power.

(f) Ocean Wave Energy Wave power refers to the energy of ocean surface waves and the capture of that energy to do useful work. Good wave power locations have a flux of about 50 kilowatts per meter of shoreline. As per an estimate, the potential for shoreline-based wave power is about 50,000 MW. Deep-water wave power resources are truly enormous, but perhaps impractical to capture. The worldwide resource of wave energy has been estimated to be greater than 2 TW.

(g) Ocean Thermal Energy Conversion OTEC technology is in infant stage. Conceptual designs of small OTEC plants have been finalized. Their commercial prospects are quite uncertain. The potential is likely to be more than that of tidal or wave energy. The resource potential for OTEC is considered to be much larger than for other ocean energy forms. Up to 88,000 TWh/yr of power could be generated from OTEC without affecting the ocean's thermal structure. While OTEC technology has been demonstrated in the ocean for many years, the engineering and commercial challenges have constrained the development of the technology.

1.16 ENERGY SCENARIO IN INDIA

1. Overall Production and Consumption (2012–13 Data) [2,15]

India is both a major energy producer and consumer. India currently ranks as the world's 5th largest energy producer after China, USA, Russian Federation and Saudi Arabia, accounting for about 4 per cent of the world's total annual energy production. Also it is the world's 4th largest energy consumer trailing China, USA and Russian Federation and accounting for 5.9 per cent of the world's total annual energy consumption. Thus India is a net energy importer, mostly due to large imbalance between oil production and consumption. The production and consumption of primary energy for top few countries are listed in Table 1.14. The per capita primary energy consumption is 637 KGOE for India, whereas the world average per capita primary energy consumption is 1,919 KGOE (2012 end data) [2].

Table 1.14 Production and consumption of primary energy for top few countries

S.N.	Country	Production (MTOE)	Consumption (MTOE)
1.	China	2,525	2,852
2.	USA	1,806	2,265
3.	Russian Federation	1,331	699
4.	Saudi Arabia	625	*
5.	India	544	595

*228 MTOE

2. Electrical Power Generation [13]

The present total installed electricity generating capacity in India is 2, 75,911 MW (as on July 31, 2015), from various resources as given in Table 1.15. During calendar year 2014, power sector has registered an annual growth rate of 10 per cent.

Table 1.15 Installed Electrical power generating capacity, as on July 31, 2015 [13]

Resource	Production (MW)	Percentage share
Thermal:	Total thermal = 1,91,663	Total thermal = 69.5 %
Coal	1,67,708	60.7 %
Gas	22,962	8.3 %
Diesel	993	0.36 %
Nuclear	5,780	2.1 %
Hydro	41,997	15.2 %
*Renewable Energy Sources (excluding large hydro)	Total RES = 36,470	Total RES = 13.2 %
Total	2,75,911	100 %

*Renewable Energy Sources, (in MW)

Small hydro ≤ 25 MW	Wind	Bio-power		Solar	Total Capacity
		Biomass power/cogen.	Waste to energy		
4101.5	23,762	4418.5	127	4060.6	36,470

The distribution of this total installed capacity in various sectors is given in Table 1.16.

Table 1.16 Sector wise distribution of installed capacity

S.N.	Ownership / Sector	Inst. Capacity in GW
1.	State	96
2.	Private	106
3.	Central	73.7
4.	Total	276

1.16.1 Availability of Primary Energy Resources

1. Conventional

(a) Fossil Fuel India has vast reserves of coal, 5th largest in the world after the USA, Russia, China and Australia. According to a rough estimate, total recoverable coal in India is 60,600 million tons, about 6.8 per cent of world's total. Our coal production is not enough to meet the growing consumption. Net coal import dependency has risen from a negligible percentage in 1990 to nearly 23 per cent in 2014. Indian coal has high ash content (25–50 per cent), low heat value (3000–4000 kcal/kg) and low sulfur content (1 per cent). We have very little oil and gas reserves. The estimated reserve of crude oil is 762 MT, which is 0.34 per cent of global oil reserves. Likewise the estimated reserve of Natural gas is 1427 bcm, which is 0.68 per cent of global gas reserves. Oil and gas reserves are insufficient even for transportation sector. India at present imports 75 per cent of oil and 25 per cent of its natural gas needs [3]. The domestic production is decreasing slowly. Largest consumer of natural gas is fertilizer industry followed by power industry.

(b) Hydro Resources India stands 7th in the list of nations with hydro resources. Total potential is 100,000 MW. Approximately 41,997 MW has been developed (as on July 31, 2015)[13]. Huge installation cost, environmental and social problems are major difficulties in its development. Also, 56 sites for pumped storage schemes with an aggregate installed capacity of 94,000 MW have been identified.

(c) Nuclear Resources India has modest (1 to 2 per cent of global) reserves of Uranium, mostly located at Jadugoda, Jharkhand. There are 21 nuclear reactors at 7 plants located at Narora, Rawatbhatta, Kakrapar, Kaiga, Kalpakkam, Kudanulam and Trombay (18 PHWR, 2BWR and 1 VVER). Present, nuclear power installed capacity is 5,780 MW, which is 2.1 per cent of total installed electricity generating capacity. (as on July 31, 2015)[13]. There are six reactors totaling 4,300 MW under construction in Tamil Nadu, Gujarat and Rajasthan. India now envisages to increase

the contribution of nuclear power to overall electricity generation capacity from 2.1 per cent to 9 per cent within 25 years. By 2020, India's installed nuclear power generation capacity is expected to increase to 20 GW.

Thorium is available in abundance in India in the form of Monazite (ore) in sand beaches of Kerala. The reserve of thorium in India is estimated at 3,00,000 tonnes, which is 25 per cent of world's thorium reserves (as per IAEA, International Atomic Energy Agency estimate). Some other estimates claim much higher than this amount. Thorium is a fertile material, which is converted into a fissionable material U^{233} in a Fast Breeder Reactor (FBR). The U^{233} so obtained may be used in a normal thermal reactor such as PHWR. The Government has established a research facility IGCAR (Indira Gandhi Center for Atomic Research) way back in 1971 at Kalpakkam, Tamil Nadu for development of the nuclear energy technology.

The founder of country's atomic energy program Dr. Homi Jehangir Bhabha outlined a three-stage program as back as 1955.

Stage 1: In the first stage, Pressurized Heavy Water Reactors (PHWRs) using natural uranium (mixture of 0.7 per cent U^{235} and 99.23 per cent U^{238}) as fuel and heavy water both as coolant as well as moderator, would be set up. A PHWR is a thermal reactor that consumes only U^{235} part of the natural uranium and mostly U^{238} is left as spent fuel.

Stage 2: The second stage envisages the construction of FBRs, which will use spent fuel (also known as depleted uranium) of the PHWRs, i.e., U^{238} and convert it to fissionable material, plutonium^{239}. The plutonium^{239} thus obtained will be used as fuel in a thermal reactor.

Stage 3: In the third stage thorium^{232} will be converted to U^{233} in a Fast Breeder Reactor. The U^{233} will then be used as fuel in a thermal reactor.

The energy generated in second stage is 60 times more than that available from PHWR by same amount of natural uranium, as in this stage uranium is fully utilized. However, in the first stage only U^{235} part, which accounts for 0.7 per cent in the natural uranium, is utilized.

India has mastered the technology of first stage with 21 commercial plants functioning in the country to date. However, the available natural uranium can support the generation of only 12,000 MW_e from PHWRs. But with FBRs that uses plutonium, we can generate 3,50,000 MW_e, which is a massive amount.

The stage 2 reactor has attained criticality in 1985 at Kalpakkam (in FBTR, 'Fast Breeder Test Reactor'), making India the seventh nation to have the technology to build and operate a breeder reactor after United States, UK, France, Japan, Germany, and Russia. The FBTR has rarely operated at its designed capacity and had to be shut down between 1987 and 1989 due to technical problems. Construction work for a more advanced 500 MW_e Prototype Fast Breeder Reactor (PFBR) has begun from 2002 at Kalpakkam and it is expected to reach criticality in late 2015. R & D work on stage 3 reactor, which will utilize thorium, is also going on at IGCAR, Kalpakkam. According to Government of India plan, 30 per cent of the Indian electricity in 2050 will be generated from thorium-based reactors.

2. Non-conventional

Located in the tropical region, India is endowed with abundant renewable energy, i.e., solar, wind and biomass including agricultural residue which are perennial in nature. Harnessing these resources is best suited to meet the energy requirement in rural areas in a decentralized manner. India has potential of generating more than 900 GW (assuming 3 per cent wasteland is made available) from commercially exploitable renewable energy resources. Up to July 31, 2015, the electrical power generation by non-conventional resource has reached 36,642.7 MW, which is about 13.2 per cent of total installed electrical power generation capacity. India aims to install 60 GW of wind power capacity and 100 GW of solar power capacity by 2022. The current status (as on 31.07. 2015) of various resources are given in Table 1.17:

Table 1.17 Status of renewable energy sources (as on 31.07. 2015)[14]

S. N.	Source / system	Estimated potential	Cumulative achievement (till 31.07.2015)
A. Grid interactive renewable power			
1.	Wind power	100 GW	23,864.9 MW
2.	Small hydro power (up to 25 MW)	20 GW	4,130.5 MW
3.	Biomass gasification (agro residue) / Cogeneration - bagasse	25 GW	4,418.5 MW
4.	Waste to energy (urban and industrial)	-	127 MW
5.	Solar power	750 GW	4,101.6 MW
Total		900 GW	36,642.7 MW
B. Captive / CHP* / Distributed renewable power			
6.	Biomass / cogeneration (non-bagasse)	-	602.3 MW
7.	Biomass gasifier Rural Industrial	-	 17.95 MW 152 MW
8.	Waste to energy	-	146.5 MW
9.	Aero generator / hybrid system	-	2.6 MW
10.	SPV system	-	234.35 MW
11	Water mills / micro hydro	-	17.2 MW
Total			1,173.1 MW
C. Other renewable energy systems			
12.	Family biogas plants (Numbers in Lakhs)	-	48.22
13.	Solar Water Heating – Collector Areas (million m^2)	-	8.9

*CHP: Combined heat and power

(a) Wind Energy The wind power program in India was initiated in 1983–84. The highly successful India's wind power programme is entirely market driven. This sector has been growing very fast for the last few years. India currently (year 2015) stands 5th in the world among countries having large installed capacity wind generators, after China, USA, Germany and Spain. Current (July 31, 2015) installed capacity for wind power stands at 23,864.9 MW, mostly located in Tamil Nadu, Gujrat, Maharashtra and Rajasthan.

(b) Solar Energy India, receives solar energy equivalent to more than 5,000 trillion kWh per year, which is far more than its total annual consumption. The average daily global radiation is around 5 kWh per sq. m per day with the sunshine ranging between 2300 and 3200 hours per year in most parts of India. Though the energy density is low and the availability is not continuous, it has now become possible to harness this abundantly available energy very reliably for many purposes by converting it to usable heat or through direct generation of electricity. The conversion systems are modular in nature and can be appropriately used for decentralized applications.

Ministry of New and Renewable Energy (MNRE) had launched a program on "Development of Solar Cities" in February 2008. The programme has been modified / revised on January 2014 for implementation during the 12th Five Year Plan. The Solar City aims at minimum 10 per cent reduction in projected demand of conventional energy at the end of five years, which can be achieved through a combination of energy efficiency measures and enhancing supply from renewable energy sources in the City.

The "Development of Solar Cities" programme is designed to support/encourage Urban Local Bodies to prepare a Road Map to guide their cities in becoming 'renewable energy cities' or 'solar cities'. A total of 60 cities / towns are proposed to be supported for development as "Solar / Green Cities". At least one city in each State to a maximum of seven cities in a State may be supported by the Ministry.

The Ministry has already initiated various programmes in the Urban Sector for promoting solar water heating systems in homes, hotels, hostels, hospitals and industry; deployment of SPV systems/devices in urban areas for demonstration and awareness creation; establishment of 'Akshya Urja Shops'; design of Solar Buildings and promoting urban and industrial waste/ biomass to energy projects. The solar city programme aims to consolidate all the efforts of the Ministry in the Urban Sector and address the energy problem of the urban areas in a holistic manner.

(c) Biomass Energy A large quantity of biomass is available in our country in the form of dry waste like agro residues, fuel wood, twigs etc. and wet wastes like cattle dung, organic effluents, sugarcane bagasse, banana stem etc. Potential for generation of electric power/cogeneration is 25 GW from agro residue and bagasse. The potential from urban waste is 1,700 MW. Also there is vast scope for production of bio diesel. The biodiesel producing plants require little care, can be grown on fallow land and can survive in harsh climatic conditions. Energy farming may be adopted in marginal and infertile land of the country.

(d) Small Hydro Resources Hydro resources of capacity less than 25 MW are called small, less than 1 MW are called mini and less than 100 kW are called micro hydro resources. Total potential is 20 GW out of which 4,130 MW has been realized.

(e) Geothermal Energy Potential in geothermal resource in the country is 10,600 MW of electric power generation. As a result of various resource assessment studies/surveys, nearly 350 potential hot springs have been identified throughout the country. Most of them are low temperature hot water resources and can best be utilized for direct thermal applications. The surface temperature of the hot springs ranges from 35 °C to as much as 98 °C. (the reservoir temperature is higher than surface temperature). Only some of them can be considered suitable for electrical power generation.

These springs are grouped into seven geothermal provinces, i.e., Himalayan (Puga, Chhumathang), Sahara Valley, Cambay Basin, Son-Narmada-Tapi (SONATA) lineament belt, West Coast, Godavari basin and Mahanadi basin. Some of the prominent geothermal resources include Puga Valley and Chhumathang in Jammu and Kashmir, Manikaran in Himachal Pradesh, Jalgaon in Maharashtra and Tapovan in Uttarakhand. A new location of geothermal power energy has also been found in Tattapani in Chhattisgarh. In addition, Gujarat is set to tap geothermal electricity through resources which are available in Cambay between Narmada and Tapi river.

A 300 kW demonstration electric power production plant is being installed at Tattapani. Geothermal resource is being used mostly for heating purpose and very little has been developed. Total thermal installed capacity is 203 MW and direct thermal use is 446 GWh/year.

(f) Ocean Energy Oceans cover 70 per cent of the earth's surface and represent an enormous amount of energy in the form of wave, tidal, marine current and thermal gradient. The energy potential of our seas and oceans well exceeds our present energy needs. India has a long coastline with the estuaries and gulfs where tides are strong enough to move turbines for electrical power generation. A variety of different technologies are currently under development throughout the world to harness this energy in all its forms including waves (40,000 MW), tides (9000 MW) and thermal gradients (180,000 MW). Deployment is currently limited but the sector has the potential to grow, fueling economic growth, reduction of carbon footprint [14].

Ocean Tidal Energy There is no functional tidal plant at present. The identified economic tidal power potential has been estimated as 8,000–9,000 MW. Three sites have been identified for development of tidal energy.

(a) Gulf of Kutch: potential = 1200 MW
(b) Gulf of Cambay (Khambat): Potential = 7,000 MW
(c) Sundarbans: potential = 100 MW

The ministry of non-conventional energy sources has sponsored the preparation of a feasibility report by the West Bengal Renewable Energy Development Agency (WBREDA) to set up a 3.75 MW capacity demonstration tidal power plant at Durgaduani Creek in the Sunderbans area of West Bengal.

Ocean Wave and OTEC Resources Primary estimates indicate that the annual wave energy potential along the Indian coast is between 5 MW to 15 MW per meter, thus a theoretical potential for a coast line of nearly 6,000 Km works out to 40,000–60,000 MW approximately. A 150 kW demonstration plant has been installed and operating at Vizhinjum harbor near Thiruvananthapuram, Kerala since 1991. There is a proposal for an OTEC plant at Minicoy Island of Lakhshdweep.

(g) Emerging Technologies Emerging technologies like 'fuel cell' and 'hydrogen energy' are suited for stationary and portable power generation, which suits for transportation purposes. In view of the growing importance of Fuel cells and Hydrogen, a National Hydrogen Energy Board has been created. The Board will provide guidance for the preparation and implementation of the National Hydrogen Energy Road Map, covering all aspects of hydrogen energy starting from production, storage, delivery, applications, safety issues, codes & standards, public awareness and capacity-building. Eco-friendly electric vehicles for transportation are being field tested for improving their performance.

1.16.2 Growth of Energy Sector and its Planning in India [16] (August 2015 Data)

Energy is a critical building block for the development of the economy of a country. It is considered as GDP multiplier. Electricity is an essential requirement for all facets of our life and it has been recognized as a basic human need. It is the key to accelerating economic growth, generation of employment, elimination of poverty and human development especially in rural areas. The Planning Commission's 12th Plan projects that total domestic energy production would reach 669.6 million tonnes of oil equivalent (MTOE) by 2016–17 and 844 MTOE by 2021–22.

India's power sector is one of the most diversified in the world. Sources of power generation range from conventional sources such as coal, lignite, natural gas, oil, hydro and nuclear power to viable non-conventional sources such as wind, solar, and agricultural and domestic waste. Electricity demand in the country has increased rapidly and is expected to rise further in the years to come. In order to meet the increasing demand for electricity in the country, massive addition to the installed generating capacity is required. The demand and supply trend of electrical energy and peak power for the period 2007–08 to 2012–13 are given in Table 1.18.

Table 1.18 Demand and supply trend of energy and peak power [13]

FY	Energy, TWh				Peak power, GW			
	Demand	Production	Deficit	%age	Demand	Production	Deficit	%age
1987-88	211	188	23	10.9%	31.9	28.2	3.7	11.7%
1992-93	305	280	25	8.3%	52.8	42	10.8	20.5%
1997-98	425	390	35	8.01%	65.4	58	7.4	11.3%
2002-03	546	498	48	8.8%	81.5	71.5	10	12.2%
2007-08	690	624	66	9.6%	101	87	14	13.8%
2012-13	998	911	87	8.7%	136	123	13	9%

India's total installed power generation capacity has increased at a Compound Annual Growth Rate (CAGR) of 9.4 per cent over the period, financial year (FY) 2009–15. As per the 12th Five Year Plan, India is targeting a total of 88.5 GW of power capacity addition by 2017, of which, 72.3 GW constitutes thermal power, 10.8 GW hydro and 5.3 GW nuclear.

India is the third largest producer of electricity in the world. Over the period FY 2010–15, electricity production expanded at a CAGR of 6.3 per cent, as shown in Fig. 1.6. In FY 2015, it generated 1,048.7 terawatt-hours (TWh) of electricity, an 8.4 per cent growth over the previous fiscal year.

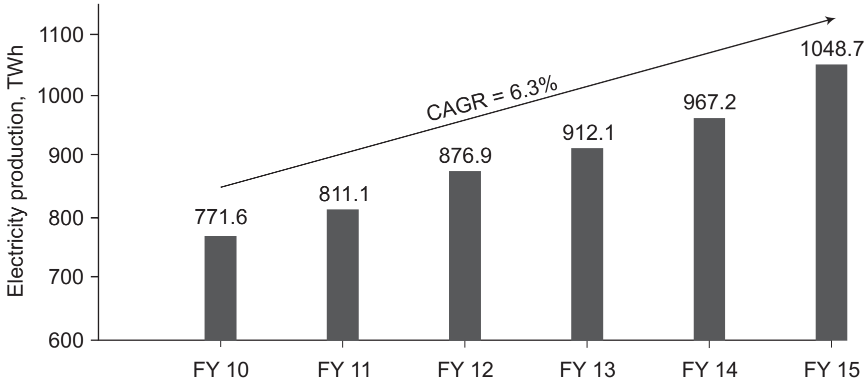


Figure 1.6 Electricity Production, TWh

Renewable energy is fast emerging as a major source of power in India. Wind energy is the largest source among all renewables. It accounts for about 65 per cent of total RES installed capacity. The government had revised the National Solar Mission with the electricity production target of 100,000 MW by 2022. The government has also sought to restart the stalled hydropower projects and increase the wind energy production target to 60 GW by 2022 from the current 23.7 GW.

The Government of India has initiated various steps to support the growth in the power sector. It has de-licensed the electrical machinery industry and also allowed 100 per cent Foreign Direct Investment (FDI) in the sector. Total FDI inflows in the power sector touched US$ 9.7 billion during the period April 2000 to May 2015.

The Government of India has identified power sector as a key sector of focus so as to promote sustained industrial growth. Some initiatives by the Government of India to boost the Indian power sector are listed below:

- A Joint Indo-US PACE Setter Fund has been established, with a contribution of US$ 4 million from each side to enhance clean energy cooperation.
- The Government of India announced a massive renewable power production target of 1,75,000 MW by 2022; this comprises generation of 100,000 MW from solar power, 60,000 MW from wind energy, 10,000 MW from biomass, and 5,000 MW from small hydro power projects.
- The Union Cabinet of India approved 15,000 MW of grid-connected solar power projects of National Thermal Power Corp Ltd (NTPC).
- The Indian Railways signed a bilateral power procurement agreement with the Damodar Valley Corporation (DVC). The agreement was signed between North Central Railway and DVC. This is the first time the Railways will directly buy power from a supplier.

- US Federal Agencies committed a total of US$ 4 billion for projects and equipment sourcing, one of the biggest deals for the growing renewable energy sector in India.
- On 20 January 2015, a Memorandum of Collaboration (MoC) was signed in New Delhi between all Indian Institute of Technology (IITs) and Oil & Natural Gas Corporation (ONGC) to work towards a collective research and development (R&D) programme for developing indigenous technologies to enhance exploration and exploitation of hydrocarbons and alternative sources of energy.
- The Reserve Bank of India (RBI) has notified to include renewable energy under priority sector lending (PSL). Therefore, banks can provide loans up to a limit of US$ 2.36 million to borrowers for renewable energy projects.
- The Andhra Pradesh Government plans to establish an 'Energy University', which would focus on research orientation and development of energy efficiency, energy conservation, and renewable sources.

Electrification of rural areas is very important for uniform development of the country. There are about 6 lakh villages in the country. About 90 per cent villages have been electrified, as on December 31, 2014 but the same pace of development has not reached up to household level in rural areas. About 45 per cent rural households still do not have access to electricity, while in urban areas 92.7 per cent households have been electrified. Under Remote Village Electrification Programme around 11,308 villages and hamlets have been covered during FY 2014–15.

1.17 APPLIED THERMODYNAMICS – A QUICK REVIEW

Thermodynamics is an axiomatic science which deals with the relations among heat, work and properties of system which are in equilibrium. It describes the state and the change in state of physical systems.

Thermodynamics basically entails four laws or axioms, known as Zeroth, First, Second and Third laws of thermodynamics.

- Zeroth law deals with thermal equilibrium and establishes a concept of temperature.
- First law throws light on the concept of internal energy.
- Second law indicates the limit of converting heat into work and introduces the principle of increase of entropy.
- Third law defines the absolute zero of entropy.

1.17.1 Important Terms and Definitions

System A system is the finite quantity of matter or a prescribed region of space.

Boundary The actual or a hypothetical envelope enclosing the system is known as boundary of the system. The boundary may be fixed or variable. The surroundings are external to the system.

Closed System If the boundary of the system is impervious to the flow of matter, it is called a closed system.

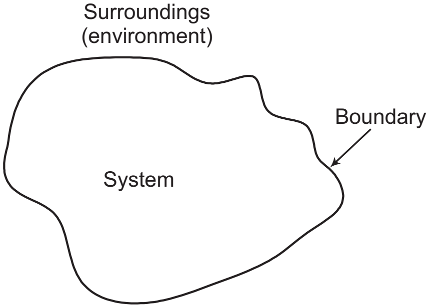


Figure 1.7 The system

Open System An open system is one in which matter flows into or out of the system. Most of the engineering systems are open systems.

Isolated System A system that exchanges neither energy nor matter with any other system or with environment is known as isolated system.

Adiabatic System An adiabatic system is one which is thermally insulated from its surroundings, i.e., it does not exchange heat with surroundings. It can, however, exchange work with its surroundings. If it does not, it becomes an isolated system.

Isothermal System An isothermal system is one which maintains constant temperature.

Intensive Property Intensive property is that property which does not depend on mass of the system, e.g. pressure, temperature.

Extensive Property Intensive property is related with mass of the system, e.g. volume, energy.

Phase A phase is quantity of matter which is homogeneous throughout in chemical composition and physical structure.

Homogeneous System A system which consists of a single phase is termed as homogeneous system. Examples are: mixture having air plus water vapor, water plus nitric acid and hydrogen plus methane.

Heterogeneous System A system which consists of two or more phases is called heterogeneous system. Examples are: mixture of water plus oil, water plus steam and ice plus water.

State Each unique condition of the system is known as a state.

Process A process occurs when the system undergoes a change in state or an energy transfer at a steady state. A process is illustrated by a curve on P-V (pressure-volume) diagram or T-S (abs. temperature-entropy) diagram. A process has certain path between starting point and end point. A process begins with certain state and ends with certain state of working fluid.

Cycle Any process or series of processes whose end states are identical is termed as a cycle.

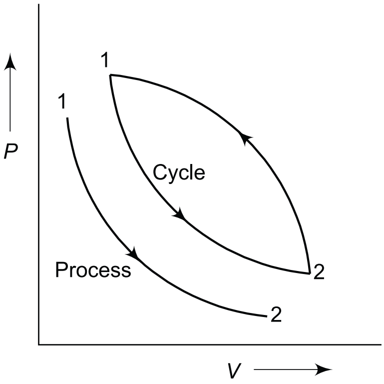


Figure 1.8 A process and a cycle

Irreversible Process An irreversible process does not trace the same path when reversed. The irreversibility may be due to the following reasons:

- friction
- heat flow (always from hot to cold)
- mixing of two different fluids in different states

Thermal Euilibrium In thermal equilibrium, the temperature will be the same at all points of the system and it does not change with time.

Mechanical Equilibrium In mechanical equilibrium, there are no unbalanced forces within the system. The pressure in the system is same at all points and does not change with time.

Chemical Equilibrium In chemical equilibrium, no chemical reaction takes place in the system and the chemical composition which is same throughout the system does not vary with time.

Thermodynamic Equilibrium A system is in thermodynamic equilibrium if it has achieved the:

- thermal equilibrium
- mechanical equilibrium and the
- chemical equilibrium states

Quasi-static Process Quasi means almost. A quasi-static process is also called a reversible process. This process is a succession of equilibrium states and infinite slowness in its characteristic features.

Specific Heats The specific heat of solids is usually defined as the heat required to raise the temperature of unit mass through one degree.

For a solid of mass m and specific heat c, the heat dQ required to increase the temperature by dT:

$$dQ = m\,c\,dT$$

For a gas two specific heats are defined:

c_v specific heat at constant volume
c_p specific heat at constant pressure

Accordingly we have,

$dQ = m\,c_p\,dT$, for a reversible non flow process at constant pressure
$dQ = m\,c_v\,dT$, for a reversible non flow process at constant volume

The values of c_p and c_v for a perfect gas are constants.

For temperature rise from T_1 to T_2:

Flow of heat in a reversible non flow process at constant pressure,

$$Q = m\,c_p\,(T_2 - T_1) \text{ and}$$

Flow of heat in a reversible non-flow process at constant volume,

$$Q = m\,c_v\,(T_2 - T_1)$$

For real gases c_p and c_v vary with temperature, but a suitable average values may be used for most practical purposes.

The relationship between the two specific heats may be shown to be:

$$c_p - c_v = R$$

where, R is gas constant.

The ratio of these two specific heats is denoted by γ.

$$\gamma = \frac{c_p}{c_v} \tag{1.1}$$

1.17.2 Joule's Law

Joule' law states that "the internal energy of a perfect gas is function of absolute temperature only". Mathematically,

$$u = f(T)$$

To evaluate this function let us consider heating of 1 kg of a perfect gas at constant volume. According to non-flow energy equation:

$$dQ = du + dW$$

But $dW = 0$, as volume remains constant,

Therefore, $dQ = du$

At constant volume of a perfect gas of 1 kg:

$$dQ = c_v\,dT$$

Therefore, $dQ = du = c_v\,dT$

Integrating, we get; $u = c_v\,dT + K$ (K being constant of integration)

For a perfect gas it is assumed that $u = 0$ when $T = 0$, hence K is zero.

Thus the internal energy of 1 kg a perfect gas,

$$u = c_v\,T$$

Internal energy for a perfect gas of mass m,

$$u = m\,c_v\,T$$

Therefore, for a perfect gas, gains of internal energy in any process (reversible or irreversible) between two states 1 and 2,

$$u_2 - u_1 = m\, c_v\, (T_2 - T_1) \tag{1.2}$$

Enthalpy Enthalpy, h is defined as the sum of internal energy, u and the pressure volume product, pv:

$$h = u + pv \tag{1.3}$$

The enthalpy of a fluid is the property of the fluid, since it consists of the sum of property and the product of two properties. Since enthalpy is property, it can be introduced into both flow as well as non flow processes.

Total enthalpy of mass, m of fluid can be given as:

$$H = mh = u + pV \tag{1.4}$$

For a perfect gas rewriting Eqn. (1.3),

$$\begin{aligned} h &= u + pv \\ &= c_v\, T + RT \\ &= (c_v + R)\, T \end{aligned}$$

$$h = c_p T \quad \text{(from Eqn.(1.1))} \tag{1.5}$$

and $$H = m\, c_p\, T \tag{1.6}$$

(Note that, since u has been to be zero at $T = 0$, therefore, $h = 0$ at $T = 0$)

1.17.3 First Law of Thermodynamics

In early part of nineteenth century scientists developed the concept of energy and hypothesis that "energy can neither be created nor destroyed", which came to be known as ***law of conservation of energy.*** The first law of thermodynamics is merely one statement of this general law with particular reference to heat energy and mechanical energy, i.e., work.

The first law of thermodynamics can be stated as, "when a system undergoes a thermodynamic cycle then the net heat supplied to the system from the surroundings is equal to net work done by the system on its surroundings."

Or $$\oint dQ = \oint dW$$

where $\oint$ represents the sum for a complete cycle.

Performance of Heat Engine and Reverse Heat Engine

Refer Fig. 1.9, a heat engine is used to produce maximum work from a given positive heat transfer. The measure of success is called the thermal efficiency of the engine and is defined by the ratio:

$$\eta_{\text{th}} = \frac{W}{Q_1} \tag{1.7}$$

where W = net work transfer from engine

Q_1 = heat transfer to the engine

For a reversed heat engine, acting as a refrigerator, when the purpose is to achieve the maximum heat transfer from the cold reservoir, the measure of success is called the coefficient of performance (C.O.P.). It is defined by the ratio:

$$(\text{C.O.P.})_{\text{refrigerator}} = \frac{Q_2}{W} \tag{1.8}$$

where Q_2 = heat transfer from cold reservoir
W = the net wok transfer to the refrigerator

For the reversed heat engine acting as heat pump, when purpose is to achieve maximum heat transfer to hot reservoir, the measure of success is again called the coefficient of performance (C.O.P.). It is defined by the ratio:

$$(\text{C.O.P.})_{\text{heat pump}} = \frac{Q_1}{W} \tag{1.9}$$

where Q_1 = heat transfer to hot reservoir
W = the network transfer to heat pump

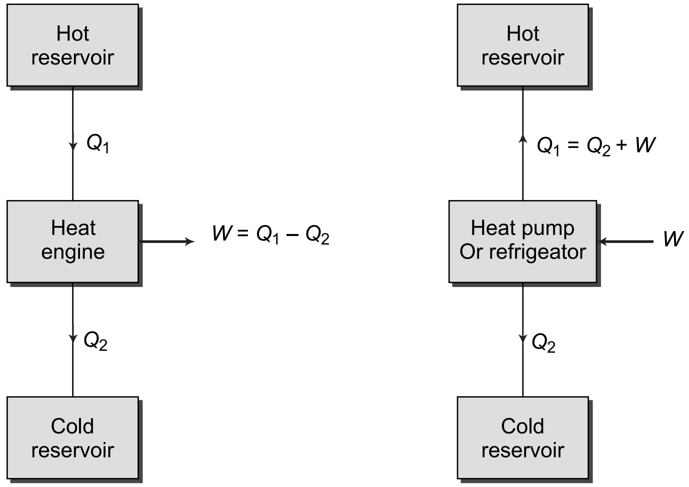
In all the above three cases application of the first law gives the relation $Q_1 - Q_2 = W$, and this can be used to rewrite the expressions for efficiency and C.O.P. solely in terms of heat transfers:

$$\eta_{th} = \frac{Q_1 - Q_2}{Q_1} \tag{1.10}$$

$$(\text{C.O.P.})_{\text{refrigerator}} = \frac{Q_2}{Q_1 - Q_2} \tag{1.11}$$

$$(\text{C.O.P.})_{\text{heat pump}} = \frac{Q_1}{Q_1 - Q_2} \tag{1.12}$$

It may be seen that values of η_{th} and $(\text{C.O.P.})_{\text{refrigerator}}$ are always less than unity while $(\text{C.O.P.})_{\text{heat pump}}$ is always greater than unity.



(a) Heat engine (b) Heat pump or refrigerator

Figure 1.9 Heat and work flow in heat engine and reversed heat engine

1.17.4 Second Law of Thermodynamics

Before going for the second law of thermodynamics, let us highlight the shortcomings of first law of thermodynamics.

Limitations of First Law of Thermodynamics

- It has been observed that energy can flow from a system in the form of heat or work. The first law of thermodynamics sets no limit to the amount of the total energy of the system which can be caused to flow as work. A limit is imposed, however, as a result of the principle enunciated in the second law of thermodynamics which states that heat will flow naturally from one energy reservoir at a higher temperature to another at a lower temperature, but not in opposite direction, without assistance.
- The first law of thermodynamics establishes equivalence between the quantity of heat used and the mechanical work but does not specify the conditions under which conversion of heat into work is possible, neither the direction in which heat transfer can take place. This gap has been bridged by the second law of thermodynamics.

There are two classical statements of the second law of thermodynamics, known as Kelvin-Planck statement and Clausius statement.

Kelvin-Planck Statement "It is impossible to construct an engine, which while operating in a cycle produces no other effect except to extract heat from a single reservoir and do equivalent amount of work".

Clausius Statement "It is impossible for a self-acting machine working in a cyclic process unaided by any external agency, to convey heat from a body at a lower temperature to a body at a higher temperature".

Entropy Entropy is an extensive property of a substance and is designated as S. It may be defined for a reversible process in accordance with the relation:

$$dS = \left(\frac{\delta Q}{T}\right)_{\text{rev}}$$

or Incremental entropy = ratio of heat change and absolute temperature.

In simple terms, it is heat (in Joules) per Kelvin. For a reversible process, if S_1 and S_2 are the respective entropy at initial state and final states, than the change in entropy depends on initial and final state only, and not on the path followed by the process. It is therefore a property. Thus, change in entropy when the system undergoes a reversible change from state 1 to state 2:

$$S_1 - S_2 = \int_1^2 \left(\frac{\delta Q}{T}\right)_{\text{rev}}$$

Isentropic Process Isentropic process is one during which the entropy of the system remains constant. It can be proved that any reversible adiabatic process is an isentropic process.

Temperature – entropy diagram for a pure substance

The thermodynamic properties of a substance are often shown on a temperature – entropy (T – S) diagram shown in Fig. 1.10. The general features of such diagrams are the same for all pure substances. These diagrams are important because they enable us to visualize the changes of state that occur in various processes.

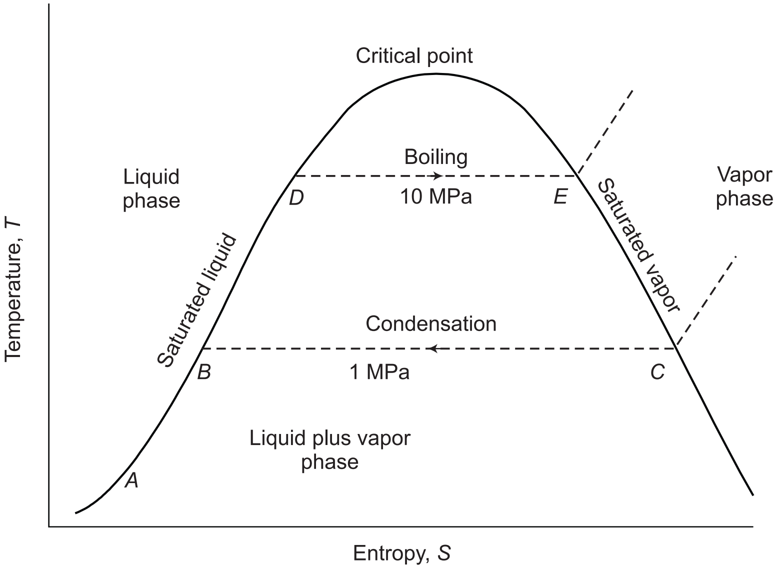


Figure 1.10 Temperature–entropy diagram for steam

1.17.5 Power Cycles

1. Carnot Cycle

The Carnot cycle was suggested by a French engineer Sadi Carnot in 1824, which works on the principle of reversible cycle. Any fluid may be used to operate the Carnot cycle, which is performed in a cylinder, as shown in Fig. 1.11(a). Heat is caused to flow into the cylinder by the application of temperature of high energy source to the cylinder head during expansion, and to flow from the cylinder by the application of a lower temperature energy source to the head during compression.

Following are the four stages of Carnot cycle:

Stage 1: (Process 1-2) Hot energy source is applied. Heat Q_1 is taken in and the fluid expands isothermally and reversibly at constant temperature, T_1.

Stage 2: (Process 2-3) The cylinder becomes a perfect insulator so that no heat flow takes place. The fluid expands adiabatically and reversibly whilst temperature falls from T_1 to T_2. Therefore, the process is an isentropic one.

Stage 3: (Process 3-4) Cold energy source (sink) is applied. Heat Q_2 flows from the fluid and it is compressed isothermally and reversibly at constant lower temperature, T_2.

Stage 4: (Process 4-1) Cylinder head becomes a perfect insulator so that no heat flow occurs. The compression is continued adiabatically and reversibly during which temperature is raised from T_2 to T_1.

The work delivered by the system during the cycle is represented by the enclosed area of the cycle. Again for a closed cycle, according to first law of thermodynamics the work obtained is equal to the difference between the heat Q_1 supplied by the source and the heat Q_2 rejected to the sink.

$$W = Q_1 - Q_2$$

The thermal efficiency,

$$\eta_{\text{th}} = \frac{\text{Work output}}{\text{Heat supplied by the source}}$$

$$= \frac{\text{Area unde curve 1-2-3-4}}{\text{Area under curve 1-2-3'-4'}}$$

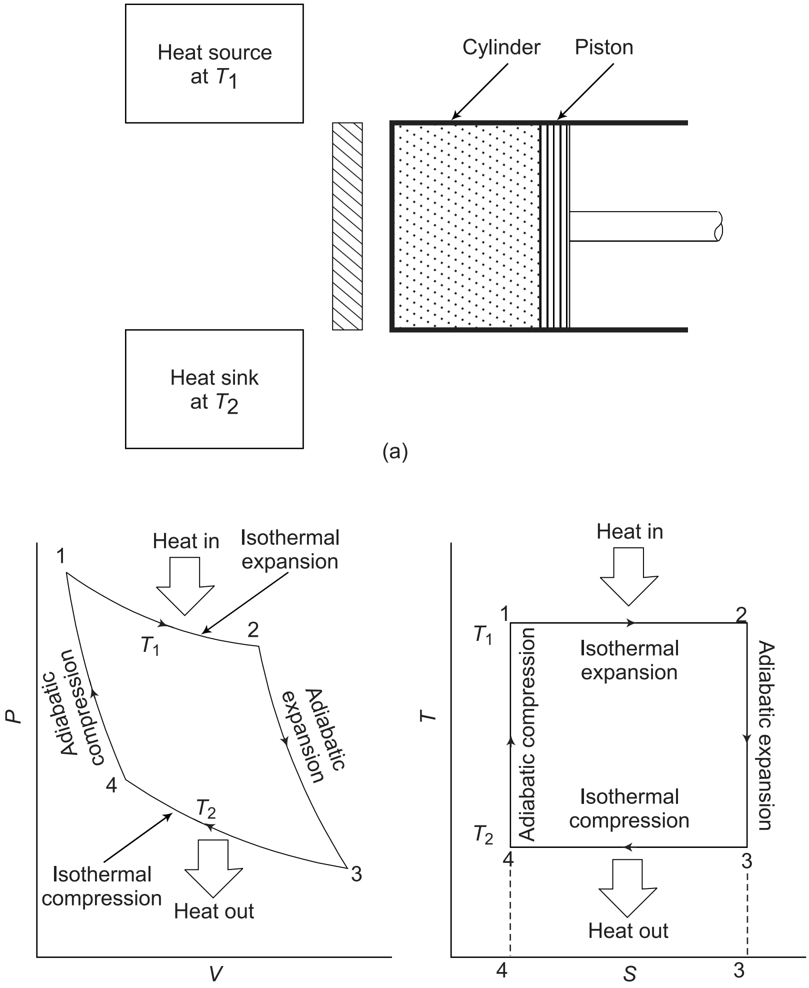
$$= \frac{Q_1 - Q_2}{Q_1}$$

$$\eta_{\text{th}} = 1 - \frac{T_2}{T_1} \quad \left(\text{as } \frac{Q_2}{Q_1} = \frac{T_2}{T_1} \right) \tag{1.13}$$

The Carnot cycle is an ideal condition requiring a reversible heat engine and cannot be performed in practice because of the following reasons.

- It is impossible to perform a friction less (i.e. reversible) process.
- It is impossible to transfer heat without temperature gradient.
- Isothermal process can be achieved only if the piston moves very slowly to allow some time for heat transfer so that the temperature remains constant. Adiabatic process requires the piston to move as fast as possible so that the heat transfer is negligible due to a short interval of time available. The adiabatic and isothermal processes take place during the same stroke, requiring the piston to move very slowly for initial part of the stroke and very fast for the remaining part of the stroke. This extreme variation of motion of the piston during the same stroke is not possible.

Though it is not a practical engine cycle, the conceptual value of the Carnot cycle is that it establishes the maximum possible efficiency for an engine cycle operating between T_1 and $T_{2.}$ The Carnot cycle can be thought of as the most efficient heat engine cycle allowed by physical laws. When the Second law of thermodynamics states that not all the supplied heat in a heat engine can be used to do work, the Carnot efficiency sets the limiting value on the fraction of the heat which can be so used.



(a)

(b) (c)

Figure 1.11 Carnot engine cycle

Example 1.4

A reversible cyclic heat engine operates between source temperature of 500 °C and 100 °C. Find the rate of heat rejection per kW net output of the engine.

Solution

Temperature of source $T_1 = 500 + 273 = 773$ K

Temperature of sink $T_2 = 100 + 273 = 373$ K

Output W = 1 kW

Thermal efficiency of the reversible engine from Eqn. (1.13):

$$\eta_{\text{th}} = 1 - \frac{T_2}{T_1} = 1 - \frac{373}{573} = 0.349$$

or $\eta_{\text{th}} = 34.9\%$

Now from Eqn. (1.7):

$$\eta_{\text{th}} = \frac{W}{Q_1}$$

$$0.349 = \frac{1}{Q_1}$$

Heat supplied, $Q_1 = 2.865$ kW

Now, heat rejected, $Q_2 = Q_1 - W = 2.865 - 1 = 1.865$ kW

Therefore, rate of heat rejection per kW of net output = 1.865 kW

Example 1.5

A domestic food refrigerator maintains a temperature of –10 °C. The ambient air temperature is 40 °C. If heat leaks into the freezer at a continuous rate of 2 kJ/s determine the least power necessary to pump this heat out continuously.

Solution

Ambient temperature $T_1 = 40 + 273 = 313$ K

Freezer temperature $T_2 = -10 + 273 = 263$ K

Rate of heat leakage into the freezer = 2 kJ/s

The refrigerator cycle removes heat from the freezer at the same rate at which heat leaks into it (to maintain constant temperature), thus $Q_2 = 2$ kJ/s

For minimum power requirement:

$$\frac{Q_1}{T_1} = \frac{Q_2}{T_2}$$

$$Q_1 = T_1 \times \frac{Q_2}{T_2} = 313 \times \frac{2}{263} = 2.38 \text{ kJ/s}$$

$$W = Q_1 - Q_2 = 2.38 - 2 = 0.38 \text{ kW}$$

Therefore, least power required to pump the heat continuously = 0.38 kW

Example 1.6

A house requires 3×10^4 kJ/h heating in winter. Heat pump is used to absorb heat from cold air outside the house. The work required to operate the heat pump is 2×10^3 kJ/h. Determine:

(i) Heat abstracted from outside.

(ii) Coefficient of performance

Solution

Heat required for the house, $Q_1 = 3 \times 10^4$ kJ/h

Work required to operate the heat pump, $W = 2 \times 10^3$ kJ/h

Heat abstracted from the outside air, $Q_2 = Q_1 - W = 28 \times 10^3$ kJ/h

$$(\text{C.O.P.})_{\text{heat pump}} = \frac{Q_1}{Q_1 - Q_2} = \frac{3 \times 10^4}{2 \times 10^3} = 15$$

Example 1.7

There are two alternative sources of heat energy. Source 1 can supply energy at the rate of 10,000 kJ/min at 320 °C. Source 2 can supply energy at the rate of 120,000 kJ/min at 65 °C. If an ideal reversible engine is used to produce power, which source out of these two will provide larger power if the temperature of the surroundings is 35°C.

Solution

Supply of energy:

Source 1, $Q_1 = 10{,}000$ kJ/min at $T_1 = 320 + 273 = 593$ K

Source 2, $Q_2 = 120{,}000$ kJ/min at $T_1 = 65 + 273 = 338$ K

Temperature of surrounding $T_2 = 35 + 273 = 308$ K

The efficiency of the Carnot engine from the two sources is given by:

Source 1, $$\eta_1 = 1 - \frac{308}{593} = 0.48$$

Source 2, $$\eta_2 = 1 - \frac{308}{338} = 0.088757$$

Work delivered by source 1, $W_1 = 10{,}000 \times 0.48 = 4{,}800$ kJ/min

Work delivered by source 2, $W_2 = 120{,}000 \times 0.088757 = 10{,}650.84$ kJ/min

Therefore, source 2 will provide larger amount of power (even though its efficiency is lower).

2. Rankine Cycle

Rankine cycle is a vapor power cycle on the basis of which a steam turbine (or engine) works. Various components and the processes involved in a Rankine cycle are shown in Fig. 1.12(a). It comprises of following processes:

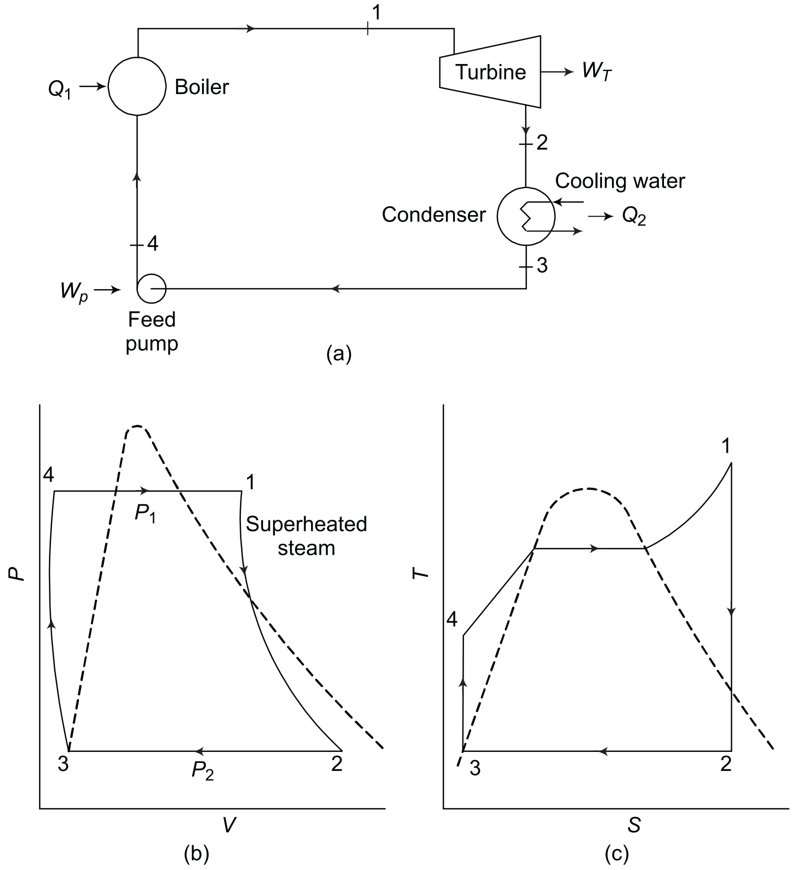
Process 1-2 Reversible adiabatic expansion in the turbine (or steam engine) to produce output work W_T.

Process 2-3 Constant pressure transfer of heat in the condenser. Steam is condensed to water and heat Q_2 is removed.

Process 3-4 Reversible adiabatic pumping process, where the system accepts some work W_p as input. However, this work is negligible compared to work output of the turbine, especially when boiler pressure is low.

Process 4-1 Constant pressure transfer of heat Q_1 in the boiler

Thermodynamic changes during the Rankine cycle are shown on P-V and T-S diagrams given in Fig. 1.12 (b, c). The area under the closed loop 1-2-3-4 represents the net work output.



(a)

(b) (c)

Figure 1.12 Rankine cycle

The efficiency of Rankine cycle can be written as:

$$\eta_{\text{Rankine}} = \frac{W_{\text{net}}}{Q_1} = \frac{W_T - W_P}{Q_1} = \frac{(h_1 - h_2) - (h_4 - h_3)}{h_1 - h_4}$$

Usually pumping power is very small as compared to power produced by turbine,

$$W_T >> W_P$$

Therefore, $$\eta_{\text{Rankine}} \approx \frac{h_1 - h_2}{h_1 - h_4} \tag{1.14}$$

Effects of Operating Conditions on Rankine Cycle Efficiency Rankine cycle efficiency can be improved by:

- increasing the temperature at which steam is supplied to the turbine.
- decreasing the temperature at which steam is rejected by the turbine.

This can be achieved by making suitable changes in the conditions of boiler and condenser.

1. *Increasing boiler pressure*: It has been observed that by increasing the boiler pressure (other factors remaining the same) the efficiency rises first and then drops after reaching its peak value (of about 35-45 per cent) at about 166 bar.
2. *Superheating the steam*: Other factors remaining the same, if the steam is superheated before entering turbine, the efficiency of Rankine cycle increases. This also increases the life of turbine blades due to absence of water particles.
3. *Reducing the condense pressure*: By reducing the condenser pressure the temperature at which heat is rejected can be reduced, thus increasing the thermal efficiency of the cycle. However, this would also increase the cost of condensation apparatus.

The efficiency of the Rankine cycle is also improved by use of following methods.

(a) regenerative feed heating
(b) reheating of steam
(c) water extraction
(d) using binary vapor

Typical data for a Rankine cycle based steam turbine (coal fired):

Steam inlet temperature = 540 °C
Steam inlet pressure = 160 atm.
Efficiency ≈ 35%

3. Brayton Cycle

Brayton cycle is a gas power cycle on the basis of which a thermodynamic device (engine or turbine) works to produce mechanical power. Various components and the processes involved in a Brayton cycle are shown in Fig. 1.13(a). It uses air as working fluid and works at temperatures well in excess of 500 °C. The expansion and compression processes are reversible and adiabatic while heat addition and rejection takes place at constant pressure. The hot compressed gas is allowed to expand through a turbine performing work. The exhaust gas from turbine is fed to heat exchanger where the heat is rejected and then compressed by the compressor to complete the cycle. It comprises of following processes:

Process 4-1 Reversible adiabatic (i.e., isentropic) compression. Here a work W_c is accepted by the system as input.

Process 1-2 Constant pressure transfer of heat Q_1 in the combustor.

Process 2-3 Reversible adiabatic expansion in the turbine. A work W_T is produced.

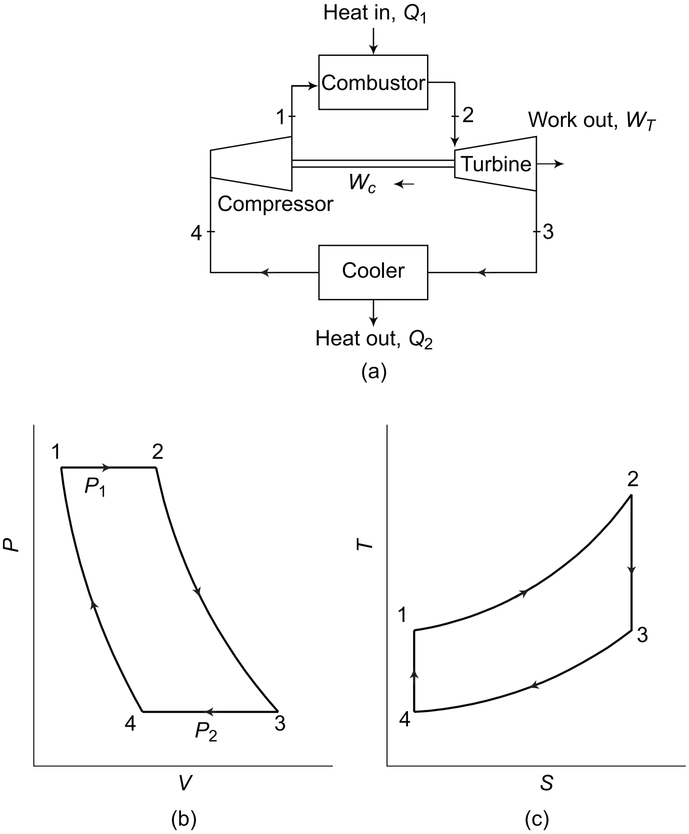
Process 3-4 Constant pressure heat output Q_2 by the condenser.

Thermodynamic changes during the Brayton cycle are shown on *P*-*V* and *T*-*S* diagrams given in Fig. 1.13 (b, c). The area under the closed loop 1-2-3-4 represents the net work output ($W_T - W_c$). The performance of Brayton cycle can be improved by inserting a regenerator between the turbine exhaust and the cooler for preheating the compressed gas prior to the combustor. The efficiency of Brayton cycle can be written as:

$$\eta_{\text{Brayton}} = 1 - \frac{1}{r_k^{\gamma-1}} \tag{1.15}$$

where r_k is compression ratio $\left(\frac{v_1}{v_2}\right)$ and γ is ratio of two specific heats. In terms of pressure ratios, r_p;

$$\eta_{\text{Brayton}} = 1 - \frac{1}{r_P^{(\gamma-1)/\gamma}} \tag{1.16}$$



(a)

(b) (c)

Figure 1.13 Brayton cycle

In Brayton cycle, the work input during compression is a significant amount as working fluid is gas. The compressor consumes roughly 50 per cent of the power produced by the turbine, reducing the overall efficiency of the cycle. This is in contrast to Rankine cycle where pumping power is negligible as working fluid is in liquid form (which is uncompressible) during compression (pumping) process.

Typical data for a Brayton cycle based gas turbine (coal fired):
Inlet temperature = 540 °C – 1425 °C
Inlet pressure ≈ 30 atm
Efficiency ≈ 26% - 39%

3. Stirling Cycle

Stirling cycle is similar to a Carnot cycle, except that two adiabatic processes are replaced by two constant volume processes. A suitable gas or air is used as working fluid. The system components are shown in Fig. 1.14(a). The heat addition and rejection takes place at constant temperatures. The cycle comprises the following processes:

Process 4-1 The working fluid receives heat at constant volume, in a regenerative heat exchanger from the exhaust fluid returning from the turbine.

Process 1-2 In this process, the working fluid receives heat at constant (high) temperature and expands in a turbine producing W_T output.

Process 2-3 Working fluid loses out heat at constant volume to the fluid incoming to the turbine.

Process 3-4 Working fluid is compressed at constant (low) temperature and heat Q_2 is rejected to the ambient.

The heat transfer in regenerative heat exchanger is accomplished reversibly by a matrix of wire gauze or small tubes. The main difficulty in Stirling cycle lies in making efficient regenerator of reasonable size which can operate at temperature comparable to that used in internal combustion engines. The efficiency of Stirling cycle is given as;

$$\eta_{\text{Stirling}} = \frac{T_1 - T_2}{T_1} \tag{1.17}$$

Typical data for a Stirling cycle based gas turbine:
Turbine inlet temperature = 750 °C – 800 °C
Inlet pressure = 30 atm.
Efficiency ≈ 30% – 40%

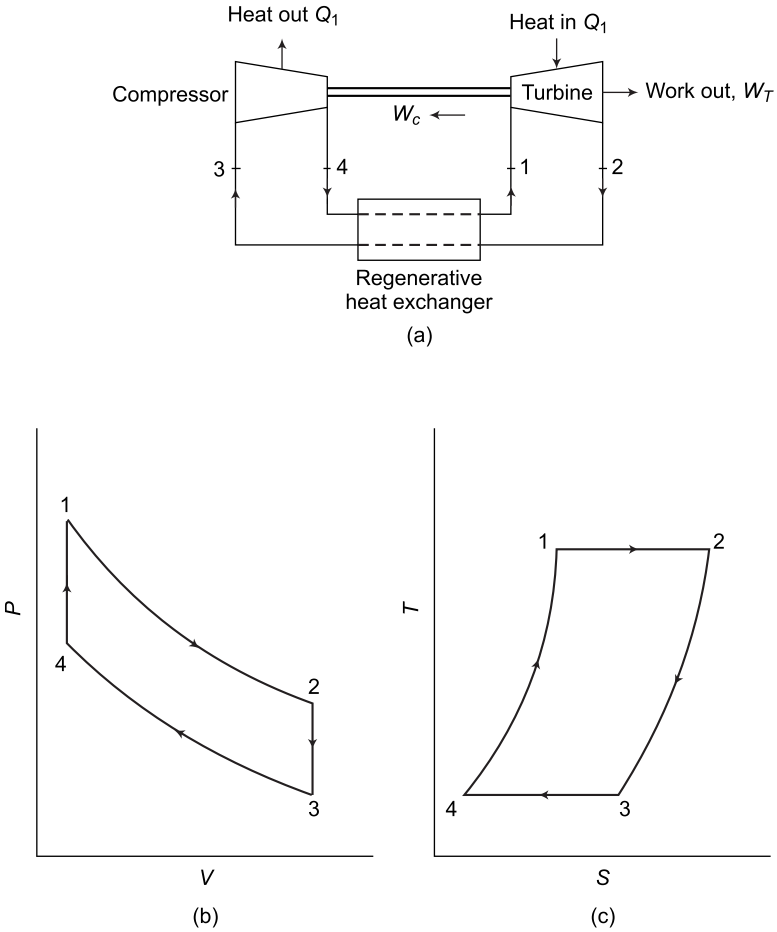


Figure 1.14 Stirling cycle

1.17.6 Comparison of Various Power Cycles

The performance of various thermodynamic cycles can be compared qualitatively on a T-S diagram shown in Fig. 1.15. These diagrams are not dawn on a common scale and only their shapes are compared. The temperature, pressure and entropy ranges are different for different cycles. As seen from this figure, the Carnot cycle is represented by a rectangle and produces maximum output. The Stirling cycle produces next maximum in the remaining three cycles. The main limitation however, is the design of suitable, efficient regenerator, especially in large sizes. Also in large power plants Stirling cycle is not preferred due to many other practical problems. Rankine cycle is generally preferred and widely used due to its superior over all cycle efficiency and component sizes.

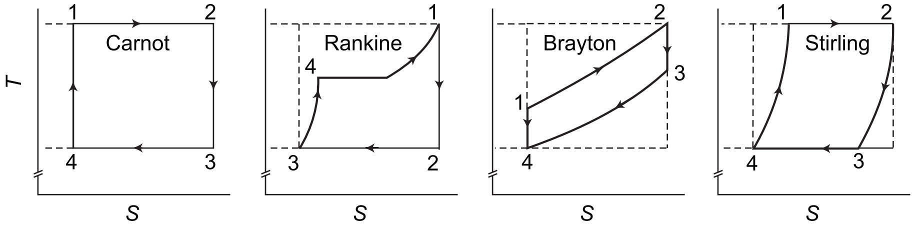


Figure 1.15 Comparison of power cycles

REVIEW QUESTIONS

1. How is per the capita energy consumption related with standard of living?
2. Comment on the oil crisis of 1973.
3. What are primary and secondary energy sources?
4. Enumerate the criteria based on which energy can be classified. **(Panjab Tech. Univ., 2008)**
5. What are conventional and non-conventional energy sources?
6. What are the forms and sources of energy? List some reasons, why nonconventional sources are preferred? **(RajasthanTech. Univ., 2011)**
7. Distinguish between renewable and non-renewable energy sources. **(Panjab Tech. Univ., 2008)**
8. List various non-conventional energy resources. Give their availability, relative merits and their classification. **(UPTU Lucknow 2005-06)**
9. Discuss the main features of various types of renewable and non-renewable energy sources and explain the importance of non-conventional energy sources in the context of global warming. **(UPTU Lucknow 2007-08)**
10. What is meant by renewable energy sources?
11. What do you understand by commercial energy?
12. What are the advantages and limitations of non-conventional energy sources?
13. What is the percentage share of fossil fuels in total energy consumption of the world?
14. What percentage of primary energy requirement is met by coal in India?
15. Discuss the main feature of non-conventional energy sources. **(UPTU Lucknow 2003-04)**
16. Discuss different renewable sources of energy with special reference to Indian context. **(UPTU Lucknow 2003-04)**
17. What do you understand by energy chain?
18. What are the advantages and disadvantages of conventional energy sources?
19. What do you understand by greenhouse effect and what are its consequences? How is it caused?
20. What are greenhouse gases?
21. What do you understand by green power?
22. Which is the cleanest of all fuels and what is its heating value?

23. Indicate the heating values of Bituminous coal, coke, peat, diesel, propane and natural uranium.

24. What is the present annual primary energy consumption of the world? At what rate it is growing?

25. Comment on the future availability trend of fossil fuels in the world.

26. What is the present world hydropower potential and how much has been tapped so far?

27. Which country relies maximum on nuclear energy for its energy requirements?

28. What is the present status of nuclear energy and what are its future prospects?

29. What is the potential in solar energy the world over? On average, how much solar power is received on the surface of the earth at noon during bright sun day?

30. What are the prospects of wind and biomass energy?

31. What is meant by renewable energy sources? What are the prospects of nonconventional energy sources in India? **(Visvesrayya Tech. Univ. 2006, Gujarat Tech. Univ., 2014)**

32. Comment on the prospects of fossil fuels in India.

33. What is the status of non-conventional energy sources in India and what are their future prospects?

34. Comment on the growth of energy sector in India.

35. Comment on rural electrification plans of the Government of India.

36. Discuss different renewable sources of energy with special reference to Indian context. **(UPTU, Lucknow, 2003-04)**

37. Describe the main features of various types of renewable and non-renewable energy resources and explain the importance of non-conventional energy sources in the context of global warming. **(UPTU Lucknow, 2007-08)**

PROBLEMS

1. Find the coefficient of performance and heat transfer rate in the condenser of a refrigerator in kJ/h which has a refrigeration capacity of 12,000 kJ/h. The power input to the Carnot engine driving the compressor is 0.75 kW. **(Ans. 4.44, 14700 kJ/h)**

OBJECTIVE TYPE QUESTIONS

1. Which parameter is used as an index for standard of living of the people of a country?
(a) Industrial production
(b) Number of vehicles per house
(c) Per capita energy consumption
(d) Population density

2. What is the per capita electrical energy consumption of India?
(a) 100 kWh/year (b) 150 kWh/year
(c) 400 kWh/year (d) 760 kWh/year

3. Which year is said to be the starting point for large scale planning of renewable energy globally?
(a) 1973 (b) 1942
(c) 1850 (d) 1991

4. What is the percentage share of fossil fuel in global consumption of primary energy?
(a) 82% (b) 50%
(c) 10% (d) 99%

5. Out of the thermal, electrical, mechanical and chemical, which energy form is considered as top grade energy?
(a) Mechanical (b) Chemical
(c) Thermal (d) Electrical

6. Out of energy, economy and environment:
(a) only energy and environment are related
(b) only energy and economy are related
(c) all the three are interrelated
(d) all the three are independent

7. Global warming is mainly caused due to:
(a) emission of heat from engines
(b) emission of CO_2 due to burning of fossil fuels
(c) use of nuclear energy
(d) air pollution

8. Use of nuclear energy is opposed due to:
(a) rapid depletion of nuclear uranium reserves
(b) its high cost
(c) ecological imbalance caused due to its use
(d) possibility of accident and radioactive pollution due to nuclear waste

9. Global warming would lead to:
(a) increase of agriculture production
(b) acid rains
(c) change of climatic pattern and its severity
(d) increase in the efficiency of heat engines

10. What is the energy density of petrol?
(a) 100 MJ/kg (b) 51 MJ/kg
(c) 10 MJ/kg (d) 150 MJ/kg

11. What percentage of global coal is produced in India annually?
(a) 20% (b) 17%
(c) 7.8% (d) 4%

12. What percentage of electric power is presently being produced by non-conventional energy sources in India?
(a) 13.7% (b) 90%
(c) 50% (d) 2.15%

13. Most desirable option for energy farming of bio-diesel is the cultivation on:
(a) good fertile land of the country
(b) roof tops of buildings
(c) sea
(d) marginal and fellow land, not suitable for normal agriculture

14. For a reversible adiabatic process, the change in entropy is:
(a) zero (b) minimum
(c) infinite (d) unity

15. The processes of Carnot cycle are:
(a) two adiabatic and two constant volume
(b) two isothermal and two constant volume
(c) two adiabatic and two isothermal
(d) two constant volume and two constant pressure

16. In a Carnot engine, when working fluid gives heat to the sink:
(a) the temperature of the sink increases
(b) the temperature of the source deceases
(c) the temperature of both the source and the sink decreases
(d) the temperature of the sink remains the same

17. The efficiency of an ideal Carnot engine depends on:
(a) the working substance
(b) the temperature of both the source as well as sink
(c) on the temperature of sink only
(d) on the construction of the engine

18. Rankine cycle efficiency of a good steam power plant may be in the range of:
(a) 35-45% (b) 90-95%
(c) 15-20% (d) 70-80%

19. Rankine cycle efficiency of steam power plant:
(a) improves in winter as compared to that in summer
(b) improves in summer as compared to that in winter
(c) is unaffected by climatic conditions
(d) None of the above

20. Regenerative cycle thermal efficiency of a Rankine cycle:
(a) is same as simple Rankine cycle thermal efficiency.
(b) is always less than that of simple Rankine cycle thermal efficiency.
(c) is always greater than that of simple Rankine cycle thermal efficiency.
(d) None of the above

21. Acid rain contains:
(a) H_2SO_4 (b) NHO_3
(c) HCO_3 (d) HCl

22. What is environment?
(a) Our surroundings like land, water and air
(b) Weather
(c) Climate
(d) Space and time

23. Renewable energy is known as "green energy" because:
(a) it is green in colour. (b) it is produced from green plants only.
(c) it is produced from wet fuels. (d) it does not produce harmful pollutants.

24. What are greenhouse gases responsible for?
(a) Warming of the country only (b) Cooling of the city only
(c) Global cooling (d) Global warming

25. The impact of development of cities and industries on our natural environment is:
(a) positive (b) negative
(c) neutral (d) uniform

26. Which of the following is not biomass?
(a) Water (b) Plants
(c) Wood (d) Cow dung

27. Which renewable energy source is the leading source globally to generate electric power?

(a) Solar (b) Wind

(c) Biomass (d) Geothermal

28. A 1MW capacity electricity plant runs on full capacity. How much energy (in Units) it will generate during one year:

(a) 1000 units (b) 8,760,000 units

(c) 365 units (d) 365,000 units

29. The energy that human beings get from food, originally comes from:

(a) vegetables (b) meat

(c) grains (d) the Sun

30. Which greenhouse gas is produced due to cultivation of rice?

(a) CO_2 (b) SF_6

(c) CH_4 (d) CCl_4

31. What is the energy density of Hydrogen:

(a) 142 MJ/kg (b) 50 MJ/kg

(c) 16 MJ/kg (d) 32 MJ/kg

32. From a 2 sq. m flat plate solar water heater, approximately how much water can be heated from room temperature of 25 °C to 100 °C:

(a) 50 litres (b) 100 litres

(c) 500 litres (d) 300 litres

CHAPTER 2

Energy Conservation and Efficiency

Learning Objectives

In this chapter you will be able to:

- Define terms like energy management, energy audit, energy efficiency, energy intensity, energy elasticity, etc.
- Discuss global energy saving potential in different sectors
- Assess energy consumption status in India and saving potential
- Outline ongoing energy conservation efforts in India
- Discuss broad guidelines of energy audit
- List various opportunities of energy saving

2.1 INTRODUCTION

It is a known fact that the reserves of all conventional forms of energy are fast depleting. Every day the human population across the world uses energy for leading a civilized life. These resources, which comprises providing adequate food, shelter, clothing, water, sanitation, medication, schooling, transportation, industrial applications, access to information, etc., are critical input for human development. In short, energy affects all facets of activities related to everyday and modern life. Per capita energy consumption is often considered an important indicator of development. As people and nation progress, consumption of energy will increase.

To overcome the problem of energy deficiency and growing demand, there are two possible options: (i) expand and optimize energy production, and/or (ii) conserve and optimize the available energy and utilize the resource to the fullest extent. The former is known as supply side management (**SSM**) while later is known as demand side management (**DSM**).

In most cases the demand and supply of energy are managed independent of each other. Increasing the energy production is an expensive and long-term option, whereas, energy conservation and energy efficiency offers a cost effective solution with short pay back and modest investment.

Since conventional energy assets are fast depleting and cost of energy is increasing, it is very important to conserve energy and utilize it more efficiently. This also helps reducing the environmental pollution. Efficient use of energy provides multiple advantages both to industry and the economy: (i) it helps cut down cost of production and gives added competitive edge to industrial enterprises, (ii) it provides the economy benefits for being cost efficient, (iii) it conserves the limited conventional assets of energy, which are largely non-renewable, and (iv) it provides environmental benefits as major part of energy is sourced from fossil fuels. To create awareness about energy conservation, 14th December is observed as ‘National Energy Conservation Day’.

2.2 IMPORTANT TERMS AND DEFINITIONS

The formal definitions of the basic terms are given below:

Energy Policy defines the overall guidelines for the efforts to achieve greater energy efficiency. It is established and maintained by the top management of the company.

Energy Planning involves setting of concrete energy targets complying with the overall energy policy and elaborate action plans to achieve the targets in a given time frame. Planning of several activities includes, forecast, budget, infrastructure, material, equipment, technology, financial resource, human resource and R & D planning.

Energy management can be defined in many ways. One way of defining it is: “The judicious and effective use of energy to maximize profit and enhance competitive positions” another comprehensive definition is: “The strategy of adjusting and optimizing energy, using systems and procedures so as to reduce energy requirements per unit of output while holding constant or reducing total cost of producing the output from these systems"

The objective of energy management is to achieve and maintain optimum energy procurement and utilization throughout the organization and to: (i) minimize energy cost/energy waste without affecting production and quality, (ii) minimize environmental effects.

Energy audit is an inspection, survey and analysis of energy flows for energy conservation in a building, process or system to reduce the amount of energy input into the system without negatively affecting the output(s). It also includes submission of technical report containing recommendations for improving energy efficiency with cost benefit analysis and an action plan to reduce energy consumption. In commercial and industrial real estate, an energy audit is the first step in identifying opportunities to reduce energy expense.

The primary objective of Energy Audit is to determine ways to reduce energy consumption per unit of product output or to lower operating costs. Energy Audit provides a "benchmark" (reference point) for managing energy in the organization and also provides the basis for planning a more effective use of energy throughout the organization.

Energy conservation is the act of saving energy by reducing a service. In other words, to conserve energy, you need to cut back on your usage. Examples include driving your car fewer kilometers per week, turning your air conditioner thermostat up a degree or two during summer and unplugging your computer or home appliances when they are not in use. In all of these examples, you are reducing the amount of energy you use by doing without or making due with less fuel or electricity.

Energy efficiency is defined as saving energy, but keeping the same level of service. For example, replace an inefficient incandescent light bulb with a more efficient compact fluorescent lamp or an LED lamp. On the other hand, if you turn off the lights when you leave a room, you are practicing energy conservation.

You can keep these terms straight by thinking of energy conservation as 'cutting back' and energy efficiency as using energy more 'effectively.' Energy efficiency uses advances in science and technology to provide services and products that require the use of less energy. Examples include replacing older model appliances, such as a refrigerator or washing machine, with newer, energy-efficient models. Modern appliances use significantly less energy than older models, yet provide the same or better service.

Another example would be adding insulation to the attic and walls of a home. This added insulation allows the homeowner to reduce heating and cooling energy while maintaining a comfortable temperature within the home. Energy efficiency in the home can also be improved by replacing drafty windows with new, energy-efficient windows.

Newer windows prevent heat from escaping in the winter months, keeping the home temperature consistent and making your furnace work less. Even the way a building is designed can help improve energy efficiency. For example, the use of skylights or structural features that reflect light into a room can provide abundant lighting while reducing the need for electric lights.

Energy intensity is a measure of the energy efficiency of a nation's economy. It is calculated as the amount of energy consumed for generating one unit of Gross Domestic Product.

Energy elasticity is the percentage change in energy consumption to achieve one per cent change in national GDP in a specific country over time.

2.3 IMPORTANT ASPECTS OF ENERGY CONSERVATION

Conserving usable energy, which is otherwise wasted, has a direct impact on economy, environment and long-term availability of non-renewable energy sources. Energy conservation implies reduction in energy consumption by reducing losses and wastage by employing energy efficient means of generation and utilization of energy. There are three important aspects of energy conservation:

1. Economic Aspect

(a) Reduction in Cost of Product Energy conservation ultimately leads to economic benefits as the cost of production is reduced. In some energy intensive industries like steel, aluminum, cement, fertilizer, pulp and paper etc., cost of energy forms a significant part of the total cost of the product. Energy cost (expressed as per cent of total cost of the product) in the entire industrial sector in India varies from as low as 0.36 per cent to as high as 65 per cent. We must strive for good energy economy using energy efficient technologies. This will reduce the manufacturing cost and lead to production of cheaper and better quality products. This is essential to stay competent with our commercial rivals.

(b) New Job Opportunities Energy conservation usually requires new investments in more efficient equipment to replace old inefficient ones, monitoring of energy consumption, training of manpower, etc. Thus, energy conservation can result in new job opportunities.

2. Environmental Aspect

Every type of energy generation / utilization process affects the environment to some extent either directly or indirectly. The extent of degradation of environment depends mainly on the type of primary energy source. Also during any energy conversion stage a part of energy escapes to surroundings and appears in the form of heat. Thus energy is generated and utilized at the expense of adverse environmental impacts. Adoption of energy conservation means can minimize this damage.

3. Conservation of Non-Renewable Energy Assets

The vast bulk of energy used in the world today comes from fossil fuels, which are non-renewable. These resources were laid down many millions of years ago and are not being made any longer. This finite, non-renewable asset is being used up very fast. The quantity of fossil fuels the world community uses up in one minute what it took the earth a millennium to create. Therefore, its prices are bound to go up relative to everything else. We must abandon wasteful practices in energy utilization and conserve this resource by all means for future generations.

2.4 GLOBAL EFFORTS, ACHIEVEMENTS AND FUTURE PLANNING

Large economies have been able to reduce their consumption of energy by observing self-discipline and strict energy conservation / efficiency measures without negatively effecting the development. The GDP per unit of energy use for some countries is shown in Fig. 2.1. As shown, the developed countries are achieving more with less investment of energy and continue to improve further. By similar measures the developing countries can also cut down their energy consumption.

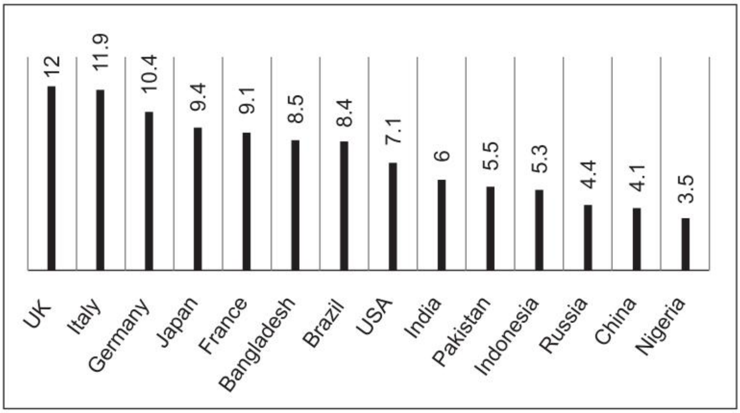


Figure 2.1 GDP per unit of energy use (PPP$ per KGOE (2011)) [1]

Developed countries are continuously improving their energy intensity through conservation and improving efficiency over the years. The trend of primary energy consumption as well as GDP from 1965 to 2015 for Japan is shown in Fig. 2.2. It is seen that after the oil shock of 1973 the energy consumption rate has slowed down (remarkably from mid-1990s) while maintaining steady growth of GDP. It has improved energy efficiency by about 40 per cent during this period. In Denmark, the economy has grown by 80 per cent in the last 30 years while energy consumption has remained more or less same. Also a significant part (about 40 per cent) of this energy is sourced from renewables. Globally, all countries are setting ambitious goals for future reduction of energy consumption. Germany has set a national target of a 20 percent reduction in primary energy consumption below 2008 levels by 2020 and 50 percent by 2050.

Figure 2.3 gives an idea of the potential of the energy improvements. The figure shows that per capita energy consumption varies by as much as a factor of three between the USA and some European countries with almost the same level of human development index. It is fair to assume that the per capita energy of USA could be reduced to the level of Europe by energy efficiency improvements and by making some structural changes. The present per capita annual energy consumption in USA is 284 GJ, which is equivalent to about 9 kW per person, whereas the average for the whole world is 2 kW. The Board of Swiss Federal Institute of Technology has developed a vision of a 2 kW per capita society by the middle of the century. A reduction of 25–30 per cent in primary energy in the industrialized countries is achievable cost

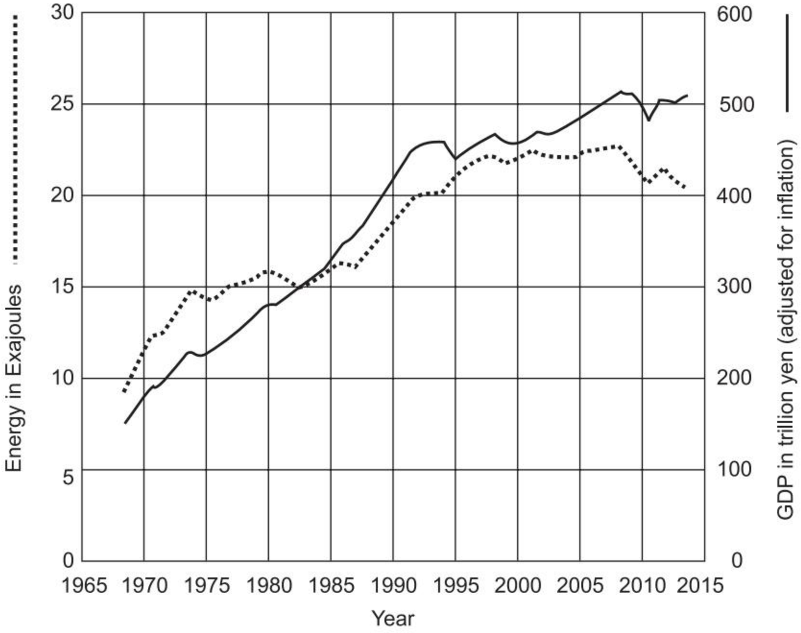
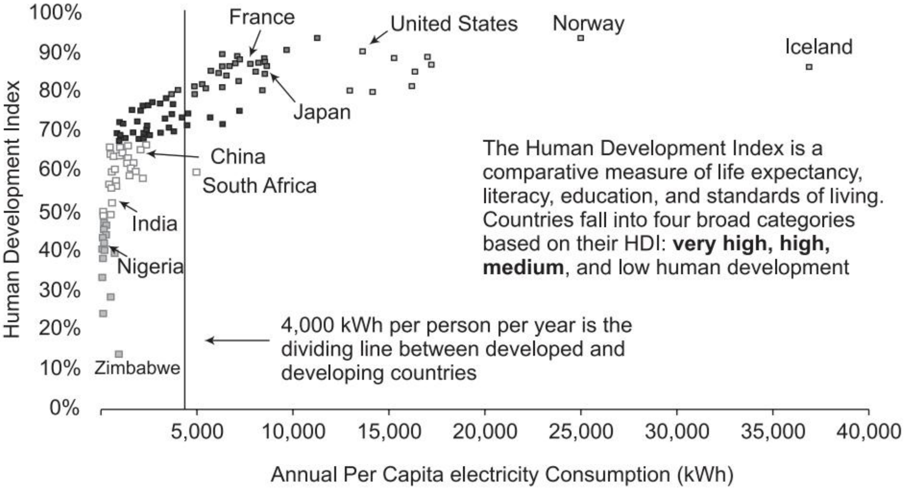


Figure 2.2 Energy consumption and GDP growth trend for Japan [1]



Source: Human Development Index - 2010 data United Nations; Annual Per Capita Electricity Consumption (kWh) - 2007 data World Bank

Updated: 4/11

Figure 2.3 Human Development Index vs and Per Capita Energy Consumption [18] effectively without affecting the level of services. A similar reduction of up to 40 per cent is achievable in transitional economies and more than 45 per cent in developing economies. As a combined result of efficiency improvement and structural changes such as increased recycling, substitution of energy intensive materials, etc. energy intensity could decline at a rate of 2.5 per cent per year over next 20 years [19].

2.5 ENERGY CONSERVATION/EFFICIENCY SCENARIO IN INDIA

Energy conservation received greater attention in India since the mid-1970s. The energy conservation efforts in India have to be viewed in terms of coal and lignite being the long-term local resources. Small resources of petroleum and natural gas may be exhausted shortly and in the medium and long term the import of oil will increase.

The Indian energy sector has been regulated and owned by government agencies and organizations. Ministry of Power is the apex body in the Government of India. The ministry is concerned with perspective planning, policy formulation and implementation, manpower development, administration and enactment of legislation. The ministry is assisted by Central Electricity Authority (CEA) in all technical and economic matters.

Energy consumption by different economic sectors—agriculture, industry, transport and residential is shown in Fig. 2.4. The industrial sector continues to be single largest commercial energy consuming sector using up about 45 per cent of total commercial energy in the country, although its share is declining gradually. The commercial energy intensity of this sector has declined over the past due largely to a relatively rapid expansion of low energy intensive industries, adoption of modern energy efficient technologies and successful implementation of energy conservation measures. Sufficient energy savings are being achieved in energy intensive aluminum, iron–and–steel, textiles, chemicals, and paper–and–pulp industries through better house-keeping, improved capacity utilization, development of cogeneration facilities, industrial heat and waste management, and arrangement for improving the quality of electric supply[20].

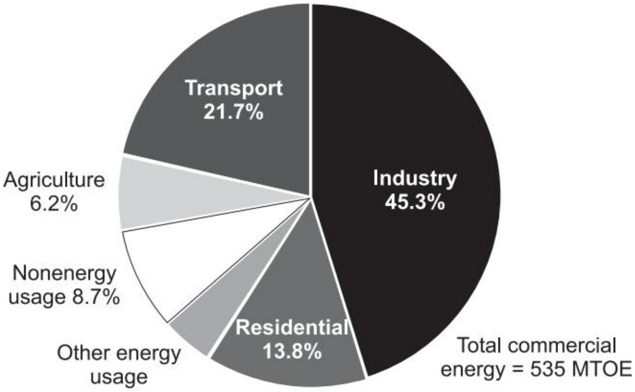


Figure 2.4 Commercial energy balance [20]

Transport infrastructure has expanded considerably and its energy intensity has grown gradually. Uncontrolled expansion of cities coupled with inadequate public transport has contributed to a phenomenal growth in the number of private enterprises leading to energy inefficiency and severe pollution problem. The strategies to check vehicular pollution, lately in a couple of metros, are now showing significantly positive results.

The domestic sector is the largest consumer of primary energy accounting for 40–50 per cent of the total primary energy consumption, but the bulk of it consists of traditional fuels in the rural households.

The electricity consumption in various sectors (only utilities) is shown in Fig. 2.5. It indicates highest consumption of electricity in industrial, domestic and agriculture sectors.

The new electricity bill of 2003 (*Electricity Act 2003*) has paved the way for delicensing of generation, nondiscriminatory open access in transmission, power trading, rural electrification, mandatory requirements of State Electricity Regulatory Commissions, mandatory metering and stringent provisions against theft of power. The trading activities of the Power Trading Corporation have already started from surplus power regions to deficit power regions.

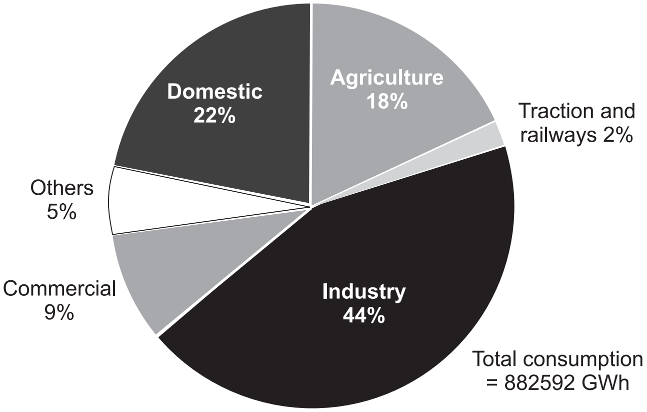


Figure 2.5 Electricity consumption in various sectors (utilities) during 2013–14[3]

The Government of India is committed to meet the growing energy needs at affordable rates required to meet the objectives of economic development. To deliver a sustained economic growth rate of 8 per cent to 9 per cent through 2031–32 and to meet life time energy needs of all citizens, India needs to increase its primary energy supply by 3 to 4 times and electricity generation capacity about 6 times. As a result energy service demand growth rates will keep on increasing because of accelerated industrialization, urbanization, and an emerging consumer society. [20]

In India, major energy intensive sectors have an average potential of 20–25 per cent of energy savings through energy conservation and energy efficiency measures. The sector wise saving potential would be Industrial (up to 25 per cent); Agriculture Sector (up to 30 per cent); Transport, Domestic Commercial and Municipal Sector (<20 per cent) [22].

During IXth Five-Year Plan, the need for an energy conservation act was realized. Considering the vast potential of energy savings and benefits of energy efficiency, the Government of India, on 29 September, 2001, enacted the "Energy Conservation Act", 2001. The Act provides the legal framework, institutional arrangement and a regulatory mechanism at the Central and State level to embark upon energy efficiency drive in the country. This act requires large energy consumers to adhere to energy consumption norms; new buildings to follow the "Energy Conservation Building Code"; and appliances to meet energy performance consumption labels.

Salient Features of "Energy Conservation Act, 2001"

The Act provides a long-range consequence, which is appended below:

- The establishment of Bureau of Energy Efficiency (BEE) in place of existing Energy Management Centre (EMC) to implement the provisions of the act
- Declaration of a user or class of users of energy as a designated consumer
- To lay down minimum energy consumption standards and labeling for identified appliances/equipment and norms for industrial processes for energy intensive industries
- Formation of energy consumption codes
- Dissemination of information and best practices
- Establishment of Energy Conservation Fund both at the central and state levels
- Provision of penalties and adjudication
- The BEE would act as a facilitator for the evolution of a self-regulatory system and organizations would regulate on their own with a view to save energy and thereby bring the commercial concept in the organization

The Central Government has established the BEE with effect from March 1, 2002. Further, the provision of sections 1–29 and sections 46–62 of the Energy Conservation Act 2001 relating to this have come into force from the same date.

2.5.1 Schemes to Promote Energy Conservation and Energy Efficiency [22]

Ministry of Power, through Bureau of Energy Efficiency (BEE), has initiated a number of energy efficiency initiatives in the areas of household lighting, commercial buildings, standards and labeling of appliances, demand side management in agriculture/municipalities, SME's (Small and Medium Enterprises) and large industries including the initiation of the process for development of energy consumption norms for industrial sub sectors, capacity building of SDA's (State Designated Agencies), etc. The target of energy savings against these schemes during the XI th Plan period was kept as 10,000 MW of avoided generation capacity. These initiatives have resulted in an avoided capacity generation of 10836 MW during the XIth plan period. The schemes initiated by BEE are discussed below:

1. Standards and Labeling

The Bureau initiated the Standards and Labeling (S and L) programme for equipment and appliances in 2006 to provide the consumer an informed choice about the energy saving and thereby the cost-saving potential of the relevant marketed product.

The scheme is invoked for 19 equipment/appliances, i.e. Room Air-Conditioners, Fluorescent Tube Lights, Frost Free Refrigerators, Distribution Transformers, Induction Motors, Direct Cool Refrigerator, electric storage type geyser, Ceiling fans, Color TVs, Agricultural pump sets, LPG stoves, Washing machine, Laptops, ballast, floor standing ACs, office automation products, Diesel Generating sets & Diesel operating pump sets of which the first 4 products have been notified under mandatory labeling from 7th January, 2010. The other appliances are presently under voluntary labeling phase. The energy efficiency labeling programmes under BEE are intended to reduce the energy consumption of appliance without diminishing the services it provides to consumers. Further, the standards and label for refrigerators and air-conditioners have been periodically made more stringent. As a result, the least-efficient products are removed from the market and more efficient products are introduced. The Corporate Average Fuel Consumption Standards (CAFC) for passenger cars has been notified on 30th January, 2014. The most recent additions to the list of labeled products are Diesel Pump Sets & Diesel Generating Set.

During the XIIth plan, Standards and Labelling programme will target at least 3 more new equipment/appliances including upgradation of energy performance standards for equipment/appliances covered during XI Plan.

2. Energy Conservation Building Codes (ECBC)

The Energy Conservation Building Code (ECBC) was developed by Govt. of India for new commercial buildings on 27th May 2007. ECBC sets minimum energy standards for new commercial buildings having a connected load of 100 kW or contract demand of 120 KVA and above. While the Central Government has powers under the EC Act 2001, the state governments have the flexibility to modify the code to suit local or regional needs and notify them. Currently eight States and Union Territories (Rajasthan, Odisha, UT of Puducherry, Uttrakhand, Punjab, Karnataka, Andhra Pradesh & Telangana) notified and adopted the code for their states. In order to promote a market pull for energy efficient buildings, Bureau of Energy Efficiency developed a voluntary Star Rating Programme for buildings which is based on the actual performance of a building, in terms of energy usage in the building over its area expressed in kWh/sq. m/year. Currently, Voluntary Star Labelling programme for 4 categories of buildings (day use office buildings / BPOs / Shopping malls / Hospitals) has been developed and put in public domain.

3. Demand Side Management (DSM) Schemes

(a) Agriculture DSM In order to tap the energy saving potential, Agriculture Demand Side Management (AgDSM) programme was initiated in XIth plan by Bureau of Energy Efficiency with an objective to induce energy efficiency in agriculture sector by creating market based framework for implementation of few pilot projects and create awareness among end users and other stakeholders for adoption of energy efficient pump sets (EEPS).

During the XIIth plan, realizing the vast energy saving potential in the sector, BEE intends to continue the programme with an objective to build up the process of acceleration of sustainable energy efficiency in the plan through following interventions:

- Regulatory mechanism to mandate the use of BEE star labeled pump sets for new connections
- Facilitate implementation of DPRs and setting up monitoring & verification protocol
- Technical assistance and capacity development of all stakeholders

(b) Municipal DSM Identifying the immense energy-saving potential in municipal sector, BEE initiated Municipal Demand Side Management (MuDSM) during XIth plan. The basic objective of the project was to improve the overall energy efficiency of the Urban Local Bodies (ULBs), which could lead to substantial savings in the electricity consumption, thereby resulting in cost reduction / savings for the ULBs.

Implementation of the project at the ground level is highly necessary which will create a market transformation among technology provider, implementing partners, financial institutions etc. In view of these facts, it is proposed that implementation of demo projects in 15 ULBs will be undertaken on pilot basis during XIIth plan. In addition, technical support will be provided to the ULBs by appointing technical experts to selected ULBs.

(c) Capacity Building of DISCOMS The objective of the programme is capacity building of DISCOMs (distribution companies) for carrying out load management programme, energy conservation programme, development of DSM action plan and implementation of DSM activities in their respective areas. This programme would help the DISCOMs for reducing peak electricity demand so that they can delay building further capacity.

(d) Energy Efficiency in Small and Medium Enterprises (SMEs) Sector To encourage the energy efficient technologies and operational practices in SME sectors in India, BEE has initiated the energy efficiency interventions in selected 25 SMEs clusters during the XIth plan. A study was conducted to assess energy use and technology gap at unit level, development of the cluster specific energy efficiency manuals, preparation of Detailed Project Reports (DPRs) on energy efficient technologies and capacity building and knowledge enhancement of man-force involved in SMEs. During the XIIth plan, implementations of 100 technology demonstration projects in five SME sectors are envisaged to facilitate large-scale replication.

4. Strengthening Institutional Capacity of States

(a) Strengthening of State Designated Agency (SDAs) As has been mentioned earlier, the implementation and enforcement of the provisions of the Energy Conservation Act in the states is to be carried out by SDAs. As on date, the SDAs have been set up in 32 states by designating one of the existing organizations as required under Section 15 (d) of the Energy Conservation Act 2001. In order to kick start the energy conservation activities at the state level with an emphasis on building institutional capacities of the SDAs, Ministry of Power had approved the scheme of Providing financial assistance to the State Designated Agencies for strengthening their institutional capacities and capabilities during the XI plan. During the XII plan, thrust is given on establishment of the enforcement machinery at the State level.

(b) Contribution to State Energy Conservation Fund (SECF) Scheme The State Energy Conservation Fund (SECF) is an instrument to overcome the major barriers for implementation of energy efficiency projects. The contribution under State Energy Conservation Fund (SECF) was made to those State Govt. / UT Administration who have created their SECF and finalized the rules and regulations to operationalize the same.

5. School Education Programme

Considering the need to make the next generation more aware regarding efficient use of energy resources, it is necessary to introduce children during their school education. In this regard, promotion of energy efficiency in schools is being promoted through the establishment of Energy Clubs. Bureau of Energy Efficiency is implementing the Students Capacity Building Programme under Energy Conservation awareness scheme for XII five year plan and intends to prepare the text / material on Energy Efficiency and Conservation for its proposed incorporation in the existing science syllabi and science textbooks of NCERT for classes 6th to 10th.

Through this project recommendations will also be made to the National Council of Education, Research and Training (NCERT) to update the science textbooks of classes VII to IX to include relevant chapters on Energy Efficiency in the school syllabus.

6. Human Resource Development (HRD)

The potential for improvement of energy efficiency of processes and equipment through awareness creation is vast. A sound policy for creation, retention and up gradation of skills of Human Resources is very crucial for penetration of energy efficient technologies and practices in various sectors. The component under HRD comprises of theory cum practice oriented training programme and providing Energy Audit Instrument Support.

7. National Mission for Enhanced Energy Efficiency (NMEEE)

The National Mission for Enhanced Energy Efficiency (NMEEE) is one of the eight missions under the National Action Plan on Climate Change (NAPCC). NMEEE aims to strengthen the market for energy efficiency by creating conducive regulatory and policy regime and has envisaged fostering innovative and sustainable business models to the energy efficiency sector.

The Mission seeks to upscale the efforts to unlock the market for energy efficiency which is estimated to be around Rs. 74,000 crore and help achieve total avoided capacity addition of 19,598 MW, fuel savings of around 23 million tonnes per year and greenhouse gas emissions reductions of 98.55 million tonnes per year at its full implementation stage.

2.6 ENERGY AUDIT

Energy Audit is the key to a systematic approach for decision-making in the area of energy management. It attempts to balance the total energy inputs with its use, and serves to identify all the energy streams in a facility. It quantifies energy usage according to its discrete functions. Industrial energy audit is an effective tool in defining and pursuing comprehensive energy management programme.

Energy Audit will help to understand more about the ways energy (electricity and fuel) are used in any industry, and help in identifying the areas where waste can occur and where scope for improvement exists. The Energy Audit would give a positive orientation to the energy cost reduction, preventive maintenance and quality control programmes which are vital for production and utility activities.

Energy Audit can be classified into the following three types.

1. Preliminary Energy Audit
2. Targeted Energy Audit
3. Detailed Energy Audit

1. Preliminary Energy Audit

Preliminary energy audit is a relatively quick exercise to:

- Establish energy consumption in the organization
- Estimate the scope for saving
- Identify the most likely and the easiest areas for attention
- Identify immediate (especially no- / low-cost) improvements / savings
- Set a 'reference point'
- Identify areas for more detailed study / measurement

Preliminary energy audit uses existing, or easily obtained data.

2. Targeted Energy Audit

Targeted energy audits are mostly based on the outcome of preliminary audit results. They provide data and detailed analysis on specific target projects. For example, an organization may target its lighting system or boiler system or compressed air system with a view to bring about energy savings. Targeted audits therefore involve detailed surveys of the targeted subjects / areas with analysis of the energy flows and costs associated with those targets.

3. Detailed Energy Audit

Detailed energy audit evaluates all systems and equipment which consume energy and audit comprises a detailed study on energy savings and costs. Detailed energy audit is carried out in three phases: (I) Phase I – Pre Audit Phase (ii) Phase II – Audit Phase and (iii) Phase III – Post Audit Phase.

(a) Phase I—Pre Audit Phase Activities

- Resource planning, establish/organize a plan and organize energy audit team
- Walk through audit
- Informal interviews
- Organize instruments and time frame, energy manager, production
- Macro data collection (suitable to type of industry) / plant manager
- Familiarization of process / plant activities
- First hand observation and assessment of current level operation and practices
- Conduct of brief meetings

- Building up cooperation awareness programme
- Issue questionnaire to all divisional heads of each department
- Orientation, awareness creation

(b) Phase II—Audit Phase Activities

- Primary data gathering
- Process flow diagram and energy utility diagram
- Conduct monitoring survey and historic data analysis
- Base line data collection
- Prepare process flow charts
- Prepare all service utilities system diagram
- Design operating data and schedule of operation annual energy bill and energy consumption pattern
- Carry out survey of motors, insulation and lighting with portable instruments for collection of more and accurate data. Compare and confirm the operating data with design data
- Conduct detailed trial/experiment for selected energy guzzlers (24 hrs. Monitoring of MD, PF, kWh, etc.), load variation trend in pumps, fans, compressors etc.
- Boiler efficiency trial for 4–8 hours
- Furnace trials, equipment performance experiments, etc.
- Perform analysis of energy use, energy and material balance, loss/waste analysis
- Identify and develop energy conservation opportunities (ECOs)
- Identify and consolidate energy conservation measures (ECMs), conceive develop and refine ideas, review the previous suggestions of unit personal, suggestions of previous audit
- Use brainstorming and value analysis technique, contact vendors for new and efficient technology
- Perform cost benefit analysis
- Assess technical feasibility, economic viability and prioritize ECOs options for implementation, select the most promising projects prioritize by low, medium and long term measures documentation
- Report presentation to top management

(c) Phase III—Post-Audit Phase Activities

- Assist and implement ECMs and monitor the performance upon action
- Make schedule for implementation
- Follow up and perform periodic review

2.7 ENERGY CONSERVATION OPPORTUNITIES

2.7.1 Classification of Energy Conservation Opportunities

Based on energy audit and analyses of the plant, a number of potential energy saving projects may be identified. These may be classified into three categories:

1. Category A: Minor ECOs

Minor ECOs are simple, easy to implement, requiring less investment and implementation time. These are related with stopping of leakage points, avoiding careless waste, housekeeping, lapses and carelessness of O & M personnel.

2. Category B: Medium ECOs

Medium ECOs or intermediate ECOs are slightly complex, requiring additional investment and moderate implementation time.

3. Category C: Major ECOs

Major ECOs provide significant energy conservation opportunity. These are high tech., complex and require heavy investment and long implementation period.

2.7.2 General Electrical ECOs

1. Class A: Simple Electrical ECOs

(a) Switching off the loads (i.e. lights, heaters, ACs, TVs, etc.) when not in use
(b) Changing from electrical heating to solar heating or gas burner heating wherever possible
(c) Proper housekeeping
(d) Reducing peak demand by staggering the use of large loads
(e) Providing automatic thermostatic (or any other) control to water heaters, refrigerators, air-conditioners, etc.
(f) Using recently developed 'tiny switches' which switch off the electronic apparatus during their sleeping mode
(g) Changing operating cycle of electrical equipment to conserve energy. For example, electrical furnaces may be used continuously in three shifts (instead of two shifts) for better economy.
(h) Replacing inefficient lamps by energy efficient lamps

2. Class B: Intermediate Electrical ECOs

(a) Installation of static VAR sources at substations
(b) Employing automatic controlled load switches
(c) Heat recovery from cooling oil associated with transformer
(d) Automatic voltage control of power consuming devices by means of ON-load tap changer
(e) Installation of shunt capacitors near inductive load for power factor improvement and reducing kVA demand
(f) Improvement in Operation and Maintenance, reducing down time

3. Class C: Comprehensive Electrical ECOs

(a) Modern more efficient and easy to maintain plant equipment may replace old less efficient ones
(b) The simple manual / semi manual controlled equipment in an electrical plant are retrofitted with energy efficient computer controlled equipment. The energy input is matched with optimum energy requirement.

2.7.3 Some Important Areas of Energy Saving in Industry

1. Conservation of Electricity

(a) Electric Motors One of the key areas for electricity conservation is to improve the efficiency of electric motors. Electric motors, on an average, consume over 60 per cent of the total electric energy consumed in the industrial sector. Selection of motors of right rating and optimum efficiency would help improve power factor. Capacitors can be used to bring the power factor near to unity.

(b) Electrolysis and Electrical Heat This is another important area which accounts for, on an average 20 per cent of the power consumption. Auto trace self-limiting electric heat technology may be adopted to enable the heater to vary its output power.

(c) Illumination This is another area of large-scale power consumption in the industrial units. To the extent possible, industrial architecture should build in active and passive system of solar energy utilization to minimize artificial lighting as also air conditioning. Illumination load could be brought down by good housekeeping practices, having the right height for electrical fixtures, choosing the right type of light, etc. Solid-state time switches or photo controls can be used to monitor and maintain lighting loads.

(d) Refrigeration and Air-conditioning This is an area where 15–20 per cent of energy saving is easily possible through simple measures such as having proper insulation, low roof and roof cooling. Use of soft water as make-up water and frequent cleaning of cooling tower with chlorine to retard algae formation are some of the other measures which can bring about energy savings.

2. Conservation of Furnace Oil

(a) Storage and Handling Better storage and handling practices such as preventing leakages and spillages along with periodical cleaning of storage tanks will save furnace oil. Elevation of service tanks to facilitate gravity flow, installation of coarse filter before the pumps and using gear pumps for pumping are other measures that will save furnace oil at this stage.

(b) Preheating To enhance the efficiency at the burning stage, preheating of furnace oil, removing suspended impurities and properly adjusting and maintaining the preheaters and thermostat will help minimize furnace oil use.

(c) Burners Antiquated burners should be replaced by standard and quality ones. Separate controls for atomizing air and primary air blowing to cope with varying load conditions would also add to energy saving.

(d) Industrial Furnaces In the industrial furnaces, apart from adequate refractory insulation and effective sealing of the furnace for flame and combustion leaks, installation of chimneys of the right height and size and monitoring of flue gas would help maximize energy savings.

(e) Boiler House Instrumentation Use of control instruments in the boiler house would help ensure combustion efficiency and keep a close watch over the operational parameters.

3. Conservation of Coal

(a) Better Storage 5–10 per cent coal savings are possible through reduction of carpet losses while storing, prevention of spontaneous combustion, correct sizing procedure and minimization of segregation of coal.

(b) Correct Sizing Inconsistent sizing of coal feeds and the use of coal of varying sizes in combustion equipment causes significant coal wastage.

(c) Selection of Boilers Conventional boilers are not suitable for solid fuel firing system needed for burning coal of varying quality. Selection of boilers should therefore, be done carefully. Antiquated boilers waste as much as 30 per cent of coal.

(d) Steam Management Efficient steam management is another important area for conservation of coal and furnace oil. Boiler houses should be provided with the requisite control instruments. The steam distribution network should be carefully designed to avoid wastes. Equally important would be to have proper insulation and to install correct steam traps. Proper monitoring and management of steam pressure would also be necessary. Excessive blow-downs as also steam leaks should also be avoided.

4. Cogeneration

Cogeneration (generation of electricity and useful heat in a single installation) should be used wherever feasible and economically viable, instead of separate generation of electricity and heat. While thermal power station has a thermal efficiency of 28–32 per cent, cogeneration installations achieve thermal efficiency up to 75 per cent. In some industries cogeneration may result in 30 per cent lower fuel consumption as compared to that where electricity and heat are generated separately.

5. Recycling and Reusing

Recycling and reusing of materials offers substantial energy savings. Every finished product has an intrinsic value depending upon original energy input during its production process. For example, newspaper material has more gained energy than the energy in raw material that goes in making the paper. Reclaiming the useful scrap material by its recycling can save that invisible energy which was used in producing and processing the original raw material. Recycling has three benefits: (a) *saving of energy**; (b) same amount of new (virgin) material is also displaced; and (c) solves the problem of waste disposal to a great extent.

Recycled aluminum cans require only 6 per cent of the energy needed to make the can in the first place. Recycling of an Aluminium can would save enough energy

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*In general, the energy spent in recycling is only a fraction of the energy needed in extraction of fresh material from raw source. Thus recycling saves and recovers a part of energy that has already been spent to process the fresh material.

to run a TV for 3 hours. Japan serves as an example of a premiere recycling country. Half of its waste material is recycled. This includes 95 per cent of all newspapers and 50 per cent of all other papers.

6. Modernization of Technology

In most cases, considerable energy savings could be affected by replacing old inefficient machinery or simply retrofitting the existing plant. Developed countries have been able to reduce the energy consumption significantly compared to developing countries by adopting energy efficient modern technology. For instance, energy used by Indian steel industry is 9.50 million kcal per ton, which is more than double the amount used by Italy or Japan, which is around 4 million kcal per ton. Similarly, in case of cement industry, energy requirement works out to be around 2 million kcal per ton as against 0.95 million kcal per ton in USA and 0.89 million kcal per ton in Italy. Therefore, modern energy efficient technology should be adopted by replacing / retrofitting the existing old inefficient equipment.

7. Waste Heat Recovery

Various industrial processes require heat of different grades. Waste heat from one process that uses intense heat can serve the need of other, which requires heat at lower grade. Let us consider an example of glass industry:

(a) Glass industry requires heat to melt glass at about 1500 °C. It produces waste heat at about 400–500 °C in the form of flue gases from the furnace.

(b) Flue gases may be used to raise medium pressure steam and fed to backpressure turbine to generate electric power. (In backpressure turbine, the exhaust steam is not condensed but is withdrawn at desired pressure for process use as against condensing turbine where the steam leaves the turbine at a very low pressure.)

(c) The exhaust from backpressure turbine, which is at about 120 °C, may further be used for crop drying or for paper drying. (In paper industry 1.5 tons of water have to be evaporated for each ton of paper produced. Approximately 30 per cent of the total energy required for paper production is utilized for drying purpose.)

(d) The condensed water vapour, which is at about 60 °C, may be used for heating of space, fish farm or greenhouse.

8. Proper Housekeeping

The elements of effective housekeeping programme are as follows:

(a) Dust and Dirt Removal Vacuum cleaners are suitable for removing light dust and dirt. Industrial models have special fittings for cleaning walls, ceilings, ledges, machinery, and other hard-to-reach places where dust and dirt may accumulate.

(b) Employee Facilities Employee facilities need to be adequate, clean and well maintained. Lockers are necessary for storing employees' personal belongings. Washroom facilities require cleaning once or more each shift. They also need to have a good supply of soap, towels plus disinfectants, if needed. The eating area should be separate from the work area and should be cleaned properly each shift.

(c) Surfaces

(i) *Floors*: Poor floor conditions are a leading cause of accidents so cleaning up spilled oil and other liquids at once is important. Allowing chips, shavings and dust to accumulate can also cause accidents. Trapping chips, shavings and dust before they reach the floor or cleaning them up regularly can prevent their accumulation. Areas that cannot be cleaned continuously, such as entrance ways, should have anti-slip flooring. Keeping floors in good order also means replacing any worn, ripped, or damaged flooring that poses a tripping hazard.

(ii) *Walls*: Light-coloured walls reflect light while dirty or dark-coloured walls absorb light. Contrasting colours, warn of physical hazards and mark obstructions such as pillars. Paint can highlight railings, guards and other safety equipment, but should never be used as a substitute for guarding. The programme should outline the regulations and standards for colours.

(d) Maintain Light Fixtures Dirty light fixtures reduce essential light levels. Clean light fixtures can improve lighting efficiency significantly.

(e) Aisles and Stairways Aisles should be wide enough to accommodate people and vehicles comfortably and safely. Aisle space allows for the movement of people, products and materials. Warning signs and mirrors can improve sight-lines in blind corners. Arranging aisles properly encourages people to use them so that they do not take shortcuts through hazardous areas.

Keeping aisles and stairways clear is important. They should not be used for temporary “overflow” or “bottleneck” storage. Stairways and aisles also require adequate lighting.

(f) Spill Control The best way to control spills is to stop them before they happen. Regularly cleaning and maintaining machines and equipment is one way. Another way is to use drip pans and guards where possible spills might occur. When spills do occur, it is important to clean them up immediately. Absorbent materials are useful for wiping up greasy, oily or other liquid spills. Used absorbents must be disposed of properly and safely.

(g) Tools and Equipment Tool housekeeping is very important, whether in the tool room, on the rack, in the yard, or on the bench. Tools require suitable fixtures with marked locations to provide orderly arrangement, both in the tool room and near the workbench. Returning them promptly after use reduces the chance of being misplaced or lost. Workers should regularly inspect, clean and repair all tools and take any damaged or worn tools out of service.

(h) Maintenance The maintenance of buildings and equipment may be the most important element of good housekeeping. Maintenance involves keeping buildings, equipment and machinery in safe, efficient working order and in good repair. This includes maintaining sanitary facilities and regularly painting and cleaning walls. Broken windows, damaged doors, defective plumbing and broken floor surfaces can make a workplace look neglected; these conditions can cause accidents and affect work practices. So it is important to replace or fix broken or damaged items as quickly as possible.

(i) Waste Disposal The regular collection, grading and sorting of scrap contribute to good housekeeping practices. It also makes it possible to separate materials that can be recycled from those going to waste disposal facilities.

(j) Storage Good organization of stored materials is essential for overcoming material storage problems whether on a temporary or permanent basis. There will also be fewer strain injuries if the amount of handling is reduced, especially if less manual materials handling is required.

(i) Stored materials should not obstruct aisles, stairs, exits, fire equipment, emergency eyewash fountains, emergency showers, or first aid stations. All storage areas should be clearly marked.

(ii) Flammable, combustible, toxic and other hazardous materials should be stored in approved containers in designated areas that are appropriate for the different hazards that they pose. Storage of materials should meet all requirements specified in the fire codes and the regulations of environmental and occupational health and safety agencies in your jurisdiction.

9. Judicial use of Proper Type of Energy

Although all forms of energy are expressed in same unit (Joules), the financial value of energy varies enormously with its grading. Some of the energy forms are mentioned here in decreasing order of grading:

(a) Electrical energy (top grade energy)
(b) Mechanical energy
(c) Thermal energy
  (i) High-grade thermal energy (500 °C and above)
  (ii) Medium-grade thermal energy (150–500 °C)
  (iii) Low-grade thermal energy (80–150 °C)

For economic reasons, one should never use a higher-grade energy then required. For example, electrical energy should preferably not be used for heating purpose; instead, thermal energy, which may be obtained directly by burning of fuel or solar thermal system, may be used.

10. Judicial use of Proper Type of Fuel

A cheaper primary source should be preferred wherever possible in place of a costly one. For example, coal (gasified, pulverized or other forms) and bio-fuel, etc. which are relatively abundant or renewable, may be considered in place of oil or gas, which are costlier and nonrenewable.

11. Training of Manpower

Manpower should be trained to adopt habits in efficient use of energy.

12. Adopting Daylight Saving Time

Daylight Saving Time may be adopted to save a significant amount of energy during certain season in a year. In summer, when the sun rises early the clock may be set one hour ahead of the local standard time. This increases the number of useful hours of the daylight and provides extra sunlight in the evenings. Due to this, daily activities of many people finish earlier and the bedtime come soon after it is dark. As a result, they do not have to use artificial light and could save fuel and electricity. The idea of daylight saving was introduced by Benjamin Franklin in 18th century to the people of Paris but it was not adopted then. Later during World War I, daylight saving laws were passed. Germany was the first country to adopt daylight saving time in 1915, followed by England (1916) and the US (1918).

13. Proper Operation and Maintenance

The system should be monitored to operate on optimum working conditions. Leakages must be carefully plugged. Proper lubrication should be maintained in moving parts. Proper thermal insulation should be utilized in thermal systems.

2.8 COGENERATION

A procedure for generating electric power and useful heat in a single installation is known as cogeneration. Heat may be supplied in the form of steam, hot water or hot air. The net result is overall increase in the efficiency of fuel utilization.

2.8.1 Cogeneration Principles

1. The Topping Cycle

Primary heat (heat at high temperature) is used to generate high pressure and temperature steam for electrical energy generation. The discharged low-grade heat, which would otherwise be dispersed to environment, is utilized in an industrial process or in other ways.

2. The Bottoming Cycle

Primary heat at high temperature is used directly for industrial process requirements. Remaining low-grade heat is then used for electrical power generation, e.g. high temperature cement kiln.

Cogeneration is advisable for industries, which can produce electricity cheaper and more conveniently than bought from utility.

The efficiency, η_{co} of a cogeneration plant is given by:

$$\eta_{co} = \frac{E + \Delta H_s}{Q_A}$$

where E = electric energy generated

ΔH_s = heat energy utilized from process steam (or hot water)

Q_A = heat added to plant (in coal, fuel, etc.)

For separate generation of electricity and process steam, the heat added per unit of total energy output is:

$$\frac{e}{\eta_e} + \frac{(1-e)}{\eta_h}$$

where e = electrical fraction of total energy output

$$e = \frac{E}{E + \Delta H_s}$$

η_e = efficiency of electric plant

η_h = efficiency of process steam generation plant

The overall efficiency, η_c of separate generation of electricity and process heat is given by:

$$\eta_c = \frac{1}{\dfrac{e}{\eta_e} + \dfrac{(1-e)}{\eta_h}}$$

Cogeneration is economical only if the efficiency of the cogeneration plant exceeds that of overall efficiency of separate generating plants of electricity and heat.

2.8.2 Cogeneration Systems

There are three general types of cogeneration systems:

1. Waste Heat Utilization

The major purpose of this system is to generate electricity (i.e. by a utility in a central power system) with heated water as a byproduct. The heat thus available can be used at a location near electric power plant. This type of cogeneration is referred to as *waste heat utilization*.

The heat discharged in steam turbine condenser cooling water from an electric power generation plant is utilized for some beneficial purpose. About 50 to 65 per cent of the heat either supplied by fossil fuel or by nuclear fuel in existing steam plants is removed by cooling water. This heat is dissipated to environment by direct discharge of warm water to the ocean or river by passing through a cooling lake or cooling tower. Various possibilities are being considered for the large amount of heat that is lost in this way.

(a) Space Heating and Cooling Warm water can be distributed to homes, offices, stores and industry for space heating and domestic use. This is referred to as district heating. Cooling could also be achieved with hot water using absorption-cooling principle. However, to be useful for space heating and cooling, the temperature of water should be 49–100 °C.

(b) Warm Water in Agriculture Warm water at a temperature 24–46 °C can be used to heat greenhouse, soil warming to extend growing season of trees and vegetables in winter.

(c) Warm Water in Aquaculture The yield of fish from a given pond relative to nutrients supplied increases if a temperature of about 32 °C is maintained throughout the year. An essential requirement for economic aquaculture is a supply of low cost nutrients. Various small plants and animal organisms upon which fish normally feed can also be produced in warm water ponds supplied with various animal and food processing wastes.

2. Total/Integrated Energy System for Residential Complex

This system is designed to meet both the electrical demand (for lighting, refrigeration, domestic electrical appliances, elevators, etc.) and heat demand (for hot water and space heating and cooling) of a large building complex or a community. The TES (Total Energy System) is a self-contained system, which works independent of external power sources. The IES (Integrated Energy System) is more flexible utility connected system and can buy from or sale energy to utility depending upon power demand and availability situation.

A total energy system utilizes a heat engine (diesel engine, gas turbine or steam turbine) to convert a part of heat to useful mechanical energy, which in turn is converted to electrical energy by a generator. The remaining rejected heat is used for thermal requirements. The electric generation efficiency of total energy system may be lower than that of a central station power plant, but the utilization of rejected heat that would otherwise be dissipated to surroundings can result in an increase of some 25 per cent in overall fuel utilization efficiency.

3. Total Energy System (TES) for Industry

Here, the objective is to produce both, total electricity and industrial process heat required in an industry. All thermal operations are integrated. The heat component may be supplied in the form of steam, hot water and/or hot air. Many industries (e.g. petroleum refineries, chemical plants, pulp and paper industries, etc.) use large amount of process heat as well as electrical energy to operate pumps, etc. In these cases cogeneration can result in 30 per cent saving of fuel compared to separate generation of electricity and process heat.

Example 2.1

An industry has a daily requirement of 200 tons of coal to meet its electrical energy and thermal energy requirements of 1.2×10^6 MJ and 1.6×10^6 MJ respectively. It uses a cogeneration plant for this purpose. What is the overall efficiency of the plant? If it makes use of two separate plants for electrical and thermal power production instead of a cogeneration plant, what will be the combined overall efficiency? The efficiency of the individual electrical and thermal plants is 30 per cent and 80 per cent respectively. The heating value of the coal may be assumed as 20 MJ/kg.

Solution

Total thermal input to the plant $Q_A = 200 \times 10^3 \times 20 = 4 \times 10^6$ MJ

Electrical energy generated $E = 1.2 \times 10^6$ MJ

Heat energy generated $\Delta H_s = 1.6 \times 10^6$ MJ

The efficiency of cogeneration plant,

$$\eta_{co} = \frac{E + \Delta H_s}{Q_A} = \frac{1.2 \times 10^6 + 1.6 \times 10^6}{4 \times 10^6} = 70\%$$

The electrical fraction of total output,

$$e = \frac{E}{E + \Delta H_s} = \frac{1.2 \times 10^6}{1.2 \times 10^6 + 1.6 \times 10^6} = 0.4286$$

Given, the efficiency of electrical plant, $\eta_e = 30\%$

Also, given, the efficiency of thermal plant, $\eta_h = 80\%$

The overall efficiency for separate generation of electrical and thermal energy is given by:

$$\eta_c = \frac{1}{\frac{e}{\eta_e} + \frac{(1-e)}{\eta_h}} = \frac{1}{\frac{0.4286}{0.30} + \frac{0.5714}{0.80}}$$

$$= \frac{1}{1.4286 + 0.714} = 0.466$$

$$\eta_c = 46.6\%$$

2.9 COMBINED CYCLE (BINARY CYCLE) PLANTS

In combined cycle plant, electric power is produced using two heat engines in tandem as prime movers. The heat discharged from one heat engine is not wasted into atmosphere but serves as the source for the next heat engine. The net result is a greater overall operating temperature range (i.e. between the initial heat source and final heat sink) than is possible with a single heat engine. The thermal efficiency of combined cycle system is thus greater than that for the two heat engines operating independently.

The highest inlet steam temperature for a steam turbine is limited by the properties of the materials to about 540 °C (and pressure of 155 kg/cm^2). However, the flame temperatures of burning fossil fuel in a boiler may be more than 1650 °C. Consequently in a combined cycle system, steam turbine is preceded by a topping cycle heat engine, which can utilize heat at higher temperatures. The working fluid leaves the topping cycle at a sufficiently high temperature to generate steam for the steam turbine.

Because the technology is well developed for the gas turbine, it is most commonly used as a topping cycle engine. The turbine exhaust gases at a temperature of 600°C or more pass through a waste heat (heat recovery steam generator) boiler where steam is produced from water under pressure. In addition to using fuel more efficiently, a combined gas and steam turbine generating system requires lesser condenser cooling water for a given electrical output than a steam turbine generator alone.

Gas turbine works on Brayton cycle and has an efficiency of about 20 per cent. The steam turbine works on Rankine cycle and has an efficiency of about 35 per cent. The efficiency of combined cycle power plant is about 45–50 per cent. Figures 2.6–2.9 show various schemes of open cycle and combined cycle power plants.

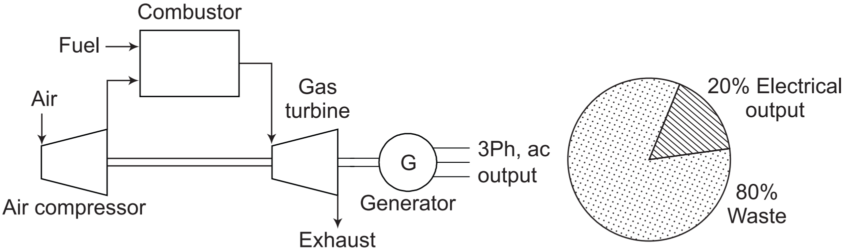


Figure 2.6 (a) Open cycle (simple cycle) gas turbine power plant

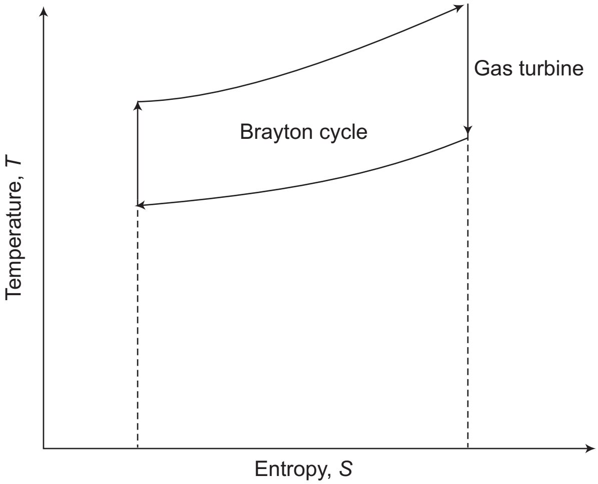


Figure 2.6 (b) T-S diagram of open cycle (simple cycle) gas turbine power plant

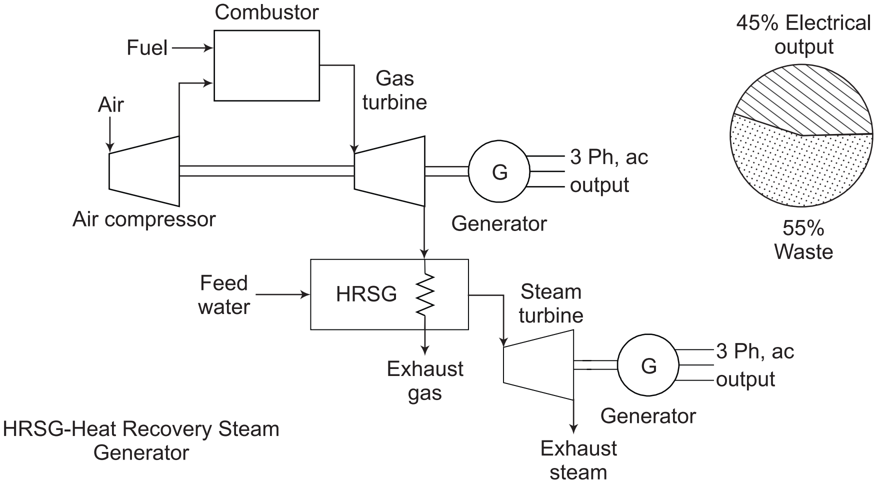


Figure 2.7 (a) Combined cycle power plant

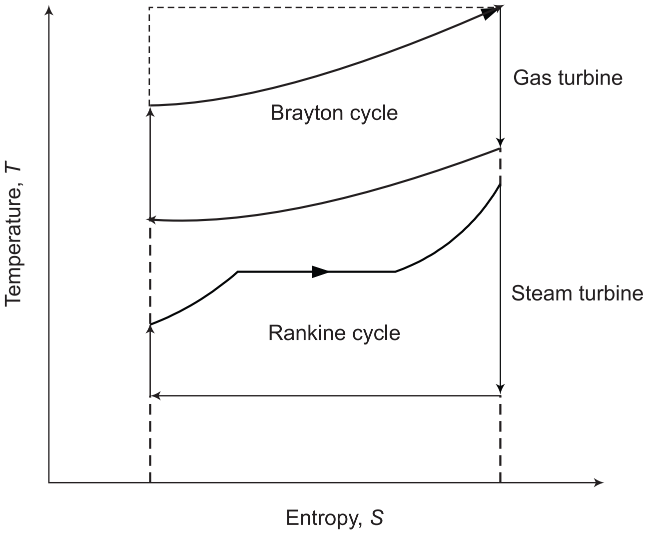


Figure 2.7 (b) T-S diagram of combined cycle power plant

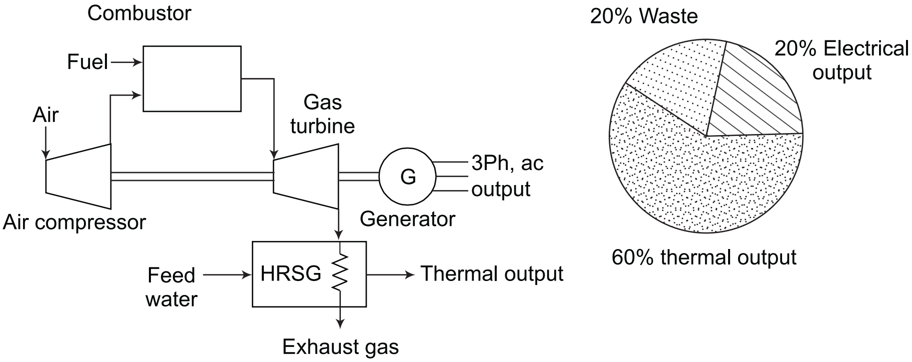


Figure 2.8 Open cycle (simple cycle) gas turbine power plant with cogeneration

An Integrated Gasification Combined Cycle (IGCC) generating plant uses a cheaper fuel, i.e. coal, after converting it to gas. Gasification is the cleanest method of utilization of coal, while combined cycle generation gives maximum efficiency. There is no air pollution due to fly ash, as it is collected as bottom ash in the gasifier and CO_2 emissions are also much less compared to coal combustion in solid form. In IGCC plant, gasification of coal along with combined cycle generation is integrated in a single installation. The higher efficiency of IGCC also results in reduction in coal consumption per MW of power generated. Cogeneration, utilizing waste heat would further increase the efficiency. It is being developed indigenously by BHEL, India.

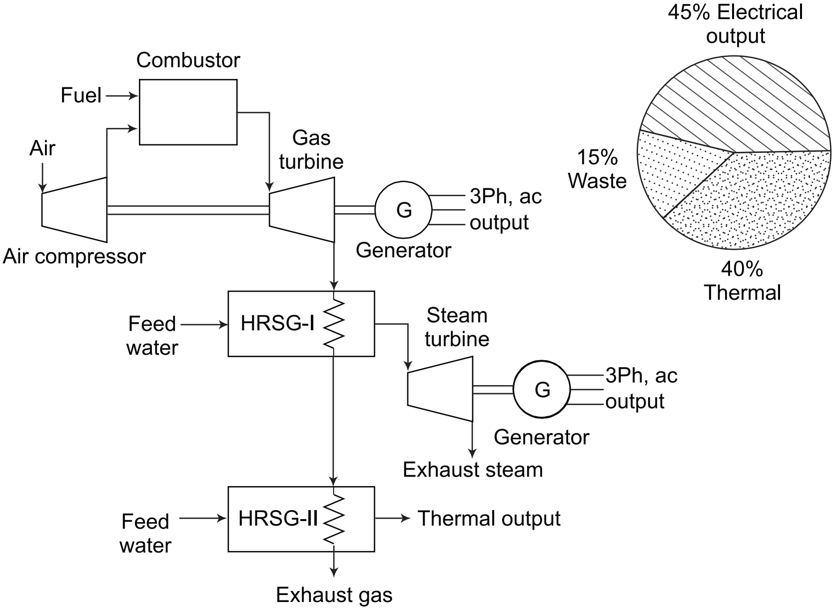


Figure 2.9 Combined cycle power plant with cogeneration

REVIEW QUESTIONS

1. What do you understand by energy conservation? Explain its various aspects.
2. For solving problem of increased energy demand evaluate the benefits of energy conservation as compared to increasing the generation capacity.
3. Write your views on the energy planning issues aiming to bridge the gap between energy demand and supply situation in India.
4. How much energy saving potential exists in Indian industry without any major investment?
5. What do you understand by energy audit?
6. What is meant by ECOs and ECMs? Enumerate some general ECOs.
7. Explain different categories of ECOs. Explain ECOs of electrical industry.
8. Explain the terms energy management, energy policy and energy planning.
9. What do you understand by cogeneration? How is TES different from Integrated Energy System?
10. Explain the principle of waste heat utilization and its various applications.
11. Why a binary cycle plant is more efficient than an open cycle plant? Comment on the amount of energy saved by using gas–steam binary cycle plant instead of a simple open cycle steam turbine based generating plant.
12. What are the advantages of an IGCC generating plant?
13. What are various principles of energy conservation?

14. Explain the concept of daylight saving as a means for energy conservation.

15. Explain various aspects of energy conservation.

PROBLEMS

1. An industry requires 20 MW electrical power and 40 MW process heat for production. There are two alternative options to meet the requirements: (i) use a cogeneration unit having an overall efficiency of 65 per cent or (ii) use two separate units for electrical and thermal outputs. The efficiencies of electrical and thermal power units are 25 per cent and 80 per cent respectively. Which option out of the above two will best serve the interest of the owner on the basis of overall efficiencies in each case?

(Ans. Cogeneration)

OBJECTIVE TYPE QUESTIONS

1. Why should energy conservation be encouraged?
(a) To halt further growth of GDP.
(b) To encourage use of manual labour.
(c) To discourage people using luxuries.
(d) To conserve non-renewable energy sources and environment.

2. What percentage of energy saving potential exists in the total spectrum of industries in India?
(a) 5%
(b) 50%
(c) 20%–25%
(d) 90%

3. Energy conservation means:
(a) reducing energy consumption by reducing the production.
(b) reducing the energy consumption without compromising the quantity or quality of production.
(c) increasing the output by consuming more energy.
(d) reducing energy consumption by reducing the output.

4. Energy audit is carried out:
(a) to check energy theft.
(b) to verify adherence of rules and regulations in financial matters.
(c) to calculate total annual energy consumed by a user.
(d) to check any lapses in respect of efficient use of energy and to suggest measures for its correction.

5. Recycling of waste:
(a) encourages production of second grade product.
(b) conserves both material and energy.
(c) causes environmental pollution.
(d) consumes more energy as compared to manufacturing from fresh material.

6. Cogeneration means:
(a) power production using binary cycle.
(b) power production using two types of primary energy sources.
(c) generation of ac as well as dc powers in the same installation.
(d) generation of electricity and heat in a single installation.

7. From energy conservation point of view, which type of energy source would you prefer for the purpose of space heating in winter:
(a) electrical energy.
(b) low grade thermal energy available as a byproduct of a process
(c) heat energy available from burning of petrol
(d) heat energy available from burning of biomass

8. Simple electrical ECOs:
(a) increase the power consumption
(b) are difficult to implement
(c) are very expensive to implement
(d) require least cost

9. The potential of saving through energy conservation exists:
(a) in all sectors of economy
(b) in domestic sector only
(c) in agriculture sector only
(d) in industrial sector only

10. Energy intensity is:
(a) per capita energy consumption
(b) percentage change in energy consumption to achieve one percent in national GDP
(c) amount of energy consumed for generating one unit of GDP
(d) energy saving using efficient energy techniques

11. Which sector consume maximum commercial energy in India?
(a) Agriculture
(b) Industry
(c) Residential
(d) Transport

12. Preliminary energy audit:
(a) identifies the potential of energy saving by replacement / retrofitting of existing machinery
(b) identifies immediate measures, especially no cost / low cost for saving of energy
(c) concentrates on the lighting system only
(d) concentrates on heating system only

CHAPTER 3

Energy Storage

Learning Objectives

In this chapter you will be able to:

- ➤ Describe concept of energy storage
- ➤ Identify situations where energy storage becomes necessary
- ➤ Compare of various energy storage devices and identify suitability of a device for specific applications
- ➤ Explain the principle of various energy storage techniques, their advantages and limitations

3.1 INTRODUCTION

In contrast to fossil fuel and nuclear fuel based energy, the initial input power of renewable energy source is outside our control. The use of renewable energy supplies constitutes a diversion of a continuing natural flow of energy; there are problems in matching supply and demand in time domain, i.e. matching the rate at which energy is used. The mismatch varies with time, on scales of months (e.g. house heating in temperate climate), days (e.g. artificial lighting) and even seconds (e.g. starting motors).

Energy storage can be defined as means of storing energy in a readily recoverable form when the supply exceeds the demand for use at other times. Storage of primary fuels (e.g. coal, oil and gas) is also a form of energy storage, but the term 'energy storage' generally applies to secondary energy rather than primary energy.

The performance of various energy storage devices can be compared on the basis of **Ragone charts** as shown in Fig. 3.1. On this chart the values of specific energy (in Wh/kg) are plotted against specific power (in W/kg). Both axes are logarithmic, which allows comparing performance of very different devices. The vertical axis describes how much energy is available, while the horizontal axis show how quickly

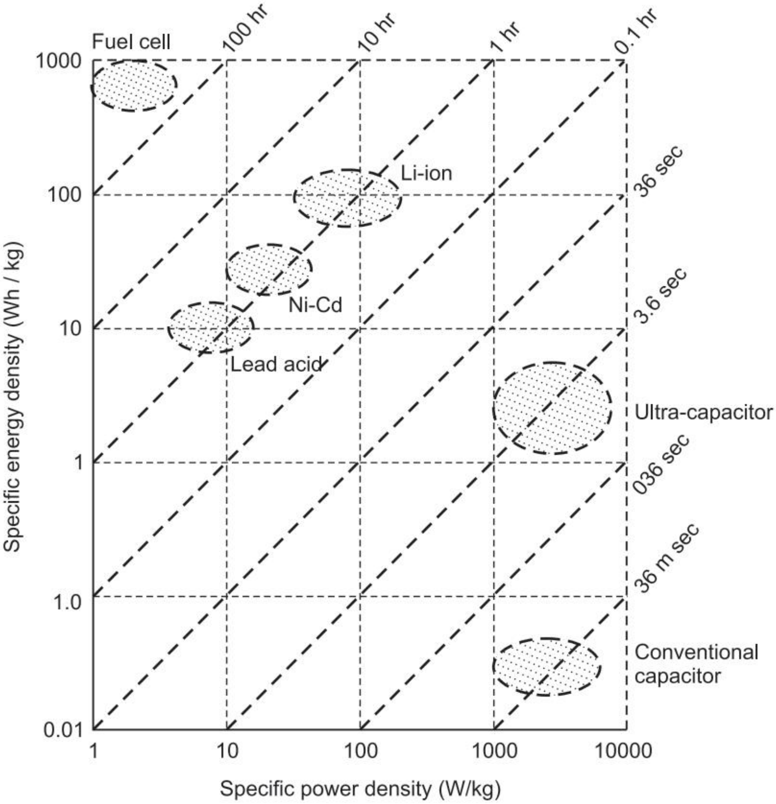


Figure 3.1 Ragone Chart

that energy can be delivered. For example, powering a small light bulb may require small amount of power, but the power should be delivered steadily for many hours of use, demanding large energy requirement. Conversely, a high-speed electronic switch inside a computer may require very little energy to activate: yet it must be delivered within few microseconds. These two types of loads would be represented at opposite corners of Ragone chart.

3.2 NECESSITY OF ENERGY STORAGE

1. The effective utilization of intermittent and variable energy source such as solar, wind, etc., often requires energy storage.
2. In some circumstances, electrical energy may be generated either on land or at sea, at a location that is too distant from a consumption center for conventional transmission lines to be used, for example Ocean Thermal Energy Conversion. Means must then be found for both storing the energy and transporting it economically to a load center.
3. Electrically Propelled Vehicles, which are expected to come into increasing use, require some form of energy storage. Since the vehicle must carry its energy supply, the storage system must be readily transportable.
4. Energy storage is also required for 'load leveling' in an electric utility to reduce the overall cost of generating electrical power. More efficient plants may be operated continuously at rated power level; the excess power during off peak period is stored for use when the demand exceeds the base load. Thus the use of less efficient units to meet the additional demand for power during peak load period is eliminated. Thus it allows operational flexibility. In addition to this, energy storage also contributes to reliability, efficiency, power quality, transmission optimization and black start functions.

3.3 SPECIFICATIONS OF ENERGY STORAGE DEVICES

All energy storage devices can be broadly categorized on the basis of few parameters: self-discharge time, unit size and efficiency. Within a category, finer selection of storage technology can be made on the basis of life cycle, specific energy, specific power, energy density, and power density.

Self-discharge time is the time required for fully charged, non-interconnected storage device to reach a certain depth of discharge (DOD). Acceptable self-discharge times vary greatly, from a few minutes to years depending on application.

Unit size describes the intrinsic scale of the technology. Some technologies have a fairly large unit size that prohibits small-scale energy storage. Similarly, if unit size is small, large number of units will be required to realize large capacity storage, increasing complexity and cost of the storage.

Efficiency is the ratio of energy output to the energy input in an energy storage system, including terminal equipment.

Cycle life is the number of consecutive charge-discharge cycles a storage installation can undergo while maintaining the installation's other specifications within specified limits.

Specific energy is measured in terms of units of energy per mass of storage system, for example MJ/kg.

Energy density is measured in terms of units of energy per volume of storage system, for example MJ/L.

3.4 ENERGY STORAGE METHODS

Energy can be stored in various forms and the storage methods are classified on the basis of the form in which it is stored. Some of the important energy storage methods are:

1. Mechanical energy storage
    - (a) Pumped storage
    - (b) Compressed air storage
    - (c) Flywheel storage
2. Electrochemical energy storage (Secondary battery storage)
3. Electrolytic hydrogen storage
4. Reversible chemical reaction energy storage
5. Electromagnetic energy storage
6. Electrostatic energy storage
7. Thermal (heat) energy storage
    - (a) Sensible heat storage
    - (b) Latent heat storage
8. Biological storage

3.4.1 Mechanical Energy Storage

1. Pumped Storage

Pumped storage is the most successful, economical and widely used energy storage technology presently available to electrical utilities for load leveling (peak shaving). It could also be used for storing electrical energy produced from solar and wind energy. Electrical power in excess of immediate demand is used to pump water from a supply (lake, river or reservoir) at a lower level to a reservoir at a higher level. During peak demand period when the demand exceeds the normal generating capacity, water is allowed to flow backwards through a hydraulic turbine, which drives an electric generator and produces power to meet additional demand. The layout diagram of typical pumped storage system is shown in Fig. 3.2.

In most pumped storage plants, the turbine generator system is reversible and can serve to pump water as well. In pumping mode, the generator works as motor and draws electrical power from the electrical network. The turbine then operates as pump, driven by the motor. Start-up of turbine-generator or reversal from motor-pump to turbine-generator requires only a few minutes. The overall energy recovery efficiency of pumped storage, that is, the recovered electrical energy as percentage of electrical energy used to pump water, is about 70–80 per cent. Pumped storage facilities up to the size of 1000 MW presently exist.

There are relatively few suitable sites where there is water supply at a lower level and a reservoir can be constructed at a higher level. However, the use of natural or excavated underground caverns as lower reservoir, now being developed, should greatly increase the number of possible sites.

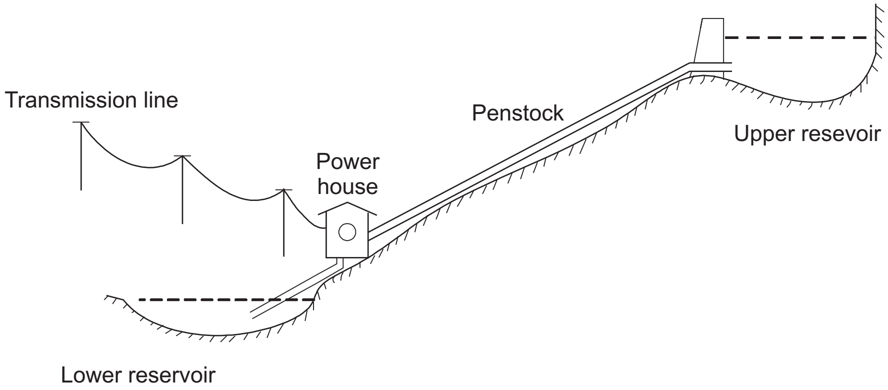


Figure 3.2 Pumped storage system

2. Compressed Air Energy Storage (CAES)

In CAES system, excess electrical energy is used to compress air, which is stored in a reservoir to be used later in combustor of a gas turbine to generate electric power. In a conventional gas turbine, roughly 60 per cent of the power generated by the turbine is consumed by the compressor supplying air to the combustion chamber.

A CAES facility performs the work of the compressor separately, stores the compressed air, and at a later time injects it into a simplified combustion chamber. Such a simplified turbine produces far more energy than a conventional turbine from the same fuel. The net efficiency of storage for CAES plant is limited by the heat energy loss occurring at compressor. The overall recovery efficiency of the storage is about 65 to 75 percent.

Electric power in excess of immediate demand is supplied to the motor/generator unit which drives the compressor. The compressed air, at about 70 atm., is stored in a suitable reservoir. The air is heated during compression and may have to be cooled prior to storage to prevent damage to the reservoir walls. When additional power is needed to meet the demand, the compressed air is released and heated in a combustor using gas or oil fuel. The hot compressed air is then expanded in a gas turbine connected to the motor/generator unit which now acts as generator. The schematic diagram is shown in Fig. 3.3. Clutch is used for coupling and decoupling the motor/generator unit with compressor/turbine.

Compressed air storage reservoirs would probably be too large and too expensive for above ground construction; hence underground reservoirs preferably the naturally existing ones, are being considered. Among the possibilities are natural caverns, deep aquifers, depleted gas or oil reservoirs, mined out rocks or salt caverns, and abandoned mines. The first commercial CAES facility was a 290 MW unit built in Huntorf, Germany in 1978. The second commercial installation was 110 MW unit built in McIntosh, Alabama in 1991.

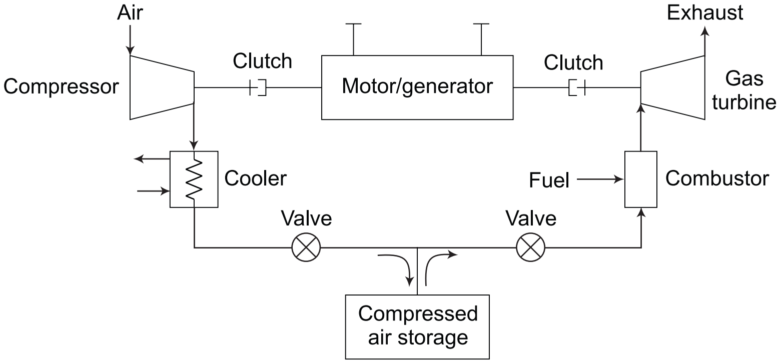


Figure 3.3 Compressed air energy storage

3. Flywheel Storage

Flywheels have been used extensively to smooth out power pulses from reciprocating engines. Same principal may be extended to store surplus electric energy. A specially designed flywheel, known as *super flywheel* is used for energy storage. The flywheel driven by an electric motor during off peak hours, stores mechanical energy (kinetic energy) as its speed is increased. The stored energy may be retrieved when required to produce electrical energy by coupling a generator to it. The same machine serves both as a motor when electric energy is supplied and as a generator when flywheel serves as a prime mover and electrical energy is regenerated. The energy recovery efficiency is estimated to be in upper 90 per cent range depending on frictional losses.

The kinetic energy of rotation of an object is:

$$E = \frac{1}{2} I\omega^2$$

where, I is moment of inertia of the object about its axis, and ω is its angular velocity (rad/s). For a uniform disk of mass m and radius a, the moment of inertia, I is given by:

$$I = \frac{1}{2} ma^2$$

Thus energy density of a uniform disk is:

$$W_m = \frac{E}{m} = \frac{1}{4} a^2\omega^2$$

When energy is added to the flywheel its speed rises to a higher value. Similarly when energy is retrieved its speed falls. For a flywheel, to serve as useful store of energy (and not just a smoothing device), it must rotate as fast as possible. However, its angular velocity is limited by strength of the material, which has to resist the centrifugal forces tending to fling it apart. For a uniform wheel of density ρ, the maximum tensile stress is:

$$\sigma_{\max} = \rho\omega^2 a^2$$

In general for a particular shape,

$$W_m = \frac{1}{4} K a^2 \omega^2$$

and

$$W_{m,\,\max} = \frac{K\sigma_{\max}}{4\rho}, \qquad \text{where } K \text{ is a constant} \cong 1.$$

Conventional materials such as steel give rather low energy densities (typically 0.06 MJm^{-3}). Much higher energy densities can be obtained by using lightweight fiber composite materials, such as fiberglass in epoxy resin, which have higher tensile strength $\sigma_{\max}$ and lower density ρ. To make best use of these materials, flywheels should be made in unconventional shapes with the strong fibers aligned in the direction of maximum stress. Such systems can have energy densities of 0.5 MJ/kg or even higher.

Advanced (or super) flywheels are those, which operate at very high speed, have high mechanical strength and low frictional losses. For eliminating bearing friction, the rotor can be magnetically levitated by permanent magnets. Wind friction is eliminated/reduced by putting the flywheel in sealed vacuum chamber. These super flywheels are used for storing mechanical energy for long/short-term basis.

Flywheel storage can be installed anywhere and take up little land area, a distinct advantage over pumped storage. Units with 100 tons flywheel would have a storage capacity of about 10 MWh. Larger storage demands would probably best be met by cascading many such units. Mobile storage is also possible with flywheel.

Some of the key features of flywheels are low maintenance, a cycle life of better than 10,000 cycles, a 20 years lifetime and environmental friendly materials. Flywheels offer an interesting alternative to storage batteries for use in battery-powered vehicles, especially since the energy in a flywheel can be replenished more quickly than a battery. In power system, flywheels can serve as a short-term ride-through before long-term storage comes alive.

3.4.2 Electrochemical Energy Storage: Secondary Battery Storage

A secondary battery allows electrical energy to be converted into chemical energy, stored and converted back to electrical energy. Thus both input and output are in the form of electrical energy though storage is in the form of chemical energy. Due to this reason some people classify it in the category of electrical storage. Batteries are made up of three parts: a negative electrode, positive electrode and an electrolyte. The speed at which chemical reaction takes place between electrodes and electrolyte is related to the internal resistance that dictates the maximum power at which the batteries can be charged and discharged.

Advantages of storage batteries can be listed as follows:

1. These are modular in nature and are easily adaptable to any type of storage with varying capacity by suitably combining a number of units.
2. These are capable of rapid reversal of operation between charging and discharging. This makes the batteries especially convenient for electric utility applications.

3. They permit dispersed distribution by locating storage facilities near load centers.

Storage batteries can be classified into the following types:

(a) Lead–Acid Battery

Although many electrochemical reactions are reversible in theory, few are suitable for a practical storage battery. The most widely used storage battery is the *lead acid battery*, invented by Gaston Plante of France in 1859. The lead acid battery technology has attained maturity and has high performance over cost ratio, even though it has the least energy density by weight (0.18 MJ/kg) and volume (0.25 MJ/L) compared to other rechargeable batteries. The specific power is 180 W/kg.

Theory A battery consists of a combination of individual cells. In any electrochemical cell, two plates (positive and negative) are immersed in a conducting solution (electrolyte). In this case the plates are in the form of grids, holding pastes of lead and lead oxides respectively. The electrolyte is sulphuric acid, which ionizes as H^+ and HSO_4^-. Figure 3.4 shows one such cell.

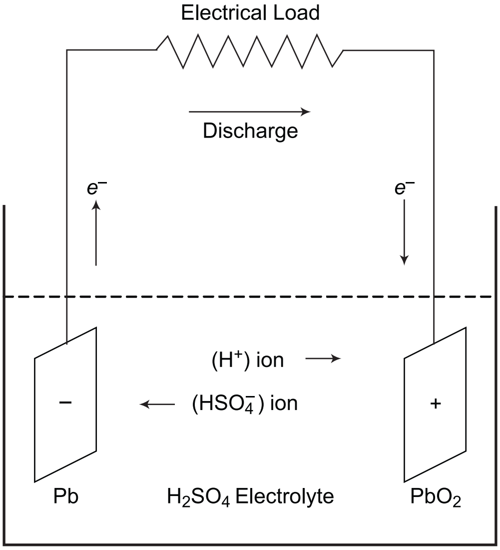


Figure 3.4 Lead–acid cell

During Discharge The reaction at the negative electrode is given by:

$$Pb + HSO_4^- \rightarrow PbSO_4 + H^+ + 2e^-$$

The lead at negative electrode is converted to lead sulphate and takes the place of lead paste in the plate. The electrons so liberated travel through the external circuit to the positive electrode.

The reaction at the positive electrode is:

$$PbO_2 + HSO_4^- + 3H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$$

This $PbSO_4$ likewise replaces the PbO_2 in that plate. The electrical current through the solution is carried by H^+ and HSO_4^- ions through the sulphuric acid. The reactions are reversed during charging operation and original active materials are regenerated at positive and negative plates.

The emf of lead acid cell depends on concentration of sulphuric acid. The voltage of a fully charged cell is close to 2.1 volts and specific gravity of the electrolyte is 1.26 at 25°C. On discharge the sulphuric acid is consumed at both electrodes, as both Pb and PbO_2 are converted to lead sulphate and water is produced, which dilutes the acid. With acid concentration the emf of the cell also decreases steadily. The cell is generally regarded as fully discharged when the specific gravity is about 1.08 at 25°C and the emf is roughly 1.7 volts. Both acid concentration and emf are restored when the cell is charged. During discharge, the specific gravity of the electrolyte falls linearly according to the equation:

$$\text{Specific gravity, SG} = \text{Open Circuit Cell Voltage} - 0.84 \text{ (for SG} > 1)$$

The amounts of active materials do not affect the cell emf, but they determine the energy storage capacity of the cell (or battery). The storage capacity is increased by increasing the area of active materials exposed to the electrolyte. This is achieved by connecting in parallel a substantial number of alternate positive and negative plates.

Lead acid batteries are commonly used as mobile source of energy for starting-lighting-ignition (SLI) system of automobiles. Except when starting the engine, the current drain from the battery is relatively small. Also these are nearly always maintained in a full charged state by the generator coupled to the engine.

Batteries for emergency or portable power systems, vehicle propulsion and electric utility applications, however, may be subjected to almost complete (or deep) discharge before being recharged. Special heavy-duty batteries are needed to withstand a series of such deep charge-discharge cycles. Tubular positive plates are often utilized in heavy-duty batteries. The plates are actually a set of connected tubes, made from an inert porous material (e.g. woven glass or plastic fibers), containing chemically prepared active lead dioxide. A central spine of lead provides electrical connection.

Limitations of Lead–Acid Storage Batteries Chief limitations are high cost and short life of the battery.

1. Battery life is limited due to two reasons mentioned below:
    - Solid Pb is almost twice as dense as $PbSO_4$ formed during discharging process. Therefore, it is difficult to fit the $PbSO_4$ crystals into the space originally occupied by the Pb paste in the negative electrode. In practice some $PbSO_4$ falls to the bottom of the cell during every discharge. This constitutes an irreversible loss of active material.
    - In SLI batteries of automobiles, the material of the grid is not pure lead but a lead-antimony alloy, which is stronger and better able to withstand the mechanical stresses during motion. But this causes self-discharge of positive electrode as antimony promotes following reaction:

      $$5PbO_2 + 2Sb + 6H_2SO_4 \rightarrow (SbO_2)_2SO_4 + 5PbSO_4 + 6H_2O$$

      This slow but irreversible reaction removes active material from the plate and reduces the life of the battery. Normal life of SLI battery is one to two years.

    Batteries for stationary applications (Photovoltaic lighting systems etc.) can use Sb free plates and have longer life (up to 7 years) if not excessively discharged.

2. An ordinary battery cannot be allowed to discharge more than about 50 per cent of its stored energy. Such a discharge is known as deep discharge. Sometimes it may not be possible to recharge or revive the battery after a deep discharge. The reason is explained below:
   If the discharge reaction is allowed to go to completion, all the lead may be consumed and there would be no electrode left for reverse reaction. Similarly, if the concentration of H_2SO_4 is allowed to fall too low, the electrolyte ceases to be an adequate conductor.
3. Heavy weight of the battery is another serious drawback. Non-active materials (separators, case, water etc.) contribute significantly to the total weight of the battery. Therefore, the specific energy of lead acid storage battery is low (typically 0.18 MJ/kg). It also has poor energy density, typically of the order of 0.25 MJ/L.
4. The cost of the battery storage is high.
5. The internal impedance of a battery is high, which cause voltage fluctuations during transient load.
6. Leaving the battery in a discharged condition causes sulphation and a recharge may not be possible.

Sulfation Lead–acid batteries lose the ability to accept a charge when they remain charge deprived for too long, due to *sulfation*, the crystallization of lead sulfate.

In normal operation, during discharge, lead and lead dioxide, the active materials on the battery's plates, react with sulfuric acid in the electrolyte to form lead sulfate. The lead sulfate first forms in a finely divided, amorphous state, and easily reverts to lead, lead dioxide and sulfuric acid when the battery recharges. As batteries cycle through numerous discharges and charges, some lead sulfate is not recombined into electrolyte and slowly converts to a stable crystalline form that no longer dissolves on recharging. Thus, not all the lead is returned to the battery plates, and the amount of usable active material necessary for electricity generation declines over time.

Sulfation occurs in lead–acid batteries when they are subjected to insufficient charging during normal operation. It impedes recharging; sulfate deposits ultimately expand, cracking the plates and destroying the battery. Eventually so much of the battery plate area is unable to supply current that the battery capacity is greatly reduced. In addition, the sulfate portion (of the lead sulfate) is not returned to the electrolyte as sulfuric acid. It is believed that large crystals physically block the electrolyte from entering the pores of the plates.

Sulfation can be avoided if the battery is fully recharged immediately after a discharge cycle. Batteries that are sulfated show a high internal resistance and can deliver only a small fraction of normal discharge current. Sulfation also affects the charging cycle, resulting in longer charging times, less efficient and incomplete charging, and higher battery temperatures.

Desulfation is the process of reversing the sulfation of a lead–acid battery. It is believed that desulfation can be achieved by high current pulses produced between the terminals of the battery. It is believed that this technique, also called *pulse conditioning*, breaks down the sulfate crystals that are formed on the battery plates.

Acid Stratification Accumulation of sulfuric acid at the bottom of the cell is called acid stratification. Lead acid battery electrolyte is a mixture of water and sulfuric acid. Sulfuric acid is heavier than water. So, when the battery is not in use, the acid tends to settle down at the bottom of the cell. Stratification also occurs if the battery is regularly charged partly up to around 80-85% only and not charged fully.

When a battery is in storage, there is more sulfuric acid at the bottom, and the bottom part of the lead plates start sulfating faster and to a greater degree than the rest of the plates. The low concentration of acid at the top induces higher corrosion and lesser plate activation. As a remedy, equalizing charge is given for a couple of hours. Equalizing charge is the charge that is 10% higher than the recommended charge level. It induces electrolysis, which mixes the electrolyte well, due to bubbling of H_2 and O_2.

Valve Regulated Lead Acid Battery (VRLA Battery) The lead acid battery discussed above is also known as *flooded lead acid battery* (or wet cell battery). During overcharging, oxygen evolved at positive plate and hydrogen evolved at negative plate leave the battery, leading to loss of water. *Valve regulated lead acid* (VRLA) battery, (also known as maintenance free battery) is a variant of lead acid battery. The electrolyte is immobilized in some manner and the battery is sealed under normal operating conditions. Therefore, it can be used in any orientation. Under excessive overcharge, the normally sealed vents open under gas pressure. This battery is designed in such a way that evolved H_2 and O_2, as a result of overcharge, recombine to produce water. In these batteries, valve is provided as a safety feature to allow H2 evolution out of the battery, for the situation when hydrogen pressure build up is dangerously high (and can cause explosion). VRLA batteries are much more expensive than ordinary lead-acid batteries.

The two most common VRLA battery designs are (i) the *absorbed glass mat* (AGM) and (ii) the *gelled* electrolyte designs. Minimum required electrolyte in an AGM battery is absorbed in glass mats which are sandwiched in layers between the plates. Gel batteries use sulfuric acid that has been turned into a gel form. VRLA batteries are much costlier as compared to flooded lead acid battery. Special care is required during their charging and discharging.

Example 3.1

A lead acid battery cell is allowed to discharge up to a level of 1.84 V. At full charge the specific gravity of electrolyte is 1.26. Calculate the specific gravity at discharge. Also calculate the voltage at full charge.

Solution

For lead acid cell,

$$\text{SG} = \text{open circuit cell voltage} - 0.84$$

At discharge:

$$\text{SG} = 1.84 - 0.84 = 1.00$$

At full charge:

$$\text{Voltage} = \text{SG} + 0.84 = 1.26 + 0.84 = 2.1 \text{ V}$$

(b) Nickel–Cadmium (Ni–Cd) Battery

The Ni–Cd cell has positive electrode made of cadmium and the negative electrode of nickel hydroxide. Nylon separator separates the two electrodes. The electrodes are contained in a sealed stainless steel casing having potassium hydroxide electrolyte. They have specific energy of about 0.27 MJ/kg, an energy density of 0.41 MJ/L and an efficiency of about 75 per cent.

The chemical reactions at the cadmium anode during discharge are:

$$Cd + 2OH^- \rightarrow Cd\,(OH)_2 + 2e^-$$

The reactions at the nickel oxide cathode are:

$$2NiO\,(OH) + 2H_2O + 2e^- \rightarrow 2Ni\,(OH)_2 + 2OH^-$$

The net reaction during discharge is:

$$2NiO\,(OH) + Cd + 2H_2O \rightarrow 2Ni\,(OH)_2 + Cd\,(OH)_2$$

During recharge, the reactions go from right to left. The alkaline electrolyte (commonly KOH) is not consumed in this reaction and therefore its specific gravity, unlike in lead–acid batteries, is not a guide to its state of charge.

Due to sealed casing and lightweight (half that of the lead-acid cell), these are preferred for most rechargeable consumer applications. They have a longer deep cycle life and are more temperature tolerant than the lead-acid batteries. However, this cell has memory effect, which degrades its capacity if not used up to full discharge state for a longer time. Also its disposal poses environment problems due to use of toxic, heavy metal, cadmium.

Due to these reasons Ni–Cd batteries are not common for large stationary applications.

(c) Nickel–Metal Hydride (Ni–MH or Ni–MH) Battery

In this cell the cadmium anode is replaced by metal hydride anode. This eliminates the environmental concern of cadmium. This also improves the energy density and has negligible memory effect. A NiMH battery has a specific energy of 0.29 MJ/kg an energy density of about 0.54 MJ/L and an energy efficiency of about 70 per cent. The cell voltage is 1.4 V. The NiMH cell, however, is less capable of delivering high peak power, has high self-discharge rate, is susceptible to damage due to overcharging and is more expensive compared to Ni–Cd cell.

The chemical reaction at the positive electrode is similar to that of the nickel–cadmium cell (Ni–Cd), with both using nickel oxyhydroxide (NiOOH). However, the negative electrodes use a hydrogen-absorbing alloy (MH) instead of cadmium.

During discharge, the reaction at metal hydride anode is:

$$OH^- + MH \rightarrow H_2O + M + e^-$$

The reaction at positive electrode is:

$$NiO\,(OH) + H_2O + e^- \rightarrow Ni\,(OH)_2 + OH^-$$

During recharge, the reactions go from right to left.

(d) Lithium–Ion Battery (LIB)

Lithium is the lightest of all metals, has the greatest electrochemical potential and provides the largest specific energy per weight. Lithium-ion battery is a newly developed technology and offers three times the energy density (typically 0.72 MJ/L) over that of lead acid battery. The specific energy is about 0.45 MJ/kg. This is due to: (i) low atomic weight of 6.9 for lithium versus 207 for lead and (ii) higher cell voltage of 3.7 V versus 2.0 V for lead-acid cell. This requires fewer cells in series for a given battery voltage thus reducing the cost. They have low internal resistance and efficiency in the 90 per cent range and above.

On the other hand, the lithium electrode reacts with any liquid electrolyte, creating a sort of passivation film. Every time when the cell is discharged and then charged, the lithium is stripped away, a free metal surface is exposed to the electrolyte and a new film is formed. This would shorten the life of the cell. To compensate for the loss, the cell uses thick electrode, adding to the cost.

The cathode in these batteries is lithiated metal oxide, ($LiCoO_2$, $LiMO_2$, etc.) and the anode is made of graphitic carbon, (C_6) with a layer structure. The electrolyte consists of lithium salts (such as $LiPF_6$) dissolved in organic carbonates.

The reactions during charging are:

At the cathode (marked +) half-reaction is:

$$\mathrm{LiCoO_2} \rightarrow \mathrm{Li_{1-\mathit{x}}CoO_2} + x\mathrm{Li}^+ + xe^-$$

At the anode (marked –) half reaction is:

$$x\mathrm{Li}^+ + xe^- + x\mathrm{C_6} \rightarrow x\mathrm{LiC_6}$$

When battery is charged, lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode. The electron detached from Li moves through external electric circuit towards anode. At anode, Li ions combine with external electrons and deposited between carbon layers as lithium atoms. This process is reversed during discharge. Overcharging can compromise the stability of cathode, resulting in the breakdown of the battery. Therefore, all Li-ion batteries require complex circuitry to prevent overcharging. Overheating is also the most prevalent problem especially in larger applications.

Lithium-ion batteries are used extensively in consumer electronics, but their use in large-scale applications has been limited to date. The primary reasons for delayed deployment are safety and high cost. The high price may be attributed to the high cost of cobalt and to the complex protective circuitry against overcharging and overheating, especially in large applications.

(e) Lithium–Polymer Battery

This is a slight variant of Li-ion battery. It replaces the electrolyte with a plastic film that does not conduct electricity but allows ions to pass through it. The solid polymer enhances the cell's specific energy by acting as both electrolyte as well as separator. Moreover, the metal in solid electrolyte reacts less than it does with liquid electrolyte. The result is a "plastic" cell, which theoretically could be thin, flexible, and manufactured in different shapes, without risk of electrolyte leakage. These batteries are available although the technology has not been fully developed and commercialized.

(f) Sodium–Sulphur Battery

A sodium-sulphur (NaS) battery consists of a liquid (molten) sulphur positive electrode and liquid (molten) sodium negative electrode, separated by a solid beta-alumina (β-Al_2O_3) ceramic electrolyte, as shown in Fig. 3.5.

The cell must be operated at sufficiently high temperature (270–350°C) to keep all the active electrode materials in a molten state and adequate ionic conductivity through the β-Al_2O_3 electrolyte. During discharge, the sodium (negative electrode) is oxidized at the sodium β-Al_2O_3 interface, forming Na^+ ions that migrate through the electrolyte and combine with the sulphur being reduced at the positive electrode to form polysulphides (Na_2S_x). The variable x in the equation is equal to 5 during early discharging to form sodium pentasulphide (Na_2S_5). The Na_2S_5 is immiscible with remaining sulphur, thus forming a two-phase liquid mixture. After all the free sulphur phase is consumed the Na_2S_5 is progressively converted into single phase, more sodium-rich Na_2S_x with lower average values of x. The cell open circuit voltage is 2.076 V for $x = 5$, which decreases to 1.78 V when the value of x reaches 3. The reactions during discharge are:

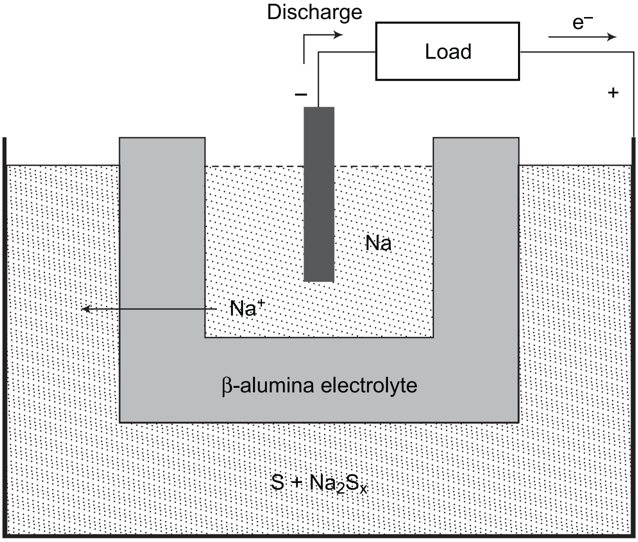


Figure 3.5 Sodium–sulphur battery

At the cathode (marked +) half-reaction is:

$$xS + 2e^- \rightarrow S_x^{-2}$$

At the anode (marked -) half reaction is:

$$2Na \rightarrow 2Na^+ + 2e^-$$

The over-all discharge reaction is:

$$2Na + xS \rightarrow Na_2S_x$$

During charge these chemical reactions are reversed. NaS batteries have a high energy density of around 0.65 MJ/L and a specific energy of 0.86 MJ/kg. The efficiency of this battery can be as high as 90 per cent and would be suitable for stationary, bulk storage applications, e.g. utility load leveling (peak shaving) and power quality, etc. In commercial applications, the cells are arranged in blocks for better conservation of heat. As the cells run, the heat produced by charging and discharging cycles is enough to maintain operating temperatures and no external heat source is required.

(g) ZEBRA Battery

Sodium-nickel-chloride batteries are also known as ZEBRA batteries (Zero Emission Battery Research Activities). ZEBRA batteries are configured similar to sodium-sulphur batteries, and also operate at about 300°C. Its efficiency is around 90 per cent, a specific energy of 0.32 MJ/kg and an energy density of 0.49 MJ/L. Its most probable application will be in automobile sector and utility sector.

During discharge, sodium ions are transported from the anode across the ceramic separator into the cathode. Nickel chloride is converted to metallic nickel, and sodium chloride precipitates. The nickel backbone of the cathode forms the electronically conductive pathway, while ionic conductivity is ensured by the molten salt electrolyte. The reactions during discharge are:

At the cathode (marked +), half-reaction is:

$$NiCl_2 + 2Na^+ + 2e^- \rightarrow Ni + 2NaCl$$

At the anode (marked –), half reaction is:

$$2Na \rightarrow 2Na^+ + 2e^-$$

The overall discharge reaction is:

$$NiCl_2 + 2Na \rightarrow Ni + 2NaCl$$

During charging these chemical reactions are reversed.

(h) Flow Batteries

Flow batteries store and release electrical energy by means of reversible electrochemical reaction in two liquid electrolytes. An electrochemical cell has two compartments-one for each electrolyte-physically separated by an ion exchange membrane. The electrolytes flow into and out of cell through separate manifolds and undergo chemical reaction inside the cell with ion or proton exchange through the membrane and electron exchange through the external electric circuit. The chemical energy in electrolytes is turned into electrical energy during discharging and vice-versa during charging.

Flow batteries have certain advantages over conventional secondary batteries. The capacity of the system is scalable by simply increasing the amount of solution. This amounts to cheaper installation cost as the system gets larger. The battery can be fully discharged with no ill effects and has little loss of electrolyte over time. Flow batteries are normally considered for relatively large (1 kWh–10 MWh) stationary applications. There are three types of flow batteries that are closing in on commercialization: vanadium redox, polysulphide bromide and zinc bromide.

(i) Vanadium Redox Flow Battery (VRB) The vanadium redox battery exploits the ability of vanadium to exist in solution in four different oxidation states, and uses this property to make a battery that has just one electro-active element instead of two. VRB uses the compounds of element vanadium in both electrolyte tanks as shown in Fig. 3.6.

During discharge:

The reaction at positive electrode is:

$$V^{5+} + e^- \rightarrow V^{4+}$$

The reaction at negative electrode is:

$$V^{2+} \rightarrow V^{3+} + e^-$$

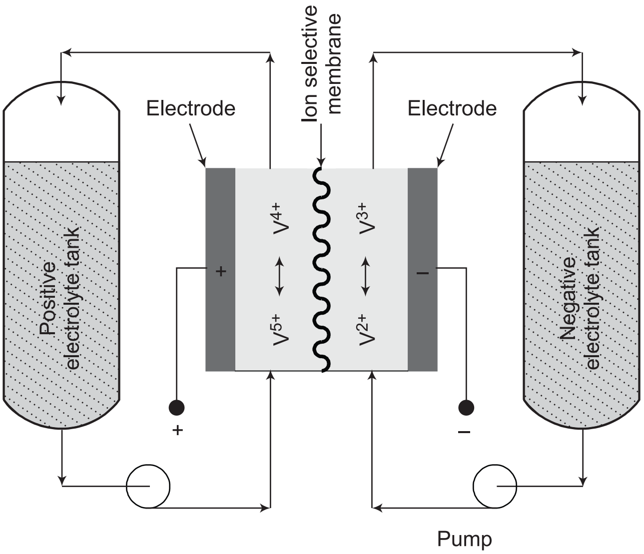


Figure 3.6 Redox Flow Battery

The direction of reaction reverses during charging. The use of vanadium compound on both sides of ion exchange membrane eliminates the possibility of cross contamination of the electrolytes and makes recycling easier. Useful properties of VFB are: open circuit voltage of 1.41 V, efficiency of 65–75 per cent, specific energy of 0.036 to 0.072 MJ/kg and energy density of 0.054 – 0.065 MJ/L.

(ii) Polysulphide Bromide Battery (PSB) The PSB utilizes two salt solution electrolytes, sodium bromide (NaBr) and sodium polysulphide (Na_2S_x). These two electrolytes are separated in the battery cell by polymer membrane that only passes positive sodium ions.

During discharge:

The reaction at positive electrode is:

$$NaBr_3 + 2Na^+ + 2e^- \rightarrow Na\,Br$$

The reaction at negative electrode is:

$$2Na_2S_2 \rightarrow Na_2S_4 + 2Na^+ + 2e^-$$

The direction of reaction reverses during charging.

(iii) Zinc Bromide Flow Battery (ZnBrB) In each cell of Zn Br battery, the electrolyte (Zinc Bromide) flow past carbon-plastic composite electrodes in two compartments separated by a micro porous membrane.

During discharge, Zn and Br combine into zinc bromide aqueous solution:

The reaction at positive electrode is:

$$Br_2 + 2e^- \rightarrow 2Br\,(aq)^-$$

The reaction at negative electrode is:

$$Zn(s) \rightarrow Zn\,(aq)^{2+} + 2e^-$$

The direction of reaction reverses during charging. On charging, metallic zinc is deposited as a thin film on negative electrode. Meanwhile, at positive electrode, bromide is converted to bromine on the other side of membrane. It reacts with other agents to make thick bromine oil that sinks to the bottom of the electrolytic tank. During discharge, a pump mixes the bromine oil with rest of the electrolyte. When the Zinc-Bromine battery is completely discharged, all the metal Zinc plated on the negative electrode is dissolved in the electrolyte.

The zinc–bromide battery can be regarded as an electroplating machine. During charging zinc is electroplated onto conductive negative electrode, while at the same time bromine is formed at positive electrode. On discharge the reverse process occurs, the metallic zinc plated on the negative electrode dissolves in the electrolyte and is available to be plated again at the next charge cycle. It can be left fully discharged indefinitely without damage. Useful properties of ZnBr battery are: open circuit voltage of 1.67 V, efficiency of about 75.9 per cent, specific energy of 0.124 to 0.190 MJ/kg and energy density of 0.0565 – 0.14 MJ/L.

3.4.3 Chemical Energy Storage

1. Hydrogen Storage

Energy can be both stored and transported as hydrogen, which serves as a secondary fuel. The input energy, usually electrical, helps decompose water by electrochemical (electrolysis) reaction into its constituent elements hydrogen and oxygen. The oxygen has no inherent energy value, but the hydrogen can contain up to 90 per cent of applied electric energy, depending on the technology. This hydrogen can be stored and later combusted to provide heat or to power fuel cell. In case of thermal energy input it is possible to decompose water by heat (thermolysis) as a result of a series of chemical reactions.

The chemical energy in hydrogen can be converted into thermal, mechanical, or electrical energy. One possibility is to burn hydrogen in air, in a manner similar to natural gas, to produce thermal energy for use in home or industry. Hydrogen can also serve as fuel, in place of gasoline in automobiles to obtain mechanical energy. Hydrogen fired steam turbine may also be used to obtain mechanical energy. Electrical energy can then be generated from mechanical energy thus obtained by using a generator. Electrical energy may also be obtained more efficiently (at about 55 to 60 per cent conversion efficiency), directly from hydrogen by means of fuel cell.

Hydrogen can be stored in three ways:

(a) Gas Form Storage of hydrogen gas, even in compressed state is bulky. It occupies more volume than natural gas. Compression to a storage pressure of 350 bar, the value usually assumed for automotive technologies, consumes up to 12 per cent of hydrogen's HHV (high heating value), if performed adiabatically.

(b) Liquid Form Hydrogen can also be stored in liquid form. But since its boiling point is 20 K, these stores are difficult to maintain due to refrigeration requirements and safety issues.

(c) Metal Hydride Form Hydrogen can be stored as reversible metal hydrides in large volumes. When required, hydrogen is released by heating of the hydride. One such example is given below:

$$Mg_2\,Ni + 2\,H_2 \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} (Mg_2\,Ni)\,H_4 + \text{heat}$$

This reaction is reversible and the hydride store can be replenished with hydrogen. A portable hydride store can be used for distribution of energy like a conventional mobile fuel tank. The store can be replenished with hydrogen at a central filling station. The main difficulty is the weight and cost of the metals used. The density of the metal hydride can be between 20 and 100 times the density of hydrogen stored. Hydrogen storage technologies are covered in more detail in Chapter 12.

2. Reversible Chemical Reactions Storage

Thermal energy can be stored in chemical bonds by means of reversible thermo-chemical reactions. A reversible chemical reaction is one that proceeds simultaneously in both directions. In this class of energy storage, a type of reversible reaction $AB + \Delta H \leftrightarrow A + B$ takes place that occur predominantly in one (forward) direction at higher temperature with absorption of heat, and predominantly in opposite (reverse) direction at lower temperature with emission of heat. The temperature above which the equilibrium shifts to forward direction and below that it shifts to reverse direction is known as turning temperature. Such type of chemical reactions can be used for energy storage. The products of forward reaction (endothermic decomposition), which store thermal energy (heat) as chemical energy, can be stored separately for a long duration at ambient temperature. The thermal energy may be recovered when the products are brought together and the conditions are changed to permit the reverse reaction (exothermic recombination) to occur.

Reversible thermochemical reactions of the type $A + B + \Delta H \leftrightarrow C + D$ may also be used for the same purpose. Some of the possible reactions suitable for thermochemical energy storage are given in Table 3.1:

Table 3.1 Thermochemical storage reactions

S.N.	Reaction	ΔH (KJ/g-mole of reactants or products)	Turning Temp. (°C)
1.	$Mg(OH)_2 \leftrightarrow MgO + H_2O$	81.6	258
2.	$NH_4HSO_4 \leftrightarrow NH_3 + H_2O + SO_3$	337	467
3.	$2NH_3 \leftrightarrow N_2 + 3H_2$	92.26	466
4.	$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$	247.4	960
5.	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	250.31	677

To be suitable for heat storage, the reaction system should involve the materials that are inexpensive and not too difficult to handle. Also the forward and reversible reactions should occur at reasonable temperatures. One or more catalyst may be needed to speed up the desired reaction, especially at lower temperature.

Some of the advantages of reversible chemical reaction storage systems are:

1. high energy density (much higher than sensible or latent heat storage)
2. storage at ambient temperature

3. low storage related investment cost suitable for both long duration thermal storage and for long distance thermal energy transport at ambient temperature

The main disadvantage is that the technology is still immature. These methods are suitable for solar-thermal power generation.

3.4.4 Electromagnetic Energy Storage (Superconducting Magnetic Energy Storage, SMES)

In this system, energy is stored in magnetic field. As an example, a coil with an inductance of 300 H carrying a current of 5000 A can store energy of $0.5LI^2 = 3.75 \times 10^9$ J, (which is nearly 1 MWh, since 1 MWh = 3.6×10^9 J) in its magnetic field. Under ordinary conditions losses result from the resistance of the wire, and energy must be supplied continuously to maintain the current. However, if the resistance of the wire were made zero, the current would remain almost constant, once initiated, without requiring any external source of voltage (energy). Therefore, stored energy in magnetic field would be maintained indefinitely. By connecting the coil to a load, the stored energy could be recovered as electrical energy. This concept forms the very basis of electromagnetic energy storage. The SMES recharges quickly and can repeat the charge / discharge sequence thousands of times without any degradation of the magnet. Recharging time can be accelerated to meet specific requirement, depending on system capability.

Electromagnetic energy storage requires the use of superconducting materials. These materials suddenly loose essentially all resistance to the flow of electric current when cooled below a critical temperature or transition temperature. All superconducting metals have transition temperature in *cryogenic* range (low temperature of the order of –273 °C to –150 °C or 0 K to 123 K). It is also observed that if a magnetic field were applied on the superconducting material, the property of superconductivity vanished abruptly at a certain value of magnetic field. Thus the property of superconductivity is balanced precariously on the magnetic field and the temperature.

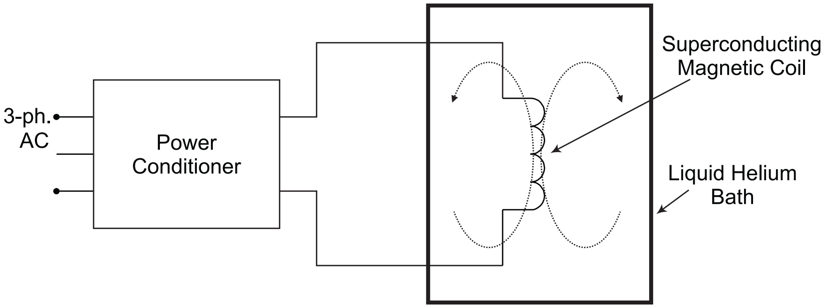


Figure 3.7 Superconducting Magnetic Energy Storage System

In the SMES, shown schematically in Fig. 3.7, the coil, immersed in a cryogenic fluid like liquid helium is charged by pumping direct current. The current then keeps on circulating and there results a high magnetic field surrounding the coil. This gives rise to axial (compression) and radial (expansion) magnetic forces. The more powerful is the radial expansion force, whereby the coil swells which must be constrained. It is therefore usual to embed the coil in a tunnel bored from underground bedrock by suitable structural members. These forces occur with a periodicity when the coil is charged and discharged. Also as the material crosses the critical state and loses its superconducting stage, explosive forces are produced, so the coil must be braced suitably.

Useful superconducting materials available commercially are niobium-titanium (Nb-Ti) alloy at temperatures below –263 °C and a compound of niobium and tin (Nb_3Sn) below –255 °C. Efforts are on for developing high temperature superconductors using oxides of yttrium and other elements. The prospects of using superconductor materials are far reaching not only for energy storage but also in other fields of electrical engineering. Mature, commercialized SMES is likely to operate at 97 per cent to 98 per cent round trip efficiency and an excellent technology for providing reactive power on demand.

A number of problems are associated with SMES. These include:

1. operation and maintenance of cryogenic (i.e. refrigeration) plant for producing the liquid helium required for low temperature
2. special structure would be needed to withstand strong magnetic forces

One very interesting SMES being used by the Bonnville Power Administration in the USA has the following details:

Maximum power capability:	10 MW
Maximum stored capacity:	30 MJ (8.33 kWh)
Coil current at full charge:	4.9 KA
Maximum coil terminal voltage:	2.18 KV
Coil operating temperature:	4.5 K
Magnetic field strength:	2.8 Tesla

The coil is restrained from deforming axially by winding pre-stressed stainless steel strips at 816 atm.

3.4.5 Electrostatic Energy Storage (Super Capacitor)

A capacitor stores energy in electro-static field when charged. To store a significant amount of energy, very large capacity (in kilo farads range) capacitors, known as super/ultra-capacitors are required. The capacity of a capacitor can be increased by increasing the area of the electrodes (plates) and minimizing the distance between them. This is achieved in ultra-capacitors by coating a layer of activated porous carbon on metal foil electrodes. These foils are separated by a paper separator and dipped in an electrolyte. The paper separator prevents electrical connection between the electrodes but allows free movement of ions across it. When connected to a dc voltage source, the electrons accumulate at the carbon coated on foil attached to negative terminal of voltage source. These electrons in turn, attract positive ions from the electrolyte into the pores of the carbon on that electrode. In the other electrode, meanwhile, positive charges accumulate, attracting negative ions into the pores of the carbon as shown in Fig. 3.8. The activated carbon's huge surface area comes from the great porosity of its microscopic nodules. It enables the positive and negative ions migrating through the electrolyte to find plenty of nooks and crannies to occupy as they insinuate themselves as closely as possible (atomically close) into the oppositely charged carriers inside the carbon. Notice that this is actually a pair of capacitors connected in series. At each electrode there is a separation of charges – electrons and positive ions at negative electrode, and positive charges and negative ions at positive electrode, each constituting a capacitor. So at each electrode there are two layers of charges, which is why ultra-capacitors are also known as electric double layer capacitors.

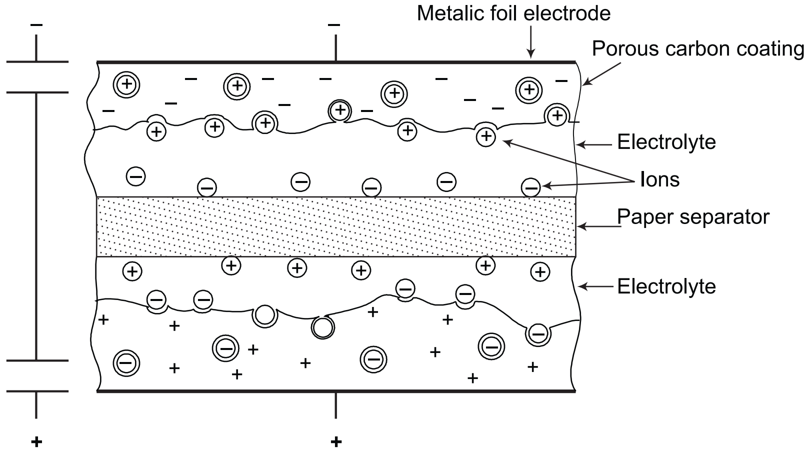


Figure 3.8 Ultra-capacitor construction

Ultra-capacitors typically store 10 to 100 times more energy per unit volume or mass than electrolytic capacitors, can accept and deliver charge much faster than batteries, and tolerate many more charge and discharge cycles than rechargeable batteries. They are however 10 times larger than conventional batteries for a given charge. Supercapacitors are used in applications requiring many rapid charge/discharge cycles rather than long term compact energy storage: within cars, buses, trains, cranes and elevators, where they are used for regenerative braking, short-term energy storage or burst-mode power delivery. There are at present about ten manufacturers of ultra-capacitors. NessCap is producing a unit of 5000 farads at 2.7 V in a package slightly bigger than a half-litre soda bottle.

A super-capacitor/ultra-capacitor has much better cycle life (typically above 5, 00,000) compared to batteries. These ultra-capacitors can be charged in seconds rather than hours and can function at more extreme temperatures. Commercially available ultra-capacitors can store about 5 Wh/kg compared to 100–200 Wh/kg delivered by lithium ion batteries. An ultra-capacitor with battery like energy density would be irresistible to a large number of users, especially hybrid electric vehicles. With their lightning-fast charge and discharge capability, ultra-capacitors could handle the power surges needed for accelerating, allowing the use of smaller battery pack in the vehicle (and eventually, perhaps no battery pack at all). It can also be used for "stop-and-go" operation in hybrid gasoline cars. In this operation the gasoline engine is extinguished at stops and started instantly again when required.

Ultra capacitor and a powerful starter motor would instantly jolt the engine back to life. Such vehicles would also make use of regenerative braking for charging of ultra-capacitor. In fuel cell powered cars, ultra-capacitors may play a very important role. Fuel cells by themselves, deliver power too sluggishly to briskly accelerate a full-size car. They must be mated to a faster energy storage device, and for this, coupling with ultra-capacitors are superior in many respects to batteries.

3.4.6 Thermal Energy Storage

1. Sensible Heat Storage

In this type of storage, thermal energy is stored by virtue of heat capacity and the change in temperature of the material during the process of charging and discharging. The temperature of storage material rises when energy is absorbed and drops when energy is withdrawn. The charging and discharging operations, in a sensible heat storage system, can be expected to be completely reversible for an unlimited number of cycles, over the life span. On the basis of heat storage media, it can be classified as: (a) liquid media storage, (b) solid media storage and (c) dual media storage.

(a) Liquid Media Storage Of available liquids, water can be considered to be the most suitable liquid media for storage below 100 °C. Water has the following advantages:

- It is abundant and inexpensive
- Easy to handle, non-toxic and non-combustible
- Its flow can take place by thermo-siphon action
- It has high density, high specific heat, good thermal conductivity and low viscosity
- Can be used both as storage medium as well as working medium (thus eliminating the need for heat exchanger, e.g. in space heating system)
- Charging and discharging of heat can occur simultaneously
- Control of water system is flexible

Main disadvantages with water as storage media are:

- Limited temperature range (0 °C to 100 °C)
- A corrosive medium
- Low surface tension (i.e. leaks easily)

A short-term thermal energy storage system is shown in Fig. 3.9, where hot water is stored in well-insulated tank. Storage in this manner is economical only for a few days since the heat losses become prohibitive over long durations.

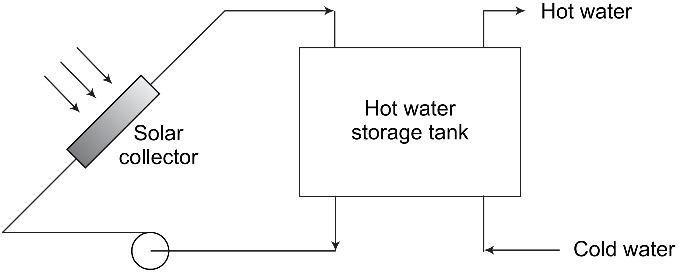


Figure 3.9 Short term thermal energy storage in water

Though water is best choice as heat storage medium in space heat system; other liquids such as oils, liquid metals and molten salts have also been used in solar thermal power plants. Table 3.2 shows the thermos-physical properties of selected liquids for sensible heat storage. Out of these, water appears to be the best sensible storage liquid available because it is inexpensive and has high specific heat. However, above 100 °C, the storage tank must be able to contain water at its vapor pressure, and therefore, the storage tank cost rises sharply. Organic oils, molten salts and liquid metals circumvent this problem.

Table 3.2 Thermo-physical properties of selected liquids for sensible heat storage

S.N.	Medium	Temp. range (°C)	Density (kg/m^3)	Heat capacity (J/kg K)
1.	Water	0 to 100	1000	4190
2.	Thermional 66	–9 to 343	750	2100
3.	Hitec (molten salt)	142 to 540	1680	1560
4.	Engine oil	Up to 160	888	1880
5.	Lithium	180 to 1300	510	4190
6.	Sodium	100 to 760	960	1300
7.	Octane (Organic liquid)	Up to 126	704	2400

Large size and long-term storage of hot water in underground reservoirs is possible without the use of special insulating materials. Fig. 3.10 shows one such system schematically. Here, cold ground water from zone A of an aquifer is heated by passing it through a heat exchanger and returned to zone B where it is stored. In the discharge mode, the hot water from zone B flows back through the heat exchanger

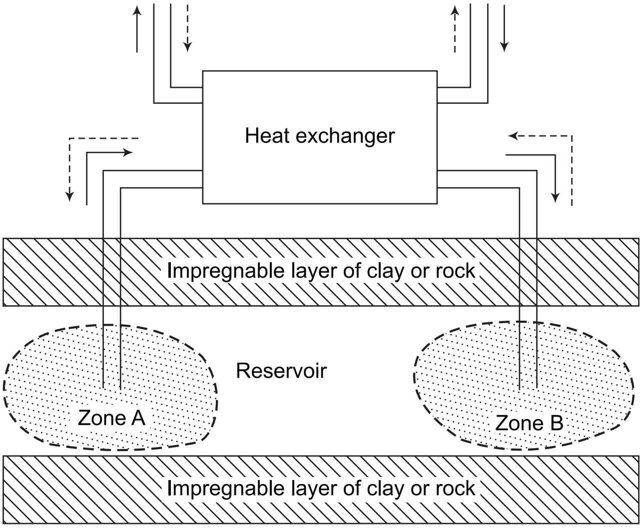


Figure 3.10 Long term thermal storage underground layers

where it gives out the stored heat and returns to zone A. The heat from such aquifers can be retrieved with negligible losses, which may be of the order of one per cent only.

(b) Solid Media Storage (Packed Bed Storage) It utilizes the heat capacity of a bed of loosely packed solid materials such as rocks, metals, concrete, sand, bricks etc. to store energy. A fluid, usually air, is circulated through the bed to add or remove energy. Here, energy can be used at neither low or high temperature since these will freeze nor boil. The energy change for 50 °C is about 10 Wh/kg for most rocks, concrete and iron ore.

A packed bed storage unit consists of a container, a screen to support the bed, support for the screen and inlet and outlet ducts. Flow is maintained through the bed in one direction, during addition of heat and in opposite direction during removal of heat. Typical packed bed storage is shown in Fig. 3.11.

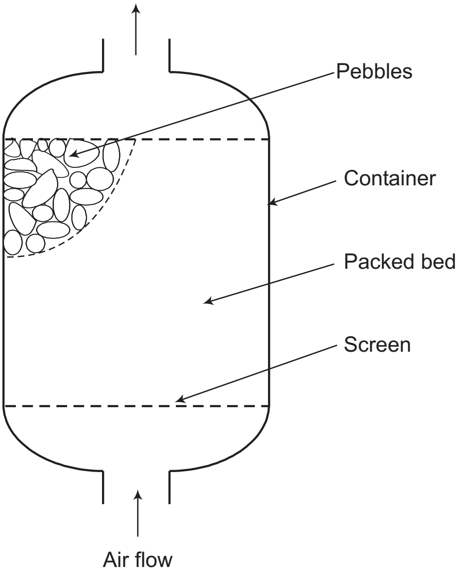


Figure 3.11 Packed bed storage unit

Main advantage and disadvantage of such a system are:

Advantages

- Rocks are abundant, low cost, easy to handle, non-toxic- and non-combustible
- High storage temperatures are possible
- Heat exchanger can be avoided
- No freezing problem
- No corrosion problem

Disadvantages

- Storage volumes are large
- High pressure drop
- Simultaneous charging and discharging are not possible

(c) Dual Media Storage In dual media storage, both solid and liquid sensible heat storage materials are used. These solid and liquid materials may be combined in a number of ways. One of them is to jointly use the bedrock and water tank: a hybrid system, with water tank surrounded by bedrock.

2. Latent Heat Storage (Storage in Phase Change Materials)

In this class of storage, energy is stored by virtue of latent heat of change of phase of the storage medium. Phase change materials have considerably higher thermal energy storage densities as compared to sensible heat storage materials and are able to absorb or release large quantities of energy at a constant temperature. Therefore, these systems are more compact but more expensive than sensible heat storage systems. Various phase changes that can occur are:

- solid-solid (lattice change)
- solid-gas
- solid-liquid
- liquid-gas

Solid-gas and liquid-gas transformations are not employed in spite of large latent heats as large changes in volume make the system complex and impracticable. In solid-solid transition, heat is stored as the material is transformed from one crystalline form to another. These transitions involve small volume changes; however, most of them have small latent heats.

The solid-liquid transformations include storage in salt hydrates. Certain inorganic salts, which are soluble in water and form crystalline salt hydrates, are employed. Let an inorganic salt, which is soluble in water represented by $X(Y)_n$. The crystalline salt hydrate is symbolized by $X(Y)_n.\ m\mathrm{H_2O}$. On heating up to transition temperature, the hydrate crystals release water of crystallization and the solid remainder (anhydrous salt) dissolves in the released water as following reaction takes place:

$$\underset{\text{(Solid)}}{X(Y)_n.\ m\mathrm{H_2O}} + \Delta\mathrm{H} \leftrightarrow \underset{\text{(Liquid: aqueous solution of anhydrous salt)}}{X(Y)_n + m\mathrm{H_2O}}$$

One problem with most salt hydrates is that the released water of crystallization is not sufficient to dissolve all the solid phase present. Due to density difference, the anhydrous salt settles down at the bottom of the container. This incongruent melting makes the process irreversible since the anhydrous salt at the bottom is unable to find water for recrystallization to the original hydrate. The recrystallization of an incongruently melting salt can be achieved either by (i) the use of suspension media or thickening agent or by (ii) mechanical means (vibration, stirring, etc.)

The heat transfer properties of some phase change materials are given in Table 3.3.

Other potential phase change materials apart from salt hydrates are paraffins (e.g. $C_{18}\ H_{38}$, etc., alkanes containing 14 to 40 C-atoms) and non-paraffin organic materials (e.g. esters, fatty acids, alcohols and glycols), which are suitable at certain situations.

Table 3.3 Heat transfer properties of phase change storage materials

S. N.	Material	Chemical compound	Melting point (°C)	Heat of fusion (kJ/kg)	Density kg/m^3
1.	Sodium sulphate decahydrate (Glauber's salt)	Na_2SO_4. $10H_2O$	31–32	251	1534
2.	Sodium thiosulphate	$Na_2S_2O_3$. $5H_2O$	48–49	209	1666
3.	Calcium chloride hexahydrate	$CaCl_2$. $6H_2O$	29–39	177	1634
4.	Sodium carbonate dehydrate	Na_2CO_3. $10H_2O$	32–36	247	1442
5.	Disodium phosphate decahydrate	Na_2HPO_4. $12H_2O$	36	265	1522

3.4.7 Biological Storage

Solar energy can be stored biologically in plants by fixing carbon from CO_2 available in the atmosphere. The fixation of carbon atom from atmospheric CO_2 to carbohydrates proceeds by a series of stages in green plants. The process is known as photosynthesis. Photosynthesis is the synthesis (making) of organic structure and chemical energy store by action of solar radiation.

If this material (dry) is burnt in oxygen, the heat released is 470 kJ per mole of carbon or 4.8 ev per carbon atom. This biomass can also be converted into various types of solid (e.g. fuel pellets and briquettes), liquid (e.g. biodiesel and ethanol) and gaseous fuels (e.g. biogas and syngas).

REVIEW QUESTIONS

1. What do you understand by energy storage?
2. Under what circumstances storage of energy becomes necessary?
3. On what basis energy storage systems are classified? Can energy available in one form be stored in another form?
4. Which types of energy storage systems are suitable for peak shaving in electrical utility?
5. State the main applications of flywheel energy storage.
6. Which type of energy storage method is employed in hybrid vehicles?
7. Which type of energy storage method is suitable to improve the transient stability of an electric power grid?
8. What are the main advantages and limitations of a battery storage system?
9. Compare the performance of Li-ion batteries with other batteries. What are the major limitations of these batteries?
10. What are the most significant advantages of flow batteries?
11. Describe various methods of storing hydrogen. Mention their relative advantages and limitations.
12. How are electrical and thermal energies converted to hydrogen energy?

13. Discuss basic principle of storing energy in reversible chemical reactions. What are their main advantages? What do you understand by turning temperature?

14. Explain the basic principle of superconducting magnetic energy storage. What are the possible superconducting materials for this system at present?

15. What are the problems associated with SMES?

16. What types of forces are produced while using SMES?

17. What are the main advantages and disadvantages of sensible heat storage with water as storage media? Compare them with that of solid media storage?

18. Why solid-gas and liquid-gas phase changes are not considered suitable for phase change storage?

19. What are the main problems associated with use of salt hydrate as phase change storage media?

20. Describe thermal energy storage system of solar energy. **(UPTU Lucknow, 2003–04)**

21. What are the main limitations of compressed air energy storage?

22. Explain main features of various types of storage batteries.

23. Explain the construction of an ultra-capacitor. What features are provided to increase the amount of energy stored?

PROBLEMS

1. A lead acid battery cell is allowed to discharge up to a level of 1.85 V. At full charge the specific gravity of electrolyte is 1.27. Calculate the specific gravity at discharge. Also calculate the voltage at full charge. (*Ans.* 1.01, 2.11 V)

OBJECTIVE TYPE QUESTIONS

1. Energy storage means:
(a) sparing primary energy for future generations
(b) storing secondary energy in an easily recoverable form
(c) conserving energy
(d) storing primary energy

2. Why is energy storage required?
(a) To match energy supply and demand in time domain
(b) To conserve energy
(c) To increase energy consumption
(d) To supply energy for many years to come

3. What is the approximate energy recovery efficiency of pumped storage?
(a) 90% (b) 50% (c) 70% (d) 20%

4. Which statement is not true about pumped storage method?
(a) It is a well-developed technology.
(b) It is site specific and it is not feasible everywhere.
(c) It is very costly method.
(d) It is portable energy storage medium.

5. Underground compressed air storage reservoirs are being considered:
  (a) as above ground construction would be too large and too expensive
  (b) for safety reasons
  (c) to make use of geothermal heat
  (d) none of the above

6. The energy recovery efficiency of flywheel storage is of the order of:
  (a) 50% (b) 30% (c) 10% (d) 90%

7. The energy-storage capacity of a flywheel is increased by increasing the:
  (a) mass of the flywheel
  (b) speed of rotation of the flywheel
  (c) density of the material of the flywheel
  (d) thickness of the flywheel

8. Energy loss of the flywheel is reduced by:
  (a) reducing its diameter
  (b) reducing its inertia
  (c) putting the flywheel in a sealed vacuum chamber and by providing magnetically levitated bearings
  (d) increasing its speed

9. Compactness of a flywheel storage:
  (a) leads to storage of only a small amount of energy
  (b) makes its handling difficult
  (c) enables to realize a portable energy storage medium
  (d) none of the above

10. Which of the following statement is not true about battery storage?
  (a) It has long life.
  (b) It has ability of rapid switch over between charging and discharging operations.
  (c) It is a modular and portable source of energy.
  (d) The cost of battery storage is high.

11. Li-ion batteries have the highest specific energy among all storage batteries because:
  (a) lithium is the lightest of metals
  (b) it uses no electrolyte
  (c) the anode is made of graphite which is very light
  (d) the amount of electrolyte required is very small

12. Best way to generate electrical power from hydrogen is through:
  (a) a hydrogen fired steam turbine coupled to a generator
  (b) conversion of hydrogen to some other liquid fuel and using IC engine coupled to generator
  (c) direct conversion using fuel cell
  (d) none of the above

13. Name the method used for conversion of thermal energy into hydrogen energy:
  (a) Electrolysis (b) Hydrolysis (c) Thermolysis (d) None of the above

14. What is the main difficulty in storing hydrogen in liquid form?
  (a) It is difficult to maintain it due to refrigeration requirement.
  (b) It is very heavy in liquid form.
  (c) It is very light in liquid form.
  (d) It is very difficult to liquefy it.

15. What is the main difficulty in storing hydrogen in metal hydride form?
  (a) Releasing hydrogen from metal hydride
  (b) Very little amount of hydrogen can be stored

(c) These metals are difficult to obtain
(d) Weight and cost of metal as well as heat management

16. In reversible chemical energy storage, the input energy is in the form of:
(a) electrical energy (b) thermal energy
(c) chemical energy (d) mechanical energy

17. Main drawback of electromagnetic energy storage is that it requires:
(a) a very bulky inductor coil (b) a very strong magnetic field
(c) a very strong electrostatic field (d) a superconducting material

18. Ultra capacitors have capacities in the range of:
(a) few micro farads (b) few farads
(c) several thousand farads (d) several hundred micro farads

19. The energy density of ultra-capacitor is in the range of :
(a) 5 Wh/kg (b) 3-4 kWh/kg
(c) 60-70 Wh/kg (d) 110-130 Wh/kg

20. Which of the following statements is not true for solid medium sensible heat storage?
(a) No freezing problem
(b) No corrosion problem
(c) Low cost
(d) Simultaneous charging and discharging are possible.

21. Phase change energy storage with solid to gas and liquid to gas transformations are not employed in spite of large latent heats because:
(a) it has low heat storage capacity
(b) it makes use of toxic materials
(c) it requires large change in volume that makes the system impracticable
(d) it requires prohibitively wide temperature range

22. A Ragone plot for energy storage system is a plot of:
(a) specific energy density versus specific power density
(b) charge density versus energy density
(c) output voltage versus stored charge
(d) stored charge versus cost

23. During charging the specific gravity of electrolyte of a lead acid battery:
(a) increases (b) decreases (c) remains same (d) becomes zero

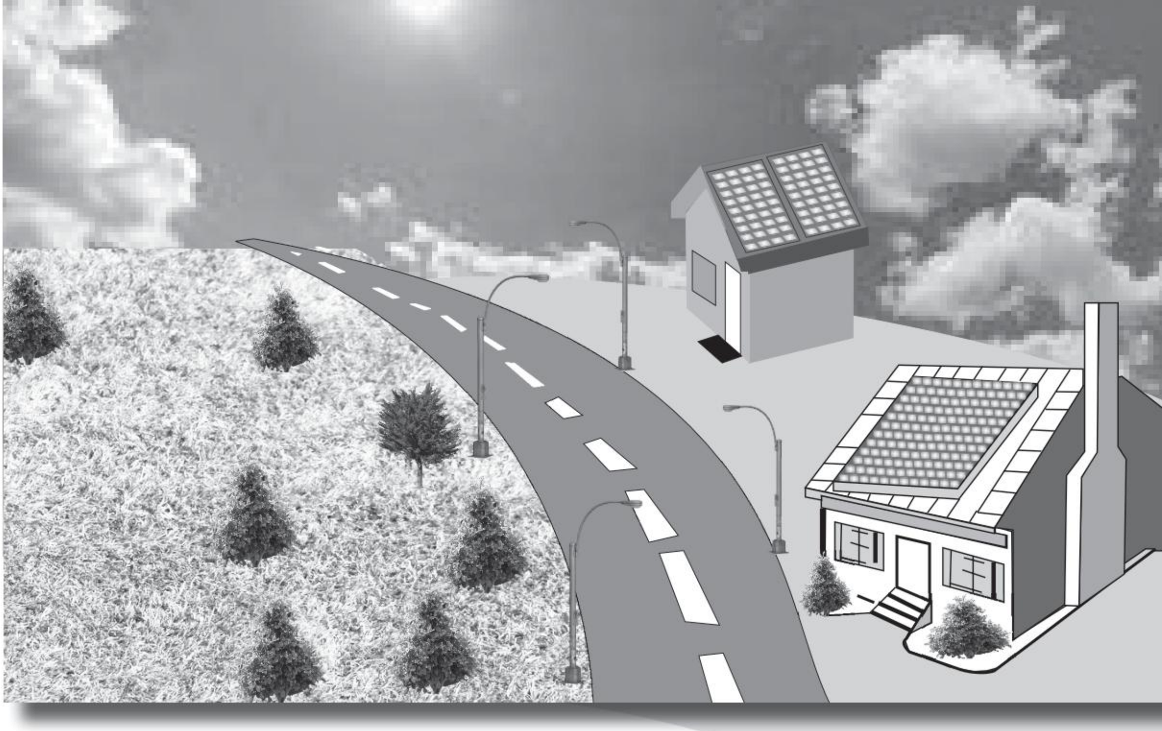
24. The ratio of ampere-hour efficiency to watt-hour efficiency of a lead acid battery is:
(a) just one (b) always greater than one
(c) always less than one (d) between one and two

25. The materials in the storage battery that take active part in the electrochemical reaction are known as:
(a) passive materials (b) active materials
(c) redundant materials (d) inert materials

26. The open circuit voltage of any storage battery depends wholly upon:
(a) its chemical constituents (b) on the strength of electrolyte
(c) its temperature (d) all of the above

27. A lead acid battery consisting of six series connected cells is allowed discharge until the electrolyte specific gravity reached 1.01. What is the battery voltage at discharge?
(a) 11.1 V (b) 10.01 V (c) 10.5 V (d) 10.2 V

28. A superconducting magnet coil has an inductance of 500 H and carries a current of 4000 A. The stored energy in the magnetic field is:
(a) 1 MJ (b) 20 MJ (c) 2 MJ (d) 4 GJ



CHAPTER

4

Solar Energy—Basic Concepts

Learning Objectives

In this chapter you will be able to:

- Know about the origin of solar energy
- Discuss the characteristics and distribution of solar radiation
- Measure various components of solar radiation
- Analyse the collection and interpretation of solar radiation data
- Explain the estimation of availability of solar radiation at a location
- Observe the effect of tilting the surface of collector with respect to horizontal surface

4.1 INTRODUCTION

The sun radiates energy uniformly in all directions in the form of electromagnetic waves. When absorbed by a body, it increases its temperature. It provides the energy needed to sustain life in our solar system. It is a clean, inexhaustible, abundantly and universally available renewable energy source. Major drawbacks of solar energy are: it is a dilute form of energy, which is available intermittently, uncertainly and not steadily and continuously. However, it is more predictable than wind energy. Also peak solar insolation (incident solar radiation) often coincides with peak daytime demand; it can be well matched to commercial power needs. The output of sun is 2.8×10^{23}kW. The energy reaching the earth is 1.5×10^{18}kWh/year.

Solar energy can be utilized directly in two ways: (i) by collecting the radiant heat and using it in a thermal system or (ii) by collecting and converting it directly to electrical energy using Photovoltaic system. The former is referred to as 'Solar Thermal' and the later as 'Solar Photovoltaic' (SPV) system.

Solar energy is also used by various well-known natural effects and appears in nature in some other forms of energy. These are indirect forms of solar energy. Thus solar energy is the mother of all forms of energy: conventional or non-conventional, renewable or non-renewable, the only exception being nuclear energy. Various sources of energy find their origin in sun, as mentioned below:

1. Wind energy
2. Biomass energy
3. Tidal energy
4. Ocean wave energy
5. Ocean thermal energy
6. Fossil fuels and other organic chemicals
7. Hydro energy

Warming the body during winters is perhaps the earliest uses of direct solar heat man has made. Indeed drying of clothes, timber, fodder, salt water (to get salt) and agriculture produce remained the most extensive use of direct solar energy in the history of mankind. All other devices for harnessing direct solar energy have fairly recent origin.

Archimedes (212 BC), it is said, set the Roman fleet on fire by concentrating solar radiation using large number of small plane mirrors at a distance of several hundred feet. Antoine Lavoisier (1740–1794), achieved temperatures up to 1700 °C by concentrating sun's rays. Solar steam boilers were developed in late 19th century to produce steam to run steam engines. In 1870s, a large-scale project using solar energy was installed in Chile where 6000 gallons of fresh water was produced per day in a desalination plant by collecting solar energy in an area of 50,000 sq. ft. In subsequent years the development of solar energy declined due to availability of cheap fossil fuels. However, after oil crisis of 1973 solar energy (as well as other non-conventional energy sources) received renewed interest.

4.2 THE SUN AS SOURCE OF ENERGY

The sun, which is the largest member of the solar system, is a sphere of intensely hot gaseous matter with a diameter of 1.39×10^9 m and, at an average distance of 1.495×10^{11} m from the earth. As observed from the earth the sun rotates on its axis about once in every four weeks, though it does not rotate as a solid body. The equator takes about 27 days and the polar region takes about 30 days for each rotation. At the innermost region, the core, the temperature is estimated between 8×10^6 to 40×10^6 K. The core has density of about 100 times that of water and pressure of 10^9 atm. Such a high inner temperature is maintained by enormous energy released due to continuous fusion reaction. Thus, the sun is a big natural fusion reactor with its constituent gases as the "containing vessel" retained by gravitational forces. Several fusion reactions have been suggested to be the source of the energy radiated by the sun. Most important of them is a reaction in which four hydrogen atoms (protons) combine to form one helium atom. The mass of the helium nucleus is less than that of four protons, the difference of mass having been converted to energy in fusion reaction as follows:

$$4({}_1H^1) \rightarrow {}_2He^{4} + 26.7 \text{ Mev}$$

The surface of the sun is maintained at a temperature of approximately 5800 K.

4.3 THE EARTH

The earth is shaped as an oblate spheroid – a sphere flattened at the poles and bulged in the plane normal to the poles. However, for most practical purposes, the earth may be considered as a sphere with a diameter of about 1.275×10^7 m. The earth makes one rotation about its axis every 24 hours and completes a revolution about the sun in a period of approximately 365.25 days. Its axis is inclined at an angle of 23.5°. As a result the length of days and nights keep changing. The earth reflects about 30 per cent of the sunlight that fall on it. This is known as earth's *albedo*.

The geometry of earth–sun relationship is shown in Fig. 4.1. The eccentricity of earth's orbit is such that the distance between the sun and the earth varies by ±1.7 per cent. The sun subtends an angle of 32′ on earth at an average sun–earth distance of 1.495×10^{11} m, a distance of one *astronomical unit*.

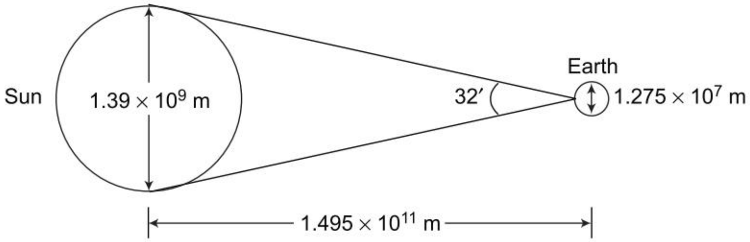


Figure 4.1 Sun–earth relationship

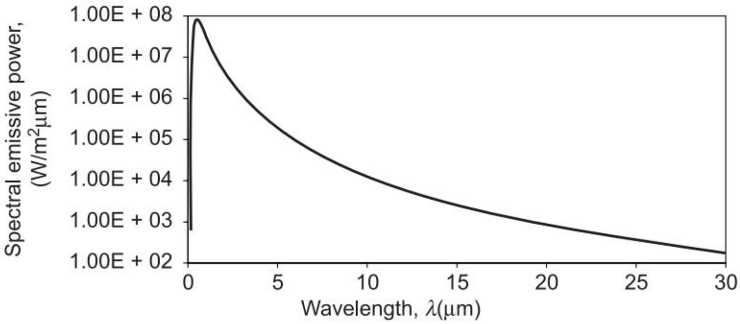
4.4 SUN, EARTH RADIATION SPECTRUM

The wavelength distribution of radiation emitted by a black body is given by Planck's law:

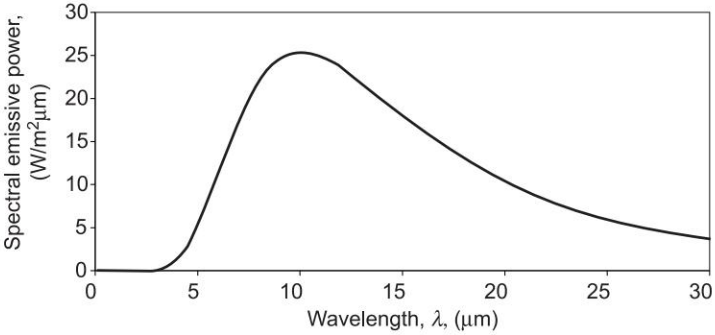
$$W_\lambda = \frac{C_1\lambda^{-5}}{\exp(C_2/\lambda T)-1} \text{ (W/m}^2\text{–unit wavelength)} \qquad (4.1)$$

where, C_1 and C_2 are often called Planck's first and second radiation constants respectively. Their suggested values are $C_1 = 3.74 \times 10^{-16}$ Wm^2, and $C_2 = 0.01439$ mK. λ is the wavelength in m and T is temperature in Kelvin. Total energy emitted by the black body at temperature T is obtained by integrating W_λ over the wavelengths.

Using this formula the power density distribution of solar radiation at the surface of the sun considering the surface temperature to be 5760 K can be calculated. Also the same for the earth surface can be found out assuming the average earth temperature to be 288 K (15 °C). The comparison of these radiations from the sun and the earth is shown in Fig. 4.2. It is clear from Fig. 4.2 (a) and (b) that the radiation emitted



(a) Blackbody emissive power at T = 5760 K (surface of sun)



(b) Blackbody emissive power at T = 288 K (surface of earth)

Figure 4.2 Radiant powers per unit wavelength at the surface of sun and earth from the sun at about 5760 K lies in the range of short wavelengths, peaking around 0.48 μm and that from earth at 288 K (15 °C) lies in the range of long wavelengths, peaking around 10 μm.

A useful term, *Solar Constant,* I_{sc} is defined as the energy received from the sun per unit time, on a unit area of surface perpendicular to the direction of propagation of the radiation, at the earth's mean distance from the sun. The World Radiation Center (WRC) has adopted a value of solar constant as 1367 W/m^2 (1.940 cal/cm^2 min, 432Btu/ft^2 hr or 4.921 MJ/m^2 hr). This has been accepted universally as a standard value of solar constant.

4.5 EXTRATERRESTRIAL AND TERRESTRIAL RADIATIONS

The intensity of solar radiation keeps on attenuating as it propagates away from the surface of the sun, though the wavelengths remain unchanged. Solar radiation incident on the outer atmosphere of the earth is known as *Extraterrestrial Radiation*, I_{ext}. The extraterrestrial radiation deviates from solar constant value due to two reasons. The first is the variation in the radiation emitted by the sun itself. The variation due to this reason is less than ±1.5 per cent with different periodicities. The second is the variation of earth–sun distance arising from earth's slightly elliptic path. The variation due to this reason is ±3 per cent and is given by:

$$I_{\text{ext}} = I_{\text{sc}}\,[1 + 0.033 \cos (360\, n/365)] \text{ W/m}^2. \tag{4.2}$$

where, n is the day of the year starting from January 1.

The extraterrestrial radiation, being outside the atmosphere, is not affected by changes in atmospheric conditions. While passing through the atmosphere it is subjected to mechanisms of atmospheric absorption and scattering depending on atmospheric conditions, depleting its intensity. A fraction of scattered radiation is reflected back to space while remaining is directed downwards. Solar radiation that reaches earth surface after passing through the earth's atmosphere is known as *Terrestrial Radiation.* The terrestrial radiation expressed as energy per unit time per unit area (i.e. W/m^2) is known as *Solar Irradiation*. The term *Solar Insolation* (incident solar radiation) is defined as *solar radiation* energy received on a given surface area in a given time (in J/m^2 or kWh/m^2). The positions of extraterrestrial and terrestrial regions are indicated in Fig. 4.3.

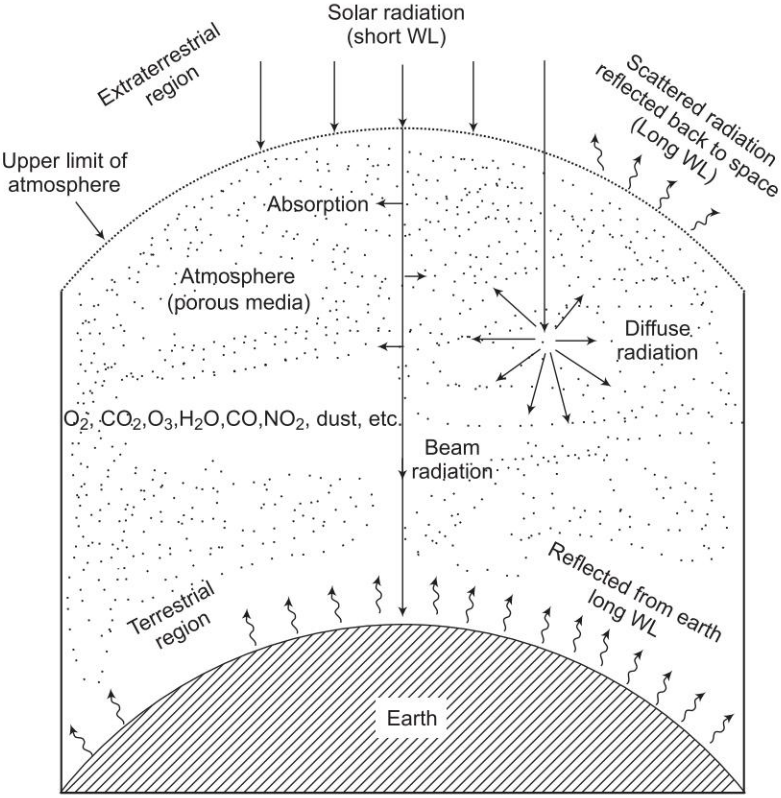


Figure 4.3 Propagation of solar radiation through atmosphere

4.6 SPECTRAL POWER DISTRIBUTION OF SOLAR RADIATION

Solar radiation covers a continuous spectrum of electromagnetic radiation in a wide frequency range. About 99 per cent of the extraterrestrial radiation has wavelengths in the range from 0.2 to 4 μm with maximum spectral intensity at 0.48 μm (green portion of visible range). About 6.4 per cent of extraterrestrial radiation energy is contained in ultraviolet region ($\lambda < 0.38$ μm); another 48 per cent is contained in the visible region (0.38 μm $< \lambda <$ 0.78 μm) and the remaining 45.6 per cent is contained in the infrared region ($\lambda > 0.78$ μm). There is almost complete absorption of short wave radiation in range ($\lambda < 0.29$ μm) and infrared radiation in range ($\lambda > 2.3$ μm) in the atmosphere. Thus, from the point of view of terrestrial applications of solar energy, the radiation only in the range of wavelengths between 0.29 and 2.3 μm is significant. The spectral solar irradiation distribution both for extraterrestrial and terrestrial radiation is shown in Fig. 4.4. The areas under these curves indicate the total radiation intensities in W/m^2 respectively for extraterrestrial and terrestrial regions.

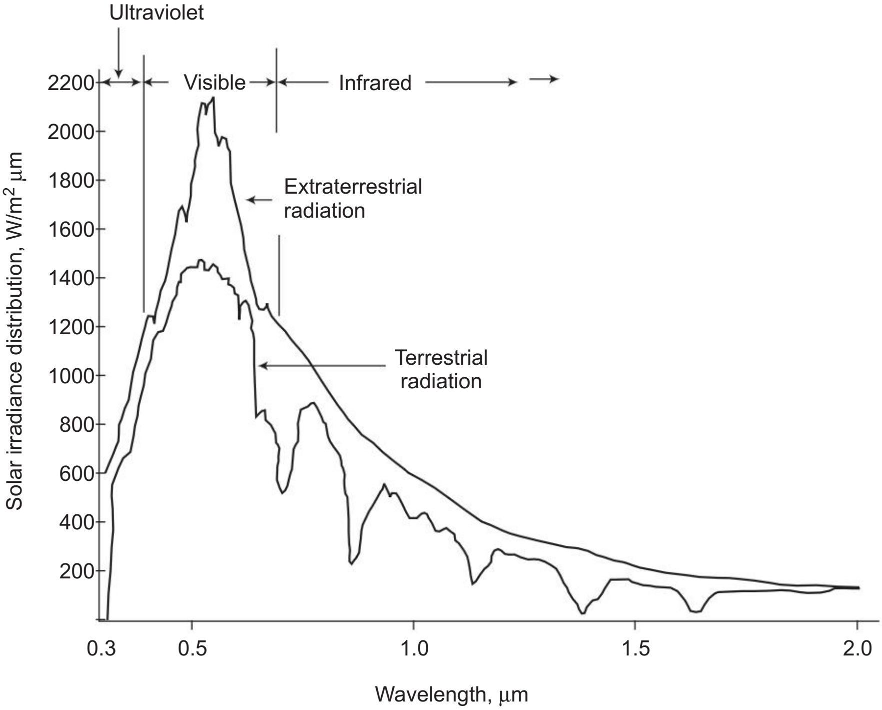


Figure 4.4 Special solar irradiation, extraterrestrial and terrestrials

4.7 DEPLETION OF SOLAR RADIATION

The earth's atmosphere contains various gaseous constituents, suspended dust and other minute solid and liquid particulate matter. These are air molecules, ozone, oxygen, nitrogen, carbon dioxide, carbon monoxide, water vapour, dust, and water droplets. Therefore, solar radiation is depleted during its passage through the atmosphere. Different molecules do different things as explained below:

1. *Absorption*

Selective absorption of various wavelengths occurs by different molecules. The absorbed radiation increases the energy of the absorbing molecules, thus raising their temperatures:

(a) Nitrogen, molecular oxygen and other atmospheric gases absorb the X-rays and extreme ultraviolet radiations.

(b) Ozone absorbs a significant amount of ultraviolet radiation in the range ($\lambda < 0.38$ μm).

(c) Water vapour (H_2O) and carbon dioxide absorb almost completely the infrared radiation in the range ($\lambda > 2.3$ μm) and deplete to some extent the near infrared radiation below this range.

(d) Dust particles and air molecules also absorb a part of solar radiant energy irrespective of wavelength.

1. Scattering

Scattering by dust particles, and air molecules (or gaseous particles of different sizes) involves redistribution of incident energy. A part of scattered radiation is lost (reflected back) to space while remaining is directed downwards to the earth's surface from different directions as *diffuse radiation.* It is the scattered sunlight that makes the sky blue. Without atmosphere and its ability to scatter sunlight, the sky would appear black, as it does on the moon.

In cloudy atmosphere, (i) a major part of the incoming solar radiation is reflected back into the atmosphere by the clouds, (ii) another part is absorbed by the clouds and (iii) the rest is transmitted downwards to the earth surface as diffuse radiation.

The energy is reflected back to the space by (i) reflection from clouds, plus (ii) scattering by the atmospheric gases and dust particles, plus (iii) the reflection from the earth's surface is called the *albedo* of earth-atmosphere system and has a value of about 30 per cent of the incoming solar radiation for the earth as a whole. Thus on the surface of earth we have two components of solar radiation: (i) *direct or beam radiation*, unchanged in direction and (ii) *diffuse radiation*, the direction of which is changed by scattering and reflection. Total radiation at any location on the surface of earth is the sum of beam radiation and diffuse radiation, what is known as *global radiation.* These terms may be properly defined as follows:

Beam radiation: Solar radiation propagating in a straight line and received at the earth surface without change of direction, i.e., in line with sun is called beam or direct radiation.

Diffuse radiation: Solar radiation scattered by aerosols, dust and molecules is known as diffuse radiation. It does not have a unique direction.

Global radiation: The sum of beam and diffuse radiation is referred to as total or global radiation.

Even on clear days, there will be some diffuse radiation depending upon the amount of dust particles, ozone and water vapour present in the atmosphere. On overcast days when the sun is not visible, all the radiation reaching the ground will be diffuse radiation.

In general, the intensity of diffuse radiation coming from various directions in the sky is not uniform. The diffuse radiation is therefore said to be anisotropic in nature. However, in many situations (like heavy cloud cover), the intensity from all directions tends to be reasonably uniform and it thus becomes isotropic in nature.

The radiation thus available on earth's surface is less than that is received outside the earth's atmosphere and this reduction in intensity depends on the atmospheric conditions (amount of dust particles, water vapour, ozone content, cloudiness, etc.) and the distance traveled by beam radiation through atmosphere before it reaches a location on earth's surface. The later factor in turn depends on solar altitude. The path length of solar beam through the atmosphere is accounted for in the term '**Air Mass**', which is defined as the ratio of the path length through the atmosphere, which the solar beam actually traverses up to the ground to the vertical path length (which is minimum) through the atmosphere. Thus at sea level the air mass is unity when the sun is at the 'zenith' (highest position), i.e., when inclination angle α is 90°. Mathematically:

$$\text{airmass, } m = \frac{\text{pathlength traversed by beam radiation}}{\text{vertical path length of atmosphere}}$$

The abbreviation AM0 refers to zero (no) atmosphere, AM1 refers to $m = 1$ (i.e., sun overhead, $\theta_z = 0$), AM2 refers to $m = 2$ ($\theta_z = 60°$); and so on.

From Fig. 4.5, the air mass may be written as:

$$\begin{aligned} m &= (\text{BA})/(\text{CA}) \\ &= \sec\theta_z \\ &= \text{cosec}\,\alpha \qquad (\text{as } \alpha + \theta_z = 90°) \end{aligned}$$

where α is inclination angle
and θ_z is zenith angle (α and θ_z are defined later in Section 4.10)

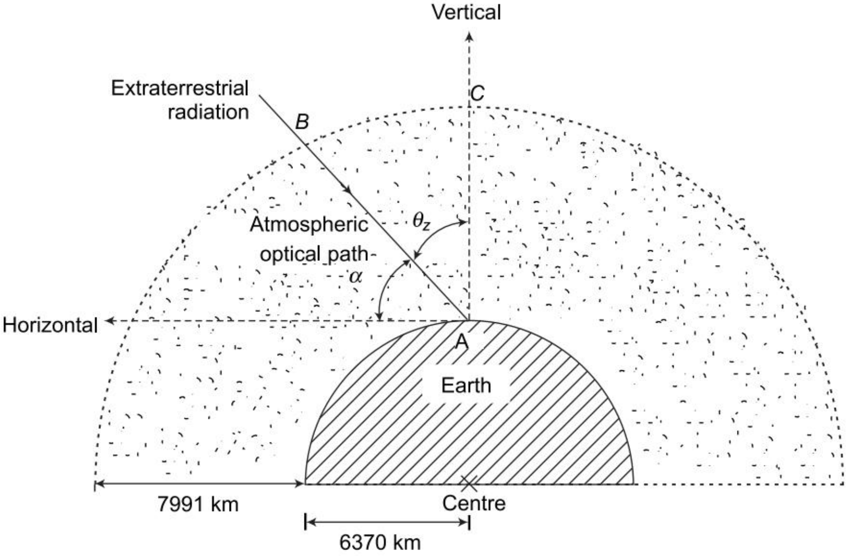


Figure 4.5 Direction of sun's ray with respect to atmosphere

4.8 MEASUREMENT OF SOLAR RADIATION

Solar radiation data are measured mainly by following instruments:

(i) *Pyranometer*: A pyranometer is designed to measure global radiation, usually on a horizontal surface but can also be used on an inclined surface. When shaded from beam radiation by using a shading ring, it measures diffuse radiation only.

(ii) *Pyrheliometer*: An instrument that measures beam radiation by using a long and narrow tube to collect only beam radiation from the sun at normal incidence.

(iii) A *sunshine recorder* measures the sunshine hours in a day.

4.8.1 Pyranometer

A precision pyranometer is designed to respond to radiation of all wavelengths and hence measures accurately the total power in the incident spectrum. It contains a thermopile whose sensitive surface consists of circular, blackened, hot junctions, exposed to the sun and cold junctions are completely shaded. The temperature difference between the hot and cold junctions is the function of radiation falling on the sensitive surface. The sensing element is covered by two concentric hemispherical glass domes to shield it from wind and rain. This also reduces the convection currents. A radiation shield surrounding the outer dome and coplanar with the sensing element, prevents direct solar radiation from heating the base of the instrument. The instrument has a voltage output of approximately 9 $\mu V/W/m^2$ and has an output impedance of 650 Ω. A precision spectral pyranometer (model: PSP) of Eppley laboratory is shown in Fig. 4.6. The pyranometer, when provided with a shadow band (or occulting disc) to prevent beam radiation from reaching the sensing element, measures the diffuse radiation only. Such an arrangement of shadow bandstand (model: SBS) is shown in Fig. 4.7.

Many inexpensive instruments are also available for measuring light intensity, including instruments based on cadmium sulphide photocells and silicon photodiodes. These instruments give good indication of relative intensity but their spectral response is not linear and thus cannot be accurately calibrated.

Figure 4.6 Pyranometer (*Courtesy:* Eppley Laboratory)

Figure 4.7 A pyranometer with shadow band (*Courtesy:* Eppley Laboratory)

4.8.2 Pyrheliometer

The normal incidence pyranometer, shown in Fig. 4.8, uses a long collimator tube to collect beam radiation whose field of view is limited to a solid angle of 5.5° (generally) by appropriate diaphragms inside the tube. The inside of the tube is blackened to absorb any radiation incident at angles outside the collection solid angle. At the base of the tube a wire wound thermopile having a sensitivity of approximately 8 $\mu V/W/m^2$ and an output impedance of approximately 200 Ω is provided. The tube is sealed with dry air to eliminate absorption of beam radiation within the tube by water vapor. A tracker is needed if continuous readings are desired.

4.8.3 Sunshine Recorder

This instrument measures the duration in hours, of bright sunshine during the course of the day. It essentially consists of glass sphere (about 10 cm in diameter) mounted

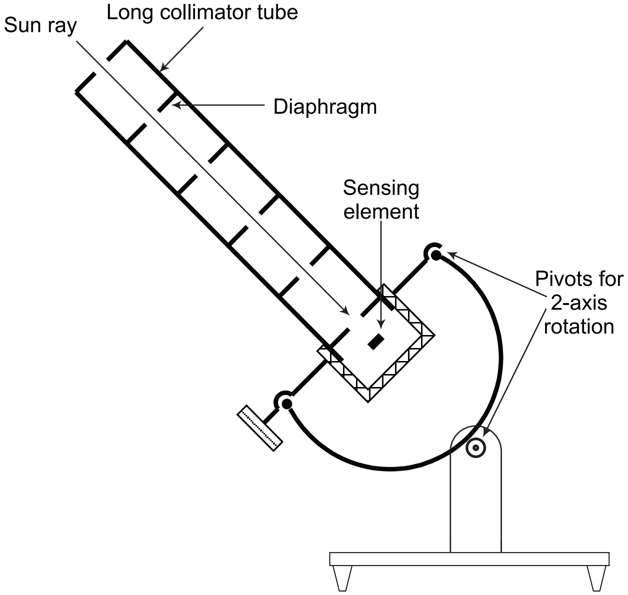


Figure 4.8 Pyrheliometer

on its axis parallel to that of earth, within a spherical section (bowl) as shown in Fig. 4.9. The bowl and glass sphere is arranged in such a way that sun's rays are focused sharply at a spot on a card held in a groove in the bowl. The card is prepared from special paper bearing a time scale. As the sun moves, the focused bright sunshine burns a path along this paper. The length of the trace thus obtained on the paper is the measure of the duration of the bright sunshine. Three overlapping pairs of grooves are provided in the spherical segment to take care of the different seasons of the year.

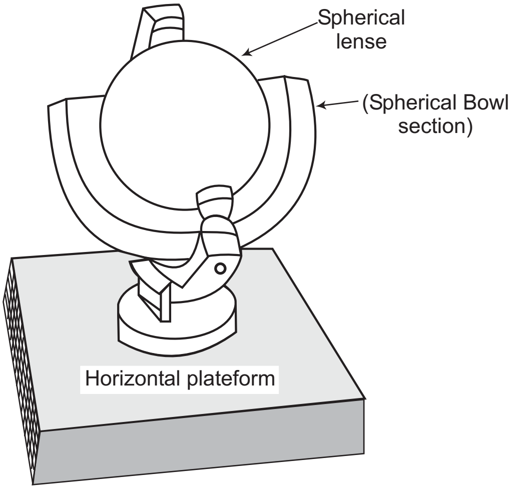
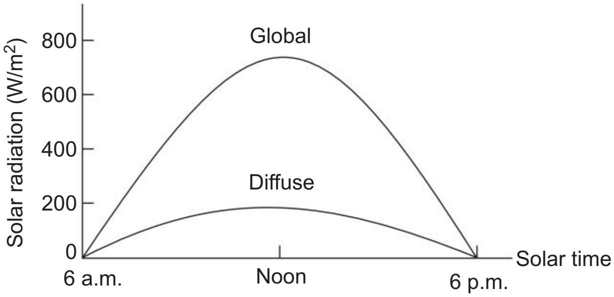


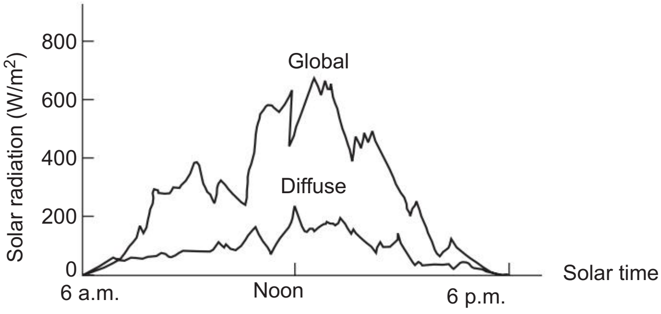
Figure 4.9 Sunshine recorder

4.9 SOLAR RADIATION DATA

The radiation data are mostly measured on a horizontal surface. Typical records of global and defuse radiation versus solar time on a horizontal surface for a clear day and partially cloudy day are shown in Fig. 4.10. Daily radiant energy is obtained from the area under the corresponding curve. Monthly average of the daily radiation is obtained by averaging over a span of the corresponding month and expressed in kJ/m^2. An alternative unit for expressing solar radiation is Langley per unit time, where one Langley is equal to 1 calory/cm^2.



(a) Clear day



(b) Cloudy day

Figure 4.10 Daily variation of global and diffuse radiation on typical (a) clear and (b) cloudy days on horizontal surface

Thus, solar radiation data are presented in three ways:

(i) Flow of energy per unit area per second, (kJ/m^2-s)
(ii) Flow of energy per unit area per hour, (kJ/m^2-h)
(iii) Flow of energy per unit area per day, (kJ/m^2-day)

The incident solar radiation is also a function of the orientation (or tilt, due south in northern hemisphere) of solar collector from horizontal. A typical pattern of relative irradiation throughout a year for three tilt angles equal to: (i) latitude, (ii) (latitude – 15°) and (iii) (latitude + 15°) is shown in Fig. 4.11. The radiation pattern indicates favouring of certain tilt during certain periods of the year. Therefore, seasonal adjustment of tilt angle may result in enhanced radiation collection. However, overall strategy changes from place to place and also on the type of application.

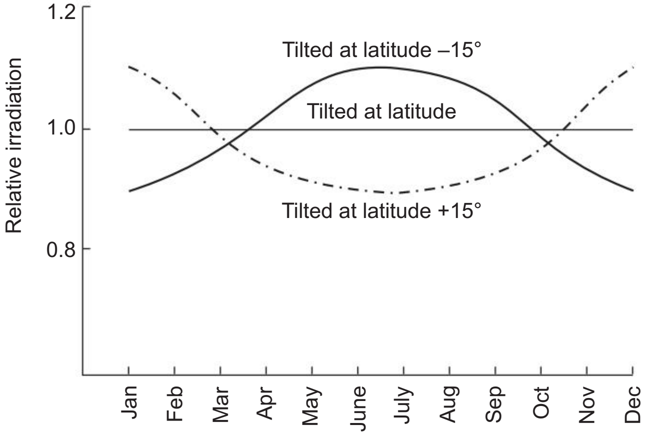


Figure 4.11 Relative irradiation at tilted surfaces throughout a year

Maximum solar radiation is received on a collector surface placed normal to incident rays. But as the position of the sun in the sky changes throughout the day, the collector has to adjust itself continuously to collect maximum radiation. Therefore, maximum energy can be collected if collector tracks the sun along two axes. However, providing for 2-axis tracking is expensive and complicated. A compromising but less expensive option is to fix the collector at suitable tilt and track the sun along 1-axis only. The most cost effective method with further compromise in the performance is to have a fix orientation for collector and possibly with some arrangement for seasonal adjustments only.

For designing a solar system or for predicting the potential of any solar application at a location, we need monthly average, daily solar radiation data (both global and diffuse) on a horizontal and possibly at certain positions of tilt angle of the surface. These data are measured at certain measuring stations in a country (at present 51 locations in case of India) and computed for other locations. This record is produced in the form of charts and tables and an atlas is prepared to help in solar systems design. Typical record of measured daily solar radiation data for New Delhi is shown in Tables C1, C2 and C3 in Appendix C.

4.10 SOLAR TIME (LOCAL APPARENT TIME)

Solar time is measured with reference to *solar noon*, which is the time when the sun is crossing observer's meridian. At solar noon the sun is at the highest position in the sky. The sun traverses each degree of longitude in 4 minutes (as earth takes 24 hours to complete one revolution). The standard time is converted to solar time by incorporating two corrections, as follows:

$$\text{Solar time} = \text{Standard time} \pm 4\,(L_{st} - L_{loc})\ (\text{min}) + E\ (\text{min}) \qquad (4.3)$$

where L_{st} and L_{loc} are the standard longitudes used for measuring standard time of the country and the longitude of observer's location, respectively. The (+ve) sign is used if the standard meridian of the country lies in western hemisphere (with reference to prime meridian) and (–ve) if that lies in the eastern hemisphere. E is the correction arising out of the variation in the length of the solar day due to variations in earth's rotation and orbital revolution, and is called *equation of time*. The *solar day,* which is the duration between two consecutive solar noons, is not exactly of 24 hours throughout the year. E can be determined either by calculation using following equation (within an accuracy of half a minute) or from the chart given in Fig. 4.12.

$$E = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B \text{ min.} \tag{4.4}$$

where $B = (360/364)(n - 81)$

and n = day of the year, starting from 1st January

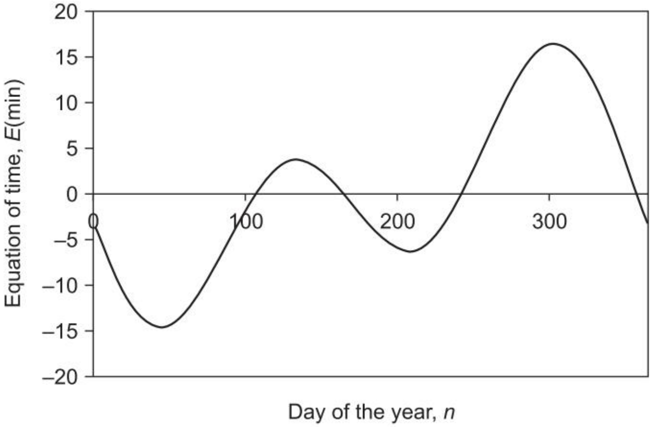


Figure 4.12 The equation of time as function of day of the year

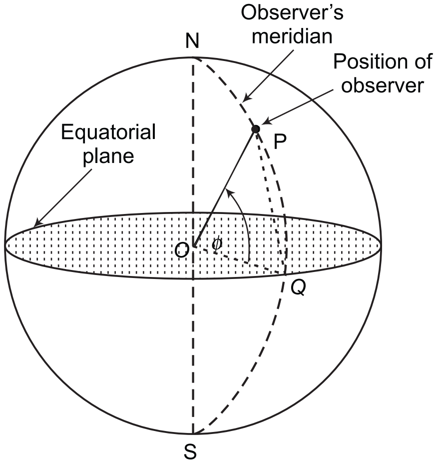
4.11 SOLAR RADIATION GEOMETRY

(a) Latitude (Angle of Latitude), (ϕ) The latitude of a location on earth's surface is the angle made by radial line, joining the given location to the center of the earth, with its projection on the equator plane as shown in Fig. 4.13(a). The latitude is positive for northern hemisphere and negative for southern hemisphere.

(b) Declination, (δ) It is defined as the angular displacement of the sun from the plane of earth's equator as shown in Fig. 4.13(b). It is positive when measured above equatorial plane in the northern hemisphere. The declination δ can be approximately determined from the equation:

$$\delta = 23.45 \times \sin\left[\frac{360}{365}(284 + n)\right] \text{ degrees} \tag{4.5}$$

where n is day of the year counted from 1st January.



(a) Latitude

(b) Declination angle δ

Figure 4.13 Latitude and declination angle

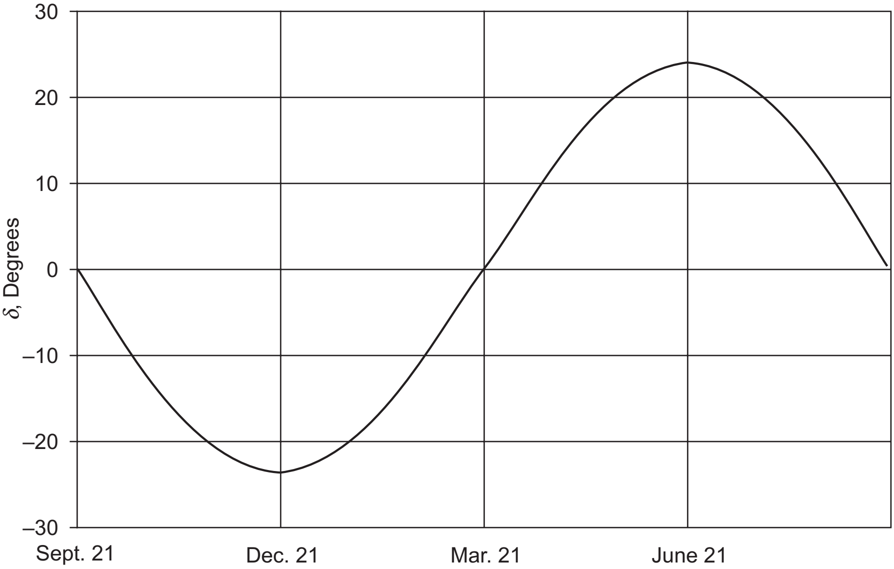


Figure 4.14 Variations in sun's declination

(c) ***Hour Angle, (ω)*** The hour angle at any moment is the angle through which the earth must turn to bring the meridian of the observer directly in line with sun's rays.

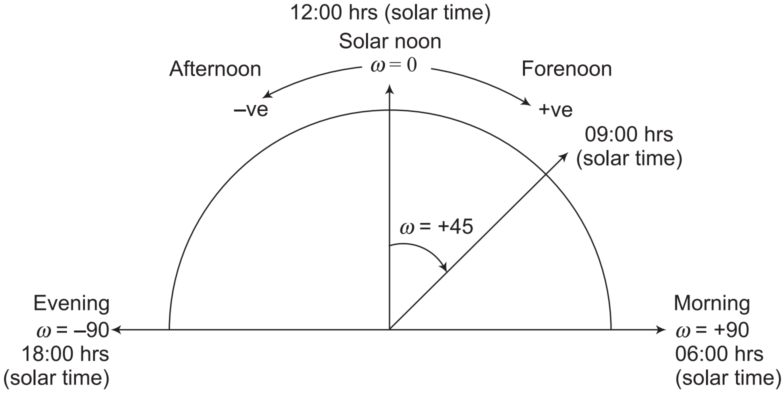


Figure 4.15 Hour angle ω

In other words, at any moment, it is the angular displacement of the sun towards east or west of local meridian (due to rotation of the earth on its axis). The earth completes one rotation in 24 hours. Therefore, one hour corresponds to 15° of rotation. At solar noon, as sunrays are in line with local meridian, hour angle is zero. It is +ve in the forenoon and –ve in the afternoon. Thus at 06:00 hrs it is +90° and at 18:00 hrs it is –90° as shown in Fig. 4.15. We adopt the convention of measuring it from noon based on LAT, being +ve in the morning and –ve in the afternoon.

It can be calculated as:

$$\omega = [12{:}00 - \text{Solar Time}]\ (\text{in hours}) \times 15 \text{ degrees} \qquad (4.6)$$

(d) ***Inclination Angle (Altitude), (α)*** The angle between sun's ray and its projection on horizontal surface is known as inclination angle, as shown in Fig. 4.16.

(e) ***Zenith Angle, (θ_z)*** It is the angle between sun's ray and perpendicular (normal) to the horizontal plane. (Refer Fig. 4.16)

(f) ***Solar Azimuth Angle (γ_s)*** It is the angle on a horizontal plane, between the line due south and the projection of sun's ray on the horizontal plane. It is taken as +ve when measured from south towards west. (Refer Fig. 4.16)

(g) ***Slope (Tilt Angle), (β)*** It is the angle between inclined plane surface, under consideration and the horizontal. It is taken to be +ve for the surface sloping towards south. (Refer Fig. 4.17)

(h) ***Surface Azimuth Angle, (γ)*** It is the angle in horizontal plane, between the line due south (*OS*) and the horizontal projection of normal to the inclined plane surface (*OQ*). It is taken as +ve when measured from south towards west. (Refer Fig. 4.17)

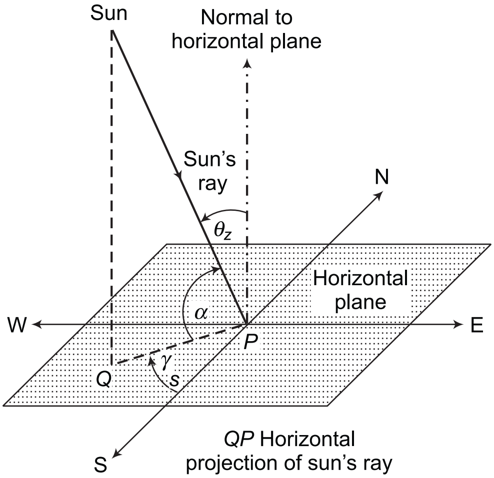


Figure 4.16 Solar inclination angle, solar azimuth angle and zenith angle

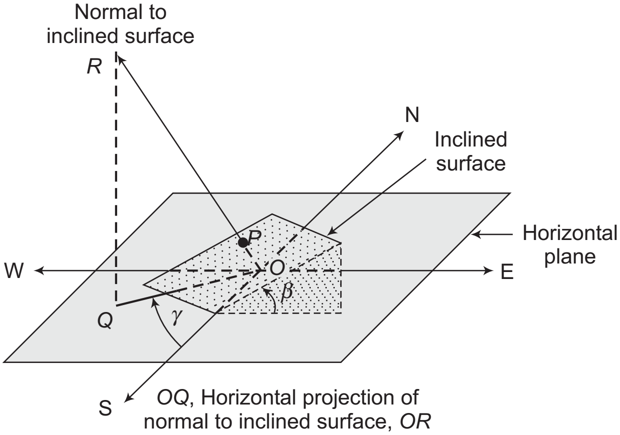


Figure 4.17 Surface azimuth angle and slope (tilt angle)

(i) *Angle of Incidence, (θ_i)* It is the angle between sun's ray incident on the plane surface (collector) and the normal to that surface. (Refer Fig. 4.18)

In general, the angle of incidence can be expressed as,

$$\cos\theta_i = \cos\delta\cos\omega(\cos\phi\cos\beta + \sin\phi\sin\beta\cos\gamma) + \cos\delta\sin\omega\sin\beta\sin\gamma + \sin\delta(\sin\phi\cos\beta - \cos\phi\sin\beta\cos\gamma) \tag{4.7}$$

Special Cases:

- **For surface facing due south, $\gamma = 0$**

$$\cos\theta_i = \cos(\phi - \beta)\cos\delta\cos\omega + \sin\delta\sin(\phi - \beta) \tag{4.8}$$

- **For horizontal surface, $\beta = 0$, $\theta_i = \theta_z$(Zenith angle)**

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\delta\sin\phi \tag{4.9}$$

- **For a vertical surface facing due south, $\gamma = 0, \beta = 90°$**

$$\cos \theta_i = -\sin \delta \cos \phi + \cos \delta \cos \omega \sin \phi \tag{4.10}$$

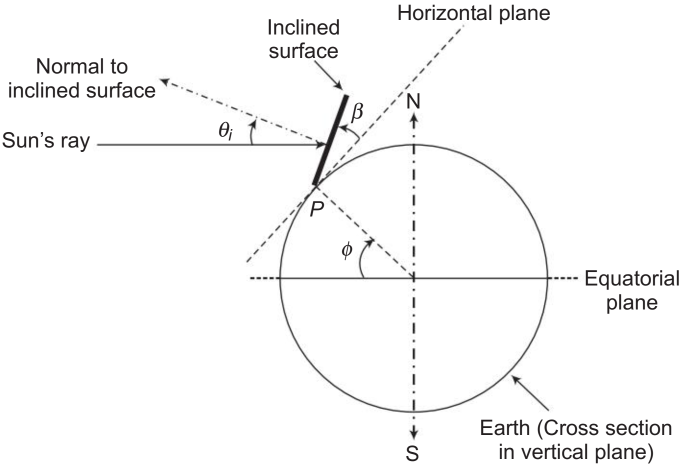


Figure 4.18 Angle of latitude, tilt angle, angle of incidence

4.12 SOLAR DAY LENGTH

At sunrise the sunrays are parallel to the horizontal surface. Hence the angle of incidence, $\theta_i = \theta_z = 90°$, the corresponding hour angle, ω_s, from Eq. (4.7):

$$\cos \theta_i = 0 = \cos \phi \cos \delta \cos \omega_s + \sin \delta \sin \phi$$

$$\omega_s = \pm \cos^{-1}(-\tan \phi \tan \delta) \tag{4.11}$$

The hour angle, ω_s at sunrise (or sunset) for horizontal surface is given by Eq. (4.11), which yields positive and negative values for ω_s. The positive value corresponds to sunrise while the negative to sunset.

The hour angle between sunrise and sunset is given by:

$$2\omega_s = 2\cos^{-1}(-\tan \phi \tan \delta)$$

Since 15° of hour angle is equivalent to one-hour duration, the duration of sunshine hours, t_d or daylight hours is given by:

$$t_d = (2/15) \cos^{-1}(-\tan \phi \tan \delta) \text{ hours} \tag{4.12}$$

The variation of t_d with latitude (ϕ) for different days (n) of the year is shown in Fig. 4.19.

The hour angle (ω_{st}) at sunrise or sunset as seen by the observer on an **inclined surface** facing due south (i.e. $\gamma = 0$) will also be given by Eq. (4.11) if the day under consideration lies between September 22 and March 21, and the location is in the northern hemisphere. However, if the day under consideration lies between March 21 and September 22, the hour angle at sunrise or sunset would be smaller in magnitude than the value given by Eq. (4.11) and would be obtained by substituting $\theta_i = 90°$ in Eq. (4.8).

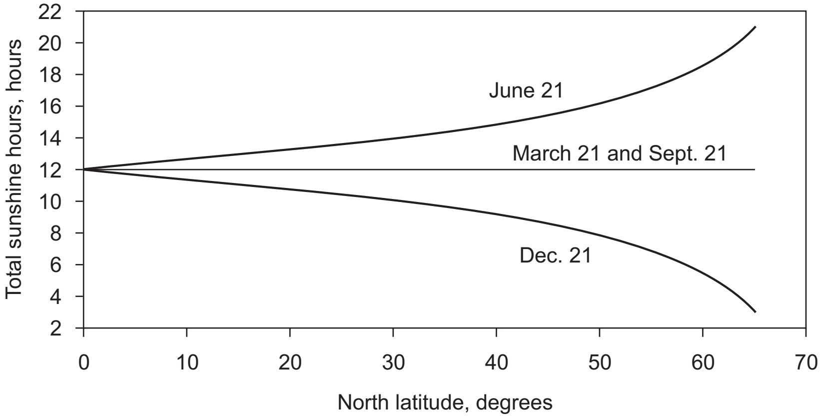


Figure 4.19 Variation of sunshine hours, t_d with latitude, on certain days of the year

Thus:

$$\omega_{st} = \pm \cos^{-1}[-\tan(\phi - \beta)\tan\delta]$$

Therefore, in general, for any day of the year, in northern hemisphere, the hour angle at sunrise or sunset on inclined surface may be given as:

$$\omega_{st} = \pm \min\left[\left|\cos^{-1}(-\tan\phi\tan\delta)\right|, \left|\cos^{-1}\{-\tan(\phi - \beta)\tan\delta\}\right|\right] \quad (4.13)$$

Example 4.1

Calculate the angle of incidence of beam radiation on a plane surface, tilted by 45° from horizontal plane and pointing 30° west of south located at Mumbai at 1:30 PM (IST) on 15th November. The longitude and latitude of Mumbai are 72° 49′ E and 18° 54′ N respectively. The standard longitude for IST is 81° 44′ E.

Solution

From given data:

$$n = 319$$

from Eq. (4.5) $\delta = -19.148°$
from Eq. (4.4) $E = 14.74$ min.

Standard Time = 1:30 PM = 13:30 hrs

from Eq. (4.3) Solar Time = 13 hours 30 min – 4(81.733° – 72.816°) min + 14.74 min
= 13:9.072 hrs

from Eq. (4.6) hour angle, $\omega = -17.27°$
Also given that, $\gamma = 30°$, $\beta = 45°$, $\phi = +18.9°$
Now the angle of incidence can be calculated using Eq. (4.7):

$$\begin{aligned}\cos\theta_i = {} & [\cos(+18.9°)\cos(45°) \\ & + \sin(+18.9°)\sin(45°)\cos(30°)]\cos(-19.148°)\cos(-17.27°) \\ & + \cos(-19.148°)\sin(-17.27°)\sin(45°)\sin(30°) \\ & + \sin(-19.148°)[\sin(+18.9°)\cos(45°) \\ & - \cos(+18.9°)\sin(45°)\cos(30°)]\end{aligned}$$

$$= 0.78229 - 0.09915 + 0.11305$$
$$\theta_i = \cos^{-1}(0.79619) = 37.23°$$

Example 4.2

Calculate the number of day light hours (sunshine hours) in Srinagar on January 1 and July 1. The latitude of Srinagar is 34° 05′ N.

Solution

From given data:

$n = 1$ and 182 respectively for January 1 and July 1.

from Eq. (4.5), $\delta = -23.01°$ and $23.12°$ respectively for January 1 and July 1.

from Eq. (4.12):

on January 1, $t_d = (2/15)\cos^{-1}[-\tan(34.083°)\tan(-23.01°)] = 9.77$ hours

on July 1, $t_d = (2/15)\cos^{-1}[-\tan(34.083°)\tan(23.12°)] = 14.24$ hours

Example 4.3

For New Delhi (28° 35′ N, 77° 12′ E), calculate the zenith angle of the sun at 2:30 P.M. on 20 February 2015. The standard IST latitude for India is 81° 44′ E.

Solution

Given, $\phi = 28° 35'\text{N} = 28.58$ degrees

For 20th February, $n = 51$

From Eq. (4.5), $$\delta = 23.45 \times \sin\left[\frac{360}{365}(284 + 51)\right] \text{ degrees}$$
$$= -11.58 \text{ degrees}$$

From Eq. (4.4), $E = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B$ min

$B = (360/364)(51 - 81) = -26.67$

$E = -14.29$ min

From Eq. (4.3), Solar time = 2:30 hrs ± 4 × (81° 44′ – 77° 12′) (min) – 14.29 (min)

= 1:57.59 hrs

From Eq. (4.6), $\omega = [12{:}00 - 1{:}57.59]$ (in hours) × 15 degrees $= -14.398$ degrees

From Eq. (4.9),

$$\cos\theta_z = \cos(28° 35')\cos(-11.58)\cos(-14.398) + \sin(-11.58)\sin(28° 35')$$
$$= 0.7366$$

Zenith angle, $\theta_z = 42.557$ degrees

4.13 EXTRATERRESTRIAL RADIATION ON HORIZONTAL SURFACE

At any point of time, the solar radiation (power) outside the atmosphere incident on a horizontal plane is given as [using Eq. (4.2) and Eq. (4.9)]:

$$I_{\text{ext},h} = I_{\text{ext}} \cos\theta_z$$

$$I_{\text{ext},h} = I_{\text{sc}}[1 + 0.033\cos(360\,n/365)](\cos\phi\cos\delta\cos\omega + \sin\delta\sin\phi) \quad (4.14)$$

where, I_{sc} is solar constant and n is the day of the year.

Daily Radiation

Extraterrestrial radiation (energy), on a horizontal surface, over a day, H_o may be obtained by integrating, $I_{\text{ext},\,h}$ over a day (where t is expressed in hours).

$$H_o = \int I_{\text{ext},h} \cos\theta_z dt$$

The relationship between hour angle, ω (in radian) and t (in hours) is given as:

$$\omega = \frac{15\pi}{180}t$$

Hence, $dt = \dfrac{12}{\pi}d\omega$ hours

Or $dt = 3600 \times \dfrac{12}{\pi}d\omega$ seconds

$$H_o = 3600 \times \frac{12}{\pi} I_{sc}\left[1 + 0.033\cos\frac{360n}{365}\right]\int_{-\omega_s}^{\omega_s} (\cos\theta\cos\delta\cos\omega + \sin\delta\sin\theta)d\omega$$

$$= 3600 \times \frac{24}{\pi} I_{sc}\left[1 + 0.033\cos\frac{360n}{365}\right](\cos\theta\cos\delta\sin\omega_s + \omega_s\sin\delta\sin\theta) \quad (4.15)$$

If I_{sc} is substituted in kW/m^2 than units of H_o will be kJ/m^2

Hourly Radiation

Proceeding on similar lines, the Extraterrestrial radiation (energy), on a horizontal surface, over an hour, I_o may be obtained by integrating, $I_{\text{ext},\,h}$ over an hour. Thus:

$$I_o = 3600 \times \frac{12}{\pi} I_{sc}\left[1 + 0.033\cos\frac{360n}{365}\right]\left\{\begin{array}{r}\cos\theta\,\cos\delta\sin(\omega_2 - \omega_1)\\ +(\omega_2 - \omega_1)\sin\delta\sin\theta\end{array}\right\} \quad (4.16)$$

where, one hour period is defined by hour angle from ω_1 to ω_2, (ω_2 is larger)

Alternatively, as change in solar radiation occur at slow pace, I_o may also be calculated by considering the instantaneous radiating power (kW/m^2) at the mid-point of the hour, i.e., $\omega = \dfrac{\omega_1 + \omega_2}{2}$, and multiplying by 3600, thus:

$$I_o = 3600 \times I_{sc}\left[1 + 0.033\cos\frac{360n}{365}\right]\left\{\cos\theta\cos\delta\cos\left(\frac{\omega_1 + \omega_2}{2}\right) + \sin\delta\sin\theta\right\} \quad (4.17)$$

4.14 EMPIRICAL EQUATIONS FOR ESTIMATING TERRESTRIAL SOLAR RADIATION ON HORIZONTAL SURFACE

Since measurements of solar radiation often are not available at every location of earth, attempts have been made by many researchers to establish relationships linking the values of radiation (global or diffuse) with meteorological parameters like number of sunshine hours, cloud cover and precipitation etc. Some of these equations will be given in the following sections.

4.14.1 Monthly Average, Daily Global Radiation

The monthly average of the terrestrial global radiation may be related to sunshine hours by a simple linear relationship [23]:

$$\frac{\bar{H}_g}{\bar{H}_o} = a + b\left(\frac{\bar{t}_d}{\bar{t}_{d\max}}\right) \tag{4.18}$$

where,

$\bar{H}_g$ = monthly average of the daily global radiation on a horizontal surface at a location

$\bar{H}_o$ = monthly average of the daily extraterrestrial radiation which would fall on a horizontal surface at the same location in absence of atmosphere

$\bar{t}_d$ = monthly average of the sunshine hours per day at a location

$\bar{t}_{d\max}$ = monthly average of the maximum possible sunshine hours per day at a location (i.e., day length of the average day of the month)

$\bar{t}_d$ is obtained by measurement for the whole month, while $\bar{t}_{d\max}$ is obtained from calculation for a day close to middle of the month as discussed in subsequent lines.

The coefficients '*a*', '*b*' are related to latitude, elevation and the sunshine hours as follows:

$$a = -0.309 + 0.539\cos\theta - 0.0693E_L + 0.29\left(\frac{\bar{t}_d}{\bar{t}_{d\max}}\right) \tag{4.19}$$

$$b = 1.527 - 1.027\cos\theta + 0.0926E_L - 0.359\left(\frac{\bar{t}_d}{\bar{t}_{d\max}}\right) \tag{4.20}$$

where θ = latitude and

E_L = elevation of the location above mean sea level (in kilometers)

The calculation of $\bar{H}_o$ can be simplified from the fact, that in each month, there is a particular day on which, H_o is nearly equal to the monthly mean value $\bar{H}_o$. The dates on which the value of H_o is equal to $\bar{H}_o$ are: January 17, February 16, Mach 16, April 15, May 15, June 11, July 17, August 16, September 15, October 15, November 14, December 10. As expected, these dates are close to the middle of the month. The values of sunshine hours for these dates are used as $\bar{t}_{d\max}$ for that month.

Equation (4.18) can be used to determine monthly average of daily global radiation on horizontal surface at a location for known sunshine hours and where the values of latitude and altitude are known.

Example 4.4

For Coimbatore (11.0183° N, 76.9725° E, and elevation of 411 m above sea level), estimate the value of average daily global radiation on horizontal surface during the month of March. The average sunshine hours per day for the month of March may be assumed as 9.5 h.

Solution

Given, $\phi = 11.0183°$, $E_L = 0.411$ km, $\overline{t_d} = 9.5$ h

For the month of March, the daily extraterrestrial radiation H_o on March 16 may be taken as average radiation $\overline{H}_o$ for the whole month.

Also day length on March 16 may be taken as $\overline{t}_{d\max}$.

For March 16, $n = 75$, the corresponding angle δ from Eq. (4.5):

$$\delta = 23.45 \times \sin\left[\frac{360}{365}(284+75)\right] \text{ degrees}$$

$$= -2.4177°$$

The hour angle at sunrise (/ sunset) may be calculated using Eq. (4.11) as:

$$\omega_s = \pm \cos^{-1}\{-\tan(11.0183°)\tan(-2.4177°)\}$$

$$= 90.47° \text{ (or 1.579 rad)}$$

$\overline{t}_{d\max}$ may be calculated using Eq. (4.12):

$$\overline{t}_{d\max} = (2/15)\cos^{-1}\{-\tan(11.0183°)\tan(-2.4177°)\} \text{ h}$$

$$= 12.0628 \text{ h}$$

H_o may be calculated using Eq. (4.15):

$$H_o = 3600 \times \frac{24}{\pi} \times 1.367 \times \left[1 + 0.033\cos\frac{360\times 75}{365}\right] \times$$

$$\{\cos(11.018°)\cos(-2.4177°)\sin(90.47°) + 1.579 \times \sin(-2.4177°)\sin(11.018°)\}$$

$$= 37595.1987 \times [1.0091] \times \{0.98066 - 0.01273\}$$

$$= 36{,}720.66 \text{ kJ/m}^2$$

Thus: $\overline{H}_o = H_o = 36{,}720.66 \text{ kJ/m}^2$

Now, the coefficients 'a' and 'b' can be calculated using Eq. (4.19) and Eq. (4.20)

$$a = -0.309 + 0.539 \times \cos(11.0183°) - 0.0693 \times 0.411 + 0.29 \times \left(\frac{9.5}{12.0628}\right)$$

$$= -0.309 + 0.52906 - 0.02848 + 0.2284$$

$$= 0.42$$

$$b = 1.527 - 1.027 \times \cos(11.0183°) + 0.0926 \times 0.411 - 0.359 \times \left(\frac{9.5}{12.0628}\right)$$

$$= 1.527 - 1.00807 + 0.03806 - 0.28273$$

$$= 0.27426$$

Therefore, from Eq. (4.18), the average daily global radiation, on horizontal surface, in Coimbatore, during the month of March may be calculated as:

$$\bar{H}_g = \bar{H}_o \times \left\{ a + b \left(\frac{\bar{t}_d}{\bar{t}_{d\max}} \right) \right\}$$

$$\bar{H}_g = 36720.66 \times \left\{ 0.42 + 0.27426 \times \left(\frac{9.5}{12.0628} \right) \right\}$$

$$= 23{,}354.05 \text{ kJ/m}^2$$

4.14.2 Monthly Average, Daily Diffuse Radiation

An empirical expression given below is suggested by Gopinath and Soler [24] for estimation of diffused radiation:

$$\frac{\bar{H}_d}{\bar{H}_g} = 0.87813 - 0.3328\bar{K}_T - 0.53039 \left(\frac{\bar{t}_d}{\bar{t}_{d\max}} \right) \tag{4.21}$$

where, $\bar{K}_T = \frac{\bar{H}_g}{\bar{H}_o}$ is called the monthly average clearness index.

The above expression was examined for radiation data available from 40 widely spread locations all over the world in latitude range from 36° N to 36° S. However, when applied to Indian locations, the estimated value is found to be significantly lower than the actual data. This is due the fact that the diffuse component is much larger in India. A more accurate estimation for Indian conditions, proposed by Garg and Garg [25], is given below:

$$\frac{\bar{H}_d}{\bar{H}_g} = 0.8677 - 0.7365 \left(\frac{\bar{t}_d}{\bar{t}_{d\max}} \right) \tag{4.22}$$

Example 4.5

From the data given in Example 4.4 for Coimbatore, estimate the monthly average of the daily-diffused radiation on a horizontal surface as per Gopinath and Soler estimate as well as Garg and Garg estimate.

Solution

As per calculation of Example 4.4:

$$\bar{H}_o = 36{,}720.66 \text{ kJ/m}^2, \ \bar{H}_g = 23{,}354.05 \text{ kJ/m}^2$$

Therefore, $\bar{K}_T = \frac{23{,}354.05}{36{,}720.66} = 0.636$

Also from given data in Example 4.4: $\bar{t}_d = 9.5$ h

As calculated in Example 4.4: $\bar{t}_{d\max} = 12.0628$ h

Therefore, $\frac{\bar{t}_d}{\bar{t}_{d\max}} = \frac{9.5}{12.0628} = 0.7875$

Now, from Eq. (4.21), as per **Gopinath and Soler** estimate:

$$\frac{\bar{H}_d}{\bar{H}_g} = 0.87813 - 0.3328 \times 0.636 - 0.53039 \times 0.7875$$

$$\bar{H}_d = 23354.05 \times 0.2488$$

$$= 5{,}810.19 \text{ kJ/m}^2$$

From Eq. (4.22), as per **Garg and Garg** estimate:

$$\frac{\bar{H}_d}{\bar{H}_g} = 0.8677 - 0.7365 \times 0.7875$$

$$\bar{H}_d = 23354.05 \times 0.2877$$

$$= 6{,}719.106 \text{ kJ/m}^2$$

4.14.3 Monthly Average, Hourly Global Radiation

An empirical expression given below is suggested for estimation of monthly average, hourly, global radiation [26]:

$$\frac{\bar{I}_g}{\bar{H}_g} = \frac{\bar{I}_o}{\bar{H}_o} \frac{(a + b\cos\omega)}{f_c} \tag{4.23}$$

where, $$f_c = a + 0.5b\left[\frac{\omega_s - \sin\omega_s\cos\omega_s}{\sin\omega_s - \omega_s\cos\omega_s}\right] \tag{4.24}$$

(in the above expression the value of ω_s is substituted in radians)

$$a = 0.409 + 0.5016\sin(\omega_s - 60°) \tag{4.25}$$

$$b = 0.6609 - 0.4767\sin(\omega_s - 60°) \tag{4.26}$$

$\bar{I}_g$ = monthly average of the hourly global radiation on a horizontal surface

$\bar{I}_o$ = monthly average of the hourly extraterrestrial radiation on a horizontal surface

The correlation is found to be satisfactory for predicting the average hourly global radiation for cities all over the world within latitude 65° S to 65° N.

Example 4.6

From the data given in Example 4.4 for Coimbatore, estimate the monthly average of the hourly global radiation on a horizontal surface during 11:00 to 12:00 hrs (LAT) for the month of March.

Solution:

For Coimbatore, $\phi = 11.0183°$

The representative day for the month of March is 16th, therefore, $n = 75$

As calculated in Example 4.4,

$\delta = -2.4177°$ and the hour angle at sun rise $\omega_s = 90.47°$ (or 1.579 rad)

$\bar{H}_o = 36{,}720.66 \text{ kJ/m}^2$ $\bar{H}_g = 23{,}354.05 \text{ kJ/m}^2$

Now, hourly radiation:

I_o on representative day (n = 75) may be taken as $\overline{I}_o$,

Also hour angle ω at the middle of the hour (11:00 to 12:00 hrs) LAT

Thus $\omega = \dfrac{\omega_1 + \omega_2}{2} = 7.5°$

From Eq. (4.17),

$$I_o = 3600 \times 1.367\left[1 + 0.033\cos\frac{360 \times 75}{365}\right]\left\{\begin{array}{r}\cos(11.0183°)\cos(-2.4177°)\cos(7.5°)\\ +\sin(-2.4177°)\sin(11.0183°)\end{array}\right\}$$

$$= 3600 \times 1.367 \times [1.009] \times \{0.9642\}$$
$$= 4{,}787.925 \text{ kJ/m}^2$$

Thus, $\overline{I}_o = I_o$ = 4,787.925 kJ/m^2

The coefficients 'a' and 'b' may be calculated using Eqs (4.25) and (4.26)

$$a = 0.409 + 0.5016 \sin(90.47° - 60°) = 0.66335$$

$$b = 0.6609 - 0.4767 \sin(90.47° - 60°) = 0.41917$$

f_c can be calculated from Eq. (4.24), using ω_s = 90.47° (or 1.579 rad)

$$f_c = 0.66335 + 0.5 \times 0.41917 \times \left[\frac{1.579 - \sin(90.47°)\cos(90.47°)}{\sin(90.47°) - 1.579 \times \cos(90.47°)}\right]$$

$$= 0.66335 + 0.209585 \times \left[\frac{1.587}{1.0129}\right]$$

$$= 0.9919$$

Now, substituting the above calculated values in Eq. (4.23)

$$\frac{\overline{I}_g}{23{,}354.05} = \frac{4787.925}{36720.66} \times \frac{\{0.66335 + 0.41917 \times \cos(7.5°)\}}{0.9919}$$

$$\frac{\overline{I}_g}{23{,}354.05} = \frac{0.13039 \times (1.0789)}{0.9919}$$

$$\overline{I}_g = 3{,}312.22 \text{ kJ/m}^2$$

The estimated value of monthly average of the hourly global radiation on a horizontal surface, during 11:00 to 12:00 hrs. (LAT) for the month of March, is **3,312.22 kJ/m^2**

4.14.4 Monthly Average, Hourly Diffuse Radiation

An empirical expression given below is suggested for estimation of monthly average, hourly, diffuse radiation [27]:

$$\frac{\overline{I}_d}{\overline{H}_d} = (a + b\cos\omega)\frac{\overline{I}_o}{\overline{H}_o} \tag{4.27}$$

where, $a = 0.4922 + \left\{\dfrac{0.27}{(\overline{H}_d/\overline{H}_g)}\right\}$ for $0.1 \le (\overline{H}_d/\overline{H}_g) \le 0.7$ (4.28) or $$a = 0.76 + \left\{ \frac{0.133}{(\bar{H}_d/\bar{H}_g)} \right\} \text{ for } 0.7 < (\bar{H}_d/\bar{H}_g) \le 0.9 \tag{4.29}$$

and $$b = \frac{2(1-a)(\sin\omega_s - \omega_s\cos\omega_s)}{(\omega_s - 0.5\sin 2\omega_s)} \tag{4.30}$$

Example 4.7

From the data given in Example 4.4 for Coimbatore, estimate the monthly average of the hourly diffuse and beam radiations on a horizontal surface during 11:00 to 12:00 hrs (LAT) for the month of March.

Solution

We shall use Eq. (4.27) for calculation of $\bar{I}_d$,

$$\frac{\bar{I}_d}{\bar{H}_d} = (a + b\cos\omega)\frac{\bar{I}_o}{\bar{H}_o}$$

Hour angle ω is considered at the middle of the hour (11:00 to 12:00 hrs) LAT,

Thus $$\omega = \frac{\omega_1 + \omega_2}{2} = 7.5°$$

As calculated in Example 4.4, the hour angle at sun rise $\omega_s = 90.47°$ (or 1.579 rad)

As calculated in Example 4.5, using Eq. (4.22), $\bar{H}_d = 6{,}719.106$ kJ/m^2

As per calculation of Example 4.4:

$$\bar{H}_o = 36{,}720.66 \text{ kJ/m}^2, \quad \bar{H}_g = 23{,}354.05 \text{ kJ/m}^2$$

As calculated in Example 4.6, $\bar{I}_o = 4{,}787.925$ kJ/m^2

As the ratio $(\bar{H}_d/\bar{H}_g) = 0.2877$, Eq. (4.28) will be used to calculate coefficient 'a'.

Thus,

$$a = 0.4922 + \{0.27/0.2877\} = 1.4307,$$

and from Eq. (4.30),

$$b = 2(1-a)(\sin\omega_s - \omega_s\cos\omega_s)/(\omega_s - 0.5\sin 2\omega_s)$$
$$= 2\times(1-1.4307)\times\{\sin(90.47°) - 1.579\times\cos(90.47°)\}/\{1.579 - 0.5\times\sin(2\times 90.47°)\}$$
$$= 2\times(-0.4307)\times\{1.0129\}/\{1.5872\}$$
$$= -0.5497$$

From Eq. (4.27),

$$\frac{\bar{I}_d}{6719.106} = \{1.4307 + (-0.5497)\times\cos(7.5°)\}\times\frac{4787.925}{36720.66}$$

$$\bar{I}_d = 6719.106 \times \{0.8857\} \times 0.13039$$

$$\bar{I}_d = 775.97 \text{ kJ/m}^2$$

As calculated in Example 4.6, $\bar{I}_g = 3{,}312.22$ kJ/m^2

Beam radiation may be calculated as:

$$\overline{I}_b = \overline{I}_g - \overline{I}_d = 3{,}312.22 - 775.97 = 2{,}536.25 \text{ kJ/m}^2$$

Therefore,

Monthly average of the hourly diffuse radiation, $\overline{I}_d$ **= 775.97 kJ/m^2**

Monthly average of the hourly beam radiation, $\overline{I}_b$ **= 2,536.25 kJ/m^2**

4.15 SOLAR RADIATION ON INCLINED PLANE SURFACE

Total radiation incident on an inclined surface consists of three components: (i) beam radiation, (ii) diffuse radiation and (iii) radiation reflected from ground and surroundings. It may be mentioned here that both beam and diffuse components of radiation undergo reflection from the ground and surroundings. Total radiation on a surface of arbitrary orientation may be evaluated as:

$$I_T = I_b\, r_b + I_d\, r_d + (I_b + I_d)\, r_r \tag{4.31}$$

where r_b, r_d and r_r are known as tilt factors for beam, diffuse and reflected components respectively. The definitions and expressions for these factors are given below:

r_b: It is defined as the ratio of flux of beam radiation incident on an inclined surface (I_b') to that on a horizontal surface (I_b).

$$I_b' = I_{bn} \cos \theta_i$$

$$I_b = I_{bn} \cos \theta_z$$

where, I_{bn} is the beam radiation on a surface normal to the direction of sunrays

$$r_b = \frac{I_b'}{I_b} = \frac{\cos\ \theta_i}{\cos\ \theta_z} \tag{4.32}$$

For a tilted surface facing south, $\gamma = 0°$, the expression for r_b may be written as:

$$r_b = \frac{\sin\delta \sin(\phi - \beta) + \cos\delta \cos\omega \cos(\phi - \beta)}{\sin\delta \sin\phi + \cos\delta \cos\omega \cos\phi} \tag{4.33}$$

r_d: It is defined as the ratio of flux of diffuse radiation falling on inclined surface to that on the horizontal surface. The value of this tilt factor depends upon the distribution of diffuse radiation over the sky and on the portion of the sky dome seen by the tilted surface. Assume that the sky is an isotropic source of diffuse radiation; we have for a tilted surface with slope β,

$$r_d = \frac{1 + \cos\beta}{2} \tag{4.34}$$

r_r: The reflected component comes mainly from the ground and surrounding objects. Since (1 + cos β)/2 is the radiation shape factor for tilted surface with respect to the sky, it follows that (1 – cos β)/2 is the radiation shape factor for the surface with respect to surrounding ground. Assume that the reflection of the beam and diffuse radiation falling on the ground is diffuse and isotropic and the reflectivity is ρ, the tilt factor for reflected radiation may be written as:

$$r_r = \rho\left(\frac{1-\cos\beta}{2}\right) \tag{4.35}$$

where ρ is reflection coefficient of the ground (equal to 0.2 for ordinary grass or concrete and 0.6 for snow-covered ground respectively)

For vertical surface, $\beta = 90°$, $r_d = 0.5$ and $r_r = 0.5\rho$. This indicates that half of the diffuse and half of the total reflected radiation is received by a vertical surface. For horizontal plane, $r_d = 1$ and $r_r = 0$, which indicates that maximum diffuse radiation is received by horizontal surface and that a horizontal surface receives no ground reflected radiation. The ratio r' of total solar energy incident on an inclined surface to that on a horizontal surface is given as:

$$r' = \frac{I_T}{I_b + I_d} = \frac{I_T}{I_g} = \left(1 - \frac{I_d}{I_g}\right) r_b + \frac{I_d}{I_g} r_d + r_r \tag{4.36}$$

Equation (4.31) can be used for calculating hourly radiation falling on tilted surface if the hour angle ω is considered at the mid-point of the hour concerned.

The monthly average, hourly value $\overline{I_T}$ can be obtained by considering the representative day of the month for calculation of I_T. The equation (4.36) will then be modified as:

$$\frac{\overline{I_T}}{\overline{I_g}} = \left(1 - \frac{\overline{I_d}}{\overline{I_g}}\right) \overline{r_b} + \frac{\overline{I_d}}{\overline{I_g}} \overline{r_d} + \overline{r_r} \tag{4.37}$$

Where $\overline{r_b} = r_b$ on representative day of the month,

also $\overline{r_d} = r_d$

$\overline{r_r} = r_r$

On similar lines the ratio of daily total radiation on tilted surface H_T to daily global radiation on a horizontal surface may be written as:

$$\frac{H_T}{H_g} = \left(1 - \frac{H_d}{H_g}\right) R_b + \frac{H_d}{H_g} R_d + R_r \tag{4.38}$$

For south facing surface, $\gamma = 0°$,

$$R_b = \frac{\omega_{st}\,\sin\delta\,\sin(\phi-\beta) + \cos\delta\,\sin\omega_{st}\,\cos(\phi-\beta)}{\omega_s\,\sin\delta\,\sin\phi + \cos\delta\,\sin\omega_s\,\cos\phi} \tag{4.39}$$

where ω_{st} = sunrise hour angle expressed in radians on tilted surface

ω_s = sunrise hour angle expressed in radians on horizontal surface

And $R_d = r_d = \dfrac{1+\cos\beta}{2}$ (4.40)

$$R_r = r_r = \rho\left(\frac{1-\cos\ \beta}{2}\right) \tag{4.41}$$

Equation (4.33) can also be used for calculating monthly average of daily radiation falling on inclined surface if the required values are calculated for representative day of the month. Equation (4.33) may then be written in its revised form,

$$\frac{\overline{H}_T}{\overline{H}_g} = \left(1-\frac{\overline{H}_d}{\overline{H}_g}\right)\overline{R}_b + \frac{\overline{H}_d}{\overline{H}_g}\overline{R}_d + \overline{R}_r \tag{4.42}$$

where $\overline{R}_b = R_b$ on the representative day of the month

and $$\overline{R}_d = R_d = \frac{1+\cos\beta}{2} \tag{4.43}$$

$$\overline{R}_r = R_r = \rho\left(\frac{1-\cos\beta}{2}\right) \tag{4.44}$$

Example 4.8

Calculate the monthly average, total daily radiation falling on a flat plate collector facing south ($\gamma = 0°$) and tilted by 30° from ground, at New Delhi (28° 35′ N, 77° 12′ E) for the month of November. Assume ground reflectivity as 0.2.

Solution

Given data:

$\phi = 28.58°$

$\beta = 30°$

Monthly average of the daily global radiation for the month of November in New Delhi (from Table C1 in Appendix C), $\overline{H}_g$ = 16,282.8 kJ/m^2

Monthly average of the daily diffuse radiation for the month of November in New Delhi (from Table C2 in Appendix C), $\overline{H}_d$ = 41,07.6 kJ/m^2

The representative day for the month of November is 14th. Therefore, the day of the year on November 14, $n = 318$

Using Eq. (4.5), $\delta = -18.91°$

Using Eq. (4.11), $\omega_s = 79.245°$, or 1.383 radians

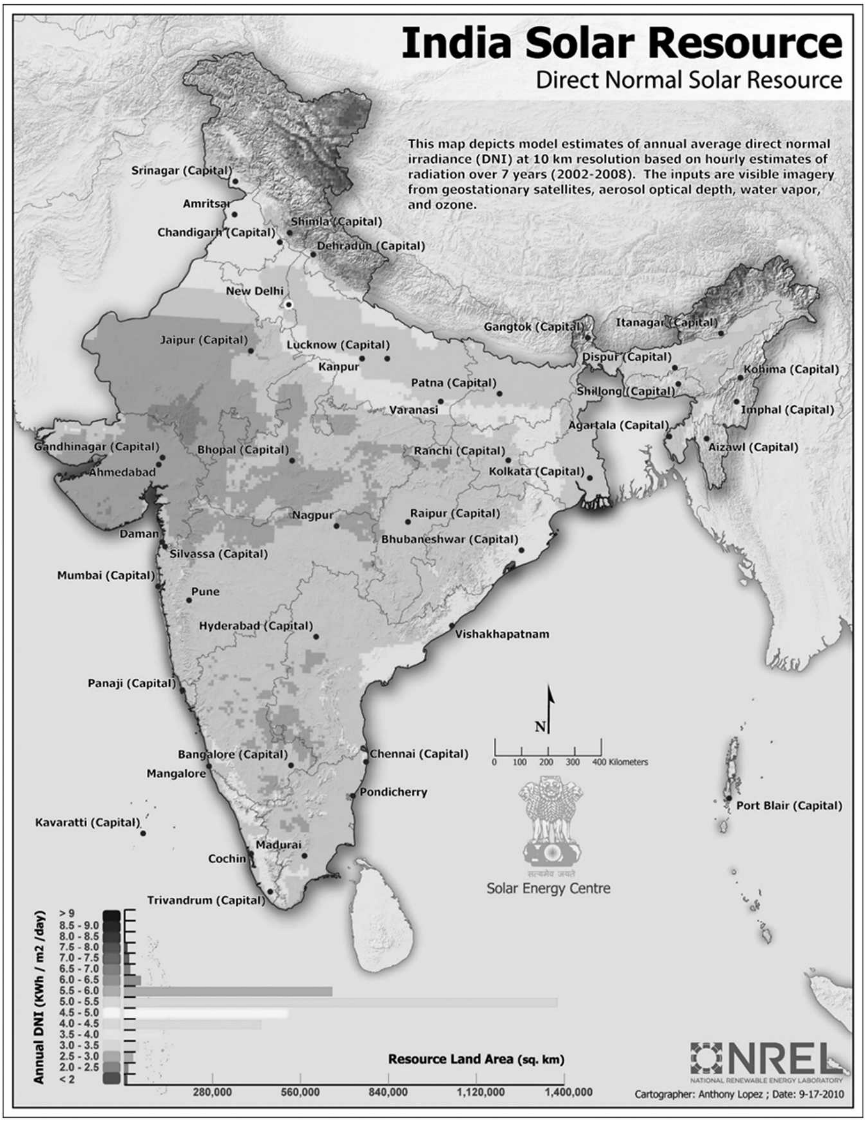
From Eq. (4.13), $\omega_{st} = 79.245°$, or 1.383 radians

Using Eq. (4.39),

$$R_b = \frac{\omega_{st}\ \sin\delta\sin(\phi-\beta)+\cos\delta\sin\omega_{st}\ \cos(\phi-\beta)}{\omega_s\ \sin\delta\sin\phi+\cos\delta\sin\omega_s\ \cos\phi}$$

$$R_b = \frac{1.383\times\sin(-18.91)\sin(28.58-30)+\cos(-18.91)\sin(79.245)\cos(28.58-30)}{1.383\times\sin(28.58)\sin(-18.91)+\cos(-18.91)\sin(79.24)\cos(28.58)}$$

$$= 1.56$$



This map depicts model estimates of annual average direct normal irradiance (DNI) at 10 km resolution based on hourly estimates of radiation over 7 years (2002-2008). The inputs are visible imagery from geostationary satellites, aerosol optical depth, water vapor, and ozone.

Cartographer: Anthony Lopez ; Date: 9-17-2010

Figure 4.20 Annual average of the daily radiation in kWh/m^2 in India

Using Eq. (4.43),

$$\overline{R}_d = \frac{1+\cos 30}{2} = 0.933$$

Using Eq. (4.44), and substituting $\rho = 0.2$,

$$\overline{R}_r = 0.2 \times \left(\frac{1-\cos 30}{2}\right) = 0.0134$$

Now, monthly average total daily radiation, $\overline{H}_T$ on tilted surface may be calculated using Eq. (4.42),

$$\frac{\overline{H}_T}{\overline{H}_g} = \left(1-\frac{\overline{H}_d}{\overline{H}_g}\right)\overline{R}_b + \frac{\overline{H}_d}{\overline{H}_g}\overline{R}_d + \overline{R}_r$$

$$\overline{H}_T = 16282.8 \times \left[\left(1-\frac{4107.6}{16282.8}\right)\times 1.56 + \frac{4107.6}{16282.8}\times 0.933 + 0.0134\right]$$

$$= 23{,}043.89\ \text{kJ/m}^2\text{-day}$$

Therefore, total daily radiation falling on a flat plate collector = **23,043.89 kJ/m^2**

REVIEW QUESTIONS

1. What are the disadvantages of solar energy?
2. What are the indirect forms of solar energy?
3. How is the energy continuously being produced in the sun?
4. What do you understand by earth's albedo?
5. At what wavelengths the radiation emitted from sun and that reflected from earth are centered?
6. Define solar irradiance, solar constant, extraterrestrial and terrestrial radiations. What is the standard value of solar constant?
7. Describe percentage wise distribution of various components in extraterrestrial radiation.
8. Explain the depletion process of solar radiation as it passes through the atmosphere to reach at the surface of the earth.
9. What is solar time and why it is different from standard clock time of the country?
10. Define the terms: altitude angle, incident angle, zenith angle, solar azimuth angle, latitude angle, declination angle, and hour angle.

    (Gujarat Technological University, 2014)
11. Derive an expression for solar day length.
12. Define beam, diffuse and global radiation. Derive an expression for total radiation on an inclined surface. Show that a horizontal surface receives no ground reflected radiation.
13. Write short notes on beam and diffuse radiation.

    (Visvesrayya Technological University, 2006)
14. Explain the construction and principle of operation of a sunshine recorder.
15. How does the collection of solar energy is affected by tilting a flat plate collector with respect to ground?
16. How does sun tracking helps in energy collection by a flat plate solar collector?
17. What are the basic features required in an ideal pyranometer?

PROBLEMS

1. Calculate the number of daylight hours (day length) at Bangalore on 21 June and 21 December in a leap year. The latitude of Bangalore is 12° 58′ N. (*Ans.* 12.76 h, 11.23 h)
2. Calculate the angle made by beam radiation with normal to a flat plate collector, tilted by 30° from horizontal, pointing due south, located at Delhi, at 11:00 hrs (IST), on June 1. The latitude and longitude of Delhi are 28° 35′ N and 77° 12′ E respectively. The standard IST longitude is 81° 44′ E. (*Ans.* 29.92°)
3. Calculate the angle of incidence on a horizontal plane surface at Kolkata, at 14:00 hrs (IST), on March 21, in a leap year. The longitude and latitude of Kolkata are 88° 20′ E and 22° 32′ N respectively. The standard longitude of IST is 81° 44′ E. (*Ans.* 40.6°)
4. For Jaipur (26° 55′ N, 75° 49′ E), calculate the zenith angle of the sun at 9:30 A.M. on 10 October 2015. The standard IST latitude for India is 81° 44′ E. (*Ans.* 22.298%)
5. Estimate the value of average daily global radiation on horizontal surface during the month of September in Chandigarh (30° 44′ N, 76° 47′ E, and elevation of 321 m above sea level). The average sunshine hours per day for the month of September may be assumed as 9.5 h. (*Ans.* 21,130.3 kJ/m^2)
6. From the data given in Problem 5 for Chandigarh, estimate the monthly average of the daily diffused radiation on a horizontal surface as per Gopinath and Soler estimate as well as Garg and Garg estimate. (*Ans.* 4,805.19 kJ/m^2, 5,757 kJ/m^2)
7. From the data given in Problem 5 for Chandigarh, estimate the monthly average of the hourly global radiation on a horizontal surface during 9:00 to 10:00 hrs (LAT) for the month of September. (*Ans.* 3,312.22 kJ/m^2)
8. From the data given in Problem 5 for Chandigarh, estimate the monthly average of the hourly diffuse and beam radiations on a horizontal surface during 9:00 to 10:00 hrs (LAT) for the month of September. (*Ans.* 627.52 kJ/m^2, 2131.76 kJ/m^2)
9. Calculate the hour angles at sunrise on June 21 and also on December 21 for a flat plate solar collector inclined due south (i.e. $\gamma = 0°$) at an angle equal to latitude of the place. The collector is located at Nagpur (21° 06’ N, 79° 03’ E) (*Ans.* 90°, 80.36°)
10. An inclined surface, facing due south, tilted at 60° with horizontal, is location at Aligarh (latitude 27° 54′ N, longitude 78° 05′ E). The reflection coefficient, ρ of the ground is 0.2. Calculate total monthly average, hourly radiation received at the surface, in the month of March at 1 PM (LAT). (The hourly radiation data for horizontal plane given in Appendix C for New Delhi may be adopted for Aligarh.) (*Ans.* 2,855.82 kJ/m^2)
11. Calculate the monthly average, total daily radiation falling on a flat plate collector facing south ($\gamma = 0°$) and tilted by an angle equal to latitude from ground, at Mumbai (19° 07′ N, 72° 51′ E) for the month of September. Assume ground reflectivity as 0.15. For the month of September at Mumbai the daily average data are given as: $\overline{H}_g = 17560.8$ kJ/m^2-h and $\overline{H}_d = 10296$ kJ/m^2-h. (*Ans.* 17202.8 kJ/m^2-h)

OBJECTIVE TYPE QUESTIONS

1. Which process is responsible for production of energy in the sun?
(a) Nuclear fission reaction
(b) Nuclear fusion reaction
(c) Exothermal chemical reaction
(d) All of the above

2. Which one of the following statements is not true for solar energy?
(a) It is a dilute form of energy.
(b) Its availability is diurnal.
(c) Availability at any instant of time is uncertain.
(d) Its harnessing at large scale is easy.

3. The diffuse radiation:
(a) has no unique direction.
(b) has unique direction
(c) has short wavelength as compared to beam radiation.
(d) has larger magnitude as compared to beam radiation.

4. In extraterrestrial radiation, what is the approximate percentage content of infra-red component?
(a) 45.5%
(b) 55.5%
(c) 20%
(d) 80%

5. Terrestrial radiation has a wavelength in the range of:
(a) 0.2 μm to 4 μm
(b) 0.2 μm to 0.5 μm
(c) 0.380 μm to 0.760 μm
(d) 0.29 μm to 2.3 μm

6. What is the standard value of solar constant?
(a) 1 kW/m^2
(b) 1.367 kW/m^2
(c) 1.5 kW/m^2
(d) 5 kW/m^2

7. When incoming solar radiation passes through the atmosphere of the earth:
(a) radiation of all wavelengths is absorbed uniformly by different types of molecules.
(b) different molecules selectively absorb the radiation of different wavelengths.
(c) there is no absorption of radiation in the atmosphere.
(d) there is total absorption of radiation.

8. The percentage of the incoming radiation reflected back to space by the earth is:
(a) 10%
(b) 20%
(c) 30%
(d) 40%

9. Air mass ratio is minimum:
(a) when the sun is at zenith.
(b) at sunrise.
(c) at sunset.
(d) at 0600 GMT.

10. At the inclination angle of 30°, what will be magnitude of zenith angle?
(a) 30°
(b) 120°
(c) 150°
(d) 60°

11. For 1 degree change in longitude, the change in solar time is:
(a) 4 min
(b) 4 sec
(c) 1 min
(d) 1 hour

12. On September 21, the declination angle will be:
(a) zero
(b) +23.45°
(c) –23.45°
(d) +180°

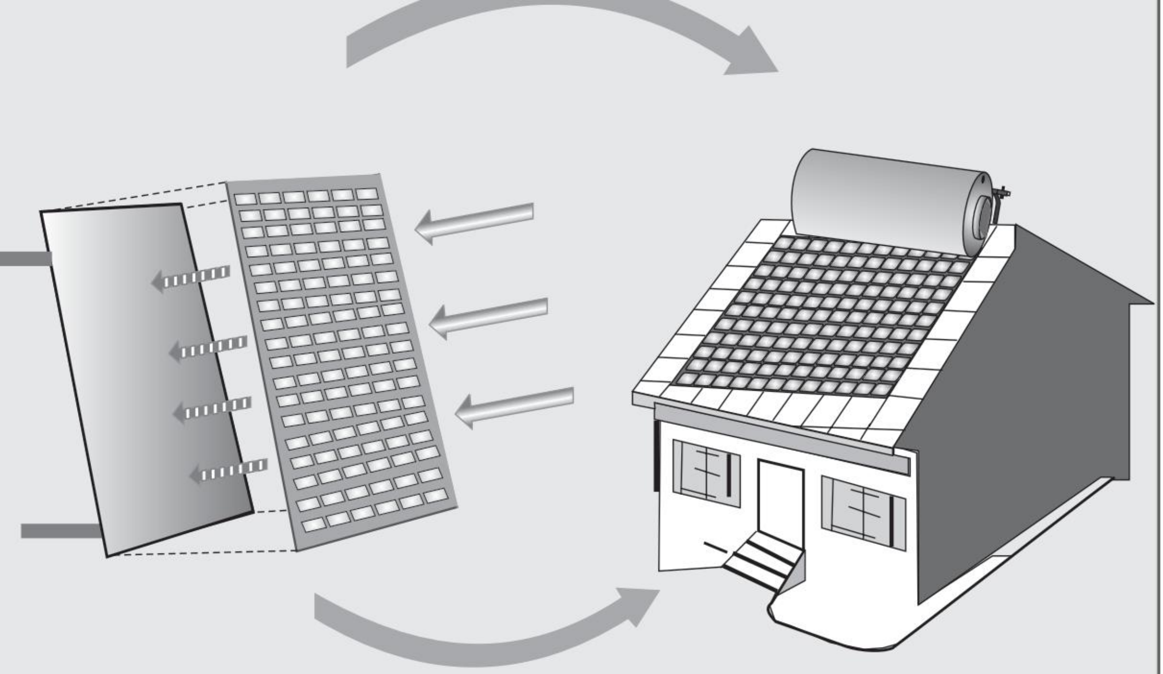
13. At solar noon, the hour angle is:

(a) +90°	(b) −90°
(c) zero	(d) +180°

14. On the representative day of each month, the extraterrestrial daily radiation may be taken as equal to:
(a) beam radiation at the location
(b) diffuse radiation at the location
(c) global radiation at the location
(d) monthly average, daily extraterrestrial radiation at the location

15. A horizontal surface receives:
(a) no reflected component of radiation.
(b) 50% of the reflected component of radiation.
(c) 50% of the diffuse component of radiation.
(d) 50% of the beam component of radiation.

16. A vertical surface receives:
(a) no reflected component of radiation.
(b) 50% of the reflected component of radiation.
(c) 100% of diffuse component of radiation.
(d) 50% of the beam component of radiation.



CHAPTER

5

Solar Thermal Systems

Learning Objectives

In this chapter you will be able to:

- Describe the process of harnessing solar energy in the form of heat
- Explain the construction and operation of various types of solar collectors
- List various useful applications of solar energy including heating, cooling and generation of mechanical energy
- Discuss the detailed mathematical analysis of flat plate collector

5.1 INTRODUCTION

Solar energy can be utilized directly by two technologies: namely (i) Solar Thermal and (ii) Solar Photovoltaic. Solar thermal systems provide thermal energy for various processes. In cold climate regions, large amount of low-grade thermal energy is required for heating air for comfort and hot water for washing, cleaning and other domestic and industrial needs. Various industrial surveys show that up to 24 per cent of all industrial heat is consumed for heating fluids to a low temperature. Solar energy is best suited for low-grade thermal applications. Even in high temperature heating applications a significant amount of fuel can be saved by using solar energy for preheating (up to about 180 °C). Due to this reason, manufacturing of solar water heaters has become a thriving industry in several countries, especially Australia, Israel, USA and Japan. Solar thermal energy is also being utilized in drying and process industries. It can also be converted and utilized as mechanical and electrical energy in the same way as in any conventional thermal system. Solar thermal systems will be discussed in detail in this chapter and solar PV systems will be dealt with in the next chapter.

5.2 SOLAR COLLECTORS

Solar power has low density per unit area (1 kW/sq. m. to 0.1 kW/sq. m.). Hence it is to be collected by covering large ground area by solar thermal collectors. Solar thermal collector essentially forms the first unit in a solar thermal system. It absorbs solar energy as heat and then transfers it to heat transport fluid efficiently. The heat transport fluid delivers this heat to thermal storage tank / boiler / heat exchanger, etc., to be utilized in the subsequent stages of the system.

5.2.1 Classification

The overall view of classification of solar collectors into categories and sub-categories is shown in Fig. 5.1. The classification is based on the way they collect solar radiation. The non-concentrating type absorbs the radiation as it is received on the surface of the collector while the concentrating type, first increases the concentration of radiation per unit area before absorbing it. Further, based on the techniques employed for concentration of radiation, the concentrating type is further subdivided into focus and non-focus types. The focus type is further divided into line or point focus depending on the focusing method.

5.2.2 Comparison of Concentrating and Non-concentrating Type (Flat Plate Type) Solar Collectors

1. In *concentrating type solar collectors*, solar radiation is converged from large area into smaller area using optical means. Beam radiation, which has a unique direction and travels in a straight line, can be converged by reflection or refraction techniques. Diffuse radiation however, has no unique direction and so does not obey optical principles. Therefore, diffuse component cannot be concentrated. Thus concentrating type solar collectors mainly make use

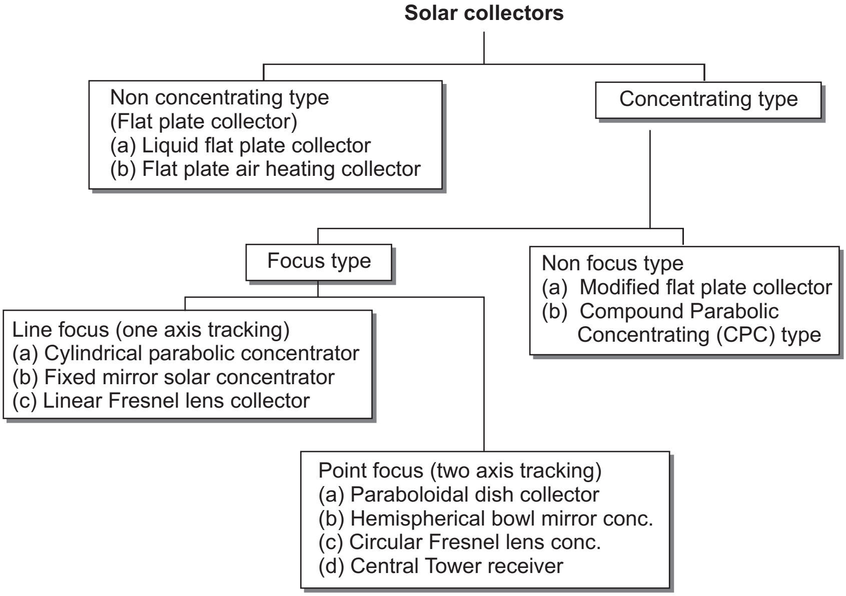


Figure 5.1 Types of solar collectors

of beam radiation component (plus very little diffuse component coming directly over absorber), while *non-concentrating (flat plate) collectors* absorb both beam as well as diffuse radiation, which is a distinct advantage of flat plate collector.

2. A *flat plate collector* is simple in construction and does not require sun tracking. Therefore, it can be properly secured on a rigid platform and thus becomes mechanically stronger than those requiring flexibility for tracking purpose. As the collector is installed outdoors and exposed to atmospheric disturbances (rain, storm, etc.), the flat plate type is more likely to withstand harsh outdoor conditions. Also because of simple stationary design, a flat plate collector requires little maintenance.
3. The principal disadvantage of flat plate collector is that because of absence of optical concentration, the area from which heat is lost is large. Also due to same reason high temperatures cannot be attained.
4. Main advantage of concentrating type collectors is that high temperatures can be attained due to concentration of radiation. This also yields high temperature thermal energy.

5.2.3 Performance Indices

The important performance indices of a solar collector are: (i) collector efficiency (ii) concentration ratio and (iii) temperature range. The performance of a solar collector is evaluated on the basis of these features.

Collector efficiency is defined as the ratio of the energy actually absorbed and transferred to heat transporting fluid by the collector (useful energy) to the energy incident on the collector.

Concentration ratio (CR) is defined as the ratio of the area of aperture of the system to the area of the receiver. The aperture of the system is the projected area of the collector facing (normal) the beam.

Temperature range is the range of temperature to which the heat transport fluid is heated up by the collector.

In flat plate collectors no optical system is utilized to concentrate the solar radiation and hence the concentration ratio is only 1 and temperature range is less than 100 °C. Line focus collectors have CR up to 100 and temperature range of the order of 150 °C to 300 °C. Concentration ratio of the order of thousands and temperature range of 500 °C to 1000 °C can be obtained by using point focus collectors.

5.2.4 Liquid Flat Plate Collector

A flat plate collector is placed at a location in a position such that its length aligns with line of longitude and suitably tilted towards south to have maximum collection. The positioning of the collector is shown in Fig. 5.2. The constructional details of a simple flat plate collector are shown in Fig. 5.3. The basic elements in a majority of these collectors are:

(i) transparent cover (one or two sheets) of glass or plastic
(ii) blackened absorber plate usually of copper, aluminium or steel,
(iii) tubes, channels or passages, in thermal contact with the absorber plate. In some designs, the tubes form integral part of absorber plate.
(iv) weather tight, insulated container to enclose the above components

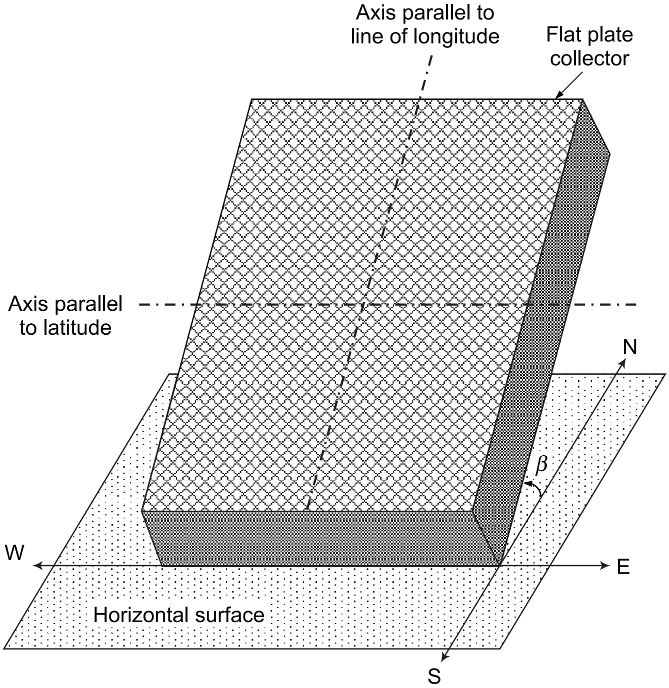


Figure 5.2 Positioning of flat plate collector

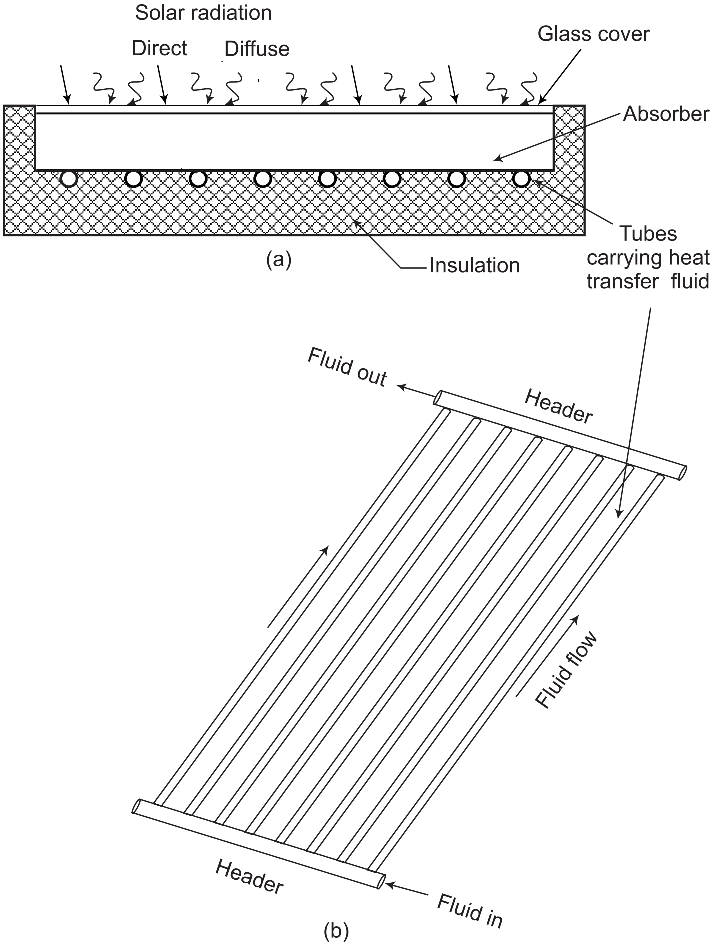
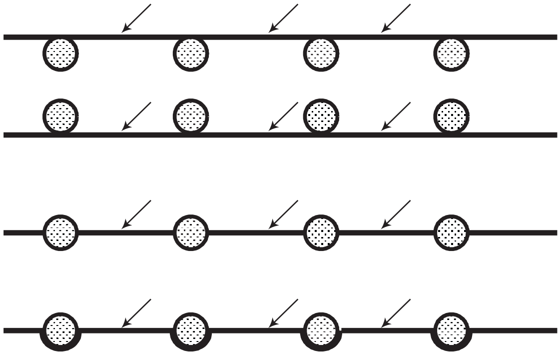
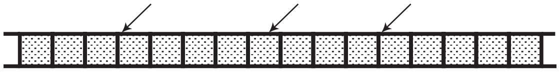


Figure 5.3 Construction of flate plate collector

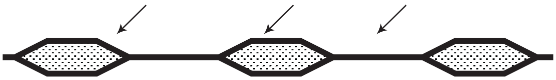
A liquid, most commonly, water is used as heat transport medium from collector to next stage of the system. However, sometimes mixture of water and ethylene glycol (antifreeze mixture) are also used if the ambient temperatures are likely to drop below 0°C during nights. As solar radiation strikes on specially treated metallic absorber plate, it is absorbed and raises its temperature. The absorber plate is usually made from a metal sheet ranging in thickness from 0.2 to 1 mm. The heat is transferred to heat transfer liquid circulating in the tube (or channels), beneath the absorber plate and in intimate contact with it. The metallic tubes range in diameter from 1 to 1.5 cm. These are soldered, brazed, welded or pressure bonded to the absorber plate with a pitch ranging from 5 to 12 cm. In some designs, the tubes are bonded to the top of absorber plate or in line with and integral to absorber plate. Some of these arrangements are shown in Fig. 5.4. Header pipes which are of slightly larger diameter, typically 2 to 2.5 cm, lead the water in and out of the collector and distributed to tubes. The metal most commonly used, both for absorber plate, the tubes and the header pipes is copper, but other metals and plastics have also been tried. In the bottom and along the sidewalls, thermal insulation, provided by 2.5 to 8-cm thick layer of glass wool, prevents heat loss from the rear surface and sides of the collector. The glass-cover permits the entry of solar radiation as it is transparent for incoming short wavelengths but is largely opaque to the longer infrared radiation reflected from the absorber. As a result, heat remains trapped in the airspace between the absorber plate and glass cover in a manner similar to green house. The glass cover also prevents heat loss due to convection by keeping the air stagnant. The glass cover may reflect some 15 per cent of incoming solar radiation, which can be reduced by applying anti reflective coating on the outer surface of the glass. The usual practice is to have one to two covers with spacing ranging from 1.5 to 3 cm. Plain or toughened glass of 4 to 5 mm thickness is most favoured material. Transparent plastics may also be used in place of glass but they often offer inferior performance as compared to glass. Most plastics are not as opaque to infrared radiation as glass. Also their transparency for incoming solar radiation decreases with aging. The life of plastic material is short when exposed to sun rays as it breaks down and cracks are developed over a span of time.



(a) Pipe and fin type



(b) Water sandwich type



(c) Semi water sandwich type (roll-bond)

Figure 5.4 Cross section through collector plates

A variety of absorber plate designs have been developed as shown in Fig. 5.4. These absorber plates can be broadly divided into three basic types depending on the extent of wetted area relative to the absorbing surface area.

(i) **Pipe and fin type** in which liquid flows only in pipe and hence comparatively low wetted area and liquid capacity.

(ii) **Rectangular or cylindrical full sandwich type** in which both the wetted area and water capacity are high

(iii) **Roll bond type or semi sandwich type** intermediate between the above two types.

The best choice depends on the particular application. For low temperature requirements, such as warming of swimming pool, the plastic, full water sandwich plate may be most appropriate. For domestic and industrial applications high temperatures are required and hence pipe and fin type plate may be more suitable.

Effect of Various Parameters on Performance

(a) Selective Surface Absorber plate surfaces which exhibit the characteristics of high value of absorptivity for incoming solar radiation and low value of emissivity for outgoing re-radiation are called selective surfaces. Such surfaces are desirable because they maximize the net energy collection. Some examples of selective surface layers are copper oxide, nickel black and black chrome.

(b) Number of Covers With increase in the number of covers, the values of both $(\tau\alpha)_b$ and $(\tau\alpha)_d$ decreases and thus the flux absorbed by absorber plate decreases. The value of heat loss from the absorber plate also decreases. However, the amount of decrease is not the same for each cover. Maximum efficiency is obtained with one or two covers.

(c) Spacing Heat loss also varies with spacing between two covers and that between temperature and also vary with tilt. Since collectors are designed to operate at different locations with varying tilts and under varying service conditions, an optimum value of spacing is difficult to specify. Spacing in range from 4 to 8 cm is normally suggested.

(d) Collector Tilt Flat plate collectors are normally used in fixed position and do not track the sun. Therefore, the tilt angle at which they are fixed is very important. Optimum tilt depends on the nature of the application. Usual practice is to recommend value of $(\phi + 10°)$ or $(\phi + 15°)$ for winter applications (e.g. water heating, space heating, etc.) and $(\phi - 10°)$ or $(\phi - 15°)$ for summer applications (e.g. absorption refrigeration plant etc.).

(e) Dust on the Top of the Cover When a collector is deployed in a practical system, dust gets accumulated over it, reducing transmitted flux through the cover. This requires continuous cleaning of the cover, which is not possible in practical situation. Cleaning is generally done once in few days. For this reason it is recommended that the incident flux be multiplied by a correction factor which accounts for the reduction in intensity because of accumulation of dust. In general, a correction factor from 0.92 to 0.99 seems to be indicated.

Material Selection for Various Parts of Flat Plate Collector

To construct a solar collector, knowledge of the properties of the materials used for fabrication of various components is necessary to predict the performance and durability of the collector. These properties include density, tensile strength, melting point, thermal conductivity, specific heat, resistance to UV degradation, moisture penetration and degradation due to atmospheric pollution, etc. Desirable properties of some materials are discussed here.

(a) Absorber Plate Absorber plate material should have high thermal conductivity, adequate tensile and compressive strength and good corrosion resistance. Copper is generally the material of choice due to high conductivity and resistance to corrosion. Other possible materials for absorber plate may be aluminium, steel, brass and zinc, etc. The properties of some of the materials for absorber plate are given in Table 5.1.

Table 5.1 Properties of some of the materials for absorber plate

Material	Density (kg/m^3)	Specific heat (kJ/kg-°C)	Thermal conductivity (W/m °C)
Aluminium	2707	0.996	204
Steel	7833	0.465	54
Copper	8954	0.383	386
Brass (70/30)	8522	0.385	111
Zinc, pure	7144	0.384	112
Silver	10524	0.234	419

Aluminium and steel require a corrosion-inhibited heat transfer fluid. In the past, absorber plates were usually constructed with tubes soldered or welded into metal plate. Recent advances have resulted in development of internal tube absorber plate such as Roll-Bond panel.

(b) Insulation The desirable characteristics of thermal insulating material are: low thermal conductivity, stability up to high usable temperature (up to 200°C), no out gassing up to 200°C, self-supporting feature without tendency to settle, ease of application and no contribution in corrosion. Some useful properties for some insulating materials are given in Table 5.2.

Table 5.2 Properties of some useful insulating materials

S.N.	Name of material	Thermal conductivity at 200 °C (W/m°C)	Density (kg/m^3)	Out gassing	Sagging
1.	Crown white wool	0.034	48	No	Yes
2.	Spintex 300 industrial	0.075	48	No	No
3.	Glass wool	0.044	48	No	Yes
Pipe sections					
4.	Isoloyd	0.021	32	No	No
5.	Thermo Cole	0.035	16	No	No
6.	Foam	0.017	32	No	No

(c) Cover Plate The characteristics of cover through which the solar energy is transmitted up to the absorber is extremely important for proper functioning of the collector. The ideal cover should (i) transmit maximum solar energy to the absorber plate, (ii) minimize upward heat loss from the absorber plate to the environment, (iii) shield the absorber from direct exposer to weathering, and (iv) be of lightweight and easy to work. The most important factors for the cover plate materials are the durability, strength, non-degradability and good incoming solar energy transmittance.

Tempered glass has proven durability and stability under exposure to UV rays and high temperatures. This is also highly resistant to breakage due to thermal cycles and mechanical impacts. Also it is largely opaque to long wavelength IR radiation reflected from absorber plate.

The transmittance of glass depends on its iron content. Glass with high iron content transmits less light. A normal sheet of window glass looks green when viewed through the edge because of presence of iron oxide. Therefore, tempered water-white crystal glass should be used.

Transparent plastic materials such as acrylic polycarbonate, Tedlar, Mylar and Lexan may be used for cover plates. Plastic materials have limited life as exposure to UV radiation reduces their transmissivity. These are also usually partially transparent to the long wavelength radiation reflected from absorber plate, therefore, less effective in reducing the radiated heat loss. Some plastics cannot withstand high stagnation temperature when no useful heat is removed from the collector. However, the main advantages of plastic material are the resistance to breakage, reduction in weight and, in some cases reduction in cost.

Most cover materials have refractive index of around 1.5. Therefore, approximately 8 per cent of the normal incident solar radiation is reflected back from the surface of a cover plate, unless special surface treatments are applied. A greater fraction is reflected at higher incident angles. Thus, maximum transmittance is 92 per cent from a single, perfectly clear, non-absorptive cover. In multi-glazed panels there is additional 8 per cent reduction of transmission per cover. In addition, there is further reduction in transmission due to absorption in the material. The cover reflection can be reduced considerably by etching or by applying anti-reflective coating on a surface. Some useful properties for some cover materials are given in Table 5.3.

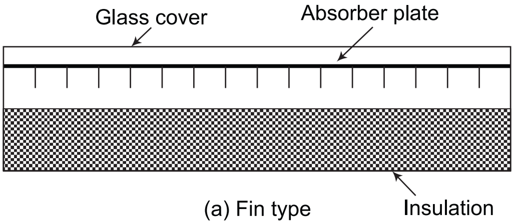
Table 5.3 Properties of some useful cover plate materials

Material	**Index of refraction**	**Normal incidence short wave transmittance (λ = 0.4–2.5 μm)**	**Normal incidence long wave transmittance (λ = 2.5–40 μm)**	**Density (kg/m^3)**	**Specific heat (J/kg-K)**
Glass	1.518	0.840	0.020	2.489×10^3	0.754×10^3
Fibreglass Reinforced polyester	1.540	0.870	0.076	1.399×10^3	1.465×10^3

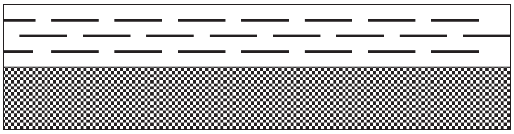
Acrylic (Plexiglass)	1.490	0.900	0.020	1.189×10^3	1.465×10^3
Polycarbonate (Lexan)	1.586	0.840	0.020	1.199×10^3	1.193×10^3
Polyvinyl Fluoride (Tedlar)	1.460	0.920	0.207	1.379×10^3	1.256×10^3
Polyester (Mylar)	1.640	0.870	0.178	1.394×10^3	1.046×10^3

5.2.5 Flat Plate Air Heating Collector (Solar Air Heater, Solar Air Collector)

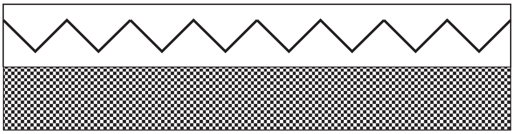
A solar air-heating collector is similar to a liquid flat plate collector with change in configuration of absorber and tube (riser) as shown in Fig. 5.5. The value of heat transfer coefficient between the absorber plate and the air is low. For this reason the surfaces are sometimes roughened or longitudinal fins are provided in the airflow passage. Corrugated, V-shape, matrix, etc., are some of the other variations of absorber plate. The principal applications of theses collectors are drying for agricultural and industrial purposes, and space heating.



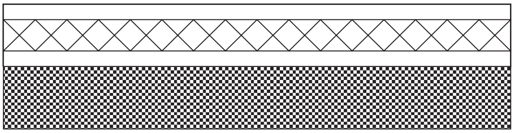
(a) Fin type



(b) Metal matrix type



(c) Corrugated type



(d) Thermal trap type

Figure 5.5 Various types of flat plate air heating collector

It has following advantages over liquid flat plate collector:

- It is compact, simple in construction and requires little maintenance.
- The need to transfer thermal energy from working fluid to another fluid is eliminated as air is used directly as working fluid.
- Corrosion is completely eliminated.
- Leakage of air from the duct is less severe.
- Possibility of freezing of working fluid is also eliminated.
- The pressure inside the collector does not become very high.

Major disadvantage of air collector are:

- Large amount of fluid is to be handled due to low density. As a result the electrical power required to blow the air through the system can be significant if the pressure drop is not kept within prescribed limits.
- Heat transfer between absorber plate and air is poor.
- There is less storage of thermal energy due to low heat capacity.

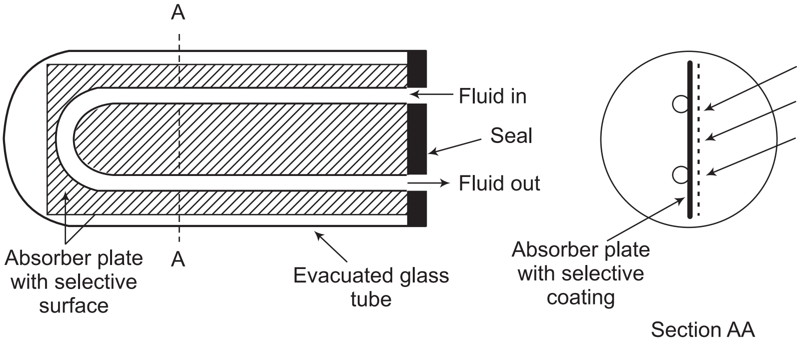
5.2.6 Evacuated Tube Collector

The performance of a flat plate collector can be improved by suppressing or reducing the heat lost from the collector by convection and conduction. This is done by having vacuum around the absorber. As a consequence, it becomes essential to use a glass tube as the cover because only a tubular surface is able to withstand the stresses introduced by the pressure differences as a result of vacuum. The collector consists of a number of long tubular modules stacked together.

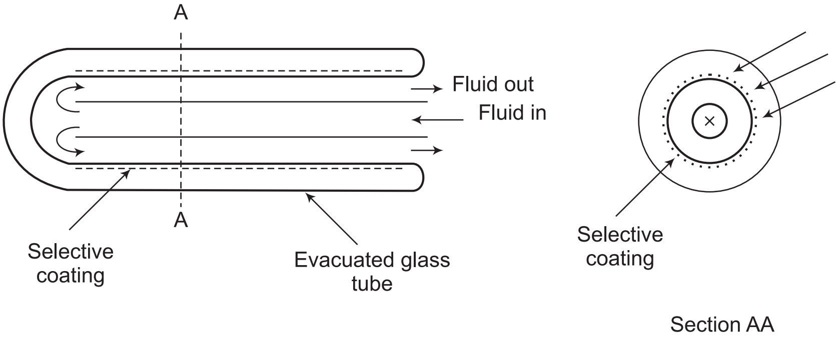
A number of designs have been developed and some of them are commercially available. In a simplest design, each module consists of a metal absorber plate with two fluid tubes housed in an evacuated, cylindrical glass tube as shown in Fig. 5.6(a). The absorber plate has a selective surface coating on it. The two tubes are joined at the other end inside the glass cover and form a "U" path for the fluid, with one tube acting as inlet tube while the other as outlet tube. Glass to metal seal is provided between the absorber tubes and the end cover of the vacuum tube. Also special precaution is required to reduce thermal contact between absorber tubes and outer tube though the seal.

In another design shown in Fig. 5.6(b), the metal to glass seal is avoided by using three concentric tubes with the space between the outer two tubes, which are made from glass, being evacuated. The outer surface of the middle tube acts as absorbing surface and has a selective surface coating on it. The liquid flows in through the innermost tube and flows out through the annulus between this tube and the middle tube.

Two types of layouts are used for the evacuated tube modules in a collector. In one type, the modules are stacked side by side without a gap between them. In another one, a spacing of few centimeters is kept between the modules and a back reflector is used. The back reflector may be a plane white surface to act as a diffuse reflector or a curved surface acting as a specular reflector. The cross-sectional view of both of these arrangements is shown in Fig. 5.7.

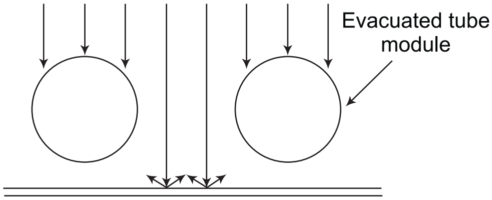


(a) Flat plate type

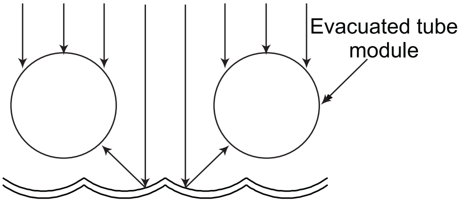


(b) Concentric tube type

Figure 5.6 Various designs of evacuated tube collector



(a) Plain diffuse reflector



(b) Curved reflector

Figure 5.7 Layout of evacuated tube modules with reflectors

The level of evacuation required for suppression of convection and conduction can be calculated from basic heat transfer theory. With increasing the level of evacuation, reduction of heat loss first occurs because of reduction of Rayleigh number. When Rayleigh number is further reduced below the lower threshold of convection, the heat transfer occurs because of conduction only. When the pressure is reduced to 10^{-3} torr, the conduction heat transfer is also completely suppressed. A vacuum of the order of 10^{-3}– 10^{-4} torr is easily achievable.

Evacuated tube collectors are very expensive compared to conventional flat plate collectors. Thus it is possible to consider them only for high fluid temperatures in range 100 to 130 °C.

5.2.7 Modified Flat Plate Collector (Flat Plate Collector with Booster Mirrors)

By providing plane reflectors at the edges of flat plate collector to reflect additional radiation into the receiver the concentration of solar radiation can be increased. These mirrors are also called booster mirrors. The concentration ratio of these concentrators has maximum value of 4. Such a design (V-trough) is aligned in East-West direction and requires periodic tilt adjustment. Different optimum depth-to-base width ratio and cone angles are possible depending on the frequency of seasonal tilt adjustment. The schematic diagram is shown in Fig. 5.8.

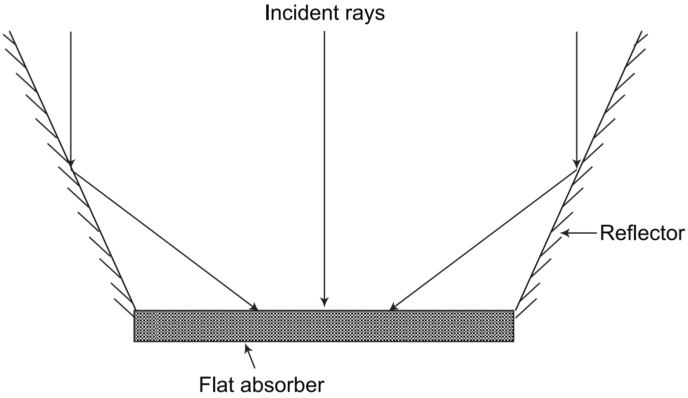


Figure 5.8 Modified flat plate collector

5.2.8 Compound Parabolic Concentrator (CPC)

Compound parabolic concentrator (shown in Fig. 5.9) consists of two parabolic mirror segments, attached to a flat receiver. The segments are oriented such that focus of one is located at the bottom end point of the other in contact with receiver. It has a large acceptance angle and need to be adjusted intermittently. Rays in the central region of the aperture reach the absorber directly whereas those near the edges undergo one or more reflections before reaching the absorber. The concentration ratio achieved from this collector is in the range of 3-7.

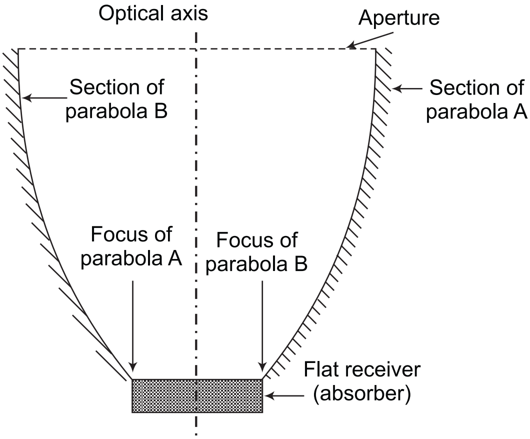


Figure 5.9 Compound parabolic concentrator

5.2.9 Cylindrical Parabolic Concentrator

It consists of a cylindrical parabolic trough reflector and a metal tube receiver at its focal line, as shown in Fig. 5.10. The receiver tube is blackened at the outside surface to increase absorption. It is rotated about one axis to track the sun. The heat transfer fluid flows through the receiver tube, carrying the thermal energy to the next stage of the system. This type of collector may be oriented in any one of the three directions: East-West, North-South or polar. The polar configuration intercepts more solar radiation per unit area as compared to other modes and thus gives best performance. The concentration ratio in the range of 5–30 may be achieved from these collectors.

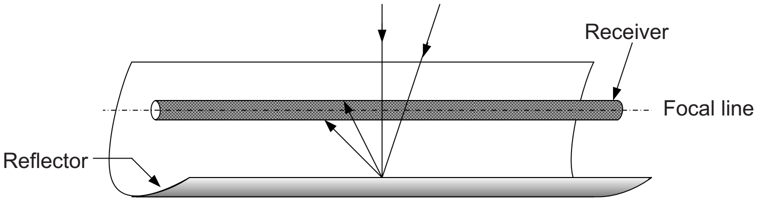


Figure 5.10 Cylindrical parabolic concentrator

5.2.10 Fixed Mirror Solar Concentrator

Due to practical difficulty in manufacturing a large mirror in a single piece in cylindrical parabolic shape, long narrow mirror strips are used in this concentrator. The concentrator consists of fixed mirror strips arranged on a circular reference cylinder with a tracking receiver tube as shown in Fig. 5.11. The receiver tube is made to rotate about the center of curvature of reflector module to track the sun. The image width at the absorber is ideally the same as the projected width of a mirror element; the concentration ratio is approximately the same as the number of mirror strips.

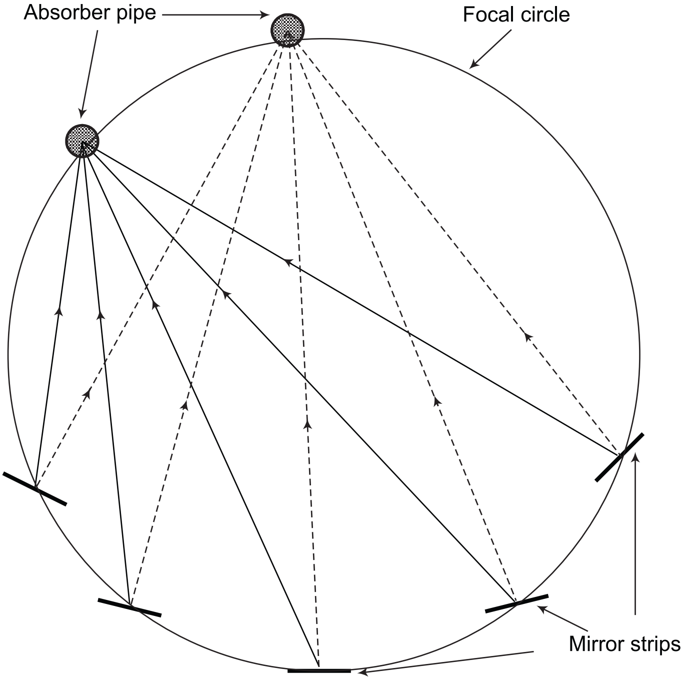


Figure 5.11 Fixed mirrors solar concentrator

5.2.11 Linear Fresnel Lens Collector

In this collector a Fresnel lens, which consists of fine, linear grooves on the surface of refracting material (generally optical quality plastic) on one side and flat on the other side, is used. The angle of each groove is designed to make the optical behavior similar to a spherical lens. The beam radiation, which is incident normally, converges on focal line, where a receiver tube is provided to absorb the radiation. A concentration ratio of 10 to 30 may be realized which yields temperatures between 150 and 300 °C. The construction of this type of collector is shown in Fig. 5.12.

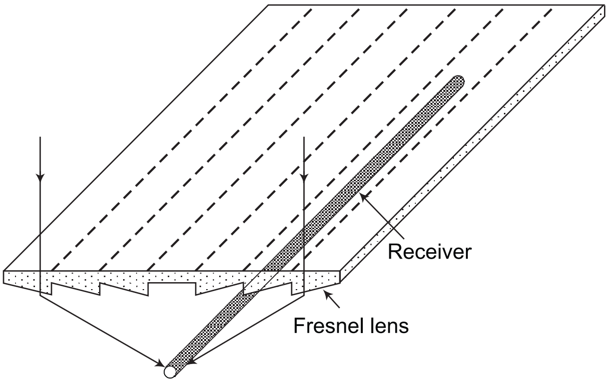


Figure 5.12 Linear Fresnel lens collector

5.2.12 Paraboloidal Dish Collector (Scheffler Solar Concentrator)

When a parabola is rotated about its optical axis a paraboloidal shape is produced. Figure 5.13 shows the details of this type of collector. Beam radiation is focused at a point in the paraboloid. This requires two-axis tracking. It can have concentration ratio ranging from 10 to few thousands and can yield temperature up to 3000 °C. Paraboloidal dish collectors of 6-7m in diameter are commercially manufactured.

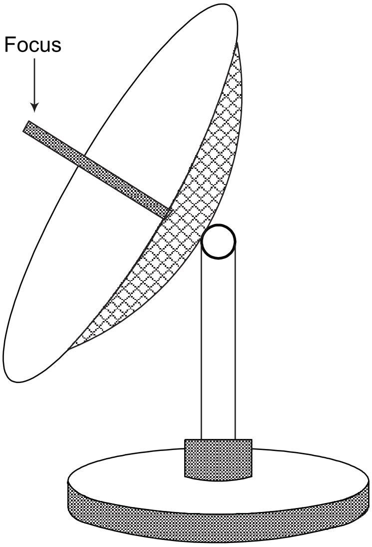


Figure 5.13 Paraboloidal dish collector (Scheffler solar concentrator)

5.2.13 Hemispherical Bowl Mirror Concentrator

It consists of hemispherical fixed mirror, a tracking absorber and supporting structure as shown in Fig. 5.14. All rays entering the hemisphere after reflection cross the paraxial line at some point between the focus and the mirror surface. Therefore, a linear absorber pivoted about the center of curvature of the hemisphere intercepts all

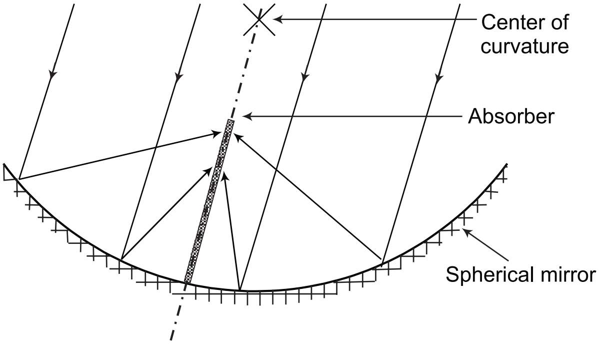


Figure 5.14 Hemispherical bowl mirror concentrator

reflected rays. The absorber is to be moved so that its axis is always aligned with solar rays passing through the center of the sphere. This requires two-axis tracking. The absorber is either driven around a polar axis at a constant angular speed of 15 degrees /hour or adjusted periodically during the day. This type of concentrator gives lesser concentration, owing to spherical aberration, than that obtained in paraboloidal concentrator.

5.2.14 Circular Fresnel Lens Concentrator

These lenses are generally used where high flux is desired, such as with silicon solar cells or with gallium arsenide solar cells as receiver. Fig. 5.15 shows the construction of a circular Fresnel lens. It is divided into a number of thin circular zones. The tilt of each zone is so adjusted that optically, the lens approximates a thin spherical lens. The concentration ratio may be as high as 2000, but is less than that obtained from a parboloidal reflector. In solar cell applications, tracking is required to keep the small solar image centered on the receiver.

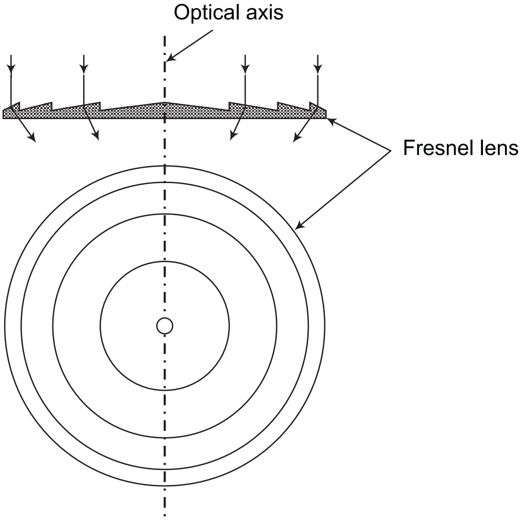


Figure 5.15 Circular Fresnel lens

5.2.15 Central Tower Receiver

In central tower receiver collector, the receiver is located at the top of a tower. Beam radiation is reflected on it from a large number of independently controlled; almost flat mirrors, known as heliostats, spread over a large area on the ground, surrounding the tower. Thousands of such heliostats track the sun to direct the beam radiation on the receiver from all sides. The heliostats, together act like a dilute paraboloid of very big size. Concentration ratio of as high value as 3000 can be obtained. The absorbed energy can be extracted from the receiver and delivered at a temperature and pressure suitable for driving turbines for power generation. The schematic view of central tower receiver is shown in Fig. 5.16.

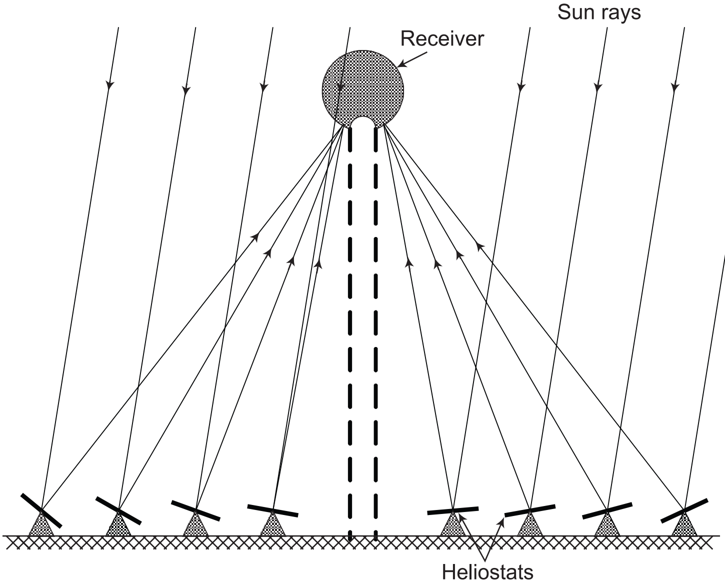


Figure 5.16 Central tower receiver

5.3 SOLAR WATER HEATER

The details of most common type of solar water heater are shown in schematic diagram of Fig. 5.17. A tilted flat plate solar collector with water as heat transfer fluid is used. A thermally insulated hot water storage tank is mounted above the collector. The heated water of the collector rises up to the hot water tank and replaces an equal quantity of cold water, which enters the collector. The cycle repeats, resulting in all the water of the hot water tank getting heated up. When hot water is taken out from hot water outlet, the same is replaced by cold water from cold-water make up tank fixed above the hot water tank. The scheme is known as passive heating scheme, as water is circulated in the loop naturally due to thermos-siphon action. When the collector is fixed above the level of hot water tank, a pump is required to induce circulation of water in the loop and the scheme will be known as active (or forced) solar thermal system. An auxiliary electrical emersion heater may be used as back up for use during cloudy periods. In average Indian climatic conditions solar water heater can be used for about 300 days in a year. A typical 100 liters per day (LPD) rooftop, solar water heater costs approximately ₹ 15,000–21,900 (year 2015) and delivers water at 60–80 °C. It has a life span of 10–12 years and payback period of 2-6 years. Figure 5.18 shows the photograph of an installed and operating solar water heater.

In other schemes the hot water from collector delivers heat to service water through a heat exchanger. In this scheme an anti-freeze solution may be used as heat transport medium to avoid freezing during cold nights.

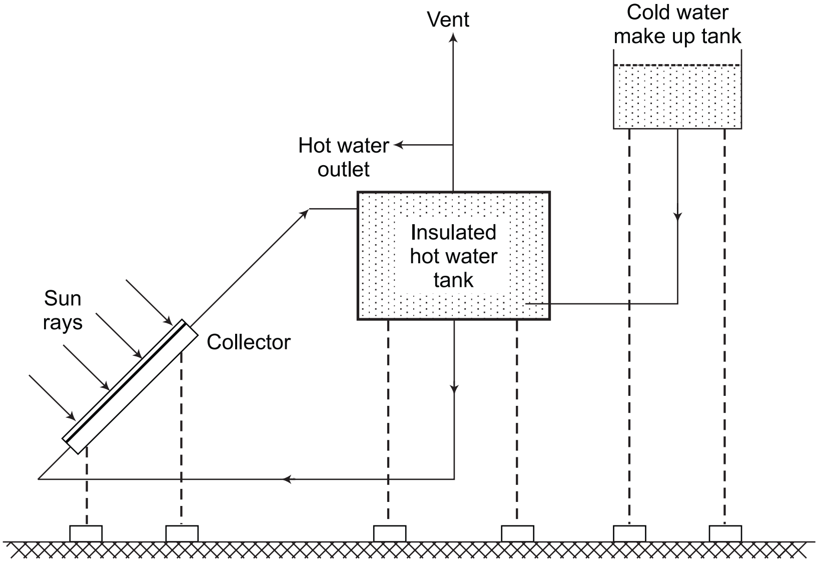


Figure 5.17 Solar water heater

Figure 5.18 Solar water heater

Source: MNES Annual Report

5.4 SOLAR PASSIVE SPACE HEATING AND COOLING SYSTEMS

Solar energy is also used for heating or cooling a building to maintain comfortable temperature inside. Passive systems do not require any mechanical device and make use of natural process of convection, radiation and conduction for transport of heat. Use of passive heating/cooling systems put restrictions on the building design to make possible the flow of heat naturally. Such a specially designed building is called "solar house". The state of the art for passive cooling is much less developed than for passive space heating. Natural passive cooling may not always be sufficient to meet the requirement and at peak load, auxiliary means may also be needed, but it greatly reduces the load on the air conditioner plant.

Active heating/cooling systems employ mechanical devices, e.g. pump, blower, etc. to circulate the working fluid for transportation of heat and therefore special building design is not necessary as required in the case of passive heating. Nevertheless, careful building design and insulation is desirable and will be less expensive than additional heating/cooling load due to poor design.

A solar passive space heating system is shown in Fig. 5.19. The south facing thick wall, called 'Trombe Wall' is made of concrete, adobe, stone or composites of brick blocks and sand, designed for thermal storage. In order to increase the absorption, the outer surface is painted black. The entire south wall is covered by one or two sheets of glass or plastic sheet with some air gap (usually 10–15 cm) between the wall and inner glazing. Solar radiation after penetration through the glazing is absorbed by the thermal storage wall. The air in the air gap between the glazing

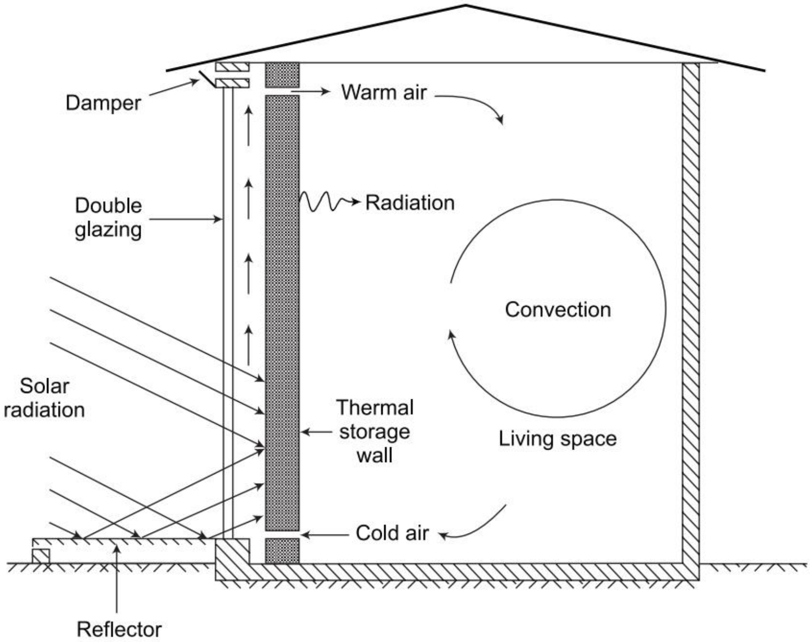


Figure 5.19 Solar space heating

and the wall thus gets heated, rises up and enters the room through the upper vent while cool air from the room replaces it from the bottom vent. The circulation of air continues till the wall goes on heating the air. Thus the thermal wall collects stores and transfers the heat to the room. Heating can be adjusted by controlling the airflow through the inlet and outlet vents by shutters. Opening the damper at the top of the glazing allows the excess heat to escape outside, when heating is not required.

Sometimes a reflective horizontal surface is also provided to make available the additional radiation for thermal storage. A movable insulation cover (not shown in figure) also sometimes used to cover the glaze to reduce the heat loss from the storage wall to outside during night. In some models the thermal storage wall is made up of water drums stacked over one another to increase the thermal storage capacity. In another variation the thermal storage mass is provided above a metallic roof of the building instead of a wall.

In Fig. 5.20 another variation of solar space heating system is shown. Here, a collector cum rock bed storage system is integrated with the apartment. During daytime when direct gain through the glaze is sufficient, the hot air from the air heater (collector) is not allowed to enter the room. The available thermal energy is stored in the rock bed to be used later, preferably during night.

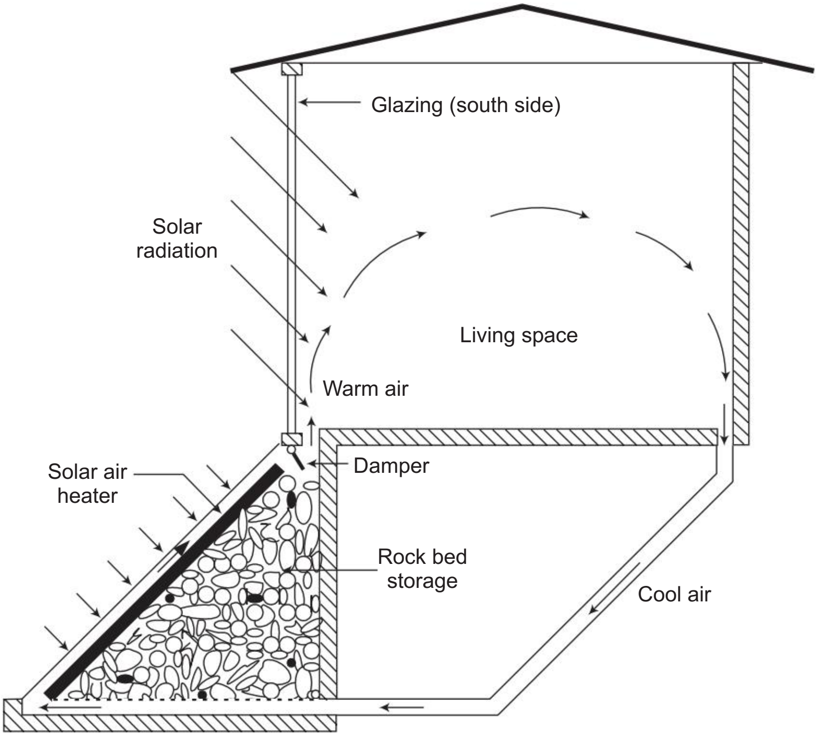


Figure 5.20 Solar space heating with rock bed storage

For natural cooling the first and best approach is to reduce unnecessary thermal loads entering the building. For example; (i) direct sunlight entering the building, which can be reduced by use of sun breakers or shading the window, walls, roofs, etc., (ii) conduction of heat through building elements, which can be reduced by proper thermal insulation and (iii) infiltration of outside warm air, which can be reduced by proper sealing. The techniques, generally used for passive cooling of the buildings include: (i) shading, (ii) ventilation, (iii) evaporation, (iv) radiation, (v) ground coupling and (vi) dehumidification.

Shading method prevents heating due to direct sun entering the house. In ventilation method, warm air is driven out and cool outside air is sucked inside by utilizing chimney effect. Evaporation method is effective in dry regions, where cooling is maintained by utilizing the internal heat to evaporate water. A pond may be used above a thin roof, to maintain cooling below it. Desert cooler is another example of evaporative cooling. In radiation cooling, black plastic water bags kept over a metal roof are exposed to the sky at night. Nocturnal radiation cools the water during night. This water absorbs heat from the space below it and maintains it cool. During daytime the roof is covered by a thermal insulating sheet to prevent heating of water due to solar radiation. Ground coupling system makes use of the fact that in summer the ground temperature is always lower than the air temperature. The lower temperature of the ground can be used for cooling a building by partially sinking it into the ground.

Figure 5.21 shows the scheme for solar passive cooling through ventilation. This scheme utilizes solar 'chimney effect' and is effective where outside temperatures are moderate. Solar radiation is allowed to heat up the air between the glazing and interior south wall. The heated air rises up and ducted outside and the warm air from the room is drawn into this space due to natural draught thus produced. As a result, cool outside air enters the room from the bottom air vent on the other side of the room.

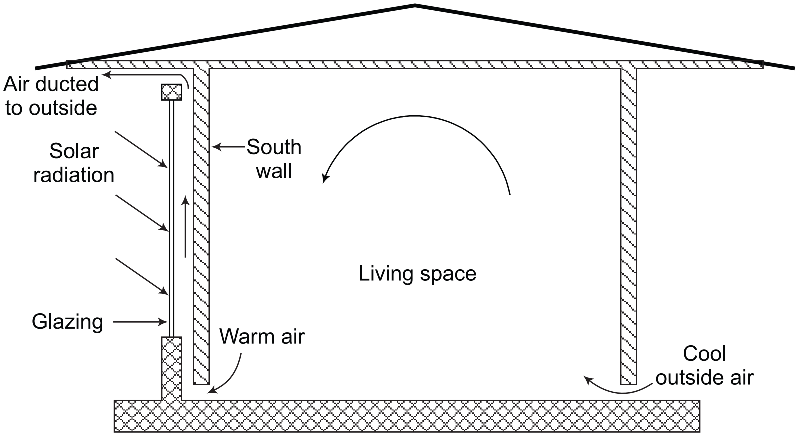


Figure 5.21 Solar passive cooling through ventilation

In dehumidification system, the moisture content of the air in the room is reduced and cooling is maintained by adsorption and evaporation. The east and west facing walls of a specially designed house are provided with solid adsorbent materials and water baths. Air circulation is maintained using 'chimney effect' as shown in Fig. 5.22. In the morning when the east wall is heated by solar radiation, the air gets heated rises up and ducted outside. Due to natural draught thus produced, air is drawn inside from the west side. The incoming west side air first gets dried up by solid adsorbent material, cooled by evaporation by passing over water baths and then enters the room. The hot air going out through the east-facing wall regenerates the solid adsorbent material. In the evening when the west wall is heated up by the sun, reversal of airflow occurs and the functions of east and west walls reverse.

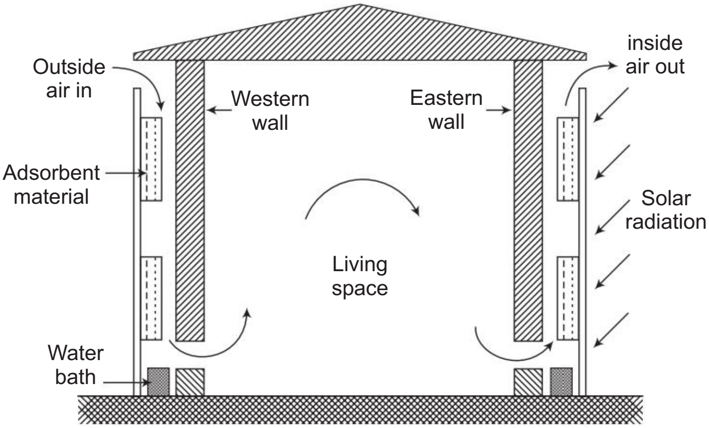


Figure 5.22 Solar passive cooling through dehumidification

5.5 SOLAR INDUSTRIAL HEATING SYSTEMS

Solar active heating systems are used for several industrial process heat requirements. The process heat in various industries is generally supplied in the form of (i) process hot water, (ii) hot air and (iii) process steam.

A hot air solar heating system is shown in Fig. 5.23. Thermal energy is transported from collector through hot air and utilized for process heat. The excess heat is stored in rock bed thermal storage to be used later when solar radiation is not available. Auxiliary heating augments the supply when the heat supplied by collector or storage is not sufficient. The used air is passed through a heat exchanger to recover the heat from the exhaust air to raise the initial temperature of fresh air entering the collector.

Figure 5.24 shows a solar process steam system. Pressurized water is circulated through concentrating collector to prevent boiling. The high-pressure heated water is throttled and flash separated in a flash separator. To maintain the necessary liquid level in the flash tank, boiler feed water is injected into the pump suction. The saturated steam obtained from the flash separator is recirculated through the collector field and distributed for use. A pressure regulator valve regulates the pressure.

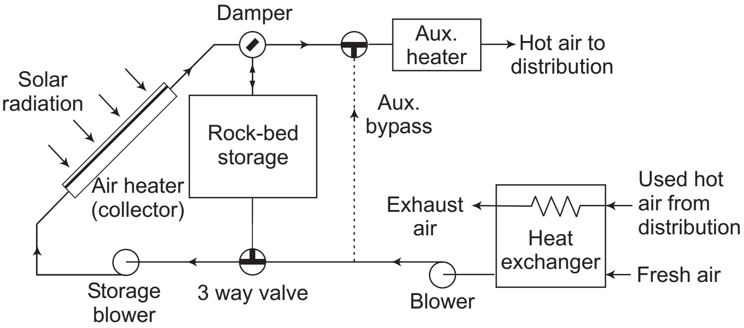


Figure 5.23 Hot air industrial process heat system

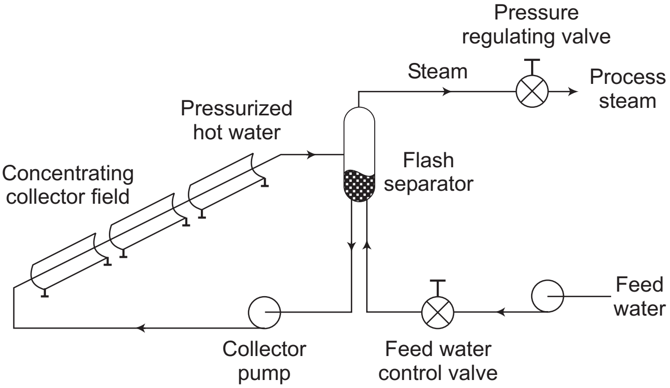


Figure 5.24 Solar process steam system

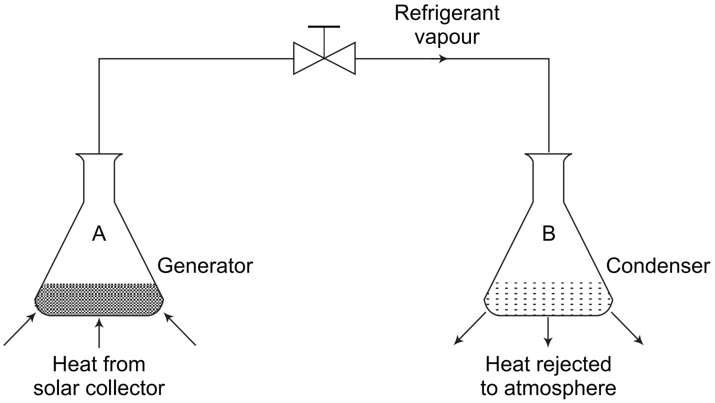
5.6 SOLAR REFRIGERATION AND AIR CONDITIONING SYSTEMS

Solar energy can also be used in air conditioning (cooling for comfort) and refrigeration (cooling for preserving food). There are several ways of using solar energy for cooling purpose. However, one based on absorption cycle cooling is most widely used at present. The principle of absorption refrigeration was first demonstrated by Faraday in 1825. Thus, this is one of the oldest cycles for producing refrigeration effect, which differs fundamentally from the conventional vapour compression cycle in the method for compressing the refrigerant.

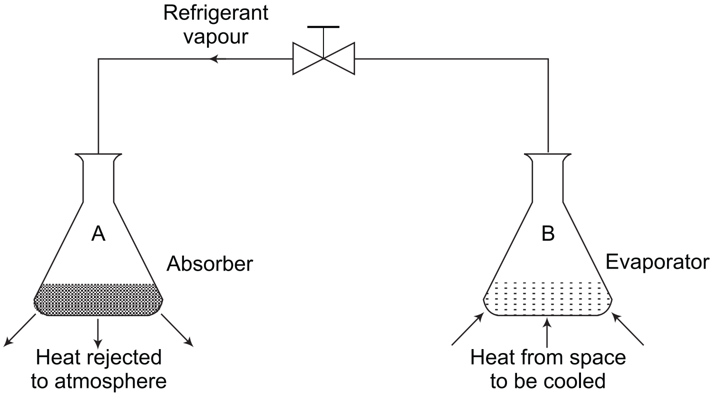
In absorption cycle cooling systems two working fluids: a refrigerant and an absorbent-refrigerant solution are used. The absorbent-refrigeration combination is so chosen that the absorbent have high affinity for the refrigerant and at the same temperature, vapour pressure of the refrigerant is higher than that of absorbent. The absorbent cooling is based on the principle that the refrigerant can be bound by a liquid or solid solvent, known as absorbent to release heat during absorption, while it absorbs heat during evaporation (and thus producing cooling effect). Though large number of refrigerant-absorbent combination is possible, the two most common and commercially tried combinations are: LiBr-water (LiBr as absorbent and water as refrigerant) and aqua-ammonia (water as absorbent and ammonia as refrigerant). In the former the absorbent is a solid (a salt) whereas in the later it is a liquid. The performance of a cooling cycle is judged from its COP (coefficient of performance), which is defined as the ratio of amount of cooling produced to the energy input.

There are four major components in absorption cycle cooling system: generator, condenser, evaporator and absorber. Cooling can be produced continuously or intermittently. An intermittent refrigerator is compact, simple in operation and is also portable. It has built in refrigeration storage. Therefore, it is most suited for rural applications using solar energy, which itself is an intermittent source of energy.

Basic principle of operation of intermittent system is demonstrated in Fig. 5.25. Two vessels A and B containing absorbent-refrigerant solution and pure refrigerant respectively are connected through a pipe via a throttle valve. Two modes of operation, regeneration and refrigeration are repeated alternately. In the first mode, vessel A acts as generator and vessel B as condenser while in second mode, vessel B acts as evaporator and vessel A as absorber. In regeneration mode, throttle valve is opened and heat is supplied to vessel A through a heat exchanger. The refrigerant



(a) Regeneration mode



(b) Refrigeration mode

Figure 5.25 International absorption cooling process vaporizes, moves from A to B and gets condensed in it. Now the valve is closed and the contents of B are cooled by circulating cold water through a heat exchanger. The system is kept in this state after closing the valve till the time cooling is required. In refrigeration mode, the valve is opened; the refrigerant evaporates and moves from B to A. In this mode it absorbs heat from vessel B and its surroundings and produces cooling effect.

While in intermittent type cooling process, the two operations regeneration and refrigeration take place alternately at different times, in continuous type cooling the two processes take place simultaneously and continuous cooling effect is produced. The continuous absorption cycle is more reliable. In most applications continuous cooling is required.

Lithium Bromide-Water Absorption Cooling System

A solar energy operated LiBr-water system is shown in Fig. 5.26. In equilibrium state the approximate pressures and temperatures maintained in four major components of the system is given in Table 5.4.

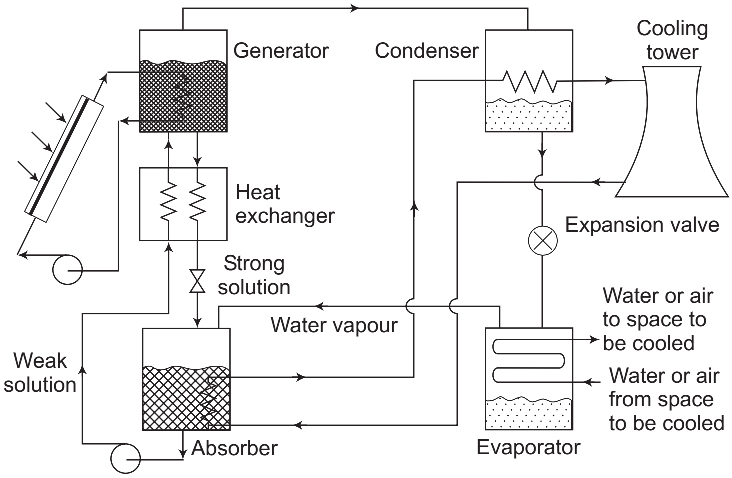


Figure 5.26 LiBr–H_2O absorption cooling system

Table 5.4 Temperatures and Pressures in various components of LiBr-water system

S.N.	Name of component	Pressure (atm.)	Temperature (°C)
1.	Generator	0.1	90
2.	Condenser	0.1	30 to 40
3.	Evaporator	0.008	4
4.	Absorber	0.008	30 to 40

A flat plate collector is used to supply heat to the generator and water vapours are raised at a temperature lower than 100 °C at low pressure. These vapours are condensed in condenser by cooling water supplied from cooling tower. The condensed water is evaporated by passing it through the expansion valve and maintaining lower pressure in the evaporator. Cooling effect is produced here and heat is absorbed from the space to be cooled through heat transport fluid. The water vapours from evaporator go to the absorber where they are absorbed in lithium bromide solution. In the absorber the liberated heat due to absorption process is removed by cooling water from the cooling tower. The generator temperature is maintained between 75–100 °C to avoid crystallization of lithium bromide, which may lead to choking of the system. Main advantages of Lithium bromide-water cooling cycle may be listed as: (i) the system is comparatively simpler, (ii) it works at comparatively higher COP, (iii) less pumping power is required due to low pressure, (iii) the refrigerant, i.e. water has high latent heat of vaporization, (iv) lithium bromide absorbent is non-volatile and therefore, avoids the need of rectifying equipment which is necessary in ammonia-water cycle, (v) water-lithium bromide solution is non-toxic and (vi) non inflammable. It also has some disadvantages, such as: (i) it can be used for air conditioning only (temperatures not lower than 4 °C), (ii) the LiBr-water solution is corrosive, (iii) the system works under high vacuum conditions, and (iv) it requires water-cooled condenser to attain temperatures corresponding to air conditioning, as the refrigerant is water.

Aqua-ammonia absorption system is similar to LiBr-water absorption system explained above. It also has all the basic building blocks as shown for LiBr-water system but the operating pressures and temperatures are quite different. It can produce cooling up to –5 °C and therefore, is suitable for refrigeration too. A rectifier and an analyzer is added after the generator to check and stop water vapour from reaching the evaporator, otherwise it will freeze in the evaporator and may choke the system. The required temperature in the generator is around 120 °C if the condenser and absorber are water-cooled. In case of air-cooled condenser and absorber the required operating temperature of the generator may be as high as 180 °C. This is too high for a simple flat plate collector to attain and a concentrating collector may be required. In equilibrium state the approximate pressures and temperatures maintained in four major components of the system is given in Table 5.5.

Table 5.5 Temperatures and Pressures in various components of aqua-ammonia system

S.N.	Name of component	Pressure (atm.)	Temperature (°C)
1.	Generator	10	120
2.	Condenser	10	40
3.	Evaporator	1	–5
4.	Absorber	1	40

Main advantages of aqua-ammonia absorption system are: (i) it can provide both air conditioning and refrigeration, (ii) the refrigerant has low molecular weight and therefore, a high heat of vaporization, (iii) the absorbent (water) is non-toxic and inexpensive. The disadvantages are: (i) as the absorbent (water) is volatile, a rectifier unit is required to separate and drain it out, (ii) comparatively high pumping power is required to pump working fluid from absorber pressure to generator pressure, and (iii) ammonia is inflammable and toxic. Therefore, special precautions are required in its use.

5.7 SOLAR COOKERS

Thermal energy requirements for cooking purpose forms a major share of total energy consumed, especially in rural areas. Variety of fuels like coal, kerosene, cooking gas, firewood, dung cakes and agricultural wastes are being used to meet the requirement. Fossil fuel is a fast depleting resource and need to be conserved, firewood for cooking causes deforestation and cow dung, agricultural waste, etc., may be better used as a good fertilizer. Harnessing solar energy for cooking purpose is an attractive and relevant option. A variety of solar cookers have been developed, which can be clubbed in four types of basic designs: (i) box type solar cooker, (ii) dish type solar cooker, (iii) community solar cooker, and (iv) advance solar cooker.

1. Box Type Solar Cooker

The construction of a most common, box type solar cooker is schematically shown in Fig. 5.27. The external dimensions of a typical family size (4 dishes) box type cooker are 60 × 60 × 20 cm. This cooker is simple in construction and operation. An insulated box of blackened aluminum contains the utensils with food material. The box receives direct radiation and also reflected radiation from a reflector mirror fixed on inner side of the box cover hinged to one side of the box. The angle of reflector can be adjusted as required. A glass cover consisting of two layers of clear window glass

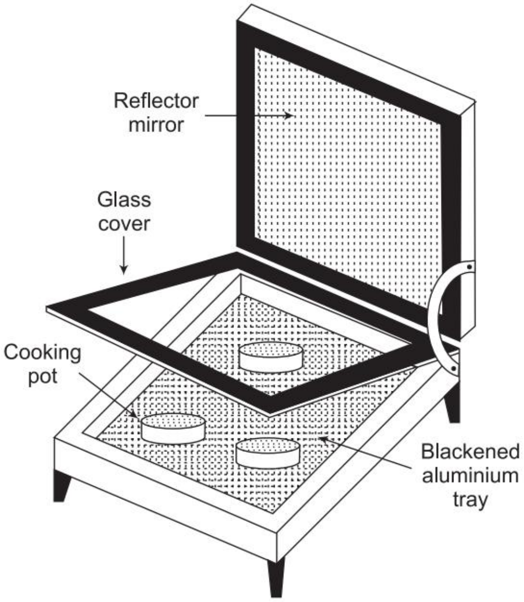


Figure 5.27 Box type solar cooker

sheets serves as the box door. The glass cover traps heat due to greenhouse effect. Maximum air temperature obtained inside the box is around 140–160 °C. This is enough for cooking the boiling type food slowly in about 2–3 hours. It is capable of cooking 2 kg of food and can save 3–4 LPG cylinder fuel in a year. Electrical backup is also provided in some designs for use during non-sunshine hours. Its cost varies from ₹ 5,000 to ₹ 6,290 (year 2016) depending on the type, size, quality and electrical backup facility etc. A more affordable, folding type model of solar cooker, made of cardboard material is also developed.

2. Paraboloidal Dish Type (Direct Type) Solar Cooker

A specially designed paraboloidal reflector surface concentrates the beam radiation at its focus, where a cylindrical brass vessel containing food material is placed. A commercial dish type solar cooker, SK 14, developed by EG solar, an NGO of Germany, and being manufactured in India is shown in Fig. 5.28. The vessel directly receives the concentrated solar radiation. The reflector is periodically adjusted to track the sun. A fairly high temperature of about 450 °C can be obtained and a variety of food requiring boiling, baking and frying can be cooked for 10–15 persons. It can save on fuel up to 10 LPG cylinders annually on full use. Cooking time is approximately 20–30 minutes. The approximate cost of the cooker is ₹ 8,500 (year 2016).

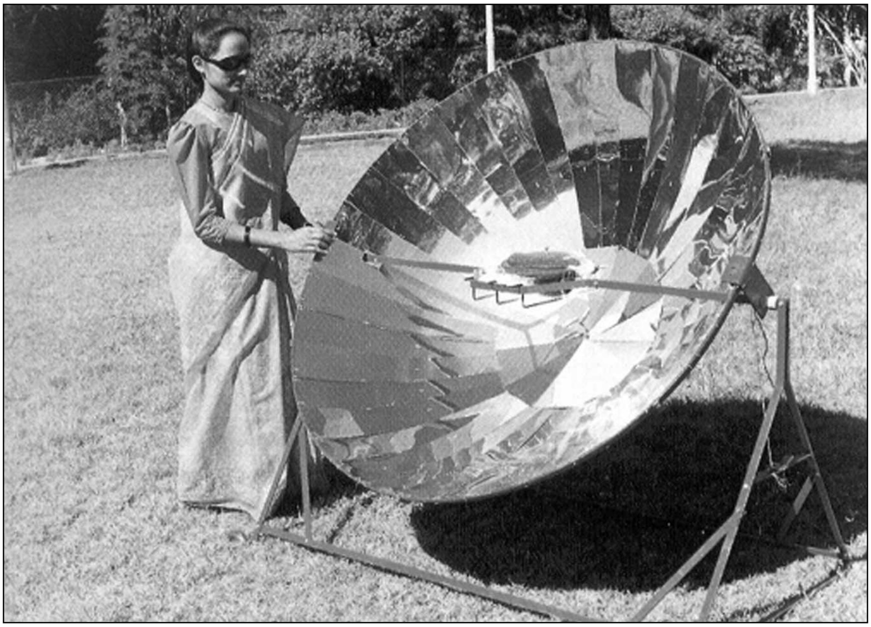


Figure 5.28 Paraboloidal dish type solar cooker

Source: MNES Annual Report

3. Community Solar Cooker

Community solar cooker has been developed for indoor cooking. It has a large automatically tracked paraboloidal reflector standing outside the kitchen.

The reflector reflects the sunrays into the kitchen through an opening in its north wall. A secondary reflector further concentrates the rays on to the bottom of the cooking pot, which is painted black. It can cook all types of food for about 40–50 people and can save up to 30 LPG cylinders in a year with optimum use.

In another design of community solar cooker, large numbers of automatically tracked paraboloidal reflectors are installed in series and parallel combinations and generate steam for cooking in community kitchen. It can cook food for thousands of people in a short time depending upon its capacity. It is normally installed in conjunction with a boiler that may also use conventional fuel when necessary.

4. Advance Solar Cooker

Main disadvantage of the above cookers is that there is no provision for storing thermal energy so that cooking is possible only when sun is available (unless auxiliary source is available). An advance type cooker has been designed to overcome these difficulties. The cooker is schematically shown in Fig. 5.29. Basically, it consists of two parts: (i) an outdoor, parabolic cylindrical reflector of a size, typically 3 × 2 × 0.5 m and (ii) an indoor, insulated hotbox reservoir of a size typically 0.4 × 0.4 × 1.2m, kept at a level higher than the collector., Oil is used as heat transport fluid from collector to hot box reservoir. The oil in the receiver tube rises up due to natural convection after absorbing heat from reflector and stores it in the reservoir. The reflector has an equatorial mounting with adjustments for seasonal variation of sun or an arrangement for automatic solar tracking using a simple clock mechanism. The temperature at the top of the reservoir on sunny days reaches to 150 °C and rarely falls below 100 °C even during nights. All types of cooking except that requires frying and roasting can be done with this cooker. Some other variations in the basic design such as a large hemispherical bowl type collector, use of heat exchanger to raise steam from heated oil, for steam cooking are also possible. Such types of solar cookers are especially useful as large size community cookers for military camps, temples, ashrams, gurdwaras and hostels.

There are four principal ways of cooking: (i) boiling, (ii) baking, (iii) frying and (iv) roasting. Box type cookers are suitable for boiling and baking type cooking. Paraboloidal dish type cookers are suitable for boiling, baking and frying as higher temperatures are achieved. Advance type cookers can perform boiling and baking operation only but have the advantage of thermal storage and indoor use. Major reasons for non-acceptability of a solar cooker are: (i) it is too expensive for an individual family ownership, (ii) it is incompatible with traditional cooking practices, (iii) it requires comparatively more time and menu has to be preplanned, (iv) it is to be used outdoors (except community and advance cookers), and (v) cannot be used during nights and cloudy days (except advance cooker).

A 15m-diameter community solar cooker has been developed at Centre for Scientific Research (CSR), Auroville (Pondicherry). Around 600 kg of steam per day could be generated from this bowl, which is sufficient to cook two meals for about 1000 people. A very large community solar cooker has recently been installed at Tirumala Tirupathi Devasthanam at A.P., under the demonstration scheme of Ministry of Non-conventional Energy Sources. This is said to be the largest solar cooker in the world and being used for cooking food for 15,000 devotees daily.

It has 106 automatic solar concentration collectors (Scheffler solar concentrator); each of 9.2 sq m diameters are producing 4000 kg steam daily at 180 °C and 10 kg/cm^2 for steam cooking. The system is expected to save 1, 18,000 liter of diesel annually. The system was set up at total cost of ₹ 110 lakh (year 2003). So far about 5, 55,000 box type and 2000 dish type solar cookers have been sold in the country. About 100 community solar cookers with steam cooking have been installed in the country.

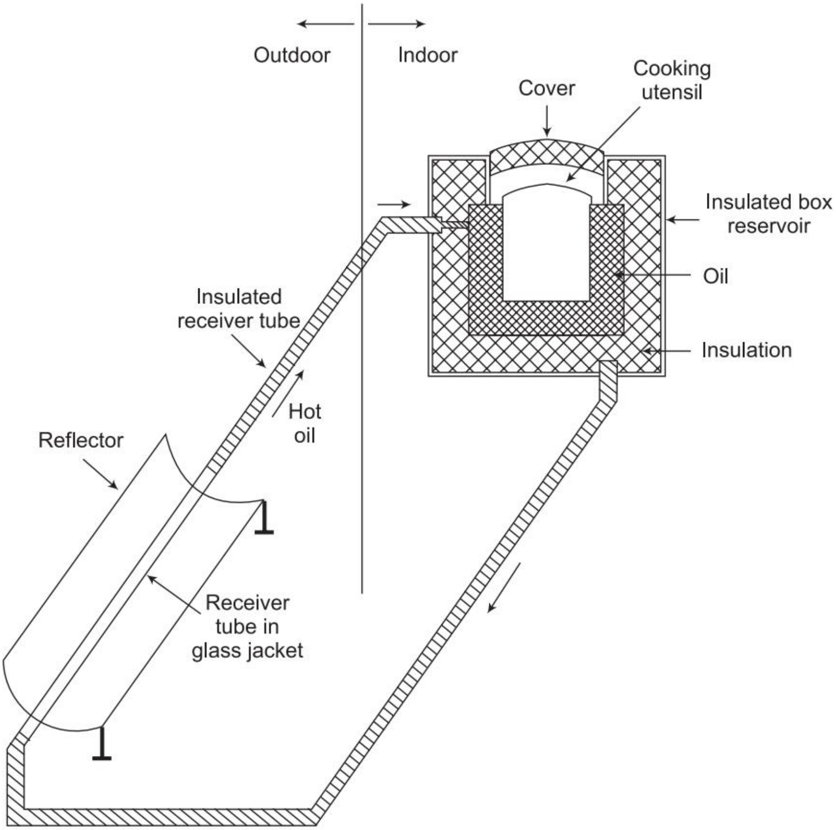


Figure 5.29 Advance solar cooker

5.8 SOLAR FURNACE

Solar furnaces are ideal tools to study the chemical, optical, electrical and thermodynamic properties of the materials at high temperatures. It is basically an optical system in which solar radiations are concentrated over a small area. It has two main components: (i) a concentrator and (ii) a single piece of a large sized heliostat or a system of large number of small heliostats. Basic principle is shown in Fig. 5.30. Large number of heliostats directs solar radiation onto a paraboloidal reflector surface. The heliostats are adjusted such that they direct the radiation parallel to the optical axis of the paraboloid. For this purpose accurate sun tracking is required. The concentrators focus the incoming rays at the target placed at its focus.

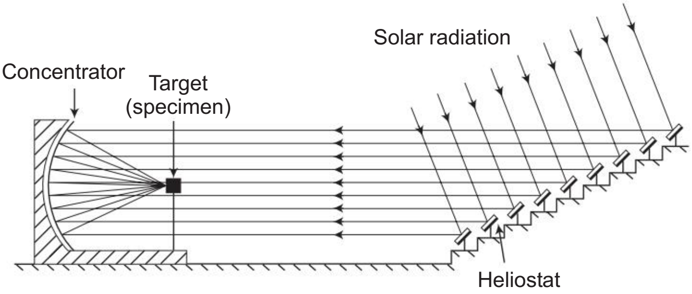


Figure 5.30 Solar furnace

There is another possible configuration of solar furnace, where the optical axis is vertical. A large heliostat directs the radiation upwards and the concentrator reflects it downward at its focus. In this arrangement the unmelted portion of specimen forms a crucible to hold the melted portion and is suitable for fusion studies.

There are few solar furnaces in countries like France, USA, Germany and Russia for scientific study. One of the world's largest solar furnace of 1000 kW output is installed at Odeillo, Font-Romeo, France in 1970. It has 63 heliostats, each 7.5 × 6 m in size. The parboloidal concentrator is 40 m high, 54 m wide and 13 m above the ground level with focal length of 18 m. Temperatures obtained are in the range of about 3,500 °C.

Some of the advantages of a solar furnace are: (i) heating without contamination, (ii) easy control of temperature, (iii) working is simple, (iv) high heat flux is obtainable, (v) continuous observation possible and (vi) absence of electromagnetic field. In spite of many advantages of solar furnaces, these have not become popular in industries due to following reasons:

(i) Its use is limited to sunny days and that too for 4–5 hours only.
(ii) Its cost is high.
(iii) Very high temperatures are obtained only over a very small area.

5.9 SOLAR GREENHOUSE

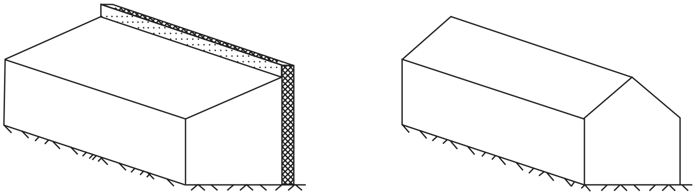
Greenhouse is an enclosure where proper environment is provided for growth and production of crops, vegetable and flower plants under adverse climatic conditions. By controlling the environment a particular vegetable or flower can be grown throughout the year. The design of a greenhouse depends on local climatic conditions. In cold countries, 'winter greenhouses' provide supplementary heat to maintain adequate temperature during cold months when solar insolation is low. In tropical countries, the solar insolation and ambient temperatures are quite high and therefore 'summer greenhouses' are used to maintain low temperatures inside and allow just sufficient sunlight for photosynthesis. Greenhouses for arid zone are designed to conserve water resources. Although, there is slight variation in the environmental needs of each variety of plants for best production, basically they all require moderate temperatures and light, adequate quantities of carbon dioxide, oxygen, mineral nutrients, air movement and water as indicated in the Table 5.6. Moderate temperatures, light and air movement are energy related needs of plants and supplied by the greenhouse. A greenhouse designed to use solar energy to meet these requirements is known as 'solar greenhouse'. If natural means are adopted to collect, store and distribute the energy inside, it is known as 'passive greenhouse'. A greenhouse, where auxiliary means are used for these functions is known to be an active one. Generally, a combination of both active and passive features is employed in solar greenhouses to minimize the need of auxiliary energy.

Table 5.6 Desirable environmental conditions for growth of a plant

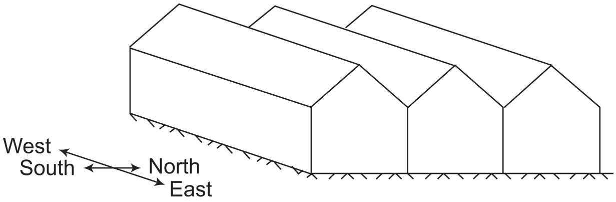
S.N.	Parameter	Optimum required level
1.	Light intensity: (about 100,000–150,000 lumen/m^2 available around noon time)	25,000–50,000 lumen/m^2
2.	Night temperature:	
	(i) Air temperature for winter crops	5–15 °C
	(ii) Air temperature for summer crops	20–30 °C
	(iii) Soil temperature	20–25 °C
3.	Relative humidity:	30–70 per cent
4.	Air movement:	0.10–0.35 m/s
5.	Carbon dioxide:	0.03–0.04 per cent
6.	Nutrients:	Per cent of dry matter
	(i) Carbon, hydrogen, oxygen	90
	(ii) Nitrogen, Phosphorous, Potassium, Calcium, Magnesium, Sulphur	10
	Availability of these nutrients can be judged from p^H value of the soil.	6.2–6.8 (recommended)
7.	Watering: Timing, quantity, frequency should be proper and adequate	Based on experience

A small greenhouse can also be constructed as an integral part of a house and free exchange of air takes place between the residence and the green house. Such a greenhouse is known as 'attached greenhouse'. A separate independent structure of a greenhouse is known as 'free standing greenhouse'. Some basic design styles of greenhouses frames are shown in Fig. 5.31.

In lean-to style design, the greenhouse rests on the wall of a building and requires minimum roof support. Single independent style looks like a tent with sloppy or hemispherical roof. Large size greenhouses are made in ridge-and-furrow style, where several greenhouses are connected together, reducing the overall cost. In this design some arrangement is to be made to melt and remove the snow collected in the gutter.



(a) Lean-to style (b) Single independent style



(c) Ridge-and-furrow style

Figure 5.31 Basic design styles of greenhouse frames

Regulation of Internal Environment of a Greenhouse

In a greenhouse, visible light, CO_2 and water are required for photosynthesis process:

$$\text{Light energy + water + } CO_2 = \text{carbohydrate + oxygen} \qquad \text{(photosynthesis)}$$

In respiration process, energy is released which is used by the plant for various functions of growth such as: nutrient uptake, protein formation, division of cells, etc.

$$\text{Carbohydrate + oxygen} = CO_2 + \text{energy + water} \qquad \text{(respiration)}$$

To make available sufficient light, glazing (glass or plastic sheet) is provided on sufficient area on the surface facing the sun. Now-a-days plastic sheets are preferred to minimize the cost. For proper thermal insulation two layers of glazing with small air gap are used. Each layer of glazing cut about 13 per cent solar radiation; therefore more than two layers are not used. Supplementary lighting may be used to maintain adequate level of light intensity or to increase the duration of light hours. Similarly, curtains can be used to decrease the duration of light hours.

Adequate availability of CO_2 can be maintained by supplying either outside air or by organic manure or by combustion of sulphur free fossil fuels or by supplying it directly from CO_2 cylinder.

In cold climate, greenhouse is designed to maximize the solar energy input by providing large glazing area with proper orientation. As most heating is required only in winter, the slope is generally decided on winter basis. The glazing behaves as transparent for incoming short wavelength visible radiation and permits its entry but becomes largely opaque to long wavelength infrared radiation reflected from ground. Thus the energy remains trapped and increases the temperature inside. Thermal losses from greenhouse are reduced by using two layers of glazing with some air gap (typically 5–7 cm), using thermally insulated walls and controlling leakage (or infiltration of ambient air) through cracks. To decrease thermal losses during night through glazing, folding type insulation cover may be placed over the glazing. The insulation cover may be rolled up again in the morning to permit entry of sunlight.

In places where solar insolation is high, cooling of greenhouse instead of heating is required. Here also thermal insulation is required to prevent entry of heat by conduction through walls, infiltration of warm air through cracks etc. To maintain moderate temperature inside, generally evaporative cooling utilizing fan and wet pad is used. The technique is same as commonly used in desert coolers for space cooling during summer months in arid zone. The cooling system is based on the principle that heat is absorbed for evaporation of water. If humidity is low, evaporative cooler can reduce space temperature by 5–10 °C. Some typical greenhouse designs are discussed below.

Typical Winter Greenhouse

A typical design of a greenhouse for cold climate is shown in Fig. 5.32. South facing wall and roof is provided with double-glazing. North facing roof is made of insulating material with reflecting inner lining to reflect solar radiation on the plant canopy. The frame of entire greenhouse is made of wood. The east and west facing walls are provided with single layer of rigid transparent fiberglass sheets. In some designs pipes are buried in the soil under the plants to store surplus thermal energy during daytime. Air from the growing area is blown out through these pipes at the time of surplus heat to store the excess heat in the ground. At night the heat is recovered by reversing the direction of airflow through these pipes.

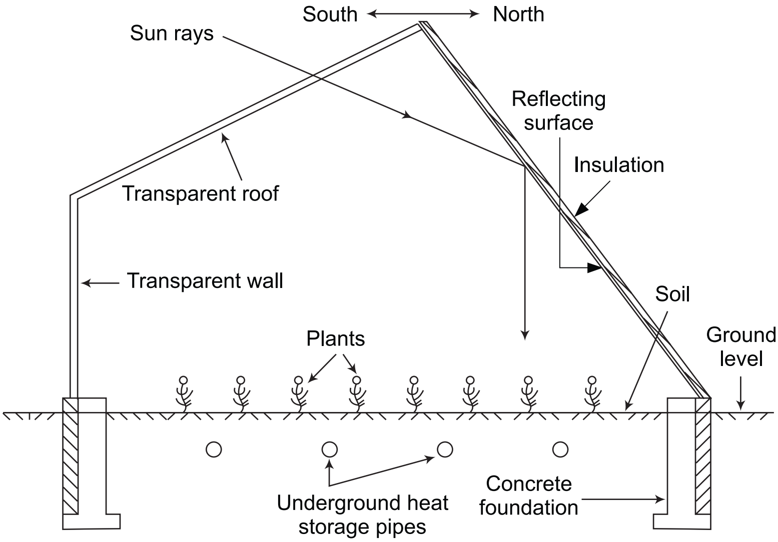


Figure 5.32 Greenhouse for cold climate

Typical Summer Greenhouse

In summer greenhouse, most important requirements are maintaining moderate temperature by reducing cooling loads and also to provide adequate solar radiation.

Typical summer greenhouse is shown in Fig. 5.33. South facing wall is provided with double-glazing, covered with white thick movable insulating blocks. These blocks can be selectively moved to admit only absolutely essential solar radiation whenever needed. Sunlight is allowed to enter only in the morning and evening hours. Solar radiation can also be admitted through east and west transparent walls of the greenhouse whenever required by removing plywood sheets covering these walls. The north-facing wall is made of insulating material, like plywood, etc., with reflective lining on the inner side to reflect solar radiation on plant canopy. A part of greenhouse is also sunken in the ground to take advantage of the low and constant ground temperature. Windows on the north and south walls are used for cooling through natural convection process when outside temperature is not very high. When the outside temperature becomes very high, south wall windows are closed and evaporative cooling is used by drawing outside air through wet pads using a powerful blower.

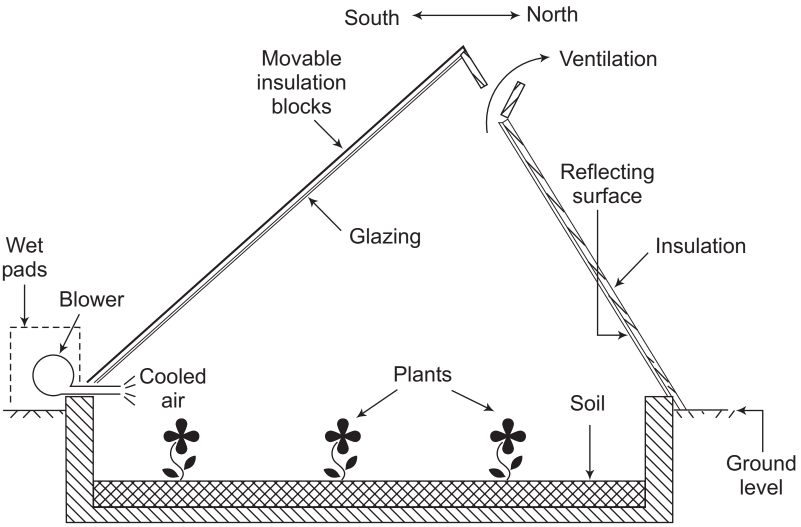


Figure 5.33 Greenhouse for warm climate

A greenhouse requires certain initial investment to construct and equip it. Greenhouse operation cost includes expenditure on environment control and agricultural inputs. As a result the cost of production per unit greenhouse area is higher as compared to open field cultivation. However, greenhouse crops yield several times more than those obtained from open field cultivation. Therefore, the monetary return per unit area is many times higher in case of greenhouse cultivation. Greenhouses are popular for growing high valued horticultural crops, raising seedlings and plant propagation material. Greenhouses are being used in almost all types of climatic conditions. Intensive greenhouse crop production has been adopted by Israel and Japan due to smaller and marginal land holdings and shorter growing seasons. Israel and Holland are exporters of greenhouse products. Large areas of land are found under greenhouse cultivation in Italy, Turkey, Spain and France.

In India greenhouses are being used only in research and educational institutions for the purpose of research.

5.10 SOLAR DRYER

Drying process removes the moisture and helps in the preservation of the product. Solar crop drying is perhaps the most ancient and widespread direct use of solar energy. The customary way is to spread the material to be dried in a thin layer on the ground. The disadvantages associated with this method are: (i) the process is slow, (ii) the product is vulnerable to attack by insects and (iii) dust gets mixed with the product. The use of solar dryer helps to eliminate these disadvantages. Also the drying may be made a faster and controlled process, and better quality product can be produced.

A simple cabinet type solar dryer is shown in Fig. 5.34. It is an enclosure with transparent cover, similar to a greenhouse. The material to be dried is placed on perforated trays. Solar radiation enters the enclosure and absorbed by the product as well as surrounding internal surfaces of the enclosure, increasing its temperature. The inside air heats up to temperature ranging from 50 to 80°C, and rises above. Natural circulation of air is ensured by providing suitable openings at the bottom and top. The circulating air removes the moisture from the product.

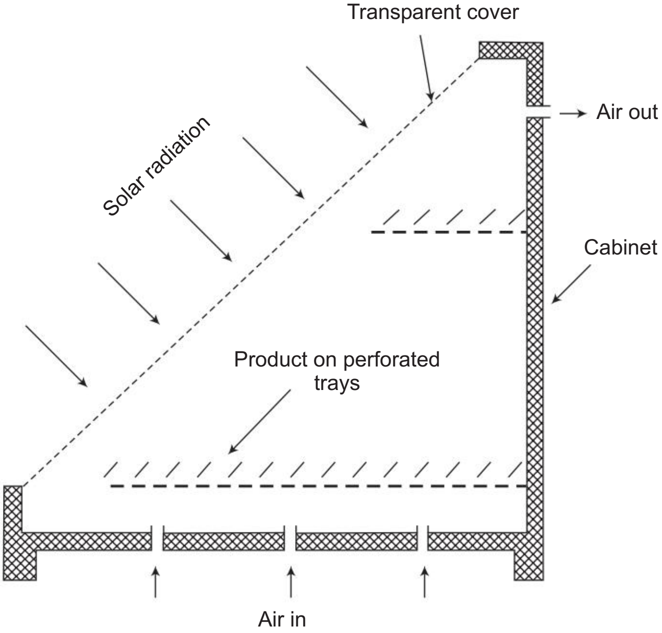


Figure 5.34 Solar cabinet dryer

For large-scale drying, forced circulation of air may be used by employing a blower. In case of green lumber, where direct exposure to sun tends to produce curling and wrapping or for products where direct sun light is not adequate a controlled temperature drying known as kiln drying may be used. Here the air is heated separately in an array of solar air heaters and then ducted to the chamber where the product to be dried is stored. Such dryers are also suitable for food grains and products like tea and tobacco.

5.11 SOLAR DISTILLATION (DESALINATION OF WATER)

Potable or fresh water (water with less than 500-ppm salt content) is one of the fundamental necessities of life for a man. Industries and agriculture also require fresh water without which they cannot thrive. Man has been dependent on rivers, lakes and underground water reservoir to fulfill his need of fresh water. It is intimately associated with evolution of civilization. Because of rapid industrialization and population explosion the demand of fresh water has been increasing enormously. With the standard of living, the average per capita consumption of water has also increased. Due to climate changes and less rainfall in many part of the world fresh water, which was available in abundance from rivers, lakes and ponds, is becoming scarce. Also the available resources are getting polluted due to discharge of industrial effluents and sewage in large quantities. Thus, due to climate change, pollution and over consumption, at present more than 2000 million people have no regular access to adequate safe water. In some villages, people travel up to 30 km to collect fresh water. According to one estimate, about 79 percent of water available on earth is salty, 20 percent is brackish (less salty water from well) and only one percent is fresh. Therefore, conversion of brackish or saline water to fresh water through distillation process using solar energy is a good idea for places where plenty of saline water and sun are available.

The use of solar energy for desalting seawater and brackish well water has been demonstrated in several moderate sized pilot plants in the Unites States, Greece, Australia and several other countries. The idea was first applied in 1872 at Las Salinas, Chile, in a plant supplying drinking water for animals working in nitrate mining and transport. The conversion device is known as solar still. Modern developments in solar distillation have been directed to the use of materials and designs for economic and durable construction with increased output, to reduce the product cost. Several types of solar stills have evolved. However, only basin type has been tried commercially on a large scale.

A simple basin type solar still consists of a shallow blackened basin filled with saline or brackish water to be distilled. The depth of water is kept about 5–10 cm. It is covered with sloppy transparent roof. Solar radiation, after passing through the roof is absorbed by the blackened surface of the basin and thus increasing the temperature of water. The evaporated water increases the moisture content, which gets condensed on the cooler underside of the glass. The condensed water slips down the slope and is collected through the condensate channel attached to the glass. The construction is schematically shown in Fig. 5.35.

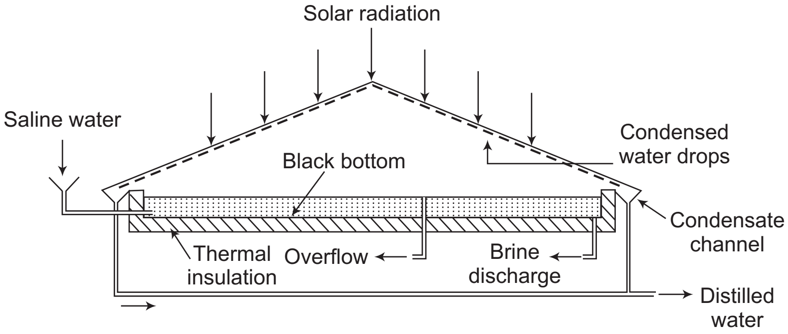


Figure 5.35 Simple basin type solar still

The still is erected in open area with its long axis facing East-West direction. The still can be fed with saline water either continuously or intermittently. The supply is generally kept at twice the rate at which the fresh water is produced but may vary depending on the initial salinity of input water. The output of a typical solar still in Indian climate varies from 5.3 l/m^2 day (in summer) to 0.9 l/m^2 day (in winter).

5.12 SOLAR THERMO-MECHANICAL SYSTEM

It is possible to convert solar thermal energy to mechanical energy through heat engines using Rankine cycle, Stirling cycle or Brayton cycle. The mechanical energy thus produced may be used for applications requiring shaft power such as water lifting, cooling (through vapour compression method), etc., or may be converted to electrical energy using alternator. Effective conversion of solar thermal energy to mechanical energy is associated with many limitations; some of them are:

1. The efficiency of collector system decreases as the collection temperature increases while the efficiency of heat engine increases as the working fluid temperature increases.
2. The conversion efficiency is low (about 9 to 18 percent).
3. A part of thermal energy is lost during transportation of working fluid from collector to heat engine.
4. Solar collectors are generally more expensive than engines.
5. Very large area is required to install the solar collector system.
6. Due to intermittent nature of solar energy, storage of thermal energy is also required, which has its own problems like degradation of storage material with time.

5.12.1 Solar Thermal Water Pump

Some features of solar energy make its utilization attractive for irrigation water pumping. These are: (i) more irrigation water is required in summer when solar energy is available most, (ii) intermittent pumping is tolerable and can serve the purpose, (iii) surplus energy can provide pumped storage in the form of a pond. Several solar irrigation pumps have recently been tested in many countries. While in lower range (i.e. 200 W to 5 kW) solar photovoltaic pumps are more successful, in higher ratings (i.e. in range 1 kW to 200 kW) solar thermal pumps have become economical and offer superior performance.

A schematic diagram of a typical Rankine cycle, solar thermal water pump is shown in Fig. 5.36. Solar collector system may consist of flat plate collectors, non-focusing type (stationary) collectors or sun tracking concentrators. Water is used as heat transport fluid, and yields its heat to a low boiling point organic working fluid (such as Freon R113, R12, Isobutane, etc.) in a heat exchanger. Surplus heat is stored in thermal storage to be used later when sun is not available. The high-pressure vapours of the working fluid expand in the turbine, condense in the condenser and return in the heat exchanger (boiler). A part of irrigation pumped water is diverted through condenser for cooling purpose.

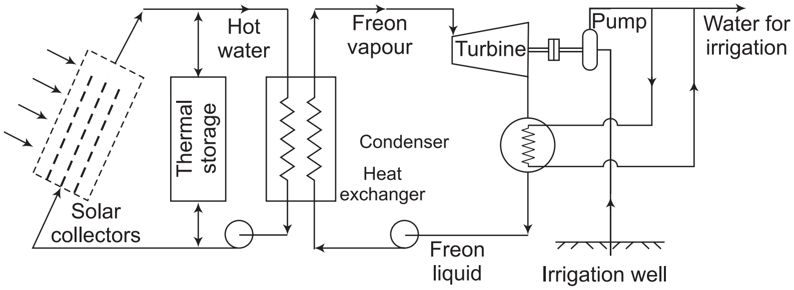


Figure 5.36 Solar thermal water pump

5.12.2 Solar Vapour Compression Refrigeration

A cooling system based on vapour compression principle has the advantage that the system apart from cooling can also be used in heat pump mode. In cooling mode the system absorbs heat from space to be cooled and delivers it to the ambient, which is at a higher temperature, whereas, in heat pump mode the system absorbs heat from the ambient and delivers it to a space, which is at a higher temperature. A solar power based vapour compressor cooling system is shown in Fig. 5.37.

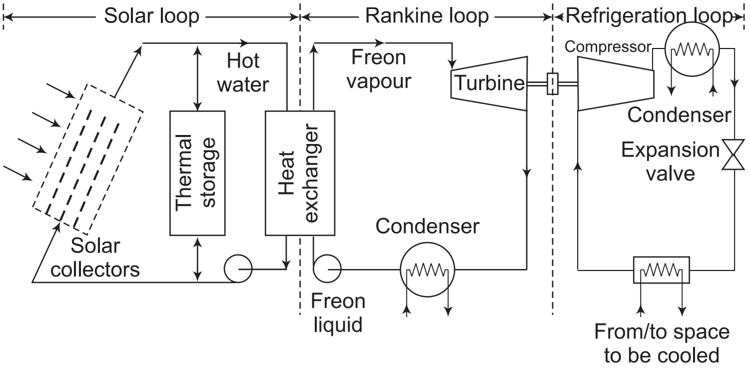


Figure 5.37 Solar vapour compression refrigeration system

Here, solar power is first converted to mechanical power in the same way as explained above. The shaft power thus produced drives the compressor of a conventional vapour compression refrigerator. A suitable refrigerant vapour is compressed and then condensed to a liquid, rejecting heat to ambient. Now the pressure is reduced by passing it through an expansion valve where it gets evaporated at low pressure producing cooling effect. Thus, the refrigerant absorbs heat in the evaporator, from the space to be cooled and rejects it in the condenser.

5.12.3 Solar Pond Electric Power Plant

A solar pond electric power plant is shown in Fig. 5.38. A non-convective solar pond serves the purpose of a large flat plate collector as well as long term thermal storage and can provide sufficient heat for the entire year. The black bottom serves as absorber and the layer of still water above it is used as insulator rather than normal glazing and air space. In a large area pond approximately 1–2 m deep, vertical gradient of salt concentration is maintained such that most concentrated and dense solutions are at the bottom. The salt concentration varies from 20–30 per cent at the bottom to almost zero at the top. Left to itself, the salt concentration gradient will disappear over a period of time because of upward diffusion of the salt. In order to maintain it, fresh water is added at the top of the pond through a horizontal diffuser, while slightly saline water is run off. At the same time concentrated brine is added at the bottom of the pond. The amount of salt required for this purpose is about 50 kg/m^2-day, which is a large quantity when considered on an annual basis. For this reason, normally the salt is recycled by evaporating the saline water run-off from the surface in an adjoining evaporation tank.

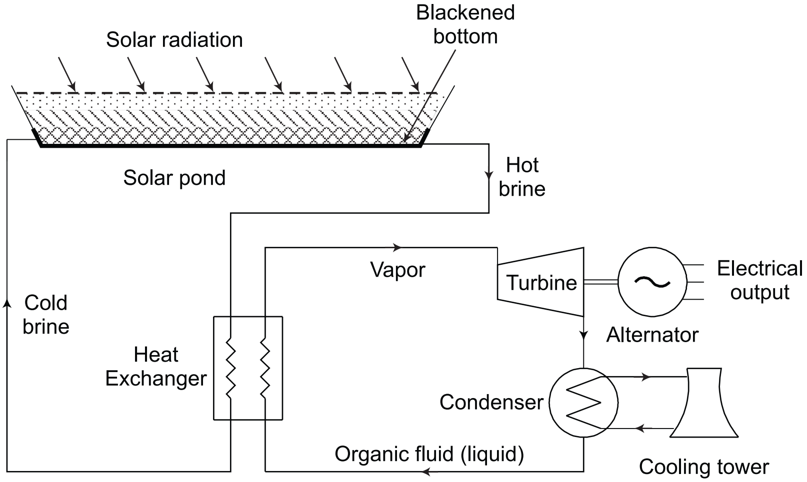


Figure 5.38 Solar pond electric power plant

Because of movement and mixing of the fluid both at the top and at the bottom, the solar pond is characterized by three zones: (i) a surface convective zone, (ii) a non-convective concentration gradient zone and a (iii) lower convective zone. The surface convective zone usually has a small thickness, around 10–20 cm. It has a uniform temperature, close to ambient air temperature and low, uniform concentration close to zero. The non-convective zone is much thicker and occupies more than half the depth of the pond. In this zone, both temperature as well as concentration increase with depth. It principally serves as an insulating layer and reduces heat loss in the upward direction. It also serves as part of heat storage as some of the heat collection takes place in this zone also. The lower convective zone is comparable in thickness to the non-convective zone. Both the temperature and concentration are nearly constant in this zone. It serves as the main heat-collection as well as thermal storage medium. This zone is also referred to as storage zone.

Solar radiation penetrates through water up to the blackened bottom, where it gets absorbed and increases the temperature near bottom. In spite of the temperature rise of the bottom layers of the brine its specific gravity remains higher than that at the top because of concentration gradient and thus, convection mixing is minimized. The bottom layers of the brine reach 70–85 °C while the top remains at 25 °C. The hot brine from the bottom is slowly withdrawn in a laminar flow pattern from the pond and used to evaporate an organic working fluid in a heat exchanger and returned to the pond. Alternatively, heat is extracted by water flowing through a heat exchanger coil submerged at the bottom. The organic working fluid produces mechanical power in a Rankine cycle, which in turn generates electrical power using alternator. The annual collection efficiency generally ranges between 15 to 20 percent. These values are lower than those obtained for a flat plate collector. Nevertheless, solar ponds are more cost effective, since their cost per square meter is much less than that for a liquid flat plate collector.

The first experimental solar pond was constructed in Israel to demonstrate its principle of working. So far, more than sixty solar ponds have been built all around the world for a variety of applications. A 2000 sq. m. solar pond equipped with a 20 kW turbine has been constructed in Australia. The largest solar pond built so far is a 2,50,000-m^2 pond at Bet Ha Arava in Israel, to generate 5 MW electric power using an organic fluid Rankine cycle. The plant operated till 1988. In India some experimental solar ponds are built for thermal applications.

Alternative Types of Solar Ponds

A number of other concepts have also been proposed for building a solar pond. Some of these are discussed below:

(a) The Solar Gel Pond (Viscosity Stabilized Pond) In this pond a thick layer of floating polymer gel acts as a non-convective zone to trap the solar energy in the lower convective zone. The gel has good optical and thermal properties. A small salt gradient in the convective zone is still necessary in order that the gel would float on the top. Main disadvantage of this pond is its high cost due to chemicals required for making gel.

(b) The Partitioned Salt Stabilized Pond In this pond a transparent membrane or partition is used to separate the lower convective zone from non-convective top zone. Thus the non-convective zone instabilities are suppressed. Other features are similar to solar gel pond.

(c) The Equilibrium Solar Pond It uses a salt whose solubility in water increases strongly with temperature. In this pond, thermal diffusion of salt occurs from lower to higher temperature zones in the fluid. In this pond the direction of this movement is downward and opposite to that of the mass diffusion occurring in the upward direction due to the concentration gradient. In the equilibrium pond the two mass fluxes are made to balance each other so that the salt flux is zero. Thus the requirement of regular operational procedure for maintaining the salt concentration gradient is eliminated. The concept has been demonstrated experimentally with potassium nitrate salt solution.

5.12.4 Distributed Collector Solar Thermal Electric Power Plant

In distributed collector system, solar thermal energy is collected from a large number of sun-tracking solar collectors, cylindrical parabolic trough type or paraboloidal dish type. Each collector transfers heat to a heat transport fluid. This heat transport fluid, available at high temperature from the collectors, is pooled at some central power station. The heat transfer fluid could be water/steam, to be used directly in a steam turbine, or it could be some thermo-chemical storage medium such as ammonia. The advantage of later scheme is that thermal energy is stored as chemical energy at ambient temperature and no heat is lost in its transmission over a long distance or in storing it overnight for continuous power generation.

The schematic diagram of a typical distributed collector power generation plant is shown in Fig. 5.39. The heat collected in collectors is used to dissociate ammonia into nitrogen and hydrogen at high pressure (approx. 300 atm). The heat of reaction, 46 kJ/mole (of NH_3) is provided by the solar energy. This nitrogen, hydrogen mixture is transported to central plant where N_2 and H_2 are recombined in a synthesizer, using a catalyst. The heat released during the reaction is utilized in a heat engine to generate electric power through an alternator. In the synthesizer only a part of nitrogen and

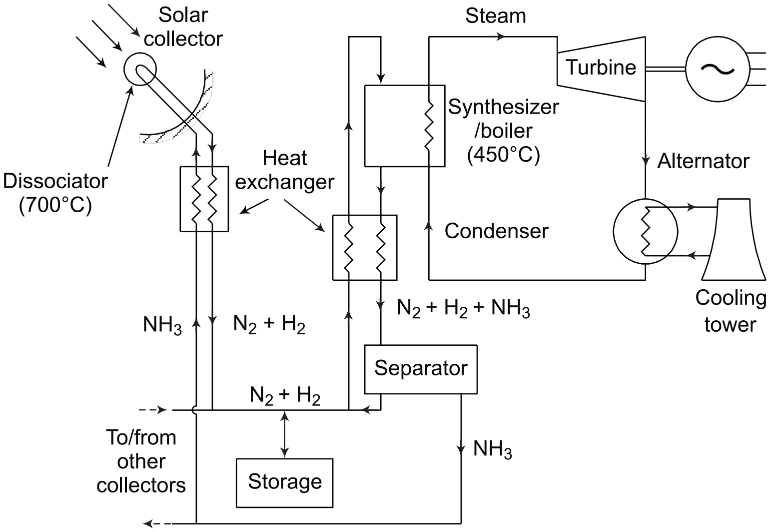


Figure 5.39 Distributed collector solar thermal electric power plant

hydrogen recombine to produce ammonia. The products of synthesizer are cooled to liquefy ammonia, separate it out and send it to collector system. The mixture of nitrogen and hydrogen that remains in gaseous state is fed back to synthesizer.

The first commercial solar electric generating system was constructed in 1984 at Daggett, California using parabolic trough collectors with an electric output of 13.8 MW. Subsequently, several other plants based on parabolic trough collectors were installed in the range of 30 MW and 80 MW.

5.12.5 Central Tower Receiver Power Plant

This power plant uses central tower receiver (discussed earlier in Section 5.2.10) to collect solar radiation from a large area on the ground. The receiver mounted at the top of the tower, converts water into high-pressure steam at around 500 °C. This high-pressure steam is expanded in a turbine coupled with an alternator. The electric power produced is fed to a grid. Thermal buffer storage is provided to continue operating the plant for some time during cloud cover and a bypass is used for starting and shut down operations. The schematic diagram is shown in Fig. 5.40.

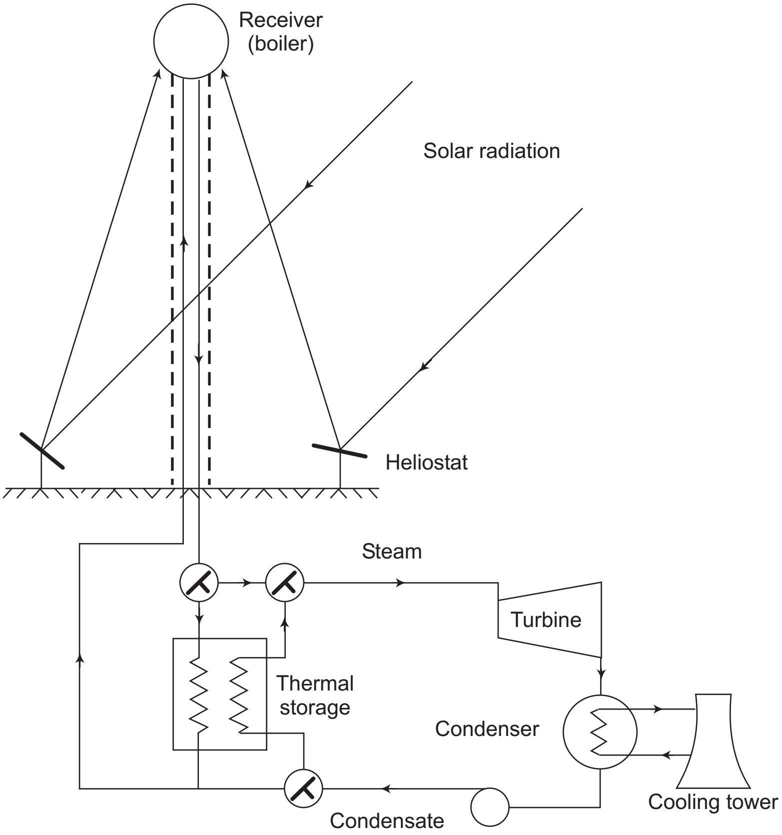


Figure 5.40 Central tower receiver power plant

A central tower power plant of 1 MW capacity has been in operation in Catania, Sicily, Italy, since 1981. It has 182 heliostats in total, with total mirror area of 6202 sq. m. Also, Southern California Edison Company has installed a 10 MW, central power plant with 1818 heliostats.

5.12.6 Solar Chimney Plant

Solar chimney is much simpler but works with much lower efficiency as compared to central tower receiver power plant. The circular field of heliostats is replaced by a circular area of land covered with glazing, i.e., circular greenhouse. The central receiver tower is replaced by a tall chimney that houses a wind turbine at the base of the chimney as shown in Fig. 5.41. Sunlight passes through the transparent cover causes the air trapped in the green house to heat up. A convection system is set up in which the air drawn up through the chimney driving the turbine coupled with a generator. The hot air continuously replenished by fresh air drawn in the periphery of the greenhouse. A 50 kW prototype had been built in Spain and worked uninterrupted from 1986 to 1989. It had 200 m high chimney with a constant diameter of 10.3 m. The solar collector area extended to a radius of 126 m from the chimney with glazing being 2 m above the ground. Further progress in this direction is hampered due to exorbitant cost involved.

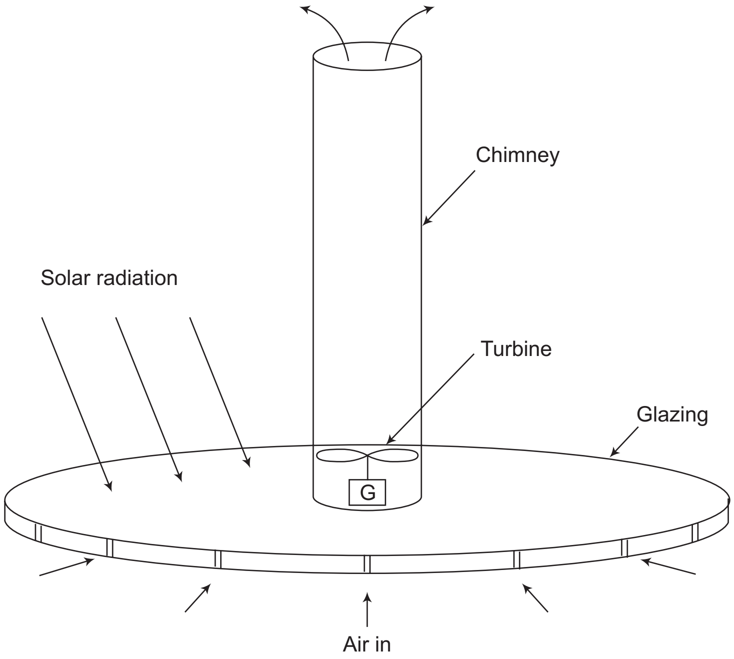


Figure 5.41 Solar chimney power plant

5.13 THERMAL ANALYSIS OF LIQUID FLAT PLATE COLLECTOR

Let us consider a flat plate solar collector shown in Fig. 5.3 for thermal analysis. The heat flow process is shown in Fig. 5.42.

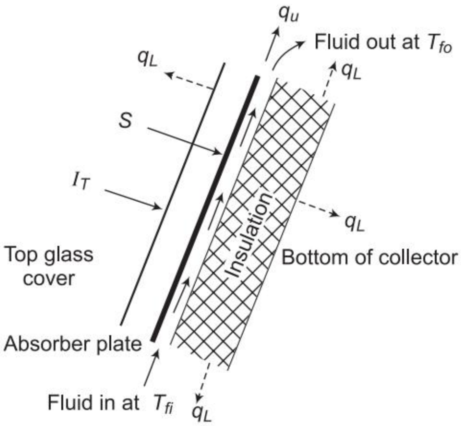


Figure 5.42 Heat transfer process in flat plate solar collector

Energy balance of the absorber plate, under steady state condition yields:

$$q_u = A_p S - q_L \tag{5.1}$$

where, q_u = useful heat gain (i.e. heat transfer rate to the working fluid), W
A_p = area of absorbing plate, m^2
S = incident solar flux absorbed in the collector plate, W/m^2
q_L = rate at which energy is lost by:

(i) convection and re-radiation from the top, and
(ii) conduction and convection from the bottom and sides of the collector

Also, the heat transfer rate to the working fluid is given by,

$$q_u = \dot{m}\, C_f (T_{fo} - T_{fi}) \tag{5.2}$$

where, $\dot{m}$ = mass flow rate of the fluid, kg/s
C_f = specific heat of the fluid, J/m^2-K
T_{fi} = fluid temperature at the input of collector, K
T_{fo} = fluid temperature at the output of collector, K

Solar flux incident on the top of the collector, is same as solar radiation received on inclined plane surface, as given in Chapter 4, Eq. (4.31), that is:

$$I_T = I_b\, r_b + I_d\, r_d + (I_b + I_d)\, r_r$$

where I_b and I_d are the beam and diffuse radiation components of solar radiation, r_b, r_d and r_r are “tilt factors” for beam, diffuse and reflected components respectively. Their expressions are given in Eq. (4.33), (4.34) and (4.35) respectively as follows:

$$r_b = \frac{\sin\delta \sin(\phi - \beta) + \cos\delta \cos\omega \cos(\phi - \beta)}{\sin\delta \sin\phi + \cos\delta \cos\omega \cos\phi}$$

$$r_d = \frac{1+\cos\beta}{2}$$

$$r_r = \rho\left(\frac{1-\cos\beta}{2}\right)$$

where ρ is reflection coefficient of the ground.

The flux S, absorbed in the absorber plate, can be given as,

$$S = I_b\, r_b\, (\tau\alpha)_b + \{I_d\, r_d + (I_b + I_d)\, r_r\}\, (\tau\alpha)_d \tag{5.3}$$

where,

τ = transmissivity of the glass cover system, defined as the ratio of the solar radiation coming through after reflection at the glass air interfaces and absorption in the glass to the radiation incident to the glass cover system.

α = absorptivity of the absorber plate.

$(\tau\alpha)_b$ = transmissivity-absorptivity product for beam radiation falling on the collector,

$(\tau\alpha)_d$ = transmissivity-absorptivity product for diffuse radiation falling on the collector

The **instantaneous collection efficiency**, η_i of a flat plate solar collector is given by,

$$\eta_i = \frac{\text{useful heat gain}}{\text{solar radiation incident on the collector}} = \frac{q_u}{A_c\, I_T} \tag{5.4}$$

where, I_T = instantaneous radiation energy rate incident on collector face (W/m^2)

A_c = the collector gross area (area of the topmost cover including the frame). A_c is usually 15 to 20 per cent more than A_p.

It is to be noted here, that the energy rate incident on the collector is $A_c I_T$. A fraction of this energy is lost in the cover system during transmission through it. The energy rate received on the absorber plate is $A_p S$. Out of this energy, q_u is the rate of heat (energy) transfer to working fluid while q_L is the energy loss rate from the absorber plate.

If the liquid flow rate through the collector is stopped, there is no useful heat gain and therefore, the efficiency is zero. In this case, total heat absorbed by plate is lost to ambient and the absorber plate attains a temperature according to $A_p S = q_L$, This is the highest temperature, the absorber plate can attain and is referred to as the **stagnation temperature**. Knowledge of the stagnation temperature is useful for comparing different collector designs. It also helps in proper material selection for the construction of collector.

To determine the efficiency of collector one needs to evaluate q_u, for which S and q_L are to be known. S can be evaluated using Eq. (5.3) provided the terms $(\tau\alpha)_b$ and $(\tau\alpha)_d$ are known. We shall now derive the expressions for evaluating theses quantities.

5.13.1 Solar Radiation Attenuation in the Cover System

1. Transmissivity of the Cover System

When a beam radiation travelling through one medium strikes another medium it partly gets reflected, refracted and absorbed in the medium. Transmissivity, τ of the cover system may be obtained by considering transmissivity due to (i) reflection-refraction and (ii) absorption separately. Thus:

$$\tau = \tau_r \tau_a \tag{5.5}$$

where, τ_r = transmissivity obtained by considering only reflection and refraction, and

τ_a = transmissivity obtained by considering absorption only

(a) Transmissivity based on Reflection-Refraction, (τ_r)

As shown in Fig. 5.43, I_{bn} is the intensity of the incoming beam radiation striking the interface of two medium at an angle of incidence of θ_1. The reflected beam has reduced intensity of I_ρ making an angle of reflection which is equal to angle of incidence. The direction of incident and refracted beams are related to each other by Snell's law as follows:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} \tag{5.6}$$

where, θ_1 = angle of incidence,

θ_2 = angle of refraction, and

n_1, n_2 = refractive indices of the two media

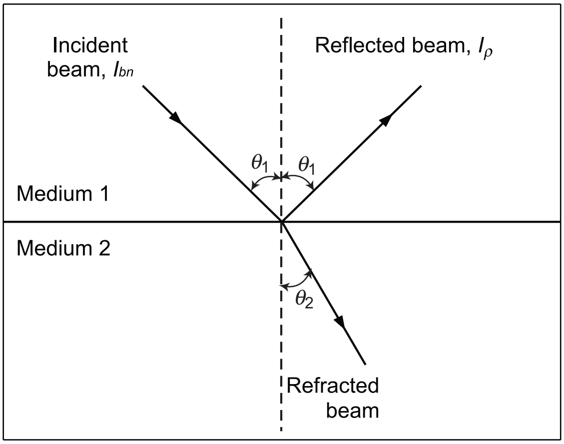


Figure 5.43 Reflection and refraction of the incident beam

The reflectivity ρ (= I_ρ/I_{bn}) is related to the angle of incidence and refraction as follows:

$$\rho = \frac{I_\rho}{I_{bn}} = \frac{1}{2}(\rho_I + \rho_{II}) \tag{5.7}$$

$$\rho_I = \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)} \tag{5.8}$$

$$\rho_{II} = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)} \tag{5.9}$$

where, ρ_I and ρ_{II} are the reflectivities of the two components of polarization.

For the special case of normal incidence ($\theta_1 = 0°$), it can be shown that,

$$\rho = \rho_I = \rho_{II} = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \tag{5.10}$$

The transmissivity τ_r is given by an expression,

$$\tau_r = \frac{1}{2}(\tau_{rI} + \tau_{rII}) \tag{5.11}$$

where, τ_{rI} and τ_{rII} are the transmissivities of the two components of polarization.

Let us now consider one of the components of polarization of beam radiation incident on single cover. As there are two interfaces in the cover, multiple reflections and refraction will occur as shown in Fig. 5.44.

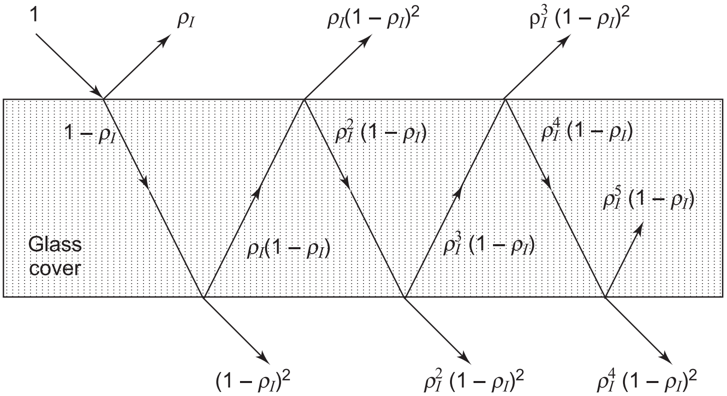


Figure 5.44 Refraction-reflection of one of the component of polarization incident on single cover

Hence,

$$\tau_{rI} = (1 - \rho_I)^2 + \rho_I^2(1 - \rho_I)^2 + \rho_I^4(1 - \rho_I)^2 + \ldots$$

$$= \frac{1 - \rho_I}{1 + \rho_I} \tag{5.12}$$

Similarly,

$$\tau_{rII} = \frac{1 - \rho_{II}}{1 + \rho_{II}} \tag{5.13}$$

Thus for a system with M number of covers, we can write,

$$\tau_{rI} = \frac{1-\rho_I}{1+(2M-1)\rho_I} \tag{5.14}$$

Similarly,

$$\tau_{rII} = \frac{1-\rho_{II}}{1+(2M-1)\rho_{II}} \tag{5.15}$$

(b) Transmissivity based on Absorption, (τ_α) Let us consider a transparent cover through which radiation is passing, as shown in Fig. 5.45. As per Bouger's law "the attenuation due to absorption is proportional to the local intensity". At depth 'x' from the top, the intensity is I_x. Now, on penetrating an elementary distance of dx, the attenuation ($-dI_x$) is given by:

$$-dI_x \; \alpha \; (I_x \, dx)$$

$$dIx = -K \, I_x \, dx \tag{5.16}$$

where, K is a constant of proportionality, known as **extinction coefficient**. Integrating over the thickness of cover, δ_c, we have

$$\tau_a = \frac{I_L}{I_{bn}} = e^{-k\delta_c} \tag{5.17}$$

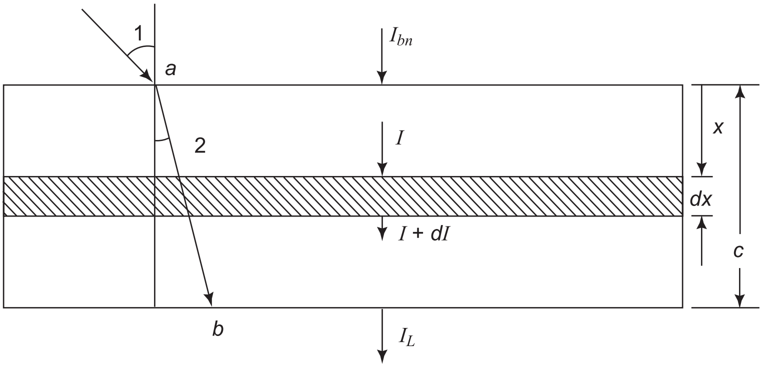


Figure 5.45 Absorption of the incident ray in a transparent cover

If the ray is incident at angle θ_1, as shown in Fig. 5.45, the path traversed through the cover would be 'ab' = $\delta_c/\cos\theta_2$, where θ_2 is angle of refraction.

$$\tau_a = e^{-k\delta_c/\cos\theta_2} \tag{5.18}$$

For M number of covers,

$$\tau_a = e^{-Mk\delta_c/\cos\theta_2} \tag{5.19}$$

The extinction coefficient K is the property of the material. For different qualities of glass its value varies from 4 to 25 per m.

Transmissivity for Diffuse Radiation As diffuse radiation, I_d come from many directions, it poses difficulty in the calculation of transmissivity for diffuse radiation.

The usual practice is to assume that diffuse radiation is equivalent to beam radiation coming at an angle of incidence of 60°. In case of diffuse radiation, since the rays come from many directions.

2. Absorptivity of Absorber Plate, (α)

Absorptivity, α, of the absorber plate is defined as the ratio of the solar radiation absorbed in the absorbing plate to the radiation incident to the absorber plate.

3. Transmissivity-Absorptivity Product ($\tau\alpha$)

The transmissivity-absorptivity product is defined as the ratio of the flux absorbed in the absorber plate to the flux incident on the cover system and is denoted by the symbol ($\tau\alpha$), an appropriate (*b* or *d*) being added to indicate the type of incident radiation.

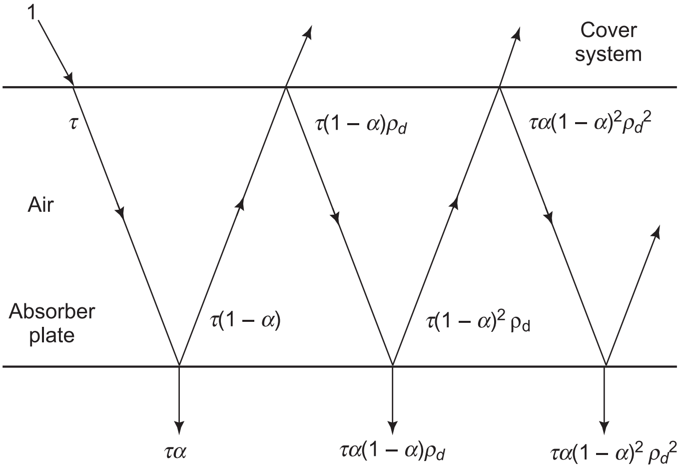


Figure 5.46 Absorption and reflection at the absorber plate

As shown in the Fig. 5.46, out of fraction τ transmitted through the cover system, a part is absorbed and a part reflected diffusedly. Out of the reflected part, a portion is transmitted out through the cover system and a portion reflected back to absorber plate. The process goes on indefinitely with successive attenuation. Thus net fraction absorbed is given by,

$$(\tau\alpha) = \tau\alpha\,[1 + (1-\alpha)\rho_d + (1-\alpha)^2\rho_d^2 + \ldots]$$

$$= \frac{\tau\alpha}{1-(1-\alpha)\rho_d} \tag{5.20}$$

where, ρ_d represents the diffuse reflectivity of the cover system. It can be shown that:

$$\rho_d = (\tau_a)_d\,\{1-(\tau_r)_d\} \tag{5.21}$$

where $(\tau_a)_d$ and $(\tau_r)_d$ are calculated for diffuse radiation considering an incidence angle of 60°. Eq. (5.20) may be applied separately to both, beam radiation and diffuse radiation. However, the values of cover system transmissivities are different for beam and diffuse radiations.

Thus for beam radiation,

$$(\tau\alpha)_b = \frac{(\tau)_b \times \alpha}{1-(1-\alpha)\rho_d} \tag{5.22}$$

And for diffuse radiation,

$$(\tau\alpha)_d = \frac{(\tau)_d \times \alpha}{1-(1-\alpha)\rho_d} \tag{5.23}$$

Same value of absorptivity α applies to both beam as well as diffuse radiations.

Example 5.1

A flat plate collector, facing due south, having two glass covers is located at Gulmarg (34.05° N, 74.38° E), have the following data:

Standard longitude for IST	82.5° E
Date	June 15
Time	12 noon
Collector tilt angle	Equal to latitude
Beam radiation, I_b (on horizontal surface)	700 W/m^2
Diffuse radiation, I_d (uniformly distributed over the sky)	200 W/m^2
Reflectivity of surrounding	0.2
Plate absorptivity of solar radiation	0.92
Extinction coefficient of glass	19 per m
Thickness of each glass cover	4 mm
Refractive index of glass with respect to air	1.526

Calculate:

(i) Angle of incidence of beam radiation on the collector

(ii) Total solar flux incident on the collector

(iii) The incident flux absorbed by the absorber plate

Solution

(a) Calculation of angle of incidence

On June 15, n = 166, from Eq. (4.5):

$$\delta = 23.45 \times \sin\left[\frac{360}{365}(284+166)\right] = 23.31°$$

From Eq. (4.3),

$$\text{Solar time} = \text{Standard time} \pm 4\,(L_{st} - L_{loc})\ (\text{min}) + E\ (\text{min})$$

$$E = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B \text{ min.}$$

and $$B = (360/364)(n - 81) = (360/364)((360/364)(n - 81)166 - 81) = 84.066$$

$$E = -0.2406 \text{ min}$$

$$\text{Solar time} = 12\text{ h} - 4 \times (82.5° - 74.38°)\ (\text{min}) - 0.2406\ (\text{min})$$

$$= 11\text{ h } 27.5\text{ min}$$

Solar hour angle, $\omega = 8.125°$

From Eq. (4.8), the angle of incidence of beam radiation, θ_1 is given by,

$$\begin{aligned}\cos\theta_1 &= \cos(\phi - \beta)\cos\delta\cos\omega + \sin\delta\sin(\phi - \beta)\\ &= \cos(0)\cos(23.31)\cos(8.125) + \sin(23.31)\sin(0)\\ &= 0.909\\ \theta_1 &= 24.6°\end{aligned}$$

Thus angle of incidence of beam radiation on collector is **24.6°**

(b) Calculation of total solar flux incident on collector, I_T

From Eq. (4.33):

$$\begin{aligned}r_b &= \frac{\sin\delta\sin(\phi-\beta)+\cos\delta\cos\omega\cos(\phi-\beta)}{\sin\delta\sin\phi+\cos\delta\cos\omega\cos\phi}\\ &= \frac{\sin(23.31)\sin(0)+\cos(23.31)\cos(8.125)\cos(0)}{\sin(23.31)\sin(34.05)+\cos(23.31)\cos(8.125)\cos(34.05)}\\ &= 1.244\end{aligned}$$

From Eq. (4.34):

$$r_d = \frac{1+\cos\beta}{2} = \frac{1+\cos(34.05)}{2} = 0.9143$$

From Eq. (4.35): (using $\rho = 0.2$),

$$r_r = \rho\left(\frac{1-\cos\beta}{2}\right) = 0.2\times\left(\frac{1-\cos(34.05)}{2}\right) = 0.01715$$

From Eq. (4.31), total radiation on collector:

$$\begin{aligned}I_T &= I_b r_b + I_d r_d + (I_b + I_d) r_r\\ &= 700\times 1.244 + 200\times 0.9143 + 900\times 0.01715\\ &= \mathbf{1{,}069\ W/m^2}\end{aligned}$$

Thus, total solar flux incident on collector is **1,069 W/m^2**

(c) Incident solar flux absorbed by the absorber plate,

Calculations for beam radiation:

From Eq. (5.6):

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} = 1.526$$

$$\begin{aligned}\sin\theta_2 &= \sin(24.6)/1.526 = 0.27279\\ \theta_2 &= 15.8°\end{aligned}$$

From Eq. (5.8),

$$\rho_I = \frac{\sin^2(\theta_2-\theta_1)}{\sin^2(\theta_2+\theta_1)} = \frac{\sin^2(15.8-24.6)}{\sin^2(15.8+24.6)} = 0.0557$$

From Eq. (5.9),

$$\rho_{II} = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)} = \frac{\tan^2(15.8 - 24.6)}{\tan^2(15.8 + 24.6)} = 0.03307$$

From Eqs (5.14) and (5.15), for 2 glass covers, we have,

$$\tau_{rI} = \frac{1-\rho_I}{1+(2M-1)\rho_I} = \frac{1-0.0557}{1+(2\times 2-1)\times 0.0557} = 0.8091$$

Similarly,

$$\tau_{rII} = \frac{1-\rho_{II}}{1+(2M-1)\rho_{II}} = \frac{1-0.03307}{1+(2\times 2-1)\times 0.03307} = 0.8796$$

From Eq. (5.11),

$$(\tau_r)_b = \frac{1}{2}(\tau_{rI} + \tau_{rII}) = \frac{1}{2}(0.8091 + 0.8796) = 0.8444$$

From Eq. (5.19),

$$\tau_a = e^{-Mk\delta_c/\cos\theta_2} = e^{-2\times 19\times 0.004/\cos(15.8)} = 0.8538$$

Thus $(\tau)_b = (\tau_r)_b \times (\tau_a)_b = 0.8444 \times 0.8538 = 0.721$

Calculations for diffuse radiation:

From Eq. (5.6): The angle of incidence for diffuse radiation is assumed as 60°

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} = 1.526$$

$$\sin\theta_2 = \sin(60)/1.526 = 0.5675$$

$$\theta_2 = 34.577°$$

From Eq. (5.8),

$$\rho_I = \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)} = \frac{\sin^2(34.577 - 60)}{\sin^2(34.577 + 60)} = 0.1855$$

From Eq. (5.9),

$$\rho_{II} = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)} = \frac{\tan^2(34.577 - 60)}{\tan^2(34.577 + 60)} = 0.001448$$

From Eqs (5.14) and (5.15), for 2 glass covers, we have,

$$\tau_{rI} = \frac{1-\rho_I}{1+(2M-1)\rho_I} = \frac{1-0.1855}{1+(2\times 2-1)\times 0.1855} = 0.5233$$

Similarly,

$$\tau_{rII} = \frac{1-\rho_{II}}{1+(2M-1)\rho_{II}} = \frac{1-0.001448}{1+(2\times 2-1)\times 0.001448} = 1.0043$$

From Eq. (5.11),

$$(\tau_r)_d = \frac{1}{2}(\tau_{rI} + \tau_{rII}) = \frac{1}{2}(0.5223 + 1.0043) = 0.7633$$

From Eq. (5.19),

$$(\tau_a)_d = e^{-Mk\delta_c/\cos\theta_2} = e^{-2\times 19\times 0.004/\cos(34.577)} = 0.8314$$

Thus $(\tau)_d = (\tau_r)_d \times (\tau_a)_d = 0.7633 \times 0.8314 = 0.6346$

Now, from Eq. (5.21),

$$\rho_d = (\tau_a)_d \{1 - (\tau_r)_d\} = 0.8314 \times \{1 - 0.7633\} = 0.1974$$

For beam radiation, from Eq. (5.22), (for given value of α as 0.92)

$$(\tau\alpha)_b = \frac{(\tau)_b \times \alpha}{1-(1-\alpha)\rho_d} = \frac{0.721\times 0.92}{1-(1-0.92)\times 0.1974} = 0.67396$$

And for diffuse radiation, from Eq. (5.23),

$$(\tau\alpha)_d = \frac{(\tau)_d \times \alpha}{1-(1-\alpha)\rho_d} = \frac{0.6346\times 0.92}{1-(1-0.92)\times 0.1974} = 0.5932$$

Now, incident solar flux absorbed by the absorber plate, from Eq. (5.3)

$$\begin{aligned} S &= I_b\, r_b\, (\tau\alpha)_b + \{I_d\, r_d + (I_b + I_d)\, r_r\}\, (\tau\alpha)_d \\ &= 700\times 1.244\times 0.67396 + \{200\times 0.9143 + (700+200)\times 0.01715\}\times 0.5932 \\ &= 704.5 \text{ W/m}^2 \end{aligned}$$

Incident solar flux absorbed by the absorber plate = **704.5 W/m^2**

5.13.2 Heat Loss Rate from Absorber Plate, q_L

It is more convenient to express the heat lost from the collector in terms of an overall loss coefficient defined by the equation:

$$q_L = U_L\, A_p\, (T_{pm} - T_a) \tag{5.24}$$

where U_L = overall loss coefficient, W/m^2-K

A_p = area of absorber plate, m^2

T_{pm} = mean (or average) temperature of the absorber plate, K

and T_a = temperature of the surrounding air, K

The heat lost from the collector is the sum of the heat lost from the top, the bottom and the sides. Therefore, total heat loss rate of the collector is given by,

$$q_L = q_t + q_b + q_s \tag{5.25}$$

where q_t = rate at which heat is lost from the top

q_b = rate at which heat is lost from the bottom

q_s = rate at which heat is lost from the sides

Each of these loss components may also be expressed in terms of individual loss coefficients, that is, top loss coefficient, bottom loss coefficient and side loss coefficient respectively, defined by the following equation.

$$q_t = U_t\, A_p\, (T_{pm} - T_a) \tag{5.26}$$

$$q_b = U_b\, A_p\, (T_{pm} - T_a) \tag{5.27}$$

$$q_s = U_s\, A_p\, (T_{pm} - T_a) \tag{5.28}$$

It is to be noted here that in the above three equations the coefficients are defined on the basis of common area A_p and also common temperature difference. This simplifies the analysis and gives simple additive equation for overall loss component of the collector. Thus:

$$U_L = U_t + U_b + U_s \tag{5.29}$$

These losses can also be depicted in terms of thermal resistances as shown in Fig. 5.5. Typical value of overall loss coefficient is in range 2 to 10 kW/m^2-K.

Equation (5.2) can now be written as:

$$q_u = A_p\, S - U_L\, A_p\, (T_{pm} - T_a) \tag{5.30}$$

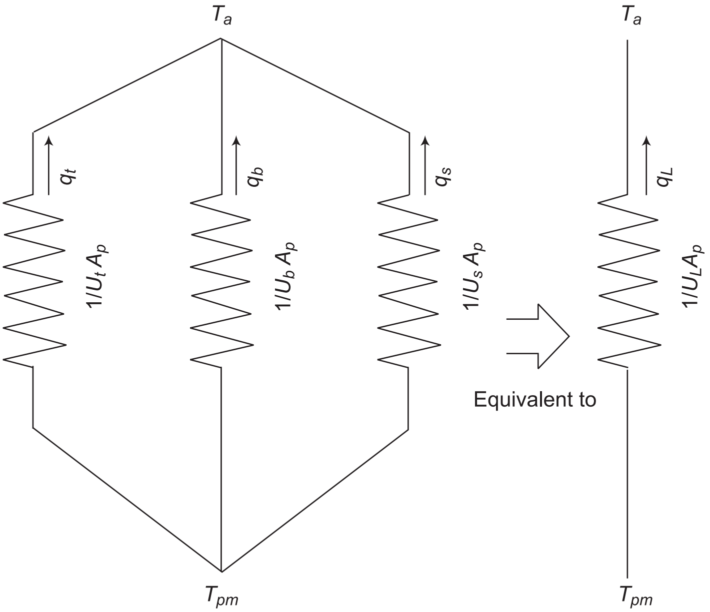


Figure 5.47 Thermal resistance network showing collector losses

A modified equation in which the term, plate temperature, T_{pm} is replaced by local fluid temperature; T_f (temperature of fluid flowing in the tubes) can also be obtained as follows:

$$q_u = F'\,[A_p\, S - U_L\, A_p\, (T_f - T_a)] \tag{5.31}$$

where, $$F' = \frac{1/U_L}{W\left[\dfrac{1}{U_L\{E_f(W-D_o)+D_o\}}+\dfrac{\delta_a}{k_a D_o}+\dfrac{1}{\pi D_i h_f}\right]} \tag{5.32}$$

D_i, D_o = inside and outside diameters of tubes, m

k_a = thermal conductivity of adhesive material, W/m-K
W = pitch of tubes (spacing between adjacent tubes), m
h_f = heat transfer coefficient on the inside surface of the tube (tube to fluid heat transfer coefficient), W/m^2-K

$$a = (U_L/k_p\delta_p)^{1/2} \tag{5.33}$$

k_p = thermal conductivity of plate, W/m-K
δ_p = thickness of absorber plate, m

$$E_f = \frac{\tanh\{a(W - D_o)/2\}}{\{a(W - D_o)/2\}} \tag{5.34}$$

E_f is known as plate effectiveness, which is defined as the ratio of the heat conducted through the plate to the fluid tube, to the heat which would have been conducted if the thermal conductivity of the plate material was infinite.

The term F' is known as collector efficiency factor and defined as the ratio of the actual useful heat collection rate to the useful heat collection rate which would occur if the collector absorber plate were at the temperature T_f. Its value ranges from 0.90 to 0.95.

The heat loss from the collector can thus be calculated if either average plate temperature or local fluid temperature is known. However, these temperatures are generally not known. By considering the heat removal process due to fluid flow, a modified expression can be obtained in terms of inlet fluid temperature, T_{fi}. This is usually a known quantity and hence the expression is more convenient to use. Thus:

$$q_u = F_R\,A_p\,[S - U_L(T_{fi} - T_a)] \tag{5.35}$$

where $$F_R = \frac{\dot{m}\,C_f}{U_L\,A_p}\left[1 - \exp\left(-\frac{F'U_L\,A_p}{\dot{m}\,C_f}\right)\right] \tag{5.36}$$

$\dot{m}$ = mass flow rate, kg/s
C_f = specific heat of fluid, J/kg-K

The term F_R is called the collector heat removal factor. It represents the ratio of actual useful heat collection rate to the useful heat collection rate which would occur if the collector absorber plate were at the temperature T_{fi} everywhere. Its value ranges from 0 to 1. Equation (5.36) is often referred to as Hottel-Whillier-Bliss equation.

Using the procedure described above the efficiency of a flat plate collector may be calculated. For a properly designed flat plate collector an instantaneous efficiency of the order of 50–60 per cent may be achieved.

5.13.3 Evaluation of Loss Coefficients

1. Top Loss Coefficient, U_t

The top loss coefficient is evaluated by considering convection and re-radiation losses from the absorber plate in the upward direction. Evaluation through normal procedure requires tedious iterative calculations. Based on calculations for a large number of cases covering the entire range of conditions normally expected for flat plate collectors, Malhotra et al. [28] suggested following empirical equation for calculation of U_t.

$$U_t = \left[\frac{M}{\left(\dfrac{C}{T_{pm}}\right)\left(\dfrac{T_{pm}-T_a}{M+f}\right)^{0.252}} + \frac{1}{h_w} \right]^{-1} + \left[\frac{\sigma(T_{pm}^2+T_a^2)(T_{pm}+T_a)}{\dfrac{1}{\varepsilon_p + 0.0425M(1-\varepsilon_p)} + \dfrac{2M+f-1}{\varepsilon_c} - M} \right] \tag{5.37}$$

where, $$f = \left(\frac{9}{h_w} - \frac{30}{h_w^2}\right)\left(\frac{T_a}{316.9}\right)(1+0.091M) \tag{5.38}$$

$$C = 204.429(\cos\beta)^{0.252}/L^{0.24} \tag{5.39}$$

$$h_w = 8.55 + 2.56\,V_\infty \tag{5.40}$$

= convective heat transfer coefficient at the cover (often referred to as wind heat transfer coefficient, W/m^2-k)

V_∞ = wind speed, m/s

M = Number of glass covers

σ = Stefan-Boltzmann constant, W/m^2-K^4

ε_p = Emissivity of absorber surface for long wavelength radiation

ε_c = Emissivity of cover for long wavelength radiation

L = Spacing between absorber plate and 1st glass cover (which is also equal to spacing between the two adjacent glass covers)

2. Bottom Loss Coefficient, U_b

The bottom loss component U_b is evaluated by considering conduction and convection losses from the absorber plate in the downward direction through the bottom of the collector as shown in Fig. 5.48.

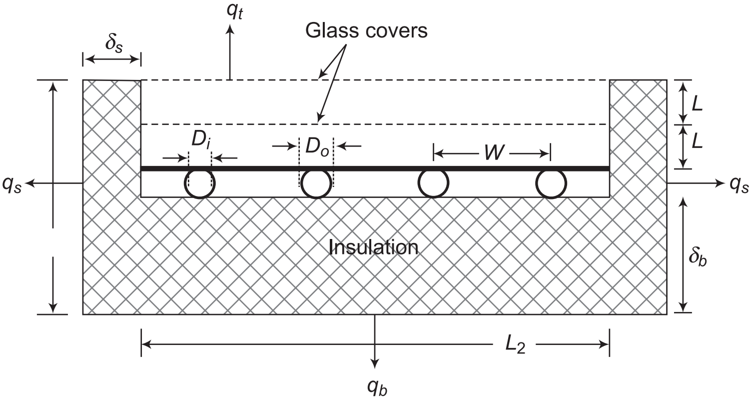


Figure 5.48 Bottom and side losses from a flat plate collector

It is assumed that the flow of heat is one dimensional and steady. In most cases, the thickness of insulation provided is such that the convection is negligible and heat loss takes place predominantly by conduction. Thus, the bottom heat loss is given by,

$$U_b = \frac{k_i}{\delta_b} \tag{5.41}$$

where, k_i = Thermal conductivity of insulation, W/m-K
δ_b = Thickness of the insulation, m

3. Side Loss Coefficient, U_s

In this case also, it is assumed that the convection is negligible, conduction losses dominate and the flow is one dimensional and steady. If the dimensions of absorber plate are $L_1 \times L_2$ and the height of collector casing is L_3, the area across which the heat flows sideways is $2(L_1 + L_2)\,L_3$. The temperature drop across which the heat flow takes place varies from $(T_{pm} - T_a)$ at the absorber level to zero, both at the top and at the bottom. Therefore, average temperature drop across the side insulation may be considered as, $(T_{pm} - T_a)/2$. The heat flow may be given as,

$$q_s = 2L_3(L_1 + L_2)k_i \frac{T_{pm} - T_a}{2\delta_s} \tag{5.42}$$

Therefore,

$$U_s = \frac{L_3(L_1 + L_2)k_i}{L_1 L_2 \delta_s} \tag{5.43}$$

where, δ_s = Thickness of the insulation, m

Example 5.2

Use following data to calculate the overall loss coefficient of a flat plate collector:

Size of the absorber plate	2.15 m × 1.15 m
Spacing between absorber plate and 1st glass cover	5 cm
Spacing between 1st and 2nd glass cover	5 cm
Glass cover emissivity	0.85
Plate emissivity	0.90
Mean plate temperature	75°C
Ambient air temperature	20°C
Collector tilt	30°
Wind speed	3 m/s
Back insulation thickness	8 cm
Side insulation thickness	4 cm
Thermal conductivity of insulation	0.035 W/m-K

Solution

We know that, Stefan–Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ W/m^2-K^4

Given:

$$L_1 \times L_2 = 2.15 \text{ m} \times 1.15 \text{ m}$$

$$L = 0.05 \text{ m}$$

$\varepsilon_p = 0.9$

$\varepsilon_c = 0.85$

$\beta = 30°$

$T_{\text{pm}} = 75 + 273 = 348$

$T_a = 20 + 273 = 293$

$V_\infty = 3$ m/s

$\delta_b = 0.08$ m

$\delta_s = 0.04$ m

$k_i = 0.035$ W/m-k

Calculation of top loss coefficient: U_t

From Eq. (5.41), $h_w = 8.55 + 2.56\ V_\infty = 8.55 + 2.56 \times 3 = 16.23$

From Eq. (5.40),

$$C = 204.429(\cos\beta)^{0.252}/L^{0.24} = 204.429(\cos 30)^{0.252}/(0.05)^{0.24} = 404.62$$

From Eq. (5.39),

$$f = \left(\frac{9}{h_w} - \frac{30}{h_w^2}\right)\left(\frac{T_a}{316.9}\right)(1 + 0.091M)$$

$$= \left(\frac{9}{16.23} - \frac{30}{16.23^2}\right)\left(\frac{293}{316.9}\right)(1 + 0.091 \times 2) = 0.481555$$

From Eq. (5.38),

$$U_t = \left[\frac{M}{\left(\frac{C}{T_{pm}}\right)\left(\frac{T_{pm} - T_a}{M + f}\right)^{0.252}} + \frac{1}{h_w}\right]^{-1} + \left[\frac{\sigma(T_{pm}^2 + T_a^2)(T_{pm} + T_a)}{\frac{1}{\varepsilon_p + 0.0425M(1 - \varepsilon_p)} + \frac{2M + f - 1}{\varepsilon_c} - M}\right]$$

$$= \left[\frac{2}{\left(\frac{404.62}{348}\right)\left(\frac{348 - 293}{2 + 0.481555}\right)^{0.252}} + \frac{1}{16.23}\right]^{-1} + \left[\frac{5.68 \times 10^{-8}(348^2 + 293^2)(348 + 293)}{\frac{1}{0.9 + 0.0425 \times 2(1 - 0.9)} + \frac{2 \times 2 + 0.481555 - 1}{0.85} - 2}\right]$$

$= 0.849496 + 3.657657$

$U_t = 4.50715$

Calculation of bottom loss coefficient: U_b

From Eq. (5.42),

$$U_b = \frac{k_i}{\delta_b} = \frac{0.035}{0.08} = 0.4375$$

Calculation of side loss component: U_s

$$L_3 = L + L + \delta_b = 0.05 + 0.05 + 0.08 = 0.18$$

From Eq. (5.44),

$$U_s = \frac{L_3(L_1 + L_2)k_i}{L_1 L_2 \delta_s} = \frac{0.18 \times (2.15 + 1.15) \times 0.035}{2.15 \times 1.15 \times 0.04} = 0.21021$$

Overall loss coefficient, $U_L = 4.50715 + 0.4375 + 0.21021 = 5.15486$

Thus the overall loss coefficient, $\boldsymbol{U_L = 5.15486}$ **W/m^2-K**

Example 5.3

Following data are given for a flat plate collector:

Size of absorber plate = 2.4 m × 1.4m
Absorber plate thickness = 0.18 mm
Thermal conductivity of plate material = 360 W/m-K
Number of tubes attached below abs. plate = 15
Fluid flow rate = 50 kg/h
Water inlet temperature = 40°C
Specific heat of fluid at 50°C = 4174 J/kg-K
Tube to fluid heat transfer coefficient = 200 W/m^2-K
Outer diameter of tubes = 15 mm
Inner diameter of tubes = 13.8 mm
Overall loss coefficient of the collector = 5 W/m^2-K
Average thickness of adhesive = negligible
Length of controller = 2.5 m
Width of controller = 1.5 m
Ambient temperature = 24°C
Beam radiation on horizontal surface = 650 W/m^2
Diffuse radiation (uniformly distributed in the sky) = 150 W/m^2
Tilt factors for beam, diffuse and reflected radiations = 0.95, 0.98 and 0.005 respectively
Transmissivity-absorptivity product for beam radiation falling on the collector = 0.8321
Transmissivity-absorptivity product for diffuse radiation falling on the collector = 0.79

Calculate:

(i) the collector heat removal factor, F_R
(ii) water outlet temperature, T_{fo}
(iii) instantaneous efficiency of collector, η_i

Solution

(i) Calculation of collector heat removal factor:

Given: $U_L = 5$ W/m^2-K, $k_p = 360$ W/m-K, $\delta_p = 0.18 \times 10^{-3}$

From Eq. (5.34),

$$a = (U_L/k_p\delta_p)^{1/2} = \{5/(360 \times 0.18 \times 10^{-3})\}^{1/2} = 8.784$$

Given: $W = L_2/N = 1.4/15 = 0.0933$ m, $D_o = 15 \times 10^{-3}$ m

From Eq. (5.35),

$$E_{ve} = \frac{\tanh\{a(W - D_o)/2\}}{\{a(W - D_o)/2\}} = \frac{\tanh\{8.784 \times (0.0933 - 15 \times 10^{-3})/2\}}{\{8.784 \times (0.0933 - 15 \times 10^{-3})/2\}} = 0.96237$$

Given: δ_a = negligible ≈ 0, $D_i = 13.8 \times 10^{-3}$ m, $h_f = 200$ W/m^2-K

From Eq. (5.32),

$$F' = \frac{1/U_L}{W\left[\dfrac{1}{U_L\{E_f(W - D_o) + D_o\}} + \dfrac{\delta_a}{k_a D_o} + \dfrac{1}{\pi D_i h_f}\right]}$$

$$= \frac{1/5}{0.0933 \times \left[\dfrac{1}{5 \times \{0.96237 \times (0.0933 - 15 \times 10^{-3}) + 15 \times 10^{-3}\}} + 0 + \dfrac{1}{\pi \times 13.8 \times 10^{-3} \times 200}\right]}$$

$= 0.92046$

Given: $\dot{m} = 50/(60 \times 60) = 0.013889$ kg/s, $C_f = 4174$ J/kg-K, $A_p = 2.4 \times 1.4$ m^2

From Eq. (5.36),

$$F_R = \frac{\dot{m}\, C_f}{U_L\ A_p}\left[1 - \exp\left(-\frac{F' U_L\, A_p}{\dot{m}\, C_f}\right)\right]$$

$$= \frac{0.013889 \times 4174}{5 \times 2.4 \times 1.4}\left[1 - \exp\left(-\frac{0.92046 \times 5 \times 2.4 \times 1.4}{0.013889 \times 4174}\right)\right]$$

$= 0.8079$

The collector heat removal factor = 0.8079

(ii) Calculation of water outlet temperature:

Given: $r_b = 0.95$, $r_d = 0.98$, $r_r = 0.005$, $(\tau\alpha)_b = 0.8321$, $(\tau\alpha)_d = 0.79$, $I_b = 650$ W, $I_d = 150$ W

From Eq. (5.3),

$$S = I_b\, r_b\, (\tau\alpha)_b + \{I_d\, r_d + (I_b + I_d)\, r_r\}(\tau\alpha)_d$$

$$S = 650 \times 0.95 \times 0.8321 + \{150 \times 0.98 + (650 + 150) \times 0.005\} \times 0.79$$

$= 633.112$ W

Given, $T_a = 24°\text{C}$, $T_{fi} = 45°\text{C}$

From Eq. (5.36),

$$\begin{aligned} q_u &= F_R A_p [S - U_L(T_{fi} - T_a)] \\ &= 0.8079 \times 2.4 \times 1.4 \times [633.112 - 5 \times (45 - 24)] \\ &= 1433.58 \text{ W} \end{aligned}$$

From Eq. (5.2),

$$q_u = \dot{m}\, C_f (T_{fo} - T_{fi}),$$

Therefore, $$T_{fo} = T_{fi} + \frac{q_u}{\dot{m} C_f} = 45 + \frac{1433.58}{0.013889 \times 4174}$$

$$= 69.7285\ °\text{C}$$

Water outlet temperature = 69.7285°C

(iii) Calculation of instantaneous efficiency of collector:

From Eq. (4.31),

$$\begin{aligned} I_T &= I_b r_b + I_d r_d + (I_b + I_d) r_r \\ &= 650 \times 0.95 + 150 \times 0.98 + (650 + 150) \times 0.005 \\ &= 768.5 \text{ W/m}^2 \end{aligned}$$

Given, Length of controller = 2.5 m, Width of controller = 1.5 m

Thus, $A_c = 2.5 \times 1.5 \text{ m}^2$

From Eq. (5.4)

$$\eta_i = \frac{q_u}{A_c I_T} = \frac{1433.58}{2.5 \times 1.5 \times 768.5} = 0.4974$$

Or η_i = 49.74 per cent

Instantaneous collector efficiency = 49.74%

REVIEW QUESTIONS

1. What percentage of industrial heating need accounts for low-grade type heating?
2. For which type of heating solar energy is best suited?
3. What is the average range of solar radiation received on earth's surface during a day?
4. Define concentration ratio of a solar collector.
5. What are the main advantages of flat plate solar collector?
   (Visvesrayya Tech. Univ. 2013)
6. Describe the flat plate collector with the help of a suitable diagram.
   (UPTU Lucknow, 2003-04, Visvesrayya Tech. Univ. 2013, 2012)

7. What is approximate value of concentration ratio obtained from a CPC collector?
8. Name three collectors requiring one axis sun tracking.
9. What range of temperature a paraboloidal dish collector may attain?
10. What range of CR is realizable from a central tower receiver collector?
11. Discuss the principle of a solar collector. How collector coating can be used to improve the performance of a collector? **(UPTU Lucknow, 2005-06)**
12. Classify different types of solar thermal collectors and show the constructional details of a flat plate collector. What are its main advantages? **(UPTU Lucknow, 2007-08, Visvesrayya Tech. Univ. 2008)**
13. Write the advantages and disadvantages of concentrating collectors over flat plate type of solar collector. **(UPTU Lucknow, 2005-06, Visvesrayya Tech. Univ. 2010)**
14. With the help of a schematic diagram, explain the working of solar water heating.
15. What is a solar house?
16. What is the basic difference between an active and passive solar heating system?
17. With the help of schematic diagram explain solar passive space cooing system through ventilation.
18. With the help of schematic diagram explain solar process steam system.
19. Compare the relative merits and demerits of LiBr-water and aqua-ammonia vapour-absorption cooling system.
20. What is the main advantage of using a glass cover in a box type cooker?
21. What is the maximum temperature obtained in a solar furnace?
22. What are the main advantages and disadvantages of a solar furnace? **(Visvesrayya Tech. Univ. 2014)**
23. What is a greenhouse? **(Visvesrayya Tech. Univ. 2014)**
24. How is the adequate supply of CO_2 maintained in a greenhouse?
25. What is the purpose of double layer of glazing in a greenhouse?
26. What is the average output of a solar still during summer in Indian climate?
27. What is a solar still? Draw its diagram and explain its working in detail. **(UPTU Lucknow, 2005-06)**
28. What are the major limitations of thermo-mechanical systems?
29. What features of solar energy make it attractive for use in irrigation water pump?
30. With the help of schematic diagram explain the working of solar thermal water pump.
31. Draw a schematic diagram of solar pond based electric power plant with cooling tower and explain its working. **(UPTU Lucknow, 2005-06, Visvesrayya Tech. Univ.2008)**
32. With the help of schematic diagram explain the working of distributed collectors' solar thermal electric power plant. **(Raj. Tech. Univ. 2011)**
33. How can solar thermal energy be converted into electrical energy? Give a diagram showing the elements of such a plant.
34. Give a neat diagram of a central tower receiver power plant and explain its operation. Give the details of an operational plant if such a plant exists anywhere in the world. **(Visvesrayya Tech. Univ. 2014)**

PROBLEMS

1. A flat plate collector, facing due south, having two glass covers is located at Ahmadabad (23.03° N, 72.58° E), have the following data:

Standard longitude for IST	82.5° E
Date	December 22
Time	3:00 P.M.
Collector tilt angle	latitude + 15°
Beam radiation, I_b (on horizontal surface)	650 W/m^2
Diffuse radiation, I_d (uniformly distributed over the sky)	150 W/m^2
Reflectivity of surrounding	0.2
Plate absorptivity of solar radiation	0.94
Extinction coefficient of glass	20 per m
Thickness of each glass cover	4 mm
Refractive index of glass with respect to air	1.5

Calculate:

(i) Angle of incidence of beam radiation on the collector
(ii) Total solar flux incident on the collector
(iii) The incident flux absorbed by the absorber plate

(*Ans.* 24.6°, 1146.27 W/m^2, 792.22 W/m^2)

2. A flat plate collector, facing due south, having one glass cover is located at Mysore (12.3° N, 76.65° E), have the following data:

Standard longitude for IST	82.5° E
Date	March 22
Time	12 noon.(LAT)
Collector tilt angle	latitude
Beam radiation, I_b	675 W/m^2
Diffuse radiation, I_d (uniformly distributed over the sky)	175 W/m^2
Reflectivity of surrounding	0.2
Plate absorptivity of solar radiation	0.95
Extinction coefficient of glass	18 per m
Thickness of each glass cover	4 mm
Refractive index of glass with respect to air	1.52

Calculate:

(i) Angle of incidence of beam radiation on the collector
(ii) Total solar flux incident on the collector
(iii) The incident flux absorbed by the absorber plate

(*Ans.* 0°, 865.8 W/m^2, 673 W/m^2)

3. Use following data to calculate the overall loss coefficient flat plate collector:

Size of the absorber plate	2.40 m × 1.40 m
Spacing between absorber plate and 1st glass cover	8 cm
Spacing between 1st and 2nd glass cover	8 cm
Glass cover emissivity	0.88
Plate emissivity	0.92
Mean plate temperature	70°C
Ambient air temperature	40°C
Collector tilt	20°

Wind speed	2.5 m / s
Back insulation thickness	10 cm
Side insulation thickness	5 cm
Thermal conductivity of insulation	0.04 W/m-K

(*Ans.* 4.2299 W/m^2-K)

4. Following data are given for a flat plate collector:

Size of absorber plate = 2.9 m × 1.9 m
Absorber plate thickness = 0.15 mm
Thermal conductivity of plate material = 350 W/m-K
Number of tubes attached below abs. plate = 20
Fluid flow rate = 60 kg/h
Water inlet temperature = 50°C
Specific heat of fluid at 50°C = 4174 J / kg-K
Tube to fluid heat transfer coefficient = 205 W/m^2-K
Outer diameter of tubes = 14 mm
Inner diameter of tubes = 12.8 mm
Overall loss coefficient of the collector = 5 W/m^2-K
Average thickness of adhesive = negligible
Length of controller = 3.1 m
Width of controller = 2.1 m
Ambient temperature = 20°C
Beam radiation on horizontal surface = 600 W/m^2
Diffuse radiation (uniformly distributed in the sky) = 150 W/m^2

Tilt factors for beam, diffuse and reflected radiations = 0.94, 0.97 and 0.005 respectively

Transmissivity-absorptivity product for beam radiation falling on the collector = 0.7921

Transmissivity-absorptivity product for diffuse radiation falling on the collector = 0.719

Calculate:

(i) the collector heat removal factor, F_R
(ii) water outlet temperature, T_{fo}
(iii) instantaneous efficiency of collector, η_i

(*Ans.* 0.76267, 74.327°C, 36.45)

OBJECTIVE TYPE QUESTIONS

1. A solar thermal collector:

(a) collects the solar energy and reflects it back
(b) absorbs the solar radiation and dissipate it to the ambient
(c) collects and coverts the solar energy into electrical energy
(d) collects and coverts the solar energy into thermal energy and delivers it to heat transfer fluid

2. The concentration type solar collectors:

(a) first absorb the radiation and then increase its concentration
(b) increase the density of solar radiation before absorbing it

(c) dilute the density of solar radiation before absorbing it
(d) increase the intensity of solar radiation and then reflect it back

3. Read the following statements about flat plate collectors and answer the questions.
(i) These are simple in construction.
(ii) They have high efficiency.
(iii) They do not track the sun.
(iv) They make use of both beam as well as diffuse radiation.
(a) (i) and (ii) are correct (b) (i), (ii) and (iii) are correct
(c) only (ii) is correct (d) (i), (iii) and (iv) are correct

4. The value of concentration ratio of flat plate collector is:
(a) 1 (b) 10
(c) 100 (d) 1000

5. Selective surface has the characteristics of:
(a) selective absorption of long wavelength radiation
(b) selective absorption of short wavelength radiation
(c) high value of absorptivity for incoming solar radiation and low value of emissivity for outgoing re-radiation
(d) low value of absorptivity for incoming solar radiation and high value of emissivity for outgoing re-radiation

6. The value of heat removal factor F_R of a flat plate collector lies in range:
(a) 0 to 0.1 (b) 0 to 1
(c) 0.9 to 0.95 (d) 0.5 to 0.6

7. For heating applications during winter in northern hemisphere, for optimal gain, the collector tilt angle must be fixed at:
(a) ϕ (b) $(\phi - 10°)$ or $(\phi - 15°)$
(c) $(\phi + 10°)$ or $(\phi + 15°)$ (d) $+10°$ or $+ 15°$

8. In evacuated tube collectors:
(a) both conductions as well as convection losses are suppressed
(b) only conductions losses are suppressed
(c) only convections losses are suppressed
(d) only radiation losses are suppressed

9. Use of booster mirrors with flat plate collector:
(a) increases the reflection to atmosphere
(b) decreases the reflection to atmosphere
(c) increases the diffuse radiation component on absorber
(d) increases the beam radiation component on absorber

10. A cylindrical parabolic concentrator requires:
(a) 2-axes tracking (b) 1-axis tracking
(c) no tracking (d) seasonal adjustment only

11. Scheffler solar concentrator:
(a) 2-axes tracking (b) 1-axis tracking
(c) no tracking (d) seasonal adjustment only

12. The payback period of an ordinary passive solar water heater is:
(a) 20–60 years (b) 1 year
(c) 2–6 years (d) 6–10 years

13. What is the typical cooking time of a paraboloidal dish cooker?
(a) 2–3 hours (b) 20–30 minutes
(c) 20–30 seconds (d) 6–12 hours

14. The most important advantage of solar furnace is:
(a) heating available throughout the day
(b) cheap low grade heating
(c) availability of both heat and light
(d) heating without contamination or electromagnetic field

15. Main advantage in storing solar thermal energy by dissociation of NH_3 is:
(a) the process is easy to implement
(b) thermal energy is stored and transported at high temperature
(c) thermal energy is stored and transported at room temperature
(d) this type of thermal energy store is more compact

16. Solar thermal water pump:
(a) uses solar thermal energy to evaporate water
(b) uses solar thermal energy to circulate hot water
(c) uses electric powered pump to circulate water heated by solar energy
(d) uses solar thermal energy for production of power to drive the pump

17. The main concern in a solar pond is:
(a) maintenance of salt gradient (b) extraction of heat
(c) replenishment of lost water (d) handling of hot brine

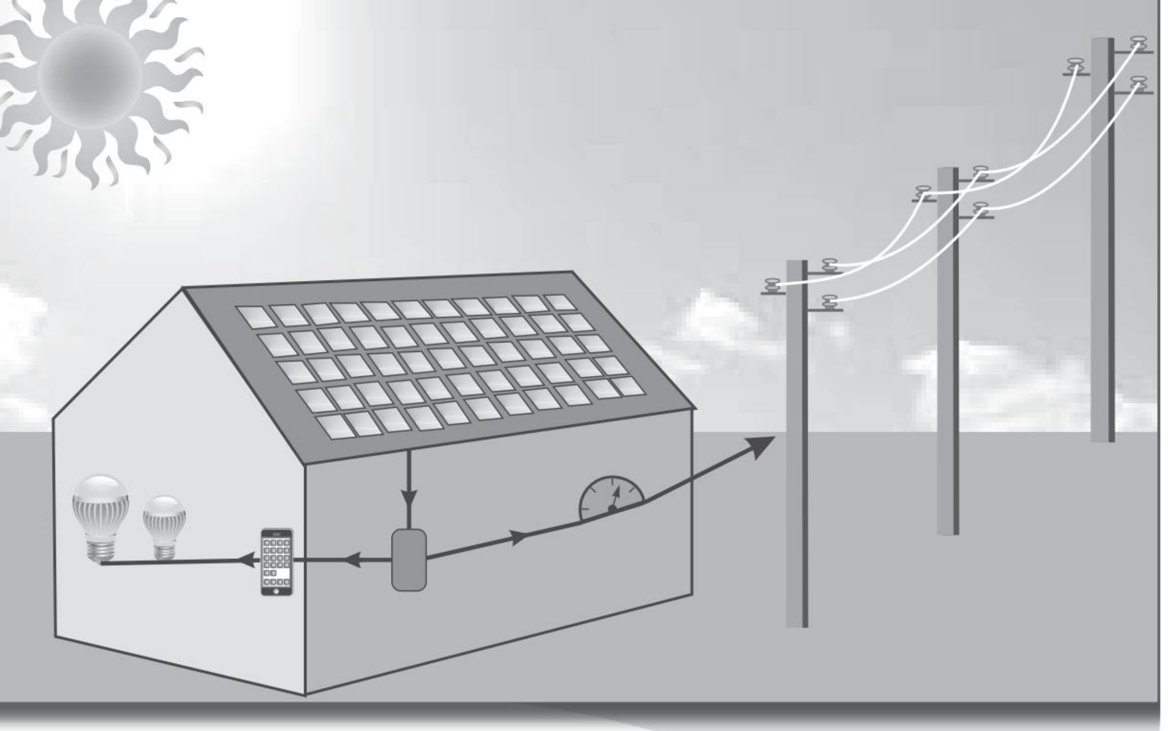
18. Which one of the following statements is not true about solar chimney plant?
(a) It requires large land area. (b) It is simple in operating principle
(c) It has affordable cost. (d) It requires a big air turbine

19. In central tower type solar collector the heliostats:
(a) have 1-axis tracking facility (b) have 2-axes tracking facility
(c) are fixed (d) are adjusted seasonally

20. A solar green house:
(a) uses solar energy to provide conducive conditions for growth of vegetation
(b) provides enhanced radiation for photosynthesis process
(c) prevents fresh air to come into contact with plants
(d) uses solar thermal pump for irrigation

21. Glass cover with high iron content:
(a) has lower conduction losses (b) has higher convection losses
(c) is mechanically more stronger (d) transmits less light through it

22. Tampered glass cover:
(a) has lower convection losses (b) transmits more light through it
(c) has higher thermal stress capability (d) is mechanically more stronger



CHAPTER 6

Solar Photovoltaic Systems

Learning Objectives

In this chapter you will be able to:

- Explain the scientific theory involved in the operation of solar cell
- Discuss the environmental effects on electrical characteristics of solar cell
- Analyse the process of fabrication of solar PV cell using different technologies
- Appraise recent developments in solar cell technologies
- Demonstrate sizing and design of typical solar PV systems
- Describe various applications of solar PV energy

6.1 INTRODUCTION

Solar photovoltaic (PV) systems convert solar energy directly into electrical energy. Basic conversion device used is known as a solar photovoltaic cell or a solar cell. Although other light sources may also produce photovoltaic electricity, only sunlight based PV cells are considered in this chapter. A solar cell is basically an electrical current source, driven by a flux of radiation. Solar cells were first produced in 1954 and were rapidly developed to provide power for space satellites based on semiconductor electronics technology. Its terrestrial applications were considered seriously only after oil crisis of 1973 when a real need of alternative energy sources was felt globally for the first time. Efficient power utilization depends not only on efficient generation in the cell, but also on the dynamic load matching in the external circuit.

Solar cell is the most expensive component in a solar PV system (about 60 per cent of the total system cost) though its cost is falling slowly. Commercial photocells may have efficiencies in the range of 10–20 per cent and can approximately produce an electrical energy of about 1 kWh per sq. m per day in ordinary sunshine. Typically, it produces a potential difference of about 0.5 V and a current density of about 200 A per sq. m. of cell area in full solar radiation of 1 kW per sq. m. A typical commercial cell of 100 sq-cm area–thus produces a current of 2A. It has a life span in excess of about 20 years. As a PV system has no moving parts it gives almost maintenance free service for long periods and can be used unattended at inaccessible locations.

Major uses of photovoltaics have been in space satellites, remote radio communication booster stations and marine warning lights. These are also increasingly being used for lighting, water pumping and medical refrigeration in remote areas especially in developing countries. Solar powered vehicles and battery charging are some of the recent interesting application of solar PV power.

Major advantages of solar PV systems over conventional power systems are:

(i) It converts solar energy directly into electrical energy without going through thermal-mechanical link. It has no moving parts.
(ii) Solar PV systems are reliable, modular, durable and generally maintenance free.
(iii) These systems are quiet, compatible with almost all environments, respond instantaneously to solar radiation and have an expected life span of 20 years or more.
(iv) It can be located at the place of use and hence no or minimum distribution network is required, as it is universally available.

It also suffers from some disadvantages such as:

(i) At present the costs of solar cells are high, making them economically uncompetitive with other conventional power sources.
(ii) The efficiency of solar cells is low. As solar radiation density is also low, large area of solar cell modules are required to generate sufficient useful power.
(iii) As solar energy is intermittent, some kind of electrical energy storage is required, to ensure the availability of power in absence of sun. This makes the whole system more expensive.

6.2 SOLAR CELL FUNDAMENTALS

6.2.1 Electric Current Conduction in Semiconductors

The best conductors (silver, copper and gold) have one valence electron, whereas the best insulators have eight valence electrons. A semiconductor is an element with electrical properties between those of a conductor and an insulator and therefore best semiconductors (Si & Ge) have four valence electrons. Various favorable characteristics of Si have made it the semiconductor of choice. It is most abundant element on earth after oxygen. However, the refining process is costly. An isolated silicon atom has 14 protons and 14 electrons. The outermost orbit (valance orbit) contains four electrons. When silicon atoms combine to form a solid, they arrange themselves into an orderly pattern called a *crystal*. Each silicon atom shares its electrons with four neighboring atoms in such a way as to have eight electrons in its valance orbit. Thus each pair of electrons belongs to two neighboring atoms and attracted by them with equal and opposite forces, which, keeps them, bonded together. Such a chemical bond is known as a *covalent bond*. This covalent bond holds the crystal together and gives it solidity.

At absolute zero temperature, a semiconductor is a perfect insulator with no charge carriers available for conduction of current. However, when temperature is increased, the vibration of atoms can occasionally dislodge an electron from the valence orbit. The dislodged electron is known as a *free electron* and the vacancy thus created in the valence orbit is known as a *hole*. Thus with breaking of a covalent bond, a free electron-hole pair is produced. At room temperature, thermal energy produces only few electron-hole pairs. Electron-hole pairs can also be produced by imparting energy by some other means such as light (photons). In pure silicon crystal, thermal energy creates equal number of free electrons and holes. The free electrons move randomly throughout the crystal. Occasionally, a free electron will approach a hole, feel its attraction, and fall into it. This merging of free electrons and a hole is known as *recombination*. The amount of time between creation and disappearance (due to recombination) of an electron-hole pair is called *lifetime*. It varies from a few nanoseconds to several microseconds, depending on how perfect the crystal is and also some other factors. At any instant, following conditions exists within the Si crystal:

(i) Some free electrons-holes are being created
(ii) Some free electrons-holes are being recombined
(iii) Some free electrons and holes exist temporarily, awaiting recombination

A silicon crystal is *intrinsic* if every atom in the crystal is a silicon atom. There are equal number of free electrons and holes in an intrinsic semiconductor. When a potential is applied across such a crystal, free electron moves away from negatively charged plate until it reaches positively charged plate and completes the path through external circuit as shown in Fig. 6.1. A hole near positively charged plate attracts a valence electron on the other side. This causes the valence electron to move into the hole creating new hole at this new location. This effect is same as moving the original hole to the right. The process continues and the valence electron moves across the crystal from negative to positive plate or the hole moves in a direction opposite to this. Thus free electrons and holes continuously move in opposite directions inside a semiconductor and constitute electrical current. These are called *charge carriers* because they carry charge from one place to another.

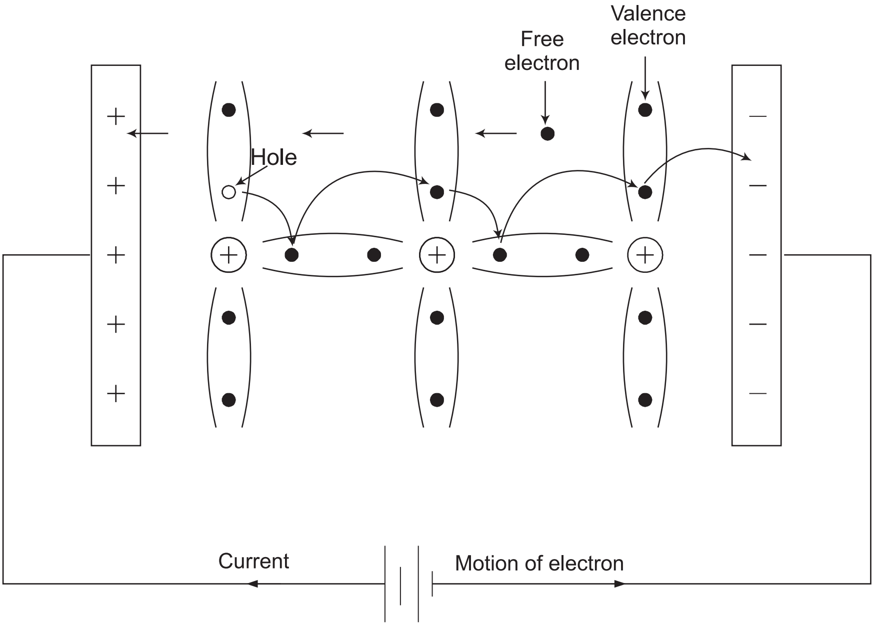


Figure 6.1 Free electron, hole flow through a semiconductor

The conductivity of a semiconductor can be increased by adding impurity atoms to intrinsic semiconductor. The process is known as *doping*. The doped semiconductor is called *extrinsic* semiconductor. When the doping atom is a pentavalent such as arsenic, antimony and phosphorous, one extra electron will be left unattached to any atom after sharing four electrons with neighboring four silicon atoms in the crystal. Thus each pentavalent atom donates one free electron and therefore known as *donors* and the doped semiconductor material is known as *N*-type silicon. In the same manner, when the doping atom is a trivalent such as aluminum, boron and gallium, one electron vacancy (hole) will remain after sharing its three electrons with neighboring four silicon atoms in the crystal. Therefore, trivalent doping elements are also known as *acceptors* and the doped semiconductor material is known as *P*-type silicon. In *N*-type Si, free electrons are in majority while in *P*-type Si, holes are in majority. By regulating the level of doping the electrical properties of the doped material are controlled. A lightly doped semiconductor has high resistance, whereas a heavily doped semiconductor has low resistance.

6.2.2 Arrangement of Electrons in an Isolated Si Atom

The behavior of a semiconductor can be best explained with the help of quantum theory, which suggests that an electron can occupy only allowed discrete energy levels and sublevels (states) depending on 4 types of quantum numbers. Some energy levels may be empty. To a good approximation, we can identify total energy of an electron with the size of its orbit. That is, we can think of each radius of an orbit as equivalent to an energy level. Since an electron is attracted by the nucleus, extra energy is needed to lift an electron into a larger orbit. Some of the external energy sources that can lift the electron to higher energy levels are heat and light.

A silicon atom has 14 electrons. These electrons are distributed in three shells ($n = 1$ to $n = 3$, where n is shell number). Each shell can have $2n^2$ energy levels (electronic states). According to quantum numbers, shell 1 will have 2 electrons, shell 2 will have 8 electrons and shell 3 will have remaining 4 electrons. These 4 electrons of shell 3 will be divided into 2 subshells, namely, *s* and *p*. The lower subshell '*s*' has 2 allowed energy levels which are occupied by 2 electrons. The upper subshell '*p*' has 6 allowed energy levels, out of which, 2 energy levels are occupied by 2 electrons and 4 energy levels (states) remain empty.

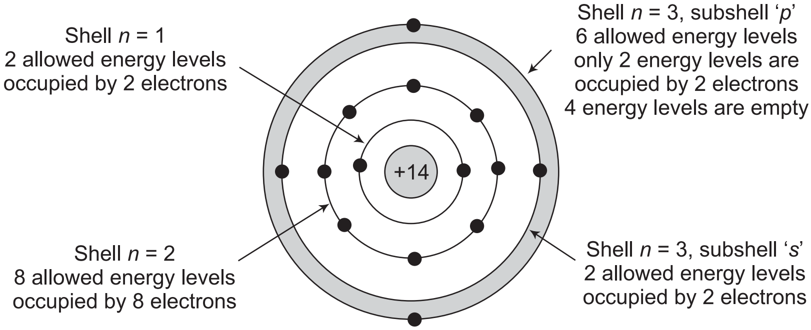


Figure 6.2 Arrangement of orbits (shells) in isolated Si atom (higher energy levels of shell $n = 3$ are not shown)

6.2.3 Formation of Energy Bands

If there are *N* isolated Si atoms, each one of these atoms will have 8*N* available energy states in the outer shell out of which 4*N* will be occupied by valance electrons and 4*N* will be empty states.

When two atoms are brought close together such that their outer subshells start interacting with each other, the similar levels of two atoms will split in order to satisfy Pauli's exclusion principle, which dictates that no two electrons can have the same quantum numbers. The split energy level due to two atoms belongs to both the atoms. That means the electrons from both the atoms can occupy any of these split energy levels. As more and more atoms are added, the splitting of energy levels continues to satisfy Pauli's exclusion principle. In a crystal where many atoms are brought together, the splitting of energy levels results in almost continuous set of energy levels, which is termed as **energy band**.

In silicon, at inter-atomic distance is 2.35 Å, two energy bands exist, separated by a gap where no energy states are available as shown in Fig. 6.3. The upper energy band is known as **conduction band** while the lower energy band is known as **valance band**. The gap between these two energy bands is known as **energy gap** or the **band gap**, E_G, which is the property of the material.

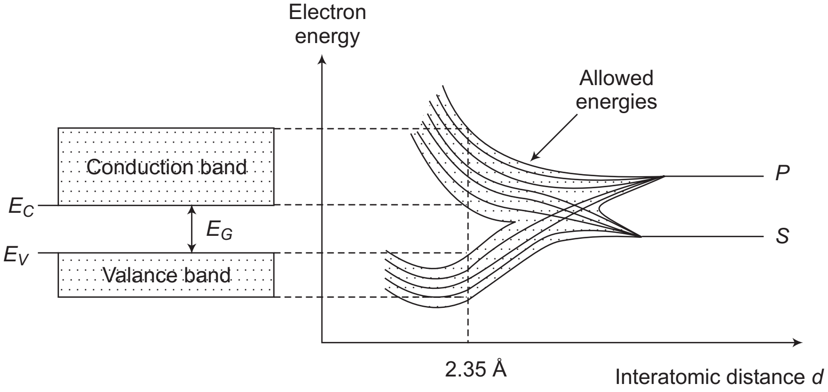


Figure 6.3 Splitting of energy bands in a crystal

In a crystal of *N* atoms, there will be total 8*N* states, out of which 4*N* will be occupied by 4*N* valance electrons while 4*N* remain empty. At 0 K, all 4N valance band states will be occupied by 4*N* electrons, while the conduction band will be completely empty. These energy bands are shown in Fig. 6.4. When an electron in valence band receives sufficient energy to overcome *energy gap*, E_G, it jumps to next higher band known as *conduction band* leaving behind a hole in *valence band*. In intrinsic Si crystal there are equal number of free electrons and hole. On application of voltage across such a crystal the free electrons move in the conduction band while holes move in valence band. No conduction is possible if all states within an energy band are occupied or when all states are empty.

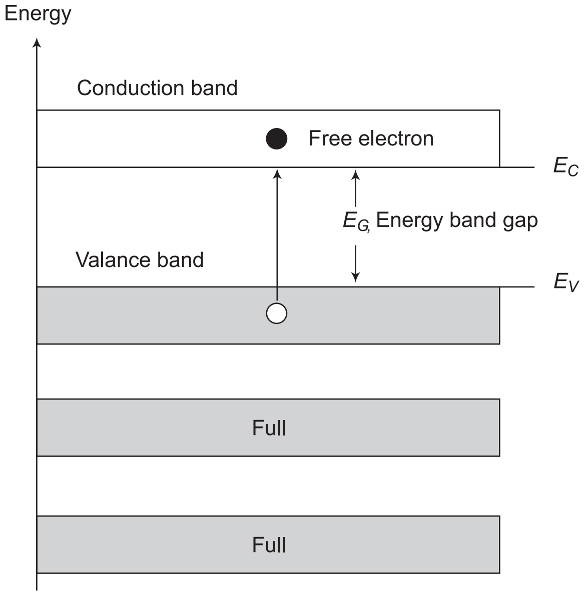
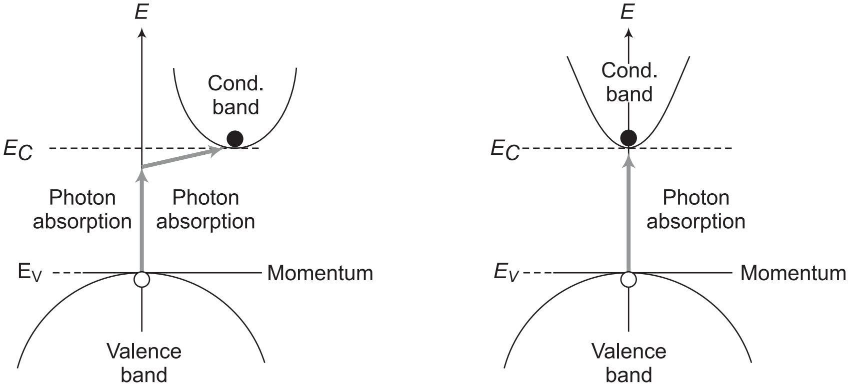


Figure 6.4 Energy bands in intrinsic Si crystal

6.2.4 Direct and Indirect Band Gap Materials

In Fig. 6.4 the energy bands are plotted as energy versus distance. When energy is plotted against electron momentum in the lattice, two types of band gaps are observed, depending on the shape of these energy bands. These are known as direct and indirect band gaps as shown in Fig. 6.5.



(a) Indirect bad gap (b) Direct band gap

Figure 6.5 Energy – momentum diagram of direct and indirect band gap materials

In direct band gap materials, the minima of conduction band, E_C and the maxima of valance band, E_V exist at the same value of electron momentum. In order to excite an electron from valance band to conduction band, only a photon of energy $E_C - E_V = E_G$ is required. A photon is considered as a particle of high energy and low momentum, therefore the electronic transition in the direct band gap material is almost vertical.

In indirect band gap materials, the conduction band minima do not exist exactly above the maxima of valance band in the energy – momentum diagram. Excitation of the electron from the valance band to conduction band requires not only the absorption of photon but also the absorption of another particle known as *phonon*. A phonon is thought of as a particle of low energy and high momentum and is related to lattice vibration. Phonon absorption is required from the point of view of conservation of momentum. Thus in indirect band gap type materials two particles (photon and phonon) are required instead of one (photon). Thus the electronic transition from valance band to conduction band is less probable. The photon has to travel more distance before getting absorbed. This is the reason a thicker layer of indirect band gap material is required to absorb complete solar spectrum as compared to direct band gap material. In some cases the path length is increased by causing multiple reflection of the incident light internally from the back surface and front surface while inside the material until it is absorbed. Crystalline silicon is an indirect band gap material. Typical thickness of commercially available crystalline Si solar cell is 200 to 300 μm. On the other hand, the *direct band gap* materials (such as gallium arsenide, GaAs, cadmium telluride, CdTe, copper indium di-selenide, CIS and amorphous silicon, a-Si) require a typical thickness of 1 to 3 μm.

6.2.5 Energy Band Model of Semiconductor

An ideal semiconductor with no lattice defects and no impurity is called intrinsic semiconductor. At 0 K, all allowable energy states in the valance band are filled with electrons and no allowable energy state in conduction band is occupied as shown in Fig. 6.6. Since the conduction process requires that charge carriers move from one state to another state within an energy band, no conduction can take place when all states are occupied or when all states are empty. Now, as the temperature is increased, some of the covalent bonds are broken and electrons become free. In this process thermally excited electrons get enough energy to jump to conduction band. The excited electron leaves behind a vacant space (hole), which can be filled by another electron. Thus a hole is an unfilled electronic state in valance band. The excited electron in conduction band and corresponding hole in valance band is known as electron-hole pair (EHP).

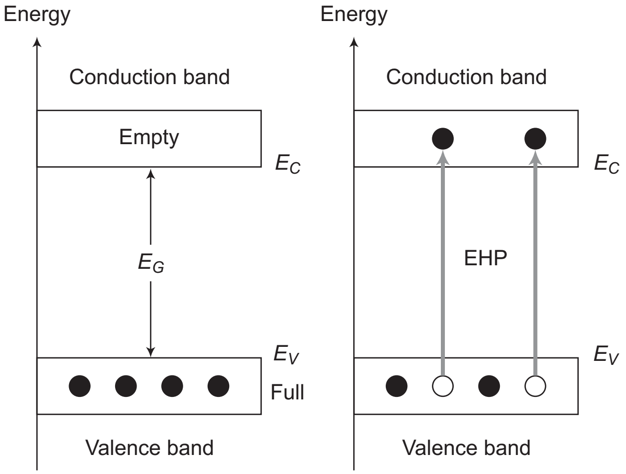


Figure 6.6 Energy bands in intrinsic semiconductor

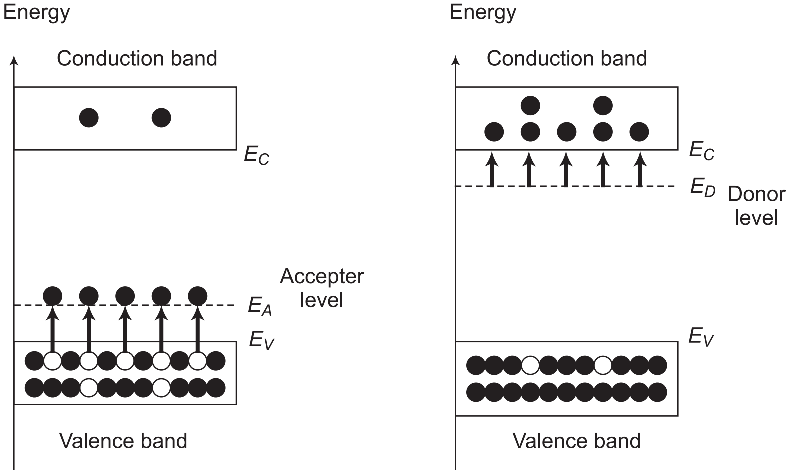
The electron in conduction band can move and conduct a current, similarly a hole in valance band can move (actually it is the movement of electrons in valance band) in a direction opposite to that of electron and conduct a current. Thus a hole can be considered a positively charged particle with charge equal and opposite to that of electron.

Thus, in intrinsic semiconductors, the electron and hole are created in pairs; hence both are equal in numbers. If n is the concentration of electrons in conduction band (number per cm^3) and p is the concentration of holes on valance band (number per cm^3), then $n = p = n_i$, where n_i is referred to as intrinsic carrier concentration. The intrinsic carrier concentration is the property of the semiconductor material and depends on band gap. At room temperature, the value of n_i is 1.5×10^{10} cm^{-3} for Si and 2×10^6 cm^{-3} for GaAs.

As explained earlier in Section 6.2.1, the number of carriers (or conductivity of the material) can also be increased by doping of material from IIIrd group or Vth group of periodic table, resulting in *P*-type and *N*-type semiconductor materials respectively. Unlike intrinsic semiconductor material, in extrinsic materials the number of electron and holes are unequal. In *N*-type semiconductor the number of electrons is significantly larger than holes; hence the electrons in *N*-type semiconductor are referred to as majority charge carriers. On the other hand, in *P*-type semiconductor the number of holes is significantly larger than electrons; hence the holes in *P*-type semiconductor are referred to as majority charge carriers.

When impurity of column III of the periodic table (like B, Al, Ga, In) is added to Si, additional energy level, called accepter level, E_A near valance band is created. Since E_A is very close to valance band edge E_V, little thermal energy is required to excite the electrons from valance band to accepter level leaving behind equal number of holes in the valance band. At room temperature all accepter levels are filled with electrons. For example, doping of 1×10^{16} atoms/cm^3 of In atoms in Si will result in same number of holes in the valance band. Thus by controlling the doping level, conductivity can be precisely controlled.

Similar explanation may extended for adding of donor atoms (like P, As, Sb) in Si to create donor energy level E_D very close to conduction band resulting in large number of electrons in conduction band. The energy bands in extrinsic semiconductor material are shown in Fig. 6.7.



(a) *P*-type Si (b) *N*-type Si

Figure 6.7 Energy bands in extrinsic semiconductors at temp > 0 K

6.2.6 Density of Energy States

As explained in Section 6.2.5, when atoms are brought closer in a crystal, large number of allowable energy levels (states) are created, both in conduction and valance bands, all of which may not be occupied by the electrons. These energy levels are distributed in conduction and valance bands as a function of energy. The density of states $g_C(E)$ in conduction band and the density of states in valance band $g_V(E)$, at any energy level E (the unit is number/cm^3-eV) is given by:

$$g_C(E) = \frac{m_n^* \sqrt{2m_n^*(E - E_C)}}{\pi^2 (h/2\pi)^3} \quad \text{for } E \geq E_C \tag{6.1}$$

$$g_V(E) = \frac{m_p^* \sqrt{2m_p^*(E_V - E)}}{\pi^2 (h/2\pi)^3} \quad \text{for } E_V \geq E \tag{6.2}$$

where m_n^* and m_p^* are the effective masses of electron and hole in semiconductor and h is Planck's constant. The effective mass of electron and hole in Si at room temperature is $1.18m_o$ and $0.81m_o$ respectively, where m_o is mass of electron in vacuum.

6.2.7 Charge Carrier Distribution Function

Apart from knowing the distribution of the available energy states, one should also know how many of them are occupied. A function called Fermi function or Fermi-Dirac distribution function gives the probability that an available energy state at energy level E will be occupied by an electron at absolute temperature T. The Fermi function is given as:

$$f(E) = \frac{1}{1 + e^{(E - E_F)/kT}} \tag{6.3}$$

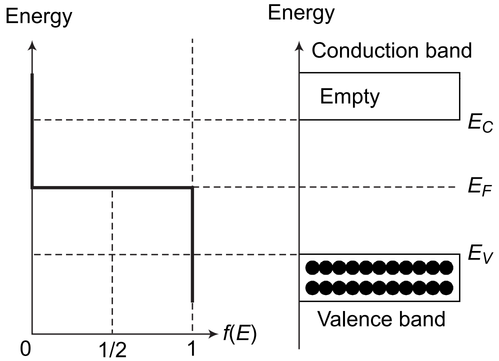
where k is Boltzmann constant (in eV/K). The parameter E_F is called Fermi level.

$f(E)$ can take up the values between 0 and 1. The unity value of $f(E)$ at energy level E means, there is 100 per cent probability that an electron will occupy that energy level. A '0' value of $f(E)$ implies that the probability that an electron will occupy that energy state is zero, which in turn means that there is 100 per cent probability that the energy state will be empty or there is a hole. The probability of having a hole at energy level E is given by $[1 - f(E)]$. At $E = E_F$, the value of $f(E)$ is 1/2. Therefore, Fermi level can be defined as the energy level at which the probability of an electron occupying that level is half. The Fermi function is symmetrical about E_F.

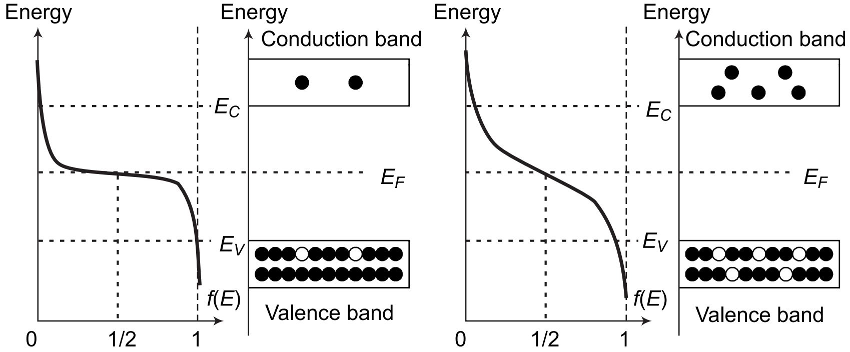
For intrinsic semiconductor material, Fermi function takes a rectangular shape at $T = 0$ K, as shown in Fig. 6.8. The value of $f(E)$ is zero for all energy levels above E_F. A nonzero value of $f(E)$ between the E_F and valance band does not mean that there will be an electron in the energy gap because there is no available energy state for electron to occupy.

At temperature $T_1 > 0$ K, some of the electrons get enough energy to jump from valance to conduction band. As the shape of Fermi function changes, and consequently the probability, $f(E_C)$ of an electron occupying the conduction band edge energy level E_C is nonzero, but it is still quite small. Similarly the probability $f(E_V)$ of an electron occupying the valance band edge level E_V will be little less than 1. At temperature T_2 (where $T_2 > T_1$) more electron will get excited to conduction band, and the corresponding probability of electron occupying a conduction band energy state will increase, while it will decrease in valance band as shown in Fig. 6.8.

As seen in the figure, in intrinsic materials E_F always remain in the middle between conduction and valance bands at any temperature. Thus the electrons concentration in conduction band and holes concentration in valance band are always equal in intrinsic semiconductor material.



(a) Intrinsic Si at 0 K

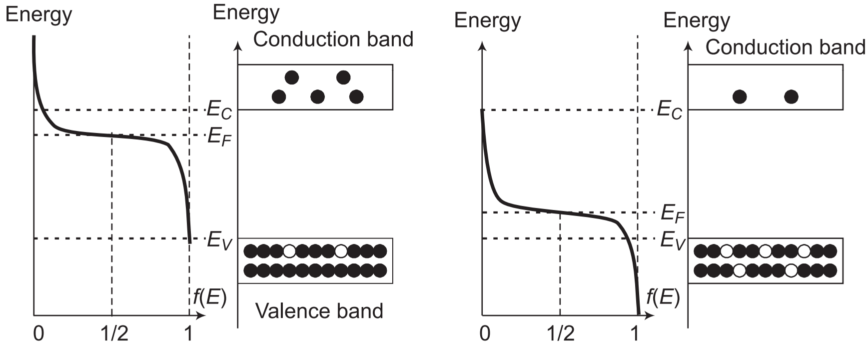


(b) Intrinsic Si at T_1 K

(c) Intrinsic Si at T_2 K ($T_2 > T_1$)

Figure 6.8 Fermi function for intrinsic semiconductor at 0, T_1 and T_2 (absolute temperatures)

In *N*-type semiconductor, there are more electrons than holes. That means there is higher probability of an electron occupying an energy state in the conduction band. Therefore, the Fermi function shifts towards the conduction band and E_F goes near conduction band. The larger is the electron concentration in a semiconductor, the closer will be E_F to E_C. Thus, the difference ($E_C - E_F$) gives an indication of equilibrium electron concentration, n_o. This also implies lesser concentration of holes in valance band. Similar explanation may be extended for *P*-type semiconductor. The situation is depicted in Fig. 6.9.



(a) N-type material

(b) P-type material

Figure 6.9 Fermi function for extrinsic semiconductor at $T > 0$ K

6.2.8 Charge Carrier Concentration in Conduction and Valance Bands

The equilibrium concentration of electrons n_o in conduction band is a product of the density of states in the conduction band and the probability of the electrons occupying these states. Thus:

$$n_o = \int_{E_C}^{\infty} f(E) g_C(E) dE \tag{6.4}$$

Similarly, the equilibrium concentration of holes p_o in valance band may be given as:

$$p_o = \int_{-\infty}^{E_V} f(E) g_V(E) dE \tag{6.5}$$

It can be noted from Eq. (6.1) that the density of states, $g_C(E)$ increases (as square root of energy) as we move away from edge of conduction band (E_C). However, the value of Fermi function becomes very small as we move to higher energy levels. Consequently, the value of $f(E)g_C(E)$ will be negligibly small in higher energy levels. Therefore, most of the electrons occupy energy states close to E_C. Similar explanation may extended for holes in valance band. The situation is illustrated in Fig. 6.10.

Instead of using Eqs (6.4) and (6.5) for calculation of n_o and p_o a simplified calculation is possible by considering effective density of states N_C at the conduction band edge E_C. The equilibrium electron concentration can be written as:

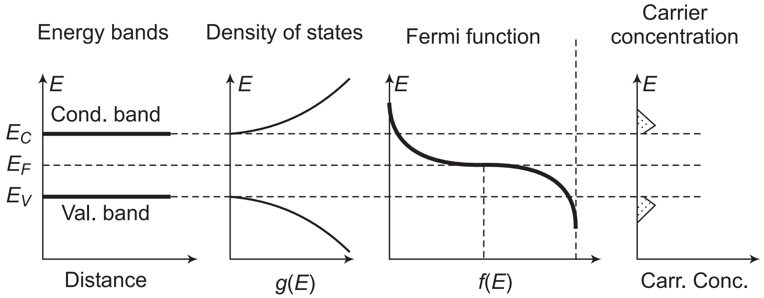
$$n_o = N_C f(E_C) \tag{6.6}$$

and in the similar manner, the equilibrium hole concentration can be written as:

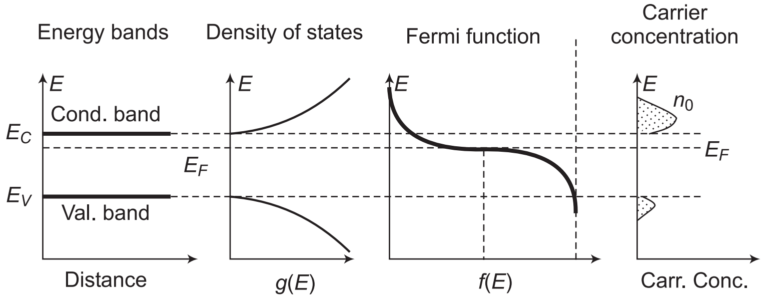
$$p_o = N_V [1 - f(E_V)] \tag{6.7}$$

where N_V is effective density of states in the valance band at the valence band edge, E_V. Now, using Eq. (6.3), we get;

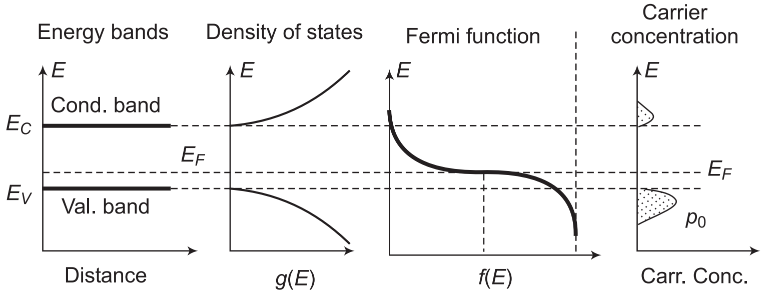
$$n_o = N_C \frac{1}{1 + e^{(E_C - E_F)/kT}} \cong N_C e^{-(E_C - E_F)/kT} \tag{6.8}$$



(a) Intrinsic semiconductor material



(b) *N*-type material



(c) *P*-type material

Figure 6.10 Energy bands, density of states, Fermi function and carrier concentration in intrinsic, *N*-type and *P*-type materials

$$p_o = N_V\left[1 - \frac{1}{1 + e^{(E_V - E_F)/kT}}\right] \cong N_V e^{-(E_F - E_V)/kT} \tag{6.9}$$

The approximation is valid for $(E_C - E_F) > few\ kT$ and $(E_F - E_V) > few\ kT$

The expression for effective densities of states N_C and N_V at the edges of conduction and valance band respectively are:

$$N_C = 2\frac{(2\pi m_n^* kT)^{3/2}}{h^2} \tag{6.10}$$

$$N_V = 2\frac{(2\pi m_p^* kT)^{3/2}}{h^2} \tag{6.11}$$

From Eqs (6.8) and (6.9) it is evident that the closer the E_F with E_C the higher the electron concentration in *N*-type semiconductor and similar logic can be extended for hole concentration in *P*-type semiconductor.

Now, various alternative expressions for n_o and p_o may also be derived.

Let E_i = Fermi level for intrinsic semiconductor, (lies in the middle of the energy gap)

$n_i = p_i$ = the intrinsic electron and hole concentration.

Now, applying Eqs (6.8) and (6.9), we can write:

$$n_i = N_C e^{-(E_C - E_i)/kT} \tag{6.12}$$

$$p_i = N_V e^{-(E_i - E_V)/kT} \tag{6.13}$$

Eliminating N_C and N_V using Eqs (6.8) and (6.9), we get,

$$n_o = n_i e^{(E_F - E_i)/kT} \tag{6.14}$$

$$p_o = p_i e^{(E_i - E_F)/kT} \tag{6.15}$$

From Eqs (6.12) and (6.13),

$$n_i p_i = n_i^2 = \sqrt{N_C N_V}\, e^{-E_g/2kT} \tag{6.16}$$

From Eqs (6.14) and (6.15),

$$n_o p_o = n_i^2 \tag{6.17}$$

It is to be noted that n_i is the material property. For silicon, it is equal to 1.5×10^{10} cm^{-3}.

At room temperature nearly all the electrons from the donor level get excited to conduction band (refer Fig. (6.8)), the equilibrium electron concentration in conduction band n_o may be assumed to be same as doping concentration, N_D of donor. From Eq. (6.8),

$$n_o = N_D = N_C e^{-(E_C - E_F)/kT} \tag{6.18}$$

or

$$E_F = E_C - kT \ln\frac{N_C}{N_D} \tag{6.19}$$

Same logic may be extended for accepter impurity, hence:

$$p_o = N_A = N_V e^{-(E_F - E_V)/kT} \tag{6.20}$$

or

$$E_F = E_V + kT \ln\frac{N_V}{N_A} \tag{6.21}$$

Example 6.1

A *P*-type silicon has effective density of states in valance band as 1×10^{22} per cm^3. An impurity from IIIrd group with concentration of 1×10^{19} per cm^3 is added. If band gap for silicon is 1.12 eV, find the closeness of Fermi level with valance band at the temperature of 27 °C.

Solution

Given:

$$T = 27 + 273 = 300 \text{ K}$$

$$N_V = 1 \times 10^{22} \text{ per cm}^3$$

$$N_A = 1 \times 10^{19} \text{ per cm}^3$$

Boltzmann constant, $k = 8.629112 \times 10^{-5}$ eV/K

Closeness of Fermi level with valance band from Eq. (6.21):

$$E_F - E_V = kT \ln \frac{N_V}{N_A}$$

$$= (8.629112 \times 10^{-5}) \times 300 \times \ln \frac{1 \times 10^{22}}{1 \times 10^{19}}$$

$$= 0.1788 \text{ eV}$$

Example 6.2

A Si sample is doped with 1×10^{17} atoms/cm^3 Phosphorous atom. What will be the minority hole concentration, p_o at room temperature.

Solution

Given: The electron concentration corresponding to 1×10^{17} atoms/cm^3 doping level of donor at room temperature is:

$$n_o = N_D = 1 \times 10^{17} \text{ atoms/cm}^3$$

The intrinsic carrier concentration for Si is $n_i = 1 \times 10^{10}$ atoms/cm^3
Using Eq. (6.17):

$$n_o p_o = n_i^2$$

or

$$p_o = \frac{(1 \times 10^{10})^2}{1 \times 10^{17}} = 1 \times 10^3 \text{ atoms/cm}^3$$

6.2.9 A *PN* Junction

A *PN* junction, where the material changes suddenly from *P* to *N* is known as abrupt *PN* junction. An abrupt junction is an idealization because the *P* side cannot suddenly end where the *N* side begins. In a more realistic *PN* junction there is a gradual change from one type of material to another. Such a junction is known as *graded junction*.

When a junction between a *P*-and *N*-type materials is formed, the carriers (free electrons and holes) diffuse from higher concentration side to lower concentration side. Soon after crossing the junction, these carriers recombine with the other types of carriers found in majority on the other side. We see that the holes, which neutralized the acceptor ions near the junction in the *P*-type side, disappeared as a result of recombination with free electrons, which have diffused from across the junction. Similarly, free electrons near the junction in the *N*-type side have recombined with holes, which have crossed the junction from *P* side. The un-neutralized ions (also known as uncovered fixed charges) in the neighborhood of the junction result in a charge density. Since this region is depleted of mobile charges it is called *depletion region*, the space charge region or transition region. Mobile charge carriers exist only outside the depletion region (both sides) known as *quasi-neutral region*. The charge distribution, which is zero at the junction, constitutes an electric dipole; that is, it is positive on one side and negative on the other side. This electrostatic potential variation causes an electric field in the depletion region, which points from positive to negative charge, i.e., *N* side to *P* side. This voltage variation constitutes a potential energy barrier against further diffusion of free electrons and holes to the other side of the junction. This is known as contact potential, *barrier voltage* V_B or potential energy hill (due to its shape). Figure 6.11 shows charge density, electric field intensity, and barrier voltage for free electrons. The shapes of the curves depend on how a junction is graded and the doping level.

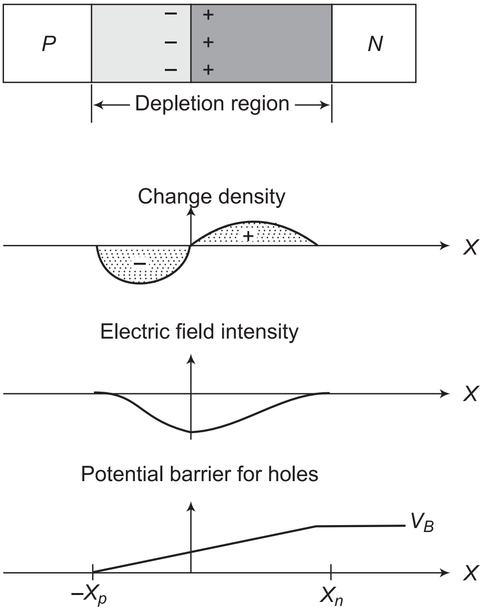


Figure 6.11 Charge density, electric field intensity and potential barrier in a *PN* junction

It is known that Fermi level is close to conduction band in *N*-type semiconductors and close to valance bend in *P*-type semiconductor. It is also known that in equilibrium condition the Fermi level of a material or a group of materials in contact should be invariant in space. Therefore, in the band diagram of a *PN* junction, Fermi level will be a straight line across *P* and *N* regions. As discussed above when *P*-type and *N*-type materials are brought in contact with each other, space charge region is developed which gives rise to electric field. Consequently, in the presence of electric field, energy bands should bend as shown in Fig. 6.12. The barrier voltage V_B can be written in terms of potential energy ($E = qV$). Thus,

$$V_B = \{E_C(-x_p) - E_C(x_n)\}/q = \{E_i(-x_p) - E_i(x_n)\}/q \tag{6.22}$$

Introducing a constant term E_F in the above equation,

$$V_B = [\{E_i(-x_p) - E_F\} + \{E_F - E_i(x_n)\}]/q$$

or
$$V_B = \{(E_i - E_F)_{P\text{-side}} + (E_F - E_i)_{N\text{-side}}\}/q \tag{6.23}$$

From Eqs (6.14) and (6.15), (assuming $n_o = N_D$ and $p_o = N_A$ at room temperature),

$$n_o = N_D = n_i e^{(E_F - E_i)/kT}$$

or
$$(E_F - E_i)_{N\text{-side}} = kT \ln (N_D/n_i) \tag{6.24}$$

$$p_o = N_A = p_i e^{(E_i - E_F)/kT}$$

or
$$(E_i - E_F)_{P\text{-side}} = kT \ln (N_A/n_i) \tag{6.25}$$

Substituting Eqs (6.24) and (6.25) in (6.23), we get

$$V_B = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) \tag{6.26}$$

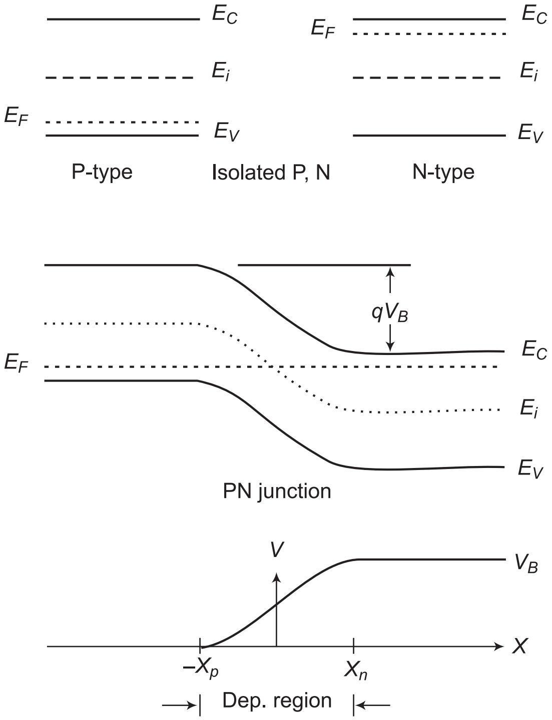


Figure 6.12 Energy band diagrams of isolated *P*, *N* materials and *PN* junction

6.2.10 Generation of Electron-Hole Pair by Photon Absorption

The energy available in a photon is given by:

$$E = \frac{h\nu}{\lambda} = \frac{hc}{\lambda} \text{ (joules)} \tag{6.27}$$

where h is Planck's constant ($h = 6.63\times10^{-34}$ joules-sec), c is the speed of light (2.988×10^{8} m / s), ν is frequency of photons in Hz and λ is the wavelength of photons in meters. Expressing λ in µm and energy in eV (1 eV = 1.6×10^{-19} joules) the expression becomes:

$$E = \frac{1.24}{\lambda} \text{ (eV)} \tag{6.28}$$

The energy in a photon must exceed the semiconductor band gap energy, E_G in order to get absorbed and generate an electron-hole pair. For energies less than band gap energy, no absorption takes place. The material appears transparent to these low energy photons. If a photon has energy much greater than the band gap, it still produces a single electron-hole pair. The remainder of photon energy is lost to the material as heat. Therefore, it is desirable that the semiconductors used for photo-absorption have band gap energy such that maximum percentage of solar spectrum is efficiently absorbed. Maximum theoretical efficiency of around 31 per cent is estimated for material having band gap of 1.45 eV with standard spectral density of solar radiation and under certain assumptions. For silicon, which has band gap of 1.12 eV, photons of $\lambda = 1.1$ µm or less are required to produce electron-hole pair.

Example 6.3

Calculate the optimum wavelength of light for photovoltaic generation in a CdS cell. The band gap for CdS is 2.42 eV.

Solution

Given: $E_G = 2.42$ eV

From Eq. (6.28): the photon energy must be greater or at least equal to E_G for generation of each pair

$$E = \frac{1.24}{\lambda} \geq E_G$$

Or

$$\lambda \leq \frac{1.24}{2.42} \text{ µm}$$

$$\leq 0.512 \text{ µm}$$

Thus, the optimum wavelength of light for photovoltaic generation in a CdS cell = 0.512 µm.

6.2.11 Photoconduction

Once an electron-hole pair is generated within the depletion region, both carriers will be acted upon by the built in electric field. Since the field is directed from *N* to *P* side, it will cause the holes to be swept quickly towards the *P* side and the electrons to be swept quickly towards the *N* side. Due to the electric field, chances of recombination of these electron-hole pairs are quite less. Once out of depletion region, these carriers become a part of the majority carriers in the respective regions and diffuse away from the depletion region as their concentration near junction has increased. Addition of excess majority charge carriers on each side of the depletion region results in a voltage across external terminals of the junction. If a load is connected across these terminals, the photon-generated current will flow through this external circuit. This current will be proportional to number of electron hole pairs generated, which in turn depends on intensity of illumination. Thus an illuminated *PN* junction becomes a photovoltaic cell with positive terminal on *P* side.

Now, consider the case when an electron-hole pair is generated outside the depletion region (i.e. in quasi-neutral region) then, depending on, how far it is located from the depletion region, it may or may not contribute to photocurrent. Suppose, for example, that an electron-hole pair is generated on *N* side. They will wander around randomly (as there is no electric force to guide them in any direction). The generated electron will become a part of majority charge carriers. Now, if the generated hole which is a minority carrier in *N* region, manage to reach near the edge of depletion region, before it gets recombined, it will experience a force due to electric field and will be pulled out at the other side of the depletion region, on the *P* side and contribute to photocurrent. If it gets recombined before reaching the edge of depletion region, it is lost from the conduction process. Similarly, if the electron-hole pair is generated in quasi-neutral region on *P* side, the generated electron must reach the edge of depletion region before getting recombined in order to contribute in photocurrent. Thus, the minority carriers, generated outside the depletion region due to optically generated electron-hole pair, must reach the edge of depletion region in a time less than the respective minority carrier lifetime to be able to contribute in photocurrent.

The minority charge carriers that are generated further away (more than diffusion length of minority charge carriers, L_p for minority hole and L_n for minority electron) from depletion region will recombine or die before reaching the depletion region edge and do not contribute to the photoconduction.

6.3 SOLAR CELL CHARACTERISTICS

6.3.1 I–V Characteristics

The well-known characteristic of an ordinary silicon *PN* junction is shown in Fig. 6.13 as dark characteristic with the junction not illuminated. Mathematically this is given by:

$$I = I_o \left\{ \exp\left(\frac{V}{V_T}\right) - 1 \right\} \tag{6.29}$$

where I_o is reverse saturation current, V_T is known as voltage equivalent of temperature and is given as:

$$V_T = \frac{kT}{q}$$

where, k is Boltzmann's constant (in J/K), T is temperature in Kelvin and q is charge of an electron in coulombs.

At room temperature (20 °C) the value of V_T is 25.283 mV.

When the *PN* junction is illuminated, the characteristics gets modified in shape and shifts downwards as photon-generated component (I_L) is added with reverse leakage current as shown in Fig. 6.13. The above diode Eq. (6.29) is modified as:

$$I = -I_L + I_o \left\{ \exp\left(\frac{V}{V_T} \right) - 1 \right\} \tag{6.30}$$

I_L is known as *light generated current* and its magnitude will depend on solar insolation. When the junction is short-circuited at its terminals, *V* becomes zero and a finite current $I_{sc} = -I_L$ flows through the external path emerging from *P* side. When the junction is left open at its terminals and no load is connected across the terminals, no current can flow, therefore, $I = 0$, the voltage available across the terminals, V_{oc} is known as *open circuit voltage*. Thus:

$$V_{oc} = V_T \ln\left\{ \left(\frac{I_L}{I_o} \right) + 1 \right\} \tag{6.31}$$

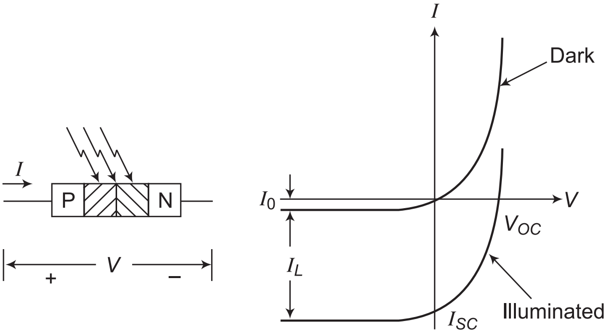


Figure 6.13 *I-V* characteristic of dark and illuminated *PN* junction

Typically for I_{sc} = 2A, I_o = 1 nA and at room temperature, V_{oc} is found to be 0.54 V. Thus an illuminated *PN* junction can be considered as an energy source, (a Photovoltaic cell) with open circuit voltage V_{oc} and short circuit current I_{sc}. However, for an energy source, by convention, the current coming out of positive terminal is considered to be positive. The schematic symbol of a solar PV cell with standard sign convention for voltage and current is shown in Fig. 6.14(a). Adopting standard sign convention for a solar PV cell the characteristic of Fig. 6.13 will be redrawn as shown in Fig. 6.14(b). Mathematically, the *I-V* characteristic of a solar cell may be written (as per standard sign convention of an energy source) as:

$$I = I_L - I_o \left\{ \exp\left(\frac{V}{V_T} \right) - 1 \right\} \tag{6.32}$$

In order to obtain as much energy as possible from the rather costly *PV* cell, it is desirable to operate the cell to produce maximum power. The maximum power (P_m) point can be obtained by plotting hyperbola defined by $V \times I$ = constant, such that it is tangential to I-V characteristic. The voltage and current corresponding to this point are peak point voltage, V_m and peak point current, I_m respectively. Thus there is only one point on the characteristic at which it will produce maximum electrical power under the incident illumination level. Operating at other than maximum power point will mean that the cell will produce lesser electrical power and more thermal power. The maximum power point is also readily found by simply plotting cell power versus cell voltage as shown in Fig. 6.14(c). Alternatively, if a rectangle of maximum possible area is inscribed in the area defined by the I-V characteristics and I-V axes, it meets the characteristics at peak point as shown in Fig. 6.14(b).

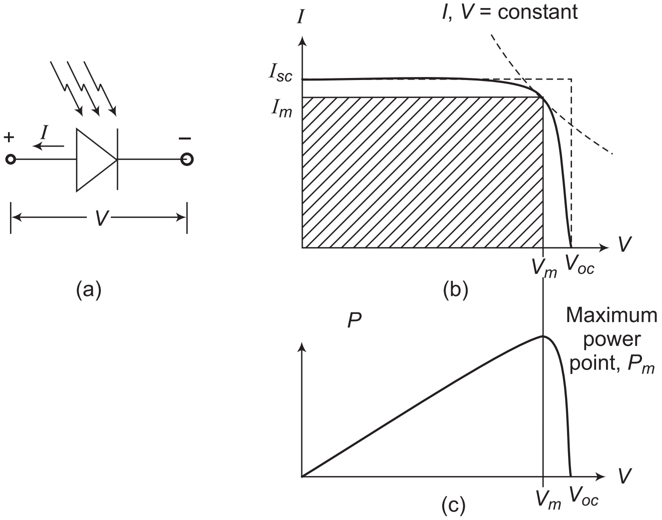


Figure 6.14 (a) Schematic symbol of photovoltaic cell (b) *I-V* characteristic, maximum power point (c) *P-V* characteristics

Closeness of the characteristics to the rectangular shape is a measure of quality of the cell. Ideal cell would have a perfect rectangular characteristic. Therefore, 'fill factor', *FF* which indicates the quality of cell, is defined as the ratio of the peak power to the product of open circuit voltage and short circuit current, i.e.,

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \tag{6.33}$$

Ideal cell will have a fill factor of unity. In order to maximize the fill factor, the ratio of photocurrent to reverse saturation current should be maximized while minimizing internal series resistance and maximizing the shunt resistance. Typically its value for a commercial silicon cell is in the range of 0.5 to 0.83. The conversion efficiency, η of a solar cell is given by:

$$\eta = \frac{V_m I_m}{P_i} = \frac{FF\, V_{oc} I_{sc}}{P_i} \tag{6.34}$$

where P_i is the incident solar power on solar cell.

6.3.2 Equivalent Circuit

The *I-V* characteristic given in Eq. (6.32) is derived for ideal condition, considering the internal series resistance of the cell as zero and shunt resistance as infinite. In actual practice, however, both have finite values, which would alter the *I-V* characteristics. The ideal and practical equivalent circuits of the solar cell are shown in Fig. 6.15. In practical cells I_{sc} is no longer equal to light generated current I_L, but is less by shunt current through R_{sh}. Further, an internal voltage drop of IR_s is also included in the terminal voltage. Thus for a practical cell the characteristic is modified as:

$$I = I_L - I_0\left[\exp\left\{\frac{(V + IR_s)}{V_T}\right\} - 1\right] - \frac{(V + IR_s)}{R_{sh}} \tag{6.35}$$

For a typical, high quality, one square inch silicon cell, R_s = 0.05 to 0.10 ohms and R_{sh} = 200 to 300 ohms.

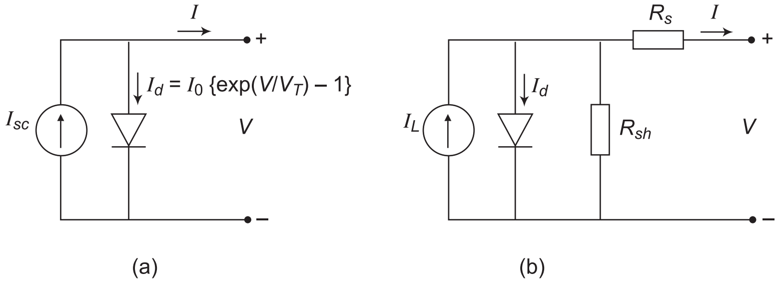


Figure 6.15 Equivalent circuit of solar cell (a) ideal, (b) practical

6.3.3 Solar Cell Design Considerations

1. Short Circuit Current

Maximum short circuit current will be obtained when there is no recombination in the material. It means that each photon will contribute to one electron flow to external circuit. In order to be absorbed, a photon is required to possess energy higher than the band gap of the material. Solar spectrum contains photons of varying energy (in the range 0.3 eV to 4.5 eV). A material with lower band gap will absorb more number of photons producing higher short circuit current. Thus short current of solar cell increases with decrease in band gap. For Si, with band gap of 1.12 eV, the maximum possible short circuit current is 46 mA under photon flux of solar spectrum (AM1.5).

2. Open Circuit Voltage

A minimum value of reverse saturation current I_o can be estimated in terms of band gap from the following expression [29]:

$$I_o = 1.5 \times 10^5\, e^{-E_G/kT} \tag{6.36}$$

Also from Eq. (6.31):

$$V_{oc} = V_T \ \ln\left\{\left(\frac{I_L}{I_o}\right)+1\right\}$$

The above expressions reveal that with increase in band gap, I_o decreases, which results in increase in V_{oc}.

3. Fill Factor

The best value of *FF* that can be obtained for a solar cell, as a function of V_{oc} can be calculated using an empirical expression. [29]:

$$FF = \frac{v_{oc} - \ln\left(v_{oc} + 0.72\right)}{v_{oc} + 1} \tag{6.37}$$

where $v_{oc} = \dfrac{V_{oc}}{kT/q}$, open circuit voltage normalized to thermal voltage.

Equation (6.37) shows that the solar cell with higher V_{oc} has higher *FF*. Good solar cells typically will have FF values of around 0.8.

4. Efficiency

It has been discussed earlier that short circuit current decreases with increase in band gap, whereas open circuit voltage increases with increase in band gap. Thus there is an optimum band gap for which the efficiency of solar cell would be maximum. Maximum efficiency of about 31 per cent is obtained for the optimum band gap of 1.45 eV for an ideal solar cell, under certain assumptions.

6.3.4 Effect of Variation of Insolation and Temperature

As the insolation keeps on varying throughout the day it is important to observe its effects on PV characteristics. If the spectral content of the radiation remains unaltered, and temperature and all other factors remain same, both I_{sc} and V_{oc} increase with increasing the intensity of radiation. The photo-generated current depends directly on insolation. Therefore, the short circuit current, depends linearly while open circuit voltage, depends logarithmically on the insolation. This is shown in Fig. 6.16(a,c).

If I_{sc} is known under standard test conditions, i.e., radiation of G_o = 1 kW/m^2 at AM 1.5, then the short circuit current I'_{sc} at any other insolation level G can be calculated to a very good approximation, as;

$$I'_{sc} = \frac{G}{G_o} \times I_{sc} \tag{6.38}$$

An illuminated PV cell converts only a small fraction (approx. less than 20 per cent) of irradiance into electrical energy. The balance is converted into heat, resulting into heating of the cell. As a result the cell can be expected to operate above ambient temperature. Keeping insolation level as constant, if the temperature is increased, there is a marginal increase in the cell current but a marked reduction in the cell voltage. An increase in temperature causes reduction in the band gap. This in turn causes some increase in photo-generation rate and thus a marginal increase in current. However, the reverse saturation current increases rapidly with temperature. Due to this, the cell voltage decreases by approximately 2.2 mV per °C rise in its operating temperature, depending on the resistivity of the silicon used: higher the silicon resistivity more marked is the temperature effect. Also the fill factor decreases slightly with temperature. This is shown in Fig. 6.16(b, d). The *I-V* characteristic is generally provided by the manufacturer for standard test conditions. The internationally accepted Standard Test Conditions (STC) refer to an incident AM1.5 irradiance of 1 kW/m^2, with operating temperature of 25 °C and wind speed of 1 m/s.

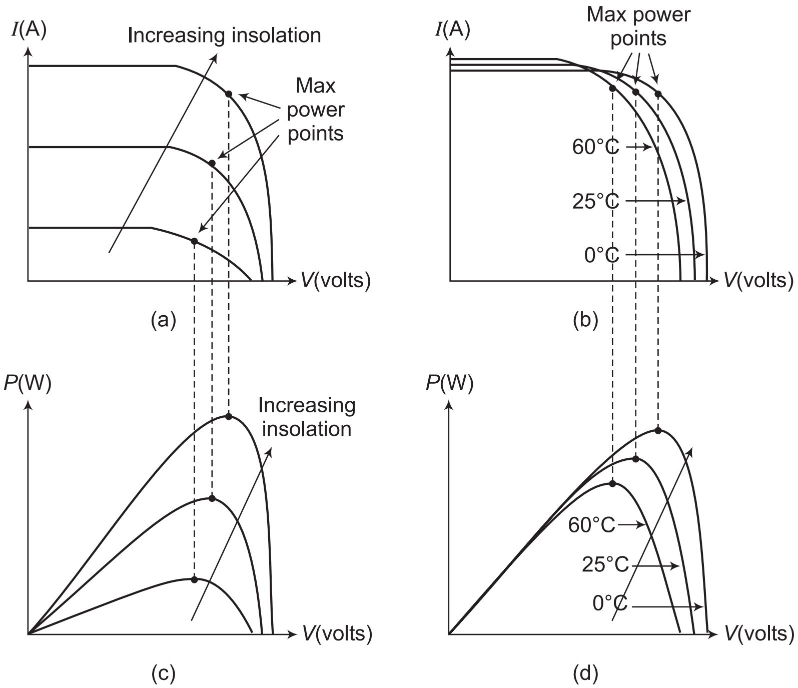


Figure 6.16 Effect of variation of (a) & (c) insolation and (b) & (d) temperature on the characteristic of solar cell

6.3.5 Energy Losses and Efficiency

The conversion efficiency of a solar cell is the ratio of electrical power output to incident solar power. The optimum possible theoretical efficiency of 31 per cent for an ideal solar cell under ideal conditions is obtained at band gap of 1.45 eV. In laboratory studies, the highest reported conversion efficiency of a single crystal silicon solar cell is about 24 per cent. Conversion efficiencies of commercially produced single crystal solar cells are in the range 12–18 per cent.

Various loss mechanisms lead to limit the conversion efficiency of the cell. Some of these losses are due to inherent nature of internal physical processes and available input. These cannot be influenced by external means. The other category of losses can be influenced by suitable selection of material, processing technology and other parameters of the cell.

1. Loss of Low Energy Photons

The photons having energy, E less than the band gap energy, E_G do not get absorbed in the material and, therefore, do not contribute to the generation of electron-hole pairs. This is referred as transmission loss, and is almost equal to 23 per cent for a single junction solar cell.

2. Loss Due to Excess Energy Photons

When the photon energy E is higher than the band gap energy E_G, the excess energy $(E - E_G)$ is given off as heat to the material. For a single junction solar cell, this is equal to about 33 per cent.

3. Voltage Loss

A fraction of developed voltage is lost due to Auger recombination. The Auger recombination occurs at high level of carrier concentration ($>10^{17}$ cm^{-3}). In this process, an electron recombining with hole gives its energy to another electron in the conduction band, pushing it into higher energy level. The second electron then goes through several scattering steps before coming back to conduction band edge.

4. Fill Factor Loss

This type of loss arises due to parasitic resistance (series and shunt resistance) of the cell. In best case FF could be 0.89.

5. Loss by Reflection

There are losses due to reflection from the active surface of the cell. As a result, a fraction of incident photons will not enter the bulk material. To minimize these losses, the active surface must be properly treated, by suitable anti-reflective coating and/or by having a pyramidal or textured structure as shown in Fig. 6.17.

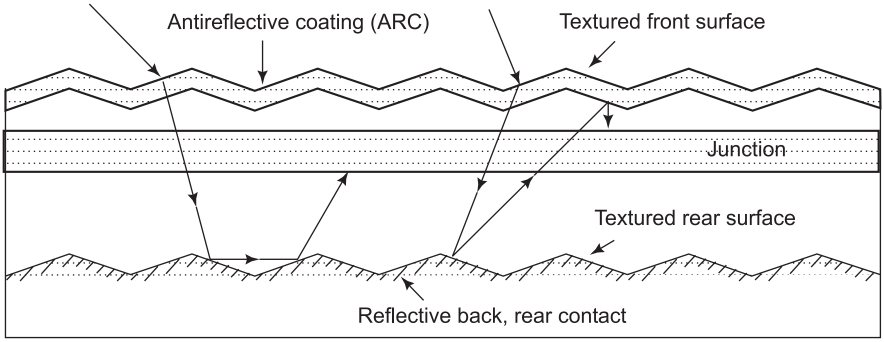


Figure 6.17 Antireflective coated, textured front surface and reflective coated, textured rear surface

6. Loss Due to Incomplete Absorption

It refers to loss of photons which have enough energy (i.e., $E > E_G$) to get absorbed in the solar cell, but do not get absorbed due to limited solar cell thickness. As discussed earlier, silicon is an indirect band gap material. Photons of adequate energy require traveling some distance in bulk material in order to get absorbed. If the thickness of the cell is not sufficient (approx. 100 micron) some photons will pass through full thickness of the material without ever getting absorbed. In order to utilize these photons, appropriate light-trapping schemes should be utilized such as; a reflecting back ohmic contact should be used on the backside, to enhance photon absorption in thinner cells, as shown in Fig. 6.17.

7. Loss Due to Metal Coverage

In wafer-based solar cells, the contact to the front side of the cell is made in the form of finger and bus bar. This metal contact shadows some light which can be up to 10 per cent. Several approaches are adopted to minimize this loss, which include one side contact cell, buried contact solar cell or transparent contacts as used in thin film solar cells.

8. Recombination Losses

Not all the generated electron hole-pairs contribute to photocurrent because some are killed due to recombination. The recombination could occur in the bulk of material or more predominantly at the surface. This type of recombination can be minimized by appropriate surface and bulk passivation techniques in order to obtain high I_L.

6.3.6 Maximizing the Performances

Desirable features of a solar cell are: Maximum values of V_{oc} and I_{sc}, low series resistance and high shunt resistance that will lead to high fill factor. I_{sc} is related to photocurrent and V_{oc} depends on ratio of I_{sc} to I_o. Shunt resistance is maximized by ensuring that no leakage occurs at the perimeter of the cell. This is done by passivation of the surface. Reduction of series resistance requires high doping of semiconductor. But high doping will also decrease the width of depletion layer, which in turn decreases the photocurrent. Therefore, both V_{oc} and I_{sc} are affected. An optimal value for doping level is chosen depending on trade-off of the performances.

6.3.7 Cell Size

Terrestrial application demands the use of large sized solar cells. As silicon is a brittle material, this fact tends to limit the area of commercially produced silicon solar cells due to handling difficulty. Also as the area of solar cell increases, it becomes difficult to maintain homogeneity of all relevant material parameters across the cell surface area and the bulk. This affects the performance of the cell. Although some companies still produce small diameter cells for specific applications, the current industry standards on the size of bulk silicon solar cells can be divided into four groups:

(a) 100 mm (4 inch) diameter, round single crystalline
(b) 100 cm^2 off square single crystalline
(c) 100 mm × 100 mm (~ 4 inch × 4 inch) square multicrystalline
(d) 125 mm × 125 mm (~ 5 inch × 5 inch) square multicrystalline

Current industry standard of the thickness of bulk silicon wafer appears to have settled in the range from 200 micron to 400 micron.

6.3.8 Energy Payback Period (EPP)

The length of time during which a solar cell generates the same amount of energy that it has consumed during its production is known as *Energy payback period*. As the production process of solar cell is highly energy intensive, energy economy can only be achieved if EPP is low. Typically the EPP of a single crystal bulk silicon solar cell under the existing state-of-the-art technology is between 1 and 2.5 years depending on the geographical location. In other words, a single crystal bulk silicon solar cell would have to continuously generate electrical energy for about 2.5 years before it starts providing energy in excess of what it has originally consumed during its manufacture.

6.4 SOLAR CELL CLASSIFICATION

Solar cells may be classified on the basis of (i) thickness of active material, (ii) type of junction structure, and (iii) the type of active material used in its fabrication, as shown in the chart below (Fig. 6.18).

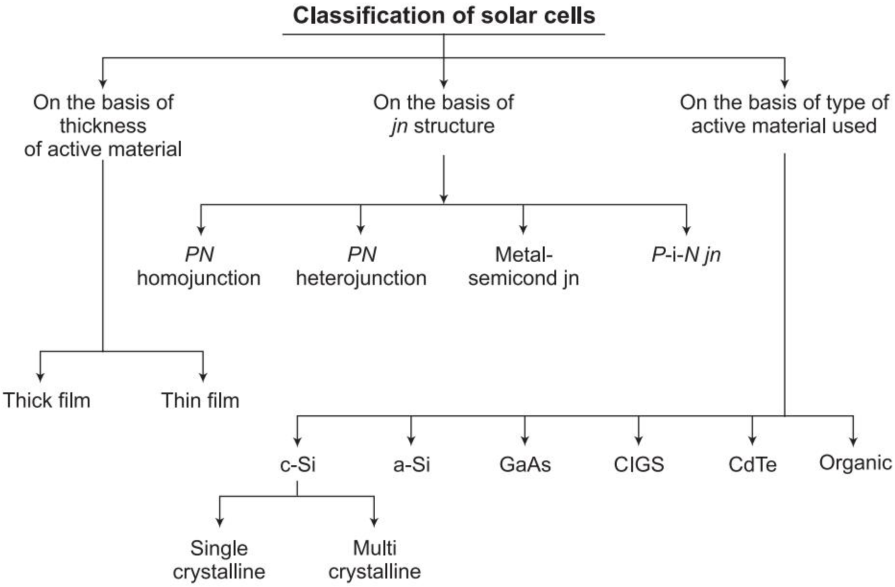


Figure 6.18 Classification of solar cells

Apart from this, solar cells are also divided into three main categories called generations. The *first generation* include wafer based mono and multicrystalline solar cells. At present, solar cells of first generating are dominating the market. The *second-generation* solar cells include thin film cells such as amorphous silicon, CIGS and Cadmium Telluride, etc. These solar cells are available commercially. The *third generation* solar cells operate on entirely different principle. They include dye-sensitized, organic and quantum dot solar cells, etc. The third generation solar cells are under development stage.

6.4.1 On the Basis of Thickness of Active Material

Depending on the thickness of the active material, they are classified as: (i) thick film cell and (ii) thin film cell. In thick film cells, base material (starting material in fabrication process) itself is an active material. In thin film cells, a thin film (few nm to 10s of μm) deposition of active material is carried out on the back support sheet, known as a *substrate*. Thin film solar cells have the major advantage of significantly low, active material consumption and the possibility of continuous sequence of production processes. This is unlike batch processing of bulk material solar cells. However, some technological difficulties of thin film cells are yet to be solved. The cell area larger than about 25 cm^2 appears to be difficult with state-of-the-art technology. Small area cells have disadvantage of cell mismatch. There are problems in texturization of the surface. In past, thin film single crystal and multicrystalline cell have been tried but could not succeed commercially. The amorphous-silicon and compound semiconductor cells are being developed using thin film technology but most of them degrade their performance when exposed to outdoor radiation. Some of them are very unstable. Therefore, at present, bulk material single crystal and multicrystalline cells are most successful for terrestrial applications.

6.4.2 On the Basis of Junction Structure

On the basis of the type of junction structure they are classified as (i) *PN* homojunction cell and (ii) *PN* heterojunction cell, (iii) *PN* multijunction cell, (iv) metal-semiconductor (Shottky) junction and (v) *P-i-N* (*P*-type-intrinsic-*N*-type) semiconductor junction.

In homogeneous *PN* junction, the semiconductor material on both sides of the junction is same, only doping materials are different. Thus the band gap remains same throughout the cell material. Most of the electron hole pairs generated in the top layer are lost to recombination when they are created more than a diffusion length from the junction. On the other hand, in heterogeneous *PN* junction, two dissimilar semiconductor materials, such as group III-V or group II-VI compound semiconductors with closely matching crystal lattice are used to form the junction. The band gap of the top material, exposed to sunlight is wider than the band gap of the material below the junction. As a result, the higher band gap region will appear transparent to photons with lower energies, so they can penetrate to the junction where the band gap is less than the incident photon energy. Thus electron-hole pairs are generated within or near depletion region, where they are collected before they recombine. Common heterogeneous solar cell structures include Gallium Arsenide–Gallium Aluminium Arsenide (GaAs-GaAlAs), Cadmium Sulphide–Copper Sulphide (CdS-Cu_2S), Cadmium Sulphide–Copper Indium Diselenide (CdS-$CuInSe_2$) or Cadmium Sulphide–Cadmium Telluride (CdS-CdTe). The elemental semiconductors used in solar photovoltaic devices is given in Table 6.1 and band gap of typical elemental and complex semiconductors used in solar PV applications are given in Table 6.2.

Table 6.1 Elemental semiconductors used in solar photovoltaic devices

Group of periodic table				
II	III	IV	V	VI
	B	C		
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In		Sb	Te

Table 6.2 Band gap of typical elemental and complex semiconductors used in solar PV applications

Element or compound	Name	Band gap (eV) at 300 K
C	Carbon (diamond)	5.5
Ge	Germanium	0.67
Si	Silicon	1.12
GaAs	Gallium Arsenide	1.43
CdS	Cadmium sulfide	2.42
CdTe	Cadmium telluride	1.5
$CuInSe_2$	Copper Indium Di-selenide	1
$CuGaSe_2$	Copper Gallium Di-selenide	1.7

When a contact is made between a metal and semiconductor, either an ohmic contact (permitting bi-directional current) or a rectifying contact (permitting only unidirectional current) is formed depending on the work functions of metal and semiconductor. The rectifying contact is known as Schottky junction. The Schottky junction has depletion layer and built in electric field on the semiconductor side of the junction. This electric field is responsible for sweeping of the minority charge carriers on the other side of the junction. The Schottky barrier junction is relatively straightforward to fabricate, but is not very efficient as a PV cell since it has relatively smaller open circuit voltage than conventional *PN* junction.

Solar spectrum has photons of varying energies (from UV to IR region). A photon is most efficiently absorbed when its energy is close to band gap. Maximum theoretical efficiency of a single junction solar cell, under irradiance of AM 1.5, using an optimal band gap of 1.34 eV, is given by Shokley-Queisser limit (or detailed balance limit) as 33.7 per cent [36]. A clever way to absorb more photon energy is to stack junctions of different band gaps, what is known as multijunction structure. The top junction has a relatively wider band gap followed by one or two more junctions in decreasing order of band gaps, in tandem (series). High-energy photons will be absorbed at the top junction followed by absorption of lower energy photons at subsequent junctions. A multijunction structure is shown in Fig. 6.19. Although the idea looks logical at the outset, problem is encountered due to the presence of unwanted reverse biased *PN* junction (shown with dotted line) in series opposition between the two junctions, which leads to power dissipation. This unwanted reverse biased junction is eliminated by (i) incorporating a $P^+ N^+$ tunnel junction in its place or (ii) a *P-i-N*-type (*P*-type-intrinsic-*N* type) junction structure, where intrinsic silicon is interposed between *N* and *P* layers. The *P-i-N* structure is used in amorphous-silicon solar cells.

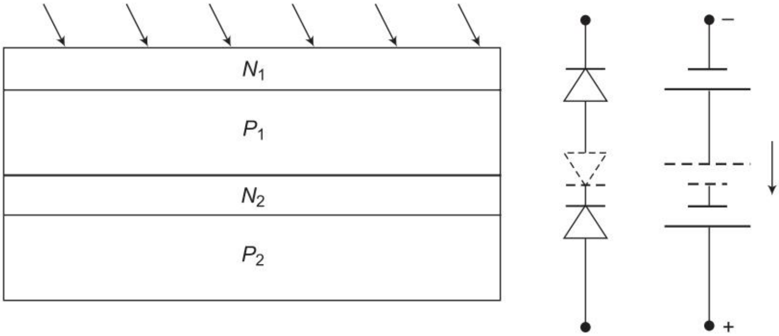


Figure 6.19 Two junctions in tandem, showing an opposing

6.4.3 On the Basis of Type of Active Material

Depending on the type of material used for fabrication of a junction, they are classified as: (i) single crystal (or monocrystalline) silicon cell, (ii) multicrystalline silicon cell, (iii) amorphous silicon (a-Si), (iv) gallium arsenide cell (GaAS), (v) copper indium (gallium) di-selenide cell (CIS), (vi) cadmium telluride cell (CdTe) and (vii) organic PV cell. At present, only single crystal, multicrystalline and to some extent CIS, CdTe and a-Si cells are being produced commercially.

In single crystal or mono crystalline silicon there is a perfect periodic arrangement of atoms. The crystal is highly ordered and its lattice is continuous and unbroken. Amorphous Si is non-crystalline and its atoms do not display any structures and they are not arranged in an ordered manner. Polycrystalline (and also multicrystalline) Si structure is in between these two extremes. These materials are composed of many **crystallites** of varying size and orientation. Crystallites are also referred to as **grains**. In multicrystalline silicon (multi c-Si) the grains size is in the range of mm to cm, whereas polycrystalline silicon or Ploy silicon has a grain size of less than 1 mm. Polycrystalline/multicrystalline silicon can be recognized by a visible grain, a “metal flake effect”. The atomic arrangement of these materials is depicted at microscopic level in Fig. 6.20.

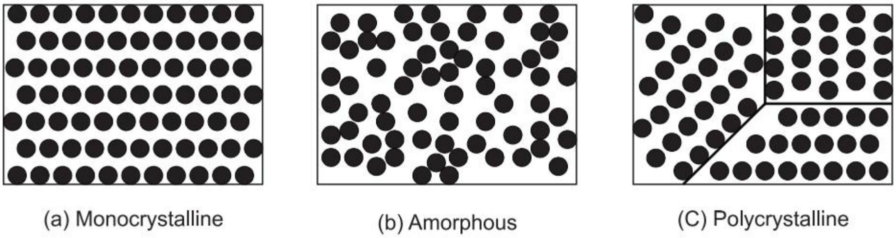

(a) Monocrystalline (b) Amorphous (C) Polycrystalline

Figure 6.20 Atomic arrangement of mono, amorphous and polysilicon

1. Single Crystal (or Mono Crystalline) Silicon Solar Cell

The first silicon PV cells were of the single crystal variety. Single crystal silicon cells are the most efficient and most robust of the silicon PV family. Their main drawbacks are: (i) they are most energy intensive in their production and (ii) unit consumption of silicon to produce one unit of PV electricity is also quite high. Other variations of PV cells are being developed to overcome mainly these two drawbacks. Let us have a brief overview of main steps involved in their production.

2. Production of Monocrystalline Silicon Cells

Second only to oxygen, silicon is the most abundant element in Earth's crust (27.7 per cent by weight). It mainly occurs as SiO_2 in the form of quartz, sand and silicates. It is normally produced from a naturally occurring ore, quartzite gravel (a form of sand stone), shown in Fig. 6.21. There are several impurities in natural occurring quartzite including Al, B, P, Cu, C, Ca, Mg, Fe, Ti, Mn, Mg, etc. The acceptable level of impurities is generally in the parts per billion (ppb) range for the electronic applications, and in parts per million (ppm) for solar cell applications. Silicon has atomic density of 5×10^{22} atoms/cm^3. Thus a ppb level of impurity means 5×10^{13} atoms/cm^3 in Si and a ppm level of impurity means 5×10^{16} atoms/cm^3 in Si. Various steps are involved in converting an impure quartzite to high purity crystal wafer.

Figure 6.21 Photograph of quartzite gravel

The first step is the production of metallurgical grade (99 per cent pure) silicon, MGS from its ore, SiO_2 by reduction reaction with carbon in an arc furnace. The energy cost of this step is 50 kWh / kg of silicon. Also in this process CO_2 is produced as a byproduct, which is a greenhouse gas. Electronic grade pure (an impurity level in range of 5×10^{13} atoms/cm^3) polysilicon (or polycrystalline silicon) is then obtained by refining it further through various complex operations at an energy cost of 200 kWh/kg of silicon. These two steps are highly energy intensive.

Worldwide, about 1 million tons of MGS is produced. A very small fraction (less than 5 per cent) of it is used in making electronic grade silicon. Most of the MGS is used in iron and aluminium industry for making alloys.

The electronic grade polysilicon is then melted and IIIrd group impurity (generally boron) in desired quantity is introduced in the melt to get *P*-type base material. The bulk resistivity of this material is chosen appropriately by controlled doping. Low doping or high resistivity should result in wider depletion layer and increased short circuit current. But this would also result into lower open circuit voltage and large series resistance leading to reduction of fill factor. On the other hand, too low resistivity, or a high doping leads to lower photocurrent due to larger carrier recombination. Such considerations have led to selection of resistivity in the range 1 to 3 ohm-cm as an optimum value for bulk silicon solar cells.

The molten mass is recrystallized into a single crystal ingot as large as 4 to 6 inches in diameter and 3 to 5 feet long, using a silicon seed crystal. This is done by Czochralski process (CZ process) or by float zone process (FZ process). Special saws are then used to cut the ingots into wafers of thickness between 200 to 400 microns. This process is called *wafer dicing*. Again this crystal growth and wafering processes are quite energy intensive. Also about 30–40 per cent of this expensive material is lost in this slicing operation. Effort is going on to fabricate thin ribbon shaped crystal (Si sheet) to avoid the need of wafering. The edges of wafers are then trimmed to make it closer to square to increase the packing density, as circular wafers mounted on a module would leave a large amount of space between them. After preparation of the surface, on each wafer a Vth group impurity (usually phosphorus) is diffused to get a thin (fraction of a micron) layer of *N*-type material and thus a *PN* junction is formed. Low resistance ohmic contacts are made on both sides for external connection after applying anti-reflective coating on the front side.

The most common commercially produced silicon cell has an *N*-on-*P* structure, where the base material is *P*-type, which has a thin diffused *N* layer on top of it. The reason for choosing a very thin diffused *N* layer at the top at the top of *P* base is as follows. Since the diffused layer is relatively heavily doped, it is likely to have large number of unwanted recombination centers. Therefore, the diffusion length of minority carriers in this region is quite small and they are not expected to contribute significantly to photocurrent. Major contribution would normally come from the base region. The minority carrier diffusion length for electron is about twice that of hole in silicon. Therefore, a *P*-type silicon base material, which has electrons as its minority carriers, is preferred for making single crystalline bulk silicon solar cell.

3. Multicrystalline Silicon Solar Cell

Multicrystalline silicon cells are less energy intensive in their production and less costly as compared to single crystal silicon cell. But they are less efficient. Commercial multicrystalline solar cells have efficiencies typically 1 per cent to 2 per cent lower as compared to their monocrystalline counter parts. Impurity segregation in grain boundaries, which act as recombination centers, has limited the achievable maximum conversion efficiency. Multicrystalline wafers are of square shape. They allow higher packing density of cells in the module. Due to this at module level, the efficiency of mono and multicrystalline Si module is nearly the same.

The first two steps of manufacturing, up to production of electronic grade polysilicon are same as explained above for the case of single crystalline cell. The polysilicon thus obtained is melted in square shaped crucible and after proper doping an ingot of multicrystalline silicon is produced by controlled cooling from the bottom of crucible, without seeding. The controlled directional solidification of crucible results in multicrystalline Si block (ingot) with grain size from mm to cm range. While single crystalline silicon cannot be grown in square shape and therefore it is physically trimmed into it, large square shaped solids can be obtained in multicrystalline silicon leading to economy in material consumption by reducing the kerf loss. In this way, it is also possible to reduce the unit energy consumption in the growth of multicrystalline ingot and the growth may be made much faster. Slicing into wafers and all further steps are similar to that for the case of single crystal silicon cell explained above.

To reduce the cost further, solar grade (SoG) silicon may be used in place of electronic grade silicon. There is no standard definition of SoG. Generally the SoG material is identified in terms of impurity level of the material. The impurity content in SoG is generally in the range of parts per million (ppm).

4. Amorphous Silicon (a-Si) Solar Cell

Amorphous silicon cells are recently developed using thin film technology. These are cheaper alternatives to single or multicrystalline cells. Their main drawbacks are that they have low efficiency (a commercial a-Si module has efficiency in range 4–9 per cent) and they degrade on exposer to light, which is known as **Staebler-Wronski effect**. Fortunately the degradation stops after some initial exposure. That is why, for a-Si cells the stabilized solar cell efficiencies are mentioned. They perform best when used indoors with diffused or indoor lights. Thus, they are ideally suited in applications such as pocket calculators, electronic watches, small radio receivers and low power hand-held electronic instruments, etc.

Amorphous silicon has no predictable crystal structure. Due to randomness of atoms many covalent bonds are incomplete. These incomplete bands cause a large number of equivalent impurity states in the band gap. The impurity states result in trapping of mobile carriers. Non-crystalline nature of material also results in very low mobility of carriers. This renders amorphous silicon as a rather poor semiconductor material.

The properties of a-Si are considerably improved when alloyed with hydrogen, to get a-Si: H material. Much of the unwanted gap states are removed by passivation with hydrogen and electronic properties are improved. Since it has low diffusion length, a *P-i-N* cell structure (incorporating an intrinsic layer between *P* and *N* layers) a reasonable electron-hole pair generation region can be created.

This material has all the advantages of thin film technology. It has high absorption coefficient, a direct band gap close to 1.75 eV, low temperature deposition is possible (low cost substrate can be used) and monolithic integration of cells in modules is possible. Only 1-μm thick absorber layer is enough. The solar cell efficiency degradation can be reduced if absorber layer thickness is lower. This is achieved by making multijunction a-Si:H solar cell. The multijunction solar cell requires material of different band gaps. The band gap of a-Si: H can be tuned by alloying it with Ge and C. Solar cell stabilized efficiencies as high as 13 per cent has been demonstrated in triple junction, a-Si/a-SiGe/a-SiGe solar cell, though the module level efficiencies are only in the range of 8 per cent to 9 per cent. Because of low carrier mobility and layer conductivity, a continuous transparent conducting oxide (TCO) is used to make front metallic contact.

The a-Si: H modules are fabricated in both substrate and superstrate configurations. In the substrate configuration, light first travels through absorber layer and then reaches the substrate, while in the superstrate configuration, light first enters the superstrate (normally glass) on which the absorber layer is deposited and subsequently it reaches the absorber layer.

The a-Si: H solar cell can also be stacked over microcrystalline Si cell to make a multijunction micromorph (MICROcrystalline + aMORPHous) cell. The band gap of amorphous Silicon (1.75eV) and microcrystalline Silicon (1.12eV) are well suited for tandem solar cells. While the thin amorphous silicon top cell absorbs the blue light, the thicker microcrystalline silicon bottom cell absorbs the red and near-infrared light, allowing this so-called tandem cell to cover a wider range of the solar spectrum. Micromorph solar cells are successfully commercialized.

5. Gallium Arsenide Cell

GaAs has a direct band gap of 1.43 eV, which makes it an attractive PV material. Simple GaAs cells have thin films of *N*-type and *P-type* GaAs, grown on a suitable substrate. Other structures have cascading of many layers of *P* and *N* materials formed using impurities from III-V elements. These are high performance extraterrestrial quality cells. Fill factor in access of 80 per cent has been achieved. Single cell open circuit voltage generally varies from 0.8 V to 0.9 V. The efficiencies in excess of 20 per cent are common and can even be enhanced on more expensive GaAs substrates (28.8 per cent record efficiency of single junction GaAS cell). However, high production cost has limited their use only in extraterrestrial and other special purpose applications.

The multijunction GaAs solar cell has been successfully developed with an efficiency of more than 40 per cent under light concentration. But these are very expensive and used only under concentrated light.

6. Chalcopyrite or Copper Indium (Gallium) Diselenide (CIGS) Cell

CIGS has a direct band gap of 1.0 eV. Incorporation of Ga into the CIGS mixture increases the band gap beyond 1.15 eV. A heterogeneous junction with *N*-type CdS and *P*-type CIGS is fabricated using thin film technology. Its main attraction is inexpensive preparation. It is more stable as compared to a-Si cell in outdoor applications and has efficiency of around 10 per cent. However, exposure to elevated temperatures results in loss of efficiency, but light soaking (starving) restores it to original efficiency level.

7. Cadmium Telluride Cell

CdTe has a favourable direct band gap of 1.5 eV. Thin film heterogeneous junction with *N*-type CdS and *P*-type CdTe is fabricated as shown in Fig. 6.22. Here a transparent conducting oxide layer is used instead of metallic contact at the top on *N* side. EVA (ethylene vinyl acetate) is used for encapsulation. No instability problem has been reported in a trial of few years of outdoor application. Its efficiency is about 10 per cent and open circuit cell voltage is around 0.8 V.

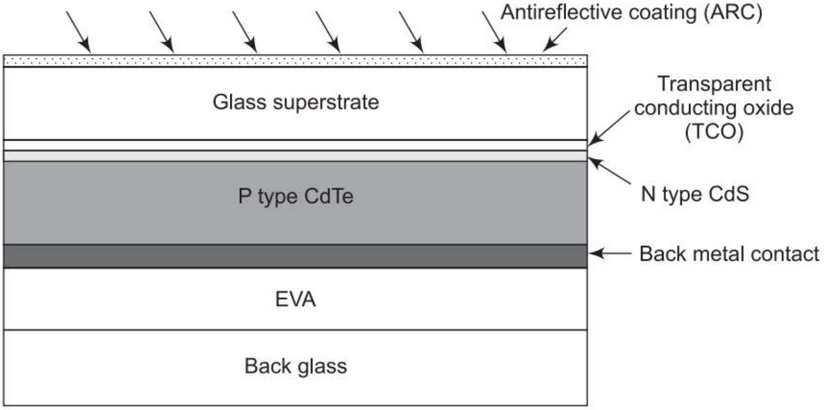


Figure 6.22 Basic structure of CdTe cell

8. Organic PV Cell

Recently, organic PV cells, fabricated out of carbon based dyes and polymers (often referred to as solar plastics) are under development stage. Their principal advantage is that they are flexible and can bend without breaking, unlike Si, which is brittle. They are also very light, cheap and rugged. They may be folded or cut into required sizes and can still be used. However, at present their efficiency is very low.

6.5 SOLAR CELL TECHNOLOGIES

6.5.1 Wafer based Si Solar Cell Technologies

Si wafer-based PV technology accounted for about 92 per cent (both mono and multicrystalline Si) of the total production in 2014. Out of this the share of multicrystalline technology is now about 56 per cent of the total production [33]. Wafer based crystalline solar cells have already proven their excellent stability and reliability, operating under outdoor conditions without any deterioration in their performance. The main disadvantage associated with this technology, however, is the resulting high module price. The high production cost is a consequence of several factors: (a) the complex production steps involved in cell manufacturing and module assembly and (b) the large amount of highly purified silicon feedstock required (roughly 5 tons of polysilicon for every MWe of module production). Until 1995, the PV industry mainly used rejects from the microelectronics industry; it could thus obtain silicon feedstock at a reduced price. With the growth of PV industry, this source of feed stock supply becomes more and more insufficient. However, recently various manufacturers started producing a cheaper, less pure (purity level in ppm) "SoG silicon" (solar grade silicon). In 2008, the number of manufacturers known to produce SoG were only 12, which rose to more than 100 by 2013. As a result the PV module prices have started falling.

6.5.2 Thin Film Amorphous Si Technologies

(Discussed in details in Section 6.4.3.)

6.5.3 Thin Film Cadmium Telluride (CdTe) and Copper Indium (Gallium) Selenide (CIGS) Technologies

The band gap in CdTe (1.5 eV) and CIGS (1 eV to 1.7 eV depending on percentage of In and Ga) are close to ideal band gap required. Both of these materials are deposited in the form of polycrystalline having grain size of few micrometers at best. However, the recombination at grain boundaries is not significant (in contrast to polycrystalline Si). This allows the manufacturing of a *PN* junction solar cell. Due to the high absorption in the material, the photon gets absorbed very close to the surface, where recombination can be significant. A CdS layer, with high band gap of 2.42 eV, is used as buffer layer to avoid front surface recombination. This CdS layer also serves as *N*-type semiconductor to form a *PN* hetrojunction. Thus both solar cells are actually CdS-CdTe and CdS-CIGS solar cells. Both of these cells use TCO layer to make front metallic contact. There are however, two concerns regarding these technologies: (a) Cd is a toxic material, its disposal at the end of useful life of the cell will pose environmental problem, (b) Cd, In and Te are not available in large quantities. The availability of Cd, In and Te in the earth's crust are 0.00002 per cent, 0.00001 per cent and 0.0000002 per cent by weight respectively.

The highest reported laboratory efficiencies of these solar cells are 16.5 per cent for CdTe and 19.5 per cent for CGIS solar cells. The complete solar cell processes in the two cases are optimized to avoid inter-diffusion of impurities from one layer to another, which adversely affect the cell performance. Due to this reason, the CdTe cells are normally produced in superstrate configuration, while CGIS cells are normally produced with substrate configuration. Solar PV modules based on these cells are now commercially available.

6.5.4 Thin Film Crystalline Si Cell Technologies

1. Microcrystalline Thin Film Technology

Microcrystalline silicon (μc-Si) or nanocrystalline silicon (nc-Si) is a complex material. It has small grains of crystalline silicon within amorphous phase as depicted in Fig. 6.23. The size of crystalline phase is of the order of 10s of nanometers. This is in contrast to polycrystalline silicon (poly-Si) which consists solely of crystalline silicon grains, separated by grain boundaries.

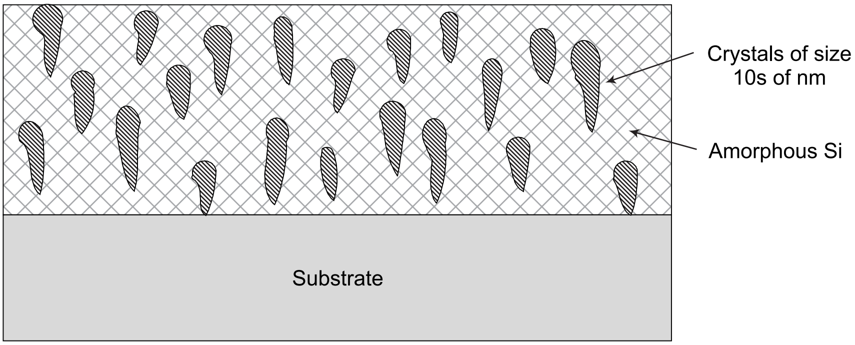


Figure 6.23 Microstructure of mc-Si:Hi

Best application of μc-Si: H is its use in fabrication of tandem cells. In tandem, double junction, solar cell, a Si: H cell is used as top cell (band gap of 1.75 eV) and a μc-Si cell is used as bottom cell (band gap of 1.1 eV). The combination is known as micromorph solar cell.

2. Polycrystalline Thin Film Technology

Polycrystalline Si is a film with grain size in the range 0.1 μm to 1 mm. It has 100 per cent crystalline phase. Its optical behaviour is similar to bulk silicon. It has indirect band gap and relatively low absorption coefficient. Due to this thicker films are required to absorb sufficient light. Generally, polycrystalline Si films as thin as 3 μm to 30 μm are considered for device fabrication. The light trapping schemes are essential for a thin film technology. The polycrystalline Si films have the advantage of low processing time and moderate processing temperature as compared to high temperature approaches used in multi- and mono-crystalline Si thin films.

3. Thin Film Epitaxial Si Solar Cells Technology

Normally in thin film Si technologies, films are deposited on a substrate which is not Si. Due to non-Si substrate, the deposited film results in a defected Si layer in the form of microcrystalline or polycrystalline (i.e. small grain size Si).

In this case a low cost Si substrate is used to deposit a thin film of Si epitaxially. This low cost substrate could be an upgraded metallurgical grade Si or a Si sheet produced with high throughput. This substrate is known as carrier substrate. The epitaxial deposition refers to the layer deposition in which the growing film follows the same crystalline structure as that of substrate. Since the carrier Si substrate can have large grain, of the order of several mm or cm, the crystalline quality of epitaxially deposited film will also be high. This results in high efficiency of the cells produced. The film thickness need not be large. Even in Si wafer solar cells, more than 90 per cent of the solar spectrum is absorbed in the first 30-μm thickness of the Si layer, and large amount of crystalline Si just acts as a mechanical support. With proper light trapping schemes the film thickness requirement can be reduced between 5-μm and 30-μm range. Thus, it retains the advantages of wafer-based technology (high efficiency, stability and reliability) and has potential of cost reduction.

6.5.5 Emerging Solar Cell Technologies

1. Dye-sensitized Solar Cell (DCS or DSSC) Technology

Dye-sensitized solar cell is a photo-electro-chemical system belonging to the group of thin film solar cells. The technology is not yet commercialized but is on the verge of commercialization. The concept of DSC, also known as Gratzel cell, was originally co-invented in 1988 by Brian O'Regan and Michael Gratzel. The operation of DSC is considered similar to that of photosynthesis process. In this cell, the function of light absorption and charge transport is performed by two different materials unlike traditional semiconductor cells where both of these functions are carried out by the same material. The light absorption material is called *dye* (such as ruthenium complex) and the carriers are being transported by wide gap semiconductor (such as TiO_2, band gap = 3.2 eV). With this type of concept, a DSC with $V_{oc} = 0.7$ V and efficiency of about 11 per cent has been demonstrated.

The DSC has a number of attractive features; it is simple to construct, it is semi-flexible, it requires low temperature processing and most of the ingredient materials used (but not all) are of low cost and it is available in large quantities. The construction is simple enough that there are hobby kits available to hand-construct them. Although they use a number of "advanced" materials, these are inexpensive compared to the silicon needed for normal solar cells because they require no expensive manufacturing steps. TiO_2, for instance, is already widely used as a paint base. Some materials, like platinum catalyst and ruthenium complex dye that are used are costly (ruthenium is a rare metal).

A typical structure of DSC is shown in Fig. 6.24. The operation of the DSC can be explained using the following steps.

Step 1: The incident photon is absorbed by dye molecule S, which is present on the surface of TiO_2. After the photon absorption the dye molecule goes into excited state S^*.

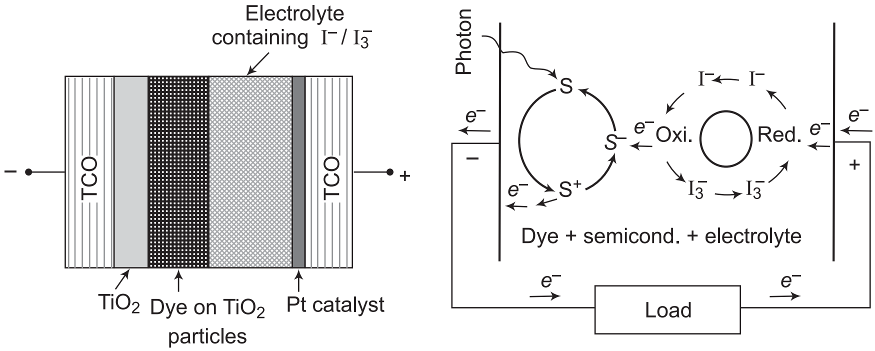
$$S + \text{Photon } (h\nu) \rightarrow S^* \text{ (excited state)}$$

Step 2: Within very short time, of the order of femtoseconds (i.e. 10^{-15} s), the electron is given off to the conduction band of semiconductor and the excited dye molecule gets oxidized (loss of electron) to S^+.

$$S^* \rightarrow S^+ + e^- \text{ (to conduction band of } TiO_2)$$

The injected electrons in the conduction band of TiO_2 are transported through TiO_2 nanoparticles with diffusion toward the TCO (electrode), where it is finally collected. Normally, fluorine doped tin oxide (SnO_2: F) is used as TCO. The electrons then flow to external load to the counter electrode which is also a TCO (i.e. SnO_2: F).

For successful cell operation it is required that the point of photon absorption in the dye should be very close to semiconductor (else the electron would recombine in the dye and lost from photoconduction process). Due to this, only dye molecules that are in direct contact of the semiconductor (TiO_2) can be photoactive. Therefore, the contact area of semiconductor and dye need to be increased. This is done by making the semiconductor a porous material. A porous layer is formed with 75 per cent to 80 per cent porosity with average TiO_2 particle size of about 20 ns. The dye molecules can easily penetrate in the pores of TiO_2 and deposited around it. Therefore, nanostructure of TiO_2 is very important and plays an important role in cell operation.



(a) Cell structure

(b) Principle of working

Figure 6.24 Dye sensitized solar cell

Step 3: The oxidized dye molecule S^+ accepts electron from I^- ion redox mediator leading to regeneration of the ground state S. The electrolyte solution contains the iodide (I^-) / tri-iodide (I_3^-) redox system in which the iodide ions are being oxidized to tri-iodide ions. The tri-iodide then recovers its missing electron by mechanically diffusing to the counter electrode where free electrons at the counter electrode reduce the tri-iodide molecules. This step requires catalytic presence of platinum at the electrode.

$$S + \frac{3}{2} I^- \rightarrow S + \frac{1}{2} I_3^- \qquad \text{(oxidation of } I^- \text{ to } I_3^-)$$

$$\frac{1}{2} I_3^- + e^- \rightarrow \frac{3}{2} I^- \qquad \text{(reduction of } I_3^- \text{ to } I^-)$$

Major disadvantages to the DSC design are:

(i) The use of the liquid electrolyte has temperature stability problems. At low temperatures the electrolyte can freeze, ending power production and potentially leading to physical damage. Higher temperatures cause the liquid to expand, making sealing the panels a serious problem.

(ii) Ruthenium (dye), platinum (catalyst) and conducting glass (contacts), needed to produce a DSC are costly materials.

(iii) The electrolyte solution contains volatile organic compounds (or VOCs), solvents which must be carefully sealed as they are hazardous to human health and the environment. This, along with the fact that the solvents permeate plastics, has precluded large-scale outdoor application and integration into flexible structure.

Replacing the liquid electrolyte with a solid has been a major ongoing field of research.

2. Organic Solar Cell Technology

The organic solar cell or plastic solar cell was first discovered in 1975. Since then a significant improvement in efficiency, from 0.001 per cent to reported efficiency of 10.8 per cent in 2015, has been demonstrated [34]. It uses conductive organic polymers or small organic molecules, for light absorption and charge transport to produce electricity from sunlight. These solar cells are flexible, cheap, solution-processable at high throughput, have low material consumption, resulting in low production costs. Molecular engineering (e.g. changing the length and functional group of polymers) allows the tuning of band gap as per requirement. The optical absorption coefficient of organic molecules is high, so a large amount of light can be absorbed with small amount of materials, usually on the order of hundreds of nanometers. The main disadvantages associated with organic photovoltaic cells are low efficiency, low stability and low strength compared to inorganic photovoltaic cells such as silicon solar cells.

In organic semiconductor physics, the HOMO (highest occupied molecular orbital) takes the role of the valence band while the LUMO (lowest unoccupied molecular orbital) serves as the conduction band. The energy separation between the HOMO and LUMO energy levels is considered the band gap of organic electronic materials and is typically in the range of 1–4 eV.

All photons with energy greater than the band gap of the active material (absorber) can be absorbed. When these materials absorb a photon, an excited state is created and confined to a molecule or a region of a polymer chain. The excited state can be regarded as an *exciton*, or an electron-hole pair bound together by electrostatic interactions. In photovoltaic cells, excitons are broken up into free electron-hole pairs by effective fields. The effective fields are set up by creating a heterojunction between two dissimilar materials, donor and accepter of electrons. The effective fields break up excitons by causing the electron to fall from the conduction band of the donor to the conduction band of the acceptor molecule. It is necessary that the acceptor material has a conduction band edge that is lower than that of the donor.

A simple organic cell structure, consisting of planar donor-accepter hetrojunction is shown in Fig. 6.25. The two active layers have different electron affinity and ionization energies. The layer with higher electron affinity and ionization potential is the electron acceptor. Due to difference in electron affinity and ionization energies, electrostatic forces are generated at the interface between the two layers. The materials are chosen to make the differences large enough that these local electric fields are strong, which splits excitons efficiently.

Another important phenomenon to be considered is the diffusion length of excitons in organic electronic materials, which is typically on the order of 10 nm. In order for most excitons to diffuse to the interface of layers and split into carriers, the layer thickness should be in the same range as the diffusion length. However, a polymer layer typically needs a thickness of at least 100 nm to absorb enough light. At such a large thickness, only a small fraction of the excitons can reach the heterojunction interface, resulting in poor efficiency of the cell.

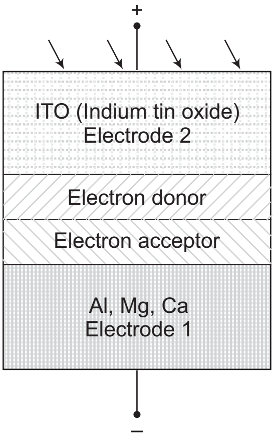


Figure 6.25 Bilayer organic solar cell

In a modified version of the above cell, the absorption layer consists of a nanoscale blend of donor and acceptor materials, which can be spin coated on a suitable substrate, as shown in Fig. 6.26. The hetrojunction will be present throughout the active material. This is known as bulk hetrojunction. The domain sizes of this blend are on the order of nanometers, allowing for excitons with short lifetimes to reach an interface and dissociate due to the large donor-acceptor interfacial area. However, efficient bulk heterojunctions need to maintain large enough domain sizes to form a percolating network that allows the acceptor material to transport the electron to the electrode and the donor material to transport the hole to counter electrode as shown in Fig. 6.26. Without this percolating network, charges might be trapped in a donor or acceptor rich domain and undergo recombination. Bulk heterojunction has an advantage over layered photoactive structure because it can be made thick enough for effective photon absorption without the difficult processing involved in orienting a layered structure while retaining similar level of performances. The nanostructural morphology of bulk heterojunctions tends to be difficult to control, but is critical to photovoltaic performance.

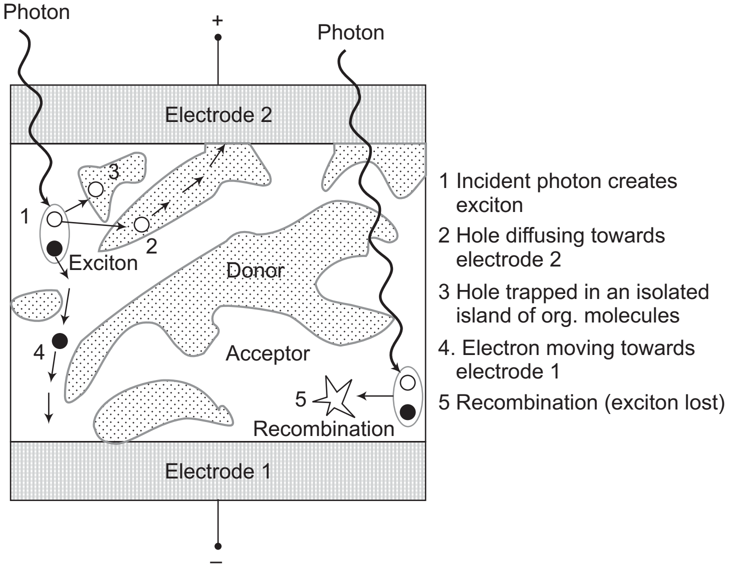


Figure 6.26 Bulk heterojunction solar cell

3. Quantum Dot Solar Cell (QD) Technology

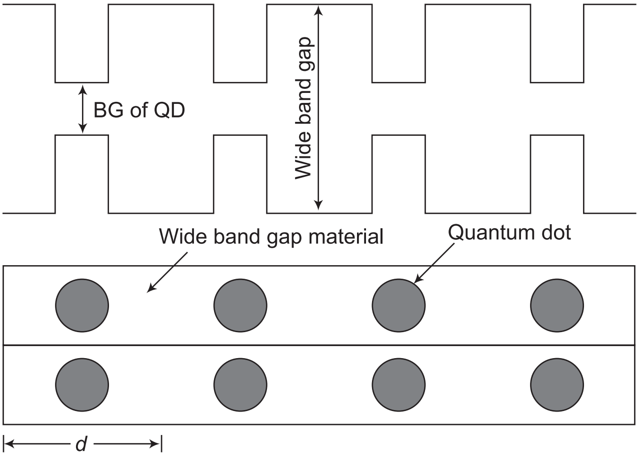
The idea of using quantum dots as a path to high efficiency of solar cell was first noted by Burnham and Duggan in 1990 [37]. A quantum dot solar cell is a solar cell design that uses quantum dots nanoparticles as absorber photovoltaic material. Quantum dots have band gaps that are tunable over a wide range of energy levels by varying the dot's size. This property makes the quantum dots attractive for multilayer solar cells. As of 2014, the reported highest efficiency of such cell is 8.7 per cent [35].

It has been observed that when the size of a semiconductor crystal is reduced below Bohr exciton radius (which is few nm depending on the material), its optical and electrical properties change. This is known as quantum dot (QD). As the size of nanoparticle is decreased further, its band gap increases as follows:

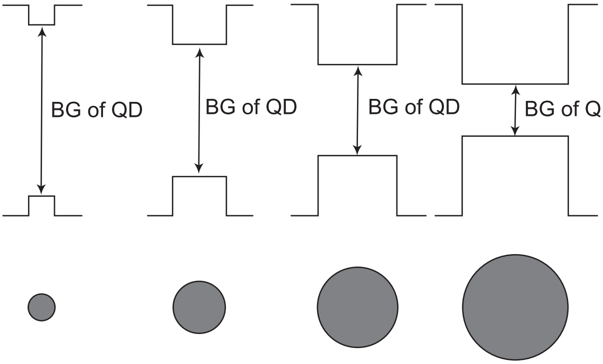
$$E_g\,(\text{eV}) = E_g\,(\text{bulk}) + \frac{k}{d^2}$$

where k = quantum confinement parameter and d is the radius of nanoparticle in nm, E_g (bulk) is the band gap of bulk material.

This small crystal (quantum dot) must be surrounded by some other wide band gap material. The energy band diagram of such a material is shown in Fig. 6.27. In this arrangement the change in the optical and electrical properties occurs due to an effect known as "quantum confinement". About half of the solar radiation received on the surface of earth is in infrared region. A QD solar cell makes infrared energy accessible by tuning of band gap.



(a) Quantum dots embedded in wide band gap material



(b) Quantum dot size and band gap variation

Figure 6.27 Quantum dots

In typical wet chemistry (colloidal quantum dot, CQD) preparations, the tuning of band gap is accomplished by varying the duration and temperature of synthesis. Thus quantum dots of different band gaps can be grown over a range of size without changing the underlying material or technique.

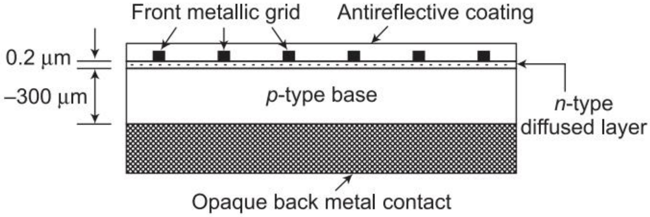
Quantum dot nanoparticles can capture multiple bands of light. Next generation solar cells are focused on 3-band gaps multijunction model. Typical QD solar cells are made of cadmium sulfide on titanium dioxide substrate coated with organic molecules to interconnect the metal substrate and the QDs. The total thickness has to be less than 1 nm. QD solar cells could be built on flexible polymer material.

In another approach, multiple exciton generation (MEG) technique is used. In this technique, quantum dots are tuned to release multiple electron-hole pairs (up to 7 reported) at low energy [38]. This increases the efficiency through increased photocurrent.

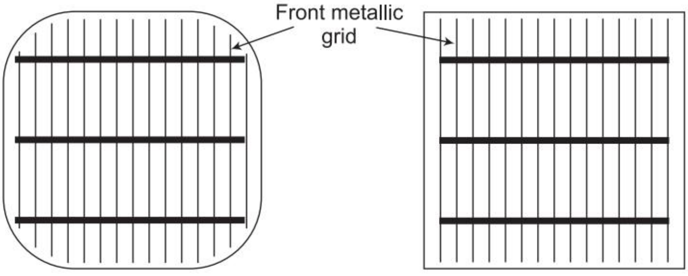
6.6 SOLAR CELL, MODULE, AND ARRAY CONSTRUCTION

6.6.1 Solar Cell

The basic cell structure of a typical *N*-on-*P*, bulk silicon cell is shown in Fig. 6.28. The bulk material is *P*-type silicon with thickness 100 to 350 microns, depending on the technology used. A thin layer of *N*-type silicon is formed at the top surface by diffusing an impurity from Vth group (phosphorus being most common) to get a *PN* junction. The top active surface of the *N* layer has an ohmic contact with metallic grid structure to collect the current produced by impinging photons. The metallic



(a) Cross section



(b) Single crystal cell (off square)

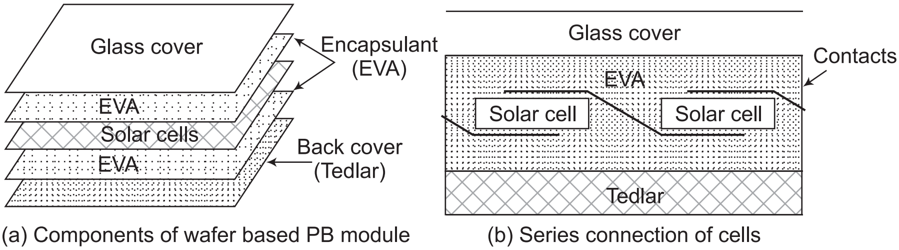
(c) Multicrystalline cell (square)

Figure 6.28 Construction of bulk silicon cell grid covers minimum possible top surface area (less than 10 per cent of the total area) to leave enough uncovered surface area for incoming photons. Similarly, the bottom inactive surface has an ohmic metallic contact over the entire area. These two metallic contacts on *P* and *N* layers respectively form the positive and negative terminals of the solar cell. In addition to basic elements, several enhancement features are also included in the construction. For example, providing antireflective coating, textured finish of the top surface and reflective, textured rear surface, to capture maximum photons and direct them toward the junction.

6.6.2 Solar PV Module

A bare single cell cannot be used for outdoor energy generation by itself. It is because (i) the output of a single cell is very small and (ii) it requires protection (encapsulation) against dust, moisture, mechanical shocks and outdoor harsh conditions. Workable voltage and reasonable power is obtained by interconnecting an appropriate number of cells. Cells from same batch are used to make PV module. This is done to ensure that mismatch losses are minimal in the module.

The electrically connected cells are encapsulated, typically by using two sheets of ethylene vinyl acetate (EVA) at either side. EVA is a good electrical insulator, transparent material and has very low water absorption. The encapsulant cannot provide rigidity to the module, for which glass is provided at the front side of the module. At the rear side of the module a hard polymer material, typically, polyvinyl fluoride (PVF, also known as tedlar) is used. Theses layers are arranged as shown in Fig. 6.29 and hermetically sealed to make it suitable for outside applications for 20-30 years without environmental degradation. This assembly is known as solar module – a basic building block of a PV system. Most common commercial modules have a series connection of 32 or 36 silicon cells to make it capable of charging a 12-V storage battery. However, larger and smaller capacity modules are also available in international market.



(a) Components of wafer based PB module (b) Series connection of cells

Figure 6.29 PV module details

1. Cell Mismatch in a Module

In a module, a number of cells are interconnected, it is very important that these cells should match as closely as possible. That means V_{oc}, I_{sc}, V_m and I_m (or fill factor) for all cells must be exactly same. Any mismatch in the characteristics of these cells leads to additional mismatch loss. Therefore, peak power of the combination is always less than the sum of individual peak power of the cells. Only under ideal case when all cells are exactly identical that the resultant peak power would be equal to arithmetic sum of that of its constituents. This is elaborated as follows.

When two cells with mismatched characteristics are connected in series and load is applied, both cells are bound to carry same current. The composite characteristics of the combination can be obtained by adding the individual output voltage of the cell corresponding to a common current, for all operating points, as shown in Fig. 6.30. At a particular operating point, while one cell may be operating at peak power, the other may not. Thus peak power of the combination is always less than the sum of individual peak power of each cell. This is also clear from the shape of composite characteristics, which has lower fill factor. Also if such a combination is short circuited, equal and opposite voltages V_1' and V_2' are produced by individual cells and therefore, one cell will be generating power while the other will be dissipating it. Had the two cells been perfectly matched no power would be generated or dissipated.

Similar conclusion may be drawn by considering a parallel combination of two mismatched cells. Here the voltages of the cells are bound to be equal, but the currents will be different and hence the maximum power points. The conclusion may be generalized for more than two cells connected in series or in parallel. It can also be shown that larger the number of cells in a module more would be the possibility and quantum of mismatch loss.

To reduce mismatch losses, modules are fabricated from cells belonging to same batch. Also *cell sorting* is carried out to categorize cells having matched parameters with specified tolerance.

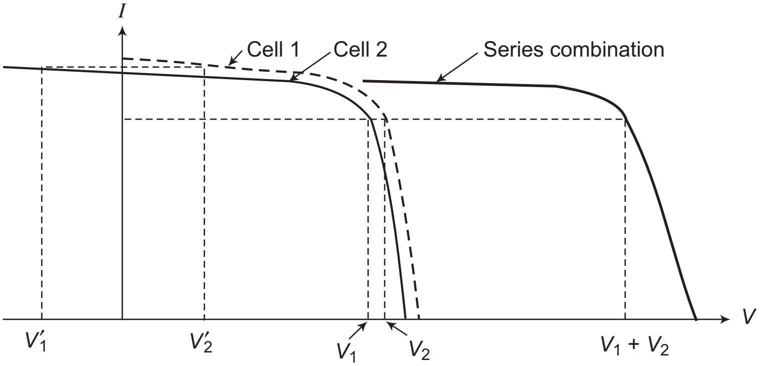


Figure 6.30 Composite characteristic of two cells in series

2. Effect of Shadowing

Partial shadowing may have serious consequences and may completely damage a module due to creation of hot spot. Let us examine the operation of a module under the conditions of: (i) partial shadowing of a cell in an open circuited, series string of cells and (ii) complete shadowing of one cell in a short circuited, series string of cells.

When a cell is partially shadowed, the shadowed portion will not produce any power but the remaining portion will remain active and produce power. The generated voltage by illuminated portion will forward bias the parallel rectifier corresponding to shadowed portion as shown in Fig. 6.31. If shadowed area is relatively small, the large circulating current through it will result in excessive heating of the shadowed portion. The phenomenon is known as hot spot effect and may completely damage the module for prolonged partial shadowing.

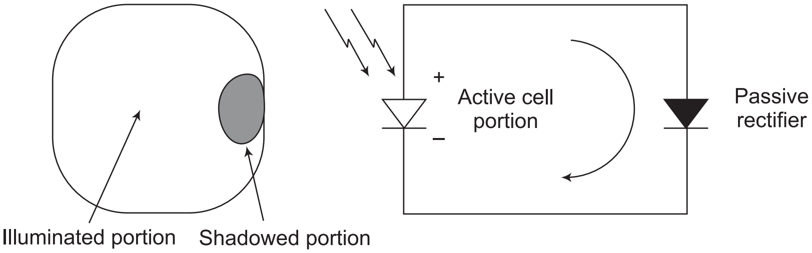


Figure 6.31 Partial shadowing of a cell

A short-circuited, series string of $(n + 1)$ cells with one cell completely shadowed is shown in Fig. 6.32. Here the voltages produced by n illuminated cells add up and appears as reverse bias voltage of nV volts across the shadowed cell. As long as peak inverse voltage (PIV) of the shadowed cell is more than the reverse bias, no current will flow. If, however, the PIV is less than total reverse voltage appearing across the shadowed cell, current will flow through the string, dissipating large power in the shadowed cell, leading to possible damage of the module. The chances of damage to the shadowed cell, due to excessive heating, increase with the number of cells in the string. If the string supplies a load instead of being short-circuited, the chances of damage still persist through to a lesser extent. The damage due to shadowing can be avoided by connecting a bypass diode across the affected cell as shown in Fig. 6.32. This bypass diode would allow an alternative path for the load current. During healthy operation, the bypass diode has no role as the cell voltage would keep it reverse biased. Even so, its use would result some loss because of finite reverse leakage current through it. It is neither practical, nor required to incorporate a bypass diode across each cell in a module. It has been the international practice to provide a bypass diode for every 18 crystalline silicon solar cells in a series string. Thus, the internationally standard module with 34–36 cells would contain two bypass diodes placed inside its terminal box.

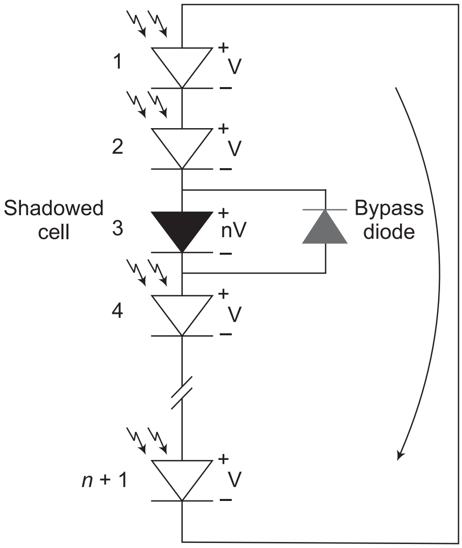


Figure 6.32 Shadowed cell and bypass diode connection

3. Detailed Specifications of a Typical Solar Module

Module type: Multi crystalline silicon module, “BP 380” from **BP Solar**

MODULE CHARACTERISTICS

Frame: Clear anodized aluminum alloy type

Construction: Front: High transmission 3 mm tempered glass; Back: Tedlar; Encapsulant: EVA

Contains 36 multicrystalline solar cells (125 × 125 mm), in 4 × 9 matrix connected in series

High efficiency- enhanced by new silicon nitride antireflective coatings

Warranty: 25 years

Number of bypass diodes: Two 9A, 45V, Schottky bypass diodes included

Fuse rating: 15 A

Type of protection: IP54

ELECTRICAL CHARACTERISTICS

Rated power (P_r)	80W
Peak power (P_p)	80W
Maximum system voltage	600V
Voltage at peak power (V_{pp})	17.6V
Current at peak power (I_{pp})	4.55A
Open-circuit voltage (V_{oc})	22.1V
Short-circuit current (I_{sc})	4.8A
Guaranteed minimum peak power	76W
Temperature coefficient of short-circuit current	(0.065 ± 0.015)%/°C
Temperature coefficient of open-circuit voltage	–(80 ± 10)mV/°C
Temperature coefficient of power	–(0.5 ± 0.05)%/°C
NOCT (air 20 °C, sun 0.8 kW/m^2, wind 1 m/s, spectrum AM 1.5)	47 ± 2 °C

MECHANICAL CHARACTERISTICS

Length	47.6 in/1209 mm
Width	21.1 in/537 mm
Depth	1.97 in/50 mm
Depth (including junction box)	2.57 in/64 mm
Weight	17.0 lb/7.7 kg

6.6.3 Solar PV Panel

Several solar modules are connected in series/parallel to increase the voltage/current ratings. When modules are connected in series, it is desirable to have each module’s maximum power production occur at the same current. When modules are connected in parallel, it is desirable to have each module’s maximum power production occur at the same voltage. Thus while interconnecting the modules; the installer should have this information available for each module. Solar panel is a group of several modules connected in series-parallel combination in a frame that can be mounted on a structure. Fig. 6.33 shows the construction of module and panel.

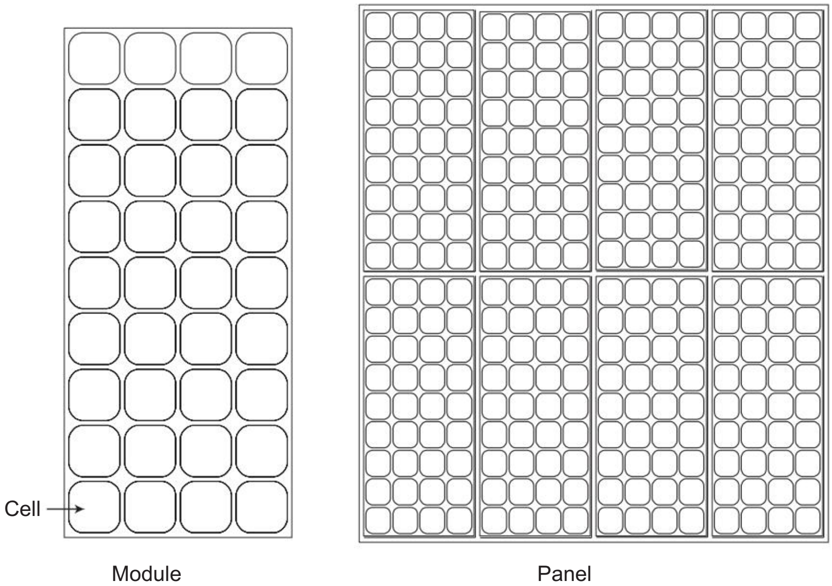


Figure 6.33 Cell, module and panel

Figure 6.34 shows a series-parallel connection of modules in a panel. In parallel connection, blocking diodes are connected in series with each series string of modules, so that if any string should fail, the power output of the remaining series strings will not be absorbed by the failed string. Also bypass diodes are installed across each module, so that if one module should fail, the output of the remaining modules in a string will bypass the failed module. Some modern PV modules come with such internally embedded bypass diodes.

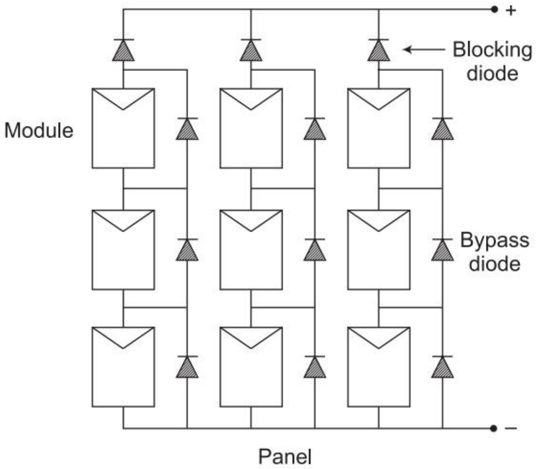


Figure 6.34 A typical panel: Series-parallel connection of modules

6.6.4 Solar PV Array

In general, a large number of interconnected solar panels, known as solar PV array, are installed in an array field. These panels may be installed as stationary or with sun tracking mechanism. It is important to ensure that an installed panel does not cast its shadow on the surface of its neighboring panels during a whole year. The layout and mechanical design of the array such as tilt angle of panels, height of panels, clearance among the panels, etc., are carried out taking into consideration the local climatic conditions, ease of maintenance, etc.

Example 6.4

A PV system feeds a dc motor to produce 1 hp power at the shaft. The motor efficiency is 85%. Each module has 36 multicrystalline silicon solar cells arranged in 9 × 4 matrix. The cell size is 125mm × 125mm and cell efficiency is 12%. Calculate the number of modules required in the PV array. Assume global radiation incident normally to the panel as 1 kW/m^2.

Solution

Motor output power = 1 hp = 746 W

Electrical power required by the motor = 746/0.85 = 877.65 W

Cell area in one module = $9 \times 4 \times 125 \times 125 \times 10^{-6} = 0.5625$ m^2

Let n number of modules is required

Solar radiation incident on panel = 1 kW/m^2 = 1000 kW/m^2

Cell efficiency = 0.12

Output of solar array = $1000 \times 0.5625 \times n \times 0.12 = 67.5 \times n$

The output of solar array is the input to the motor;

$$67.5 \times n = 877.65$$

$$n = 13$$

Therefore 13 modules are required in the panel.

6.7 MAXIMISING THE SOLAR PV OUTPUT AND LOAD MATCHING

To make best use of solar PV system, the output is maximized in two ways. The first is mechanically tracking the sun and always orienting the panel in such a direction as to receive maximum solar radiation under changing positions of the sun. That means adjusting the panel such that the sun rays always fall normal to its surface. The second is electrically tracking the operating point by manipulating the load to maximize the power output under changing conditions of insolation and temperature.

The operating point of an electrical system is determined by the intersection of source characteristics (source line) and load characteristics (load line). The operation for a solar PV system connected to a resistive load is shown in Fig. 6.35. For a low value of resistance, R_1 the system operates at Q_1. As the resistance is increased to R_2 and subsequently to $R_{3,}$ the operating point moves respectively to Q_2 and Q_3. Maximum power is available from the PV system for load resistance of R_2. Such load matching is required for extracting maximum power from PV system.

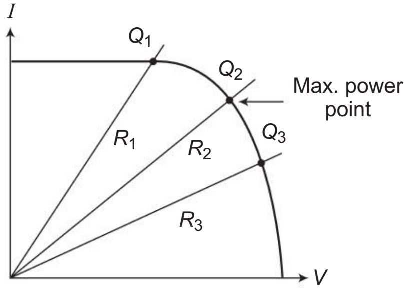


Figure 6.35 Load matching with resistive load

6.8 MAXIMUM POWER POINT TRACKER

When a solar PV system is deployed for practical applications, the *I-V* characteristic keeps on changing with insolation and temperature. In order to receive maximum power the load must adjust itself accordingly to track the maximum power point. The I-V characteristics of PV system, along with some common loads, are shown in Fig. 6.36. An ideal load is one that tracks the maximum power point.

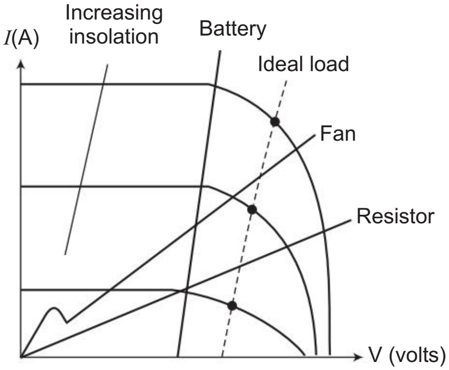


Figure 6.36 Characteristics of PV and some loads

If the operating point departs significantly from maximum power point, it may be desirable to interpose an electronic maximum power point tracker (MPPT) between PV system and load. Generally MPPT is an adaptation of dc-dc switching voltage regulator. Coupling to the load for maximum power transfer may require either providing higher voltage at a lower current or lower voltage for higher current. A buck-boost scheme is commonly used with voltage and current sensors tied into a feedback loop using a controller to vary the switching times. Basic elements of a buck boost converter that may be used in an MPPT are shown in Fig. 6.37. The output voltage of the buck-boost converter is given by:

$$V_{\text{out}} = \frac{D}{1-D} V_{\text{in}} \tag{6.38}$$

where D is the duty cycle of the MOSFET, expressed as fraction ($0 < D < 1$). Details of operation and design of the converter may be found in any standard book of power electronics.

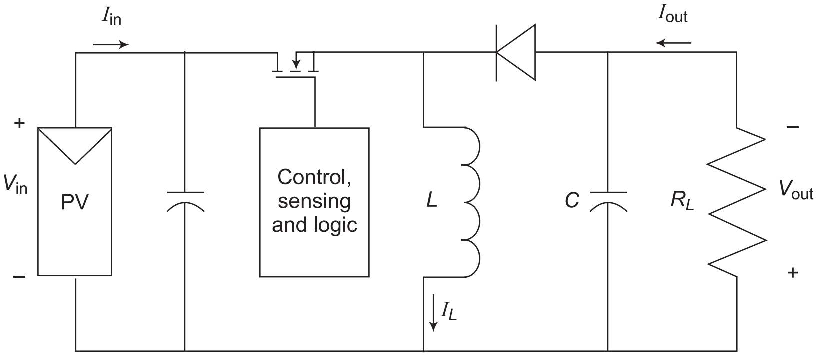


Figure 6.37 Maximum point tracker using buck-boost converter

The power output of a PV system is given by:

$$P = V.I \tag{6.39}$$

With incremental change in current and voltage, the modified power is given by:

$$P + \Delta P = (I + \Delta I).(V + \Delta V) \tag{6.40}$$

which, after ignoring small terms simplifies to

$$\Delta P = \Delta V.I + \Delta I.V \tag{6.41}$$

ΔP must be zero at peak point. Therefore, at peak point the above expression in the limit becomes:

$$\frac{dV}{dI} = -\frac{V}{I} \tag{6.42}$$

It may be noted here that $\frac{dV}{dI}$ is the dynamic impedance of the source, which is required to be equal to negative of static impedance, $\frac{V}{I}$.

There are three possible strategies for operation of an MPPT:

(a) By Monitoring Dynamic and Static Impedances A small signal current is being periodically injected into an array bus and the dynamic as well as static bus impedances (Z_d and Z_s respectively) are being measured. The operating voltage is then adjusted until the condition $Z_d = -Z_s$ is achieved.

(b) By Monitoring Power Output From the shape of P-V characteristics given in Fig. 6.14(c) it is clear that the slope, dP/dV is zero at maximum power point. This property is utilized to track the maximum power point. Voltage is adjusted and power output is sensed. The operating voltage is increased as long as dP/dV is positive. That is, voltage is increased as long as we get increased output. If dP/dV is sensed negative, the operating voltage is decreased. The voltage is held unaltered if dP/dV is near zero within a preset dead band.

(c) By Fixing the Output Voltage as a Fraction of V_{oc} This method makes use of the fact that for most PV cells the ratio of the voltage at maximum power point to the open circuit voltage, is approximately constant (say k). This is also evident from Fig. 6.14. For high quality crystalline silicon cell $k = 0.72$. In order to implement this principle, an additional identical unloaded cell is installed on the array to face same environment as the module in use and its open circuit voltage V_{oc} is continuously measured. The operating voltage of the array is then set at $k.V_{oc}$. The implementation of this scheme is simplest among all the available schemes.

Example 6.5

A PV source having IV characteristics as shown in Fig. 6.38 is supplying power to a load whose load line intersects the characteristics at (10 V, 8 A). Determine the additional power gained if an MPPT is interposed between the source and the load. If the cost of the MPPT is Rs. 4000.00, for how long the system needs to operate in order to recover the cost of MPPT. The cost of electricity may be assumed as Rs 7.00 per kWh. The efficiency of MPPT may be assumed as 95%.

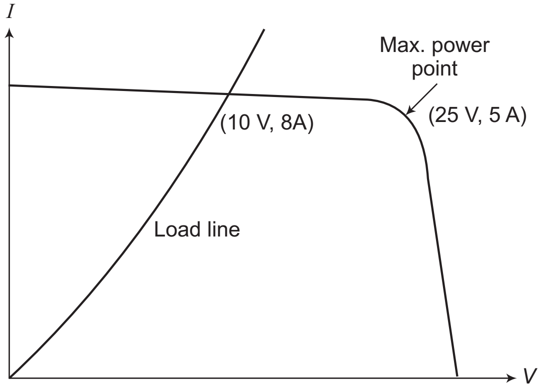


Figure 6.38 PV system – load characteristics

Solution

Power produced without MPPT = $10 \times 8 = 80$ W

Maximum power production capability of the PV module = $25 \times 5 = 125$ W

As the efficiency of the MPPT is 95%, actual power produced with MPPT = $125 \times 0.95 = 118.75$ W

Surplus power produced by use of MPPT = $118.75 - 80 = 38.75$ W

Surplus energy produce in t hours = $\dfrac{38.75 \times t}{1000} = 0.03875 \times t$ kWh

Cost of surplus energy = $7 \times 0.03875 \times t = 0.27125 \times t$

Cost of MPPT = Rs 4000

Time, t (in hours) required to recover the cost of MPPT = $\dfrac{4000}{0.27125} = 14746.54$ hours

6.9 BALANCE OF SYSTEM (BOS) COMPONENTS

The balance of system (BOS) includes components other than PV panel. These are batteries, charges, charge controllers, MPPT, inverter, mounting materials for the module, wire and all wiring components (including distribution panel, junction box and miscellaneous connectors), lightning protectors, grounding connections, battery fuses, battery cables and battery containers. In some cases, the connected loads are also considered to be part of BOS, for example, when the system is installed to operate a specific load.

Certain BOS components are regulated by codes or standards. Array mounts for example must meet wind-loading requirements of applicable building codes. Battery compartments are covered in the NEC (National Electrical Code). Also BOS components may need to be appropriate for environmental considerations.

6.9.1 Batteries

As solar energy is not available continuously and steadily, some form of energy storage is normally required in most PV systems. Lead acid battery, Nickle cadmium battery and Lithium ion storage batteries are commonly used in PV applications for this purpose. The principles of operation of these batteries are already covered in Section 3.4.2. Some general parameters of batteries are discussed here.

(a) Battery Voltage Three types of voltage available across its terminals are specified: (a) open circuit voltage (maximum voltage); (b) nominal or working voltage (available operating voltage during use), (c) cut-off voltage (minimum voltage after which the battery should be disconnected from the load for recharging). Rechargeable batteries are available with nominal voltages of 3 V, 6 V, 12 V, 24 V, etc.

(b) Battery Capacity It is the maximum charge storage capacity of a battery expressed in Ah. (Ampere-hour). Higher Ah requires more active material. Therefore, as the Ah capacity of a battery increases, the size of the battery also increases. Multiplying Ah with voltage gives energy storage of the battery in Wh (Watt-hours).

(c) Battery Life Cycle It is defined as the number of complete charge/discharge cycles that a battery can perform before its storage capacity falls below 80 per cent of its rated capacity. The aging process (for instance shedding of active material from plates) results in gradual reduction in storage capacity over time. The battery can still be used but its available storage capacity will be lower.

(d) State of Charge (SoC) The SoC at a particular instant indicates the amount of charge available with the battery at that instant. In lead acid battery, the electrolyte's specific gravity provides a convenient indication of the state of charge of the battery.

(e) Depth of Discharge (DoD) This is a measure of energy withdrawn from the battery expressed as percentage of its full capacity. If a battery has a state of charge as 60 per cent, it indicates that its DoD is 40 per cent. The DoD increases as the battery is discharged more and more. Large DoD adversely affects the life cycle of the battery.

(f) Discharge Rate or C-rating C-rating is defined as the charge or discharge current given in terms of capacity of the battery divided by number of hours for full

charge or discharge. For instance a 120 Ah capacity battery with C-rating of C/10 (or 0.1C), will have a charge or discharge current of 120/10 = 12 A. Similarly, a 180 Ah capacity battery with C-rating of C/20 (or 0.05C) will have a charge or discharge current of 180/20 = 9 A.

(g) Self-discharge Self-discharge is the loss of stored charge (or energy) when the battery is not in use. It is caused due to internal electrochemical processes and may be considered as equivalent to having a small external load. The self-discharge capacity increases with increase in temperature. Therefore, in order to reduce self-discharge, batteries must be stored at lower temperatures. In SIL batteries some antimony is alloyed with lead to improve mechanical strength. But it also results in increased self-discharge of the battery.

Deep Discharge Batteries

Ordinary batteries are not allowed to discharge beyond 50 per cent DoD. Batteries allowed discharging up to 80 per cent or more are known as deep discharge batteries. In traction applications where batteries are used to supply the load for longer duration, deep discharge batteries are used. Normal SLI (starting, lighting and ignition) batteries are shallow discharge batteries. They cannot be used in such applications as battery life cycle is significantly reduced due to deep discharge. In deep discharge batteries, the electrode plates are made thicker and stronger to avoid possible wrap of plates. In case of lead acid batteries, tubular batteries are used for such applications. SLI batteries remain at float charging most of the time. They are normally subjected to only 2–5 per cent depth of discharge during starting of a vehicle. Therefore, these batteries use thin plates with large surface area to supply large current during starting process.

Battery Temperature During Discharge

Both battery capacity and battery voltage decrease, if used at lower temperature. At high temperature also, its capacity may decrease due to deterioration in chemical reaction. Normally, the best battery performance is obtained in temperature range of 20 to 40 °C.

Battery Charging

Different methods of charging are suggested for different type of batteries. A lead acid battery may be charged by constant current, constant voltage or a combination of the two. A typical charging cycle for a lead acid battery is shown in Fig. 6.39. The lead acid battery is charged in three stages: (i) constant-current charge, (ii) topping charge and (iii) float charge (or trickle charge). The battery is first charged with a constant current (specified in data sheet) until its terminal voltage reaches the float potential value, $V_{B,\text{float}}$ (typically 2.3 V to 2.45 V per cell). The constant current charge applies the bulk of the charge (about 70 per cent) and takes up roughly half of the required charge time. Thereafter the battery is charged by constant voltage $V_{B,\text{ float},}$ as the current into the battery tappers off. This phase is known as topping charge phase and continues for few hours to fill the remaining 30 per cent. The battery is fully charged when the current drops to a set low level. Subsequently the applied voltage across the battery is reduced so that small amount of charge keeps trickling into the battery. The float charge compensates for the loss caused by self-discharge. Lead acid battery charging is sluggish and cannot be charged as quickly as other battery systems.

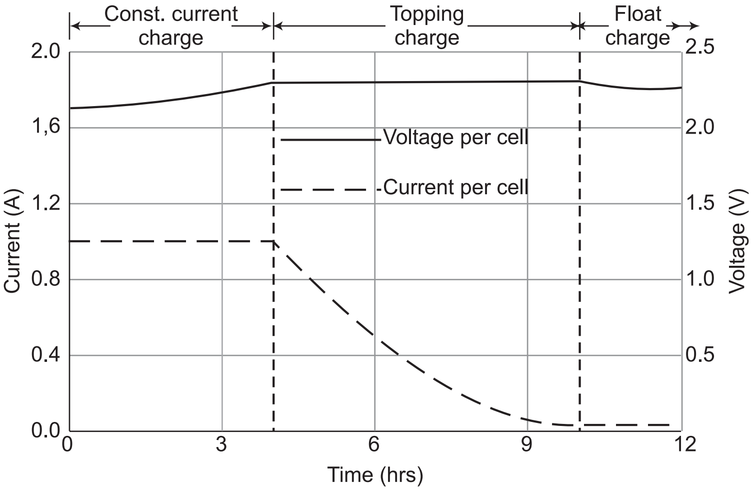


Figure 6.39 Typical charging of a lead acid battery

When a nickel-cadmium battery is charged, its temperature drops as does its voltage. The negative voltage slope or lowering of temperature below a threshold value can be used to stop the charging process.

Batteries used in PV Applications

The most commonly used batteries in PV applications are the lead acid and nickel-cadmium batteries. Lithium-ion and nickel-metal hydride are also used, but to a much lesser extent. Lead acid batteries are most popular. These batteries perform well in deep discharging mode than any other battery.

Table 6.3 Some of the comparative data for popular batteries used in PV applications

Battery type	Cell nominal voltage (V)	Self-discharge (% per month)	Battery life (in no. of cycle)	Energy density (Wh/kg)
Lead acid	2.0	5	700	30
Ni-Cd	1.2	10	1000-1500	45
Lithium-ion	3.7	3-5	500-1000	90
Nickel-metal hydride	1.2	30	500	80

6.9.2 Charge Controller

When PV systems are used for stand-alone applications, a battery backup is necessary to compensate for the balance power demand of the load, as it is fluctuating and unreliable source of energy. Battery feeds the load when PV output power is less than the load demand. It stores the energy when output PV power is more than load demand. In these applications it is important to prevent overcharging or deep discharging of the batteries to preserve their life and ensure better performance. A *charge controller* is used for this purpose. A block diagram of stand-alone PV system with battery backup and charge controller is shown in Fig. 6.40.

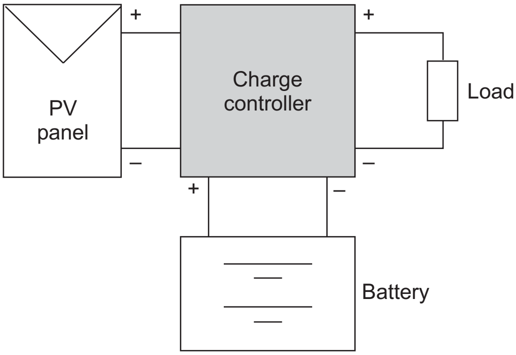


Figure 6.40 Stand alone PV system with charge controller and battery back-up

Commonly used Set Points in Charge Controllers

Charge controllers sense the SoC (state of charge) of the battery and prevent battery from overcharge or deep discharge by disconnecting the battery from source (solar panel) or load. The set points, on the basis of which the decisions for connection/ disconnection are taken, are shown in Fig. 6.41.

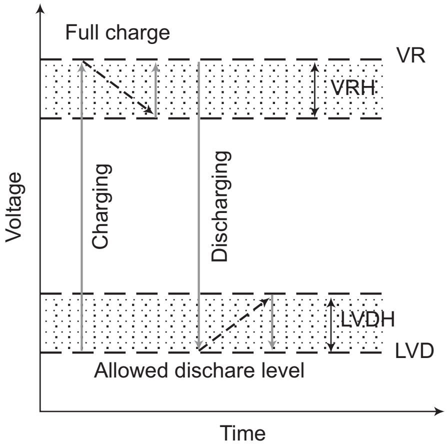


Figure 6.41 Charge controller set points

Voltage Regulation (VR) Set Point

This set point is the maximum voltage a controller allows the battery to reach. At this point a controller will either discontinue battery charging or begin to regulate the amount of current delivered to the battery. Proper selection of this set point depends on the specific battery chemistry and operating temperature.

Voltage Regulation Hysteresis (VRH)

This set point is voltage span or difference between the VR set point and the voltage when the full array current is reapplied. The greater this voltage span, the longer the array current is interrupted from charging the battery. If the VRH is too small, it will result in tighter regulation but the control element will oscillate, inducing noise and possibly harming the switching element. At the same time, large value of VRH may lead to slight overcharging of the battery during every cycle. The VRH is an important factor in determining the charging effectiveness of a controller.

Low Voltage Disconnect (LVD)

This set point is voltage at which the load is disconnected from the battery to prevent over discharge. The LVD defines the actual allowable maximum depth-of-discharge and available capacity of the battery. The available capacity must be carefully estimated in the system design and sizing process. The proper LVD set point will maintain good battery health while providing the maximum available battery capacity to the system.

Low Voltage Disconnect Hysteresis (LVDH)

This set point is the voltage span or difference between the LVD set point and the voltage at which the load is reconnected to the battery. If the LVDH is too small, the load may cycle on and off rapidly at low battery state-of-charge, possibly damaging the load and/or controller. If the LVDH is too large, the load may remain off for extended periods until the array fully recharges the battery. With a large LVDH, battery health may be improved due to reduced battery cycling, but this will reduce load availability. The proper LVDH selection will depend on the battery chemistry, battery capacity, and PV and load currents.

Types of Charge Controllers

Broadly, there are three types of charge controllers:

(i) Switch ON/OFF type charge controller
    (a) Shunt type charge controller
    (b) Series type charge controller
(ii) PWM (pulse width modulation) charge controller
(iii) MPPT (maximum power point tracking) charge controller

(a) Shunt Type Charge Controller The basic shunt type charge controller is shown in Fig. 6.42. In this type of charge controller, a switch S_1 is connected in shunt with PV panel. This switch is turned on when the battery voltage reaches its over voltage (VR) limit. The blocking diode prevents short-circuiting of the battery through S_1 as well as reverse current from battery to PV panel during night and low insolation periods. The switch S_2 allows the battery to supply the load till the battery voltage reaches the threshold voltage (LVD). Once the threshold voltage is reached, S_2 is turned off preventing deep discharge of the battery.

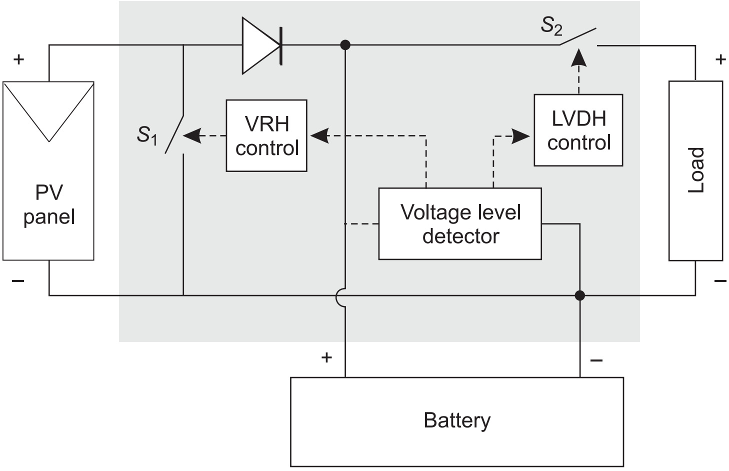


Figure 6.42 Shunt type charge controller

(b) Series Type Charge Controller The basic series type charge controller is shown in Fig. 6.43. Switch $S_{1,}$ which is connected in series with PV panel is turned off to prevent overcharge of the battery.

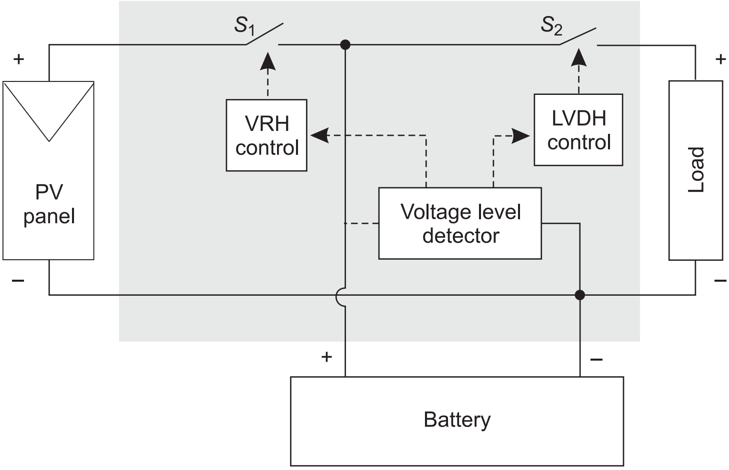


Figure 6.43 Series type charge controller

(c) PWM (Pulse Width Modulation) Charge Controller These are the most commonly used regulators in PV systems. By electronically controlling the high speed switching or regulation element, the PWM controller breaks the array current into pulses at some constant frequency, and varies the width and time of the pulses to regulate the amount of charge flowing into the battery. When the battery is discharged, the current pulse width is practically fully ON all the time. As the battery

voltage rises, the pulse width is decreased, effectively reducing the magnitude of the charge current. The PWM design allows greater control over exactly how a battery approaches full charge and generates less heat.

(d) MPPT (Maximum Power Point Tracking) Charge Controller These are the ultimate in controllers. By using a DC-DC converter between the PV panel and the battery, the PV output voltage and battery input voltage are decoupled. So the PV can be operated at a point of maximum power output. In this way maximum power is extracted from PV panel and battery charges in most efficient manner. With MPPT controller, sometimes, the PV module may be producing extra energy, which the load cannot consume and the battery is fully charged. In such cases a dump load may be required to absorb extra energy produced.

6.10 SOLAR PV SYSTEMS

6.10.1 Classification

Solar PV systems are broadly classified as:

1. Central Power Station System

Central PV power stations are conceptually similar to any other conventional central power station. They feed power to grid. These are being proposed in few MW range to meet daytime peak loads only. Central PV power stations of up to 6 MW_p (peak MW) capacities have already been experimented within USA and Europe. While the concept has been demonstrated through such experimental plants, the capital costs are currently somewhat high for their commercial exploitation.

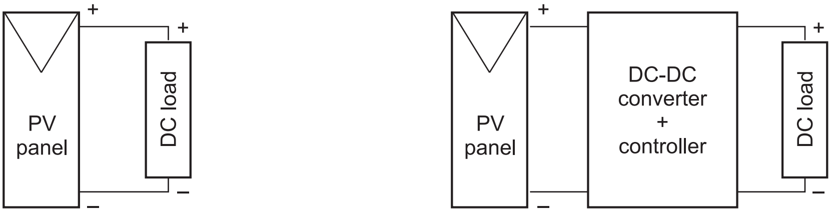
2. Distributed System

Distributed form of energy use is unique and much more successful with solar and most other renewable energy sources. These systems can be further divided into three groups:

(a) Stand Alone or Off Grid It is located at the load center and dedicated to meet all the electrical loads of a village/community or a specific set of loads. Energy storage is generally essential. It is most relevant and successful in remote and rural areas having no access to grid supply. Indicative capacity of such a system is 10 W_p–100 kW_p.

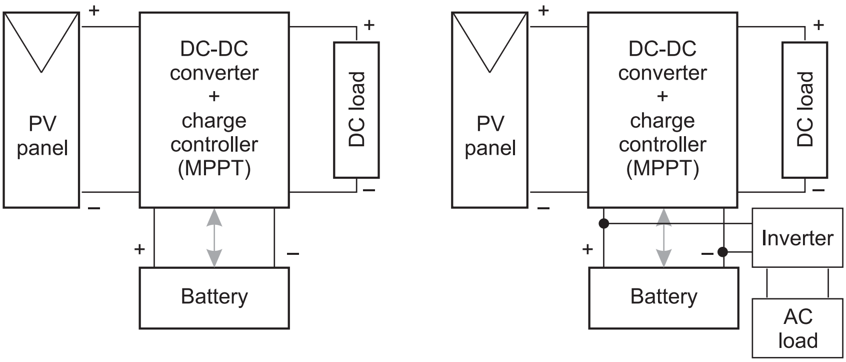
Various types of configuration for stand-alone PV system are shown in Fig. 6.44. In Config. 1, a dc load is directly connected to PV panel. This is the simplest possible configuration. Power is available only during sunshine hours and no arrangement is made for power storage. Such type of arrangement may be used for supplying raw dc load such as minor irrigation.

In Config. 2, a regulated power is supplied to the load. A DC-DC converter is inserted between panel and load. The converter may be controlled using MPPT algorithm to extract maximum power from the PV panel. Usually when MPPT is implemented a battery is used to absorb excess power, which the load cannot consume.



Config. 1: Unregulated system with dc load

Config. 2: Regulated system with dc load



Config. 3: Regulated system with battery and dc load

Config. 4: Regulated system with battery and dc/ac load

Figure 6.44 Various stand alone system configurations

Config. 3 is used for loads such as lighting for which battery storage is required. For safe charging and discharging operation a charge controller is also required. The use of battery ensures uninterrupted and smooth power availability. In the charge controller operation, MPPT may also be implemented to optimize the use of solar power.

Config. 4 also includes ac loads for which an inverter is also required. Since most of the commonly available loads are ac type, this configuration is suitable for most domestic and commercial applications.

(b) Grid-Interactive or Grid Tied This system is connected to the utility grid with two-way metering system. It may be a small rooftop system owned and operated by the house owner or a relatively bigger (rack mounted) system meant for the whole village or a community. It meets daytime requirements of the house owner without any battery backup and surplus power is fed to the grid. During peak hours and during nights the energy shortage may be met from grid. The grid serves as infinite source or sink of energy.

Grid-connected PV systems usually employ two stages, to appropriately condition the available solar power for feeding into the grid, as shown in Fig. 6.45. While the first stage is used to track the maximum solar power, the second stage inverts this DC power into high quality AC power.

Other configurations such as, single stage configuration as well as multistage (more than two) are also available for certain applications, which have their own merits and demerits.

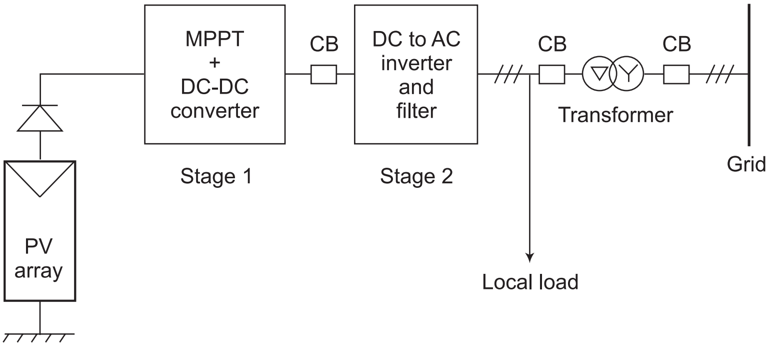


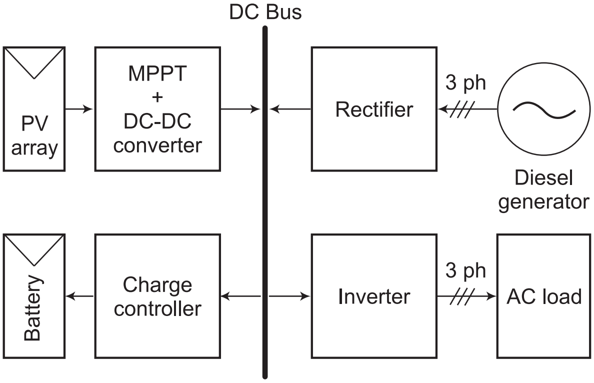
Figure 6.45 A typical grid connected solar PV system

(c) Hybrid PV System Sometimes it is not economical or practical to provide all energy from PV system. In such cases, it may be more economical to provide some of the system energy needs by another means, such as diesel/gasoline generator or any other non-conventional source like wind or fuel cell. Such a system is called hybrid system. The best cost-effectiveness is generally obtained when none of the PV generated energy is wasted. The integrated system provides auxiliary support and better reliability. Such a system is known as hybrid system. A hybrid system requires lesser amount of battery storage. Two typical hybrid configurations, known as series and parallel are shown in Fig. 6.46.

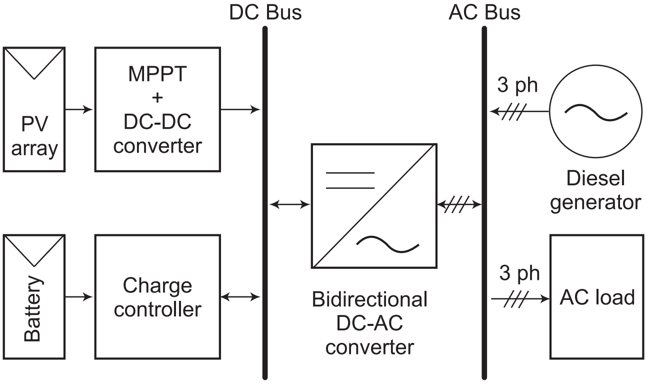
In series configuration, the PV array is connected to DC bus through charge controller and DC-DC converter to extract maximum PV power and raise its voltage to required level. The power generated by diesel source is first rectified to DC and then again converted to AC to feed the AC load. Battery is used to manage the balance of power. The configuration is known as series configuration because the two ac sources, diesel generator and inverter are not connected in parallel but in series. The generator supplies the load through series of rectifier and inverter. Therefore, the inverter supplies the total ac load current.

In parallel configuration, the two sources, the diesel generator and the inverter are connected in parallel to AC load. As a result the rating of the inverter is less and the efficiency is higher. However, proper synchronization is required between the output of diesel generator and inverter.

(d) Small System for Consumer Applications These systems are meant for low energy consumer devices requiring power in the range of microwatts to 10 W_p and mostly designed for indoor applications e.g. calculators, watches, electronic games, etc.



(a) Series configuration



(b) Parallel configuration

Figure 6.46 Solar PV hybrid configurations

6.10.2 Some Typical Design Examples

Example 6.6

Design a PV water pumping system for daily requirement of 7000 liters of water from a depth of 42 m (elevation = 10 m, standing water level = 30 m, drawdown = 2 m). Use following data:

Solar PV module used : “BP380” from **BP Solar**
Peak power = 80 W_p
Voltage at peak power (V_{pp}) = 17.6 V
Current at peak power ((I_{pp}) = 4.55 A
Operating factor = 0.8
(Due to various environmental factors, a solar panel does not operate at its rated peak power)
Mismatch factor = 0.85
(This factor arises due to operation at a point other than maximum power, if MPPT is used, this factor may be assumed to be unity)

Mono block (Pump + motor) efficiency = 30%
Water density = 1000 kg/m^2
Sunshine hours = 5 h/day (peak of 1000 W/m^2 equivalent)

Solution

A typical water pumping system is shown Fig. 6.47. Stand-alone PV configuration 1, as shown in Fig. 6.44 is employed.

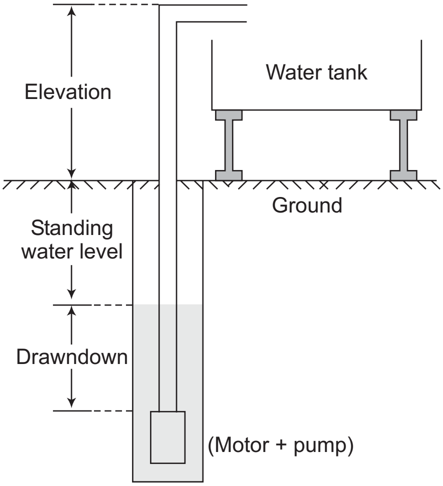


Figure 6.47 A typical water pumping system

Daily requirement of water = 7000 liter/day = 7 m^3/day
Total vertical lift = 42 m
Frictional losses = 5% of the total vertical lift = 42 × 0.05 = 2.1 m
Total dynamic head, h = 42 + 2.1 = 44.1 m
Hydraulic energy required per day to lift water

$$= m \times g \times h$$
$$= (1000 \text{ kg/m}^3)\ (7 \text{ m}^3)\ (9.8 \text{ m/s}^2)\ (44.1 \text{ m})$$
$$= 30,\ 25{,}260 \text{ J}$$
$$= 840.35 \text{ Wh}$$

Given: Sunshine hours = 5 h/day (peak of 1000 W/m^2 equivalent)
The required energy of 840.35 Wh is to be supplied by the (motor + pump) in 5 hours
Thus, required output power of (motor + pump) = 840.35 / 5 = 168.07 W
The efficiency of (motor + pump) = 30%
The input energy required by the (motor + pump) = 168.07/0.3 = 560.23 W
Power rating of (motor + pump) = 560.23 W = 560.23/746 = 0.75 hp
Thus 560.23 W is to be supplied by the panel
Considering the losses due to mismatch of operating point (op. point not same as MPP);
Required panel power = 560.23/0.85 = 659.1 W
Considering operating factor (system losses);
Required panel power = 659.1/0.8 = 823.87 W
Required number PV module (80 W$_p$ each) = 823.87 / 80 = 10.3 ≈ 11

Example 6.7

Design a pole mounted street lighting with 15 W CFL (DC) for a place near New Delhi. The solar insolation data for New Delhi are given in Table 6.4.

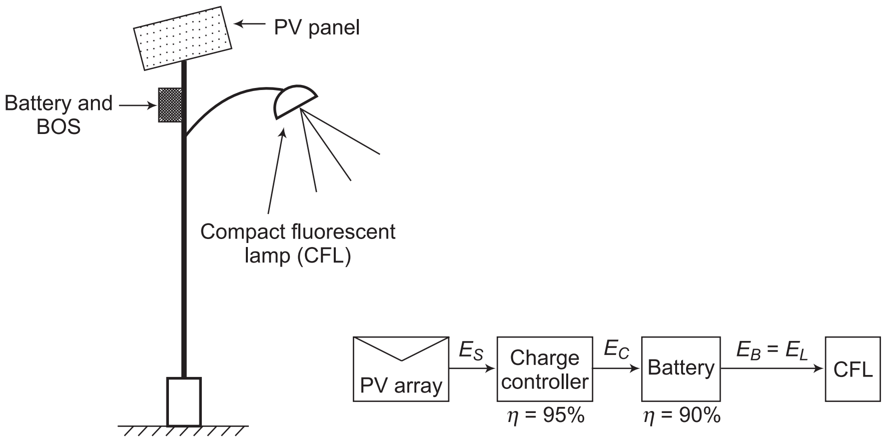
Table 6.4 Average daily peak sun hours, kW/m^2 at New Delhi, India

(Latitude: 28° 3′ N, Longitude: 77° 12′ E)

Month	Array tilted at Latitude –15°		Array tilted at latitude		Array tilted at latitude +15°		2-axis tracking array
	Fixed array	1-axis tracker	Fixed array	1-axis tracker	Fixed array	1-axis tracker	
Jan	5.04	6.38	5.83	7.38	6.28	7.87	7.92
Feb	6.37	8.09	7.04	8.97	7.31	9.23	9.24
Mar	7.05	8.60	7.31	9.02	7.18	8.83	9.05
Apr	7.12	9.23	6.94	9.17	6.42	8.50	9.30
May	7.38	9.83	6.87	9.36	6.08	8.25	9.86
Jun	6.76	9.15	6.19	8.53	5.38	7.32	9.23
Jul	4.50	6.31	4.20	5.94	3.75	5.17	6.34
Aug	5.53	7.44	5.30	7.27	4.83	6.60	7.46
Sep	5.66	7.23	5.70	7.44	5.46	7.13	7.45
Oct	6.09	7.34	6.57	7.99	6.69	8.09	8.13
Nov	5.62	7.49	6.43	8.56	6.88	9.05	9.08
Dec	4.87	6.06	5.73	7.11	6.26	7.68	7.77
Ann Avg	6.00	7.76	6.18	8.06	6.04	7.81	8.40
Min Value	4.5	6.06	4.2	5.94	3.75	5.17	6.34

Solution

In this problem, stand-alone configuration 3, as shown in Fig. 6.44 is employed. Main components of pole-mounted streetlight are shown in Fig. 6.48(a) and energy flow diagram is given in Fig. 6.48(b).



(a) Main components (b) Energy flow diagram

Figure 6.48 Solar powered pole mounted street lighting

Estimation of load requirement: Load is estimated in terms of energy requirement on daily basis. If the street light has to remain switched ON all night, it is necessary to determine the longest night of the year. Suppose the longest winter night at New Delhi is 16 hours. This means the shortest summer night will be 8 hours. It also means that the PV module on the shortest day of the year must produce enough energy to operate the CFL through the longest night of the year. On the other extreme, during the longest days, the PV module will produce electricity in excess of demand. A charge controller should be used to disconnect the battery from PV module to prevent over charging and thus reducing its life. The system will waste excess energy generated during longest days. A 15 W CFL for longest night (16 hours) means a maximum load requirement of $E_L = 15 \times 16 = 240$ Wh.

Deciding the system voltage: System voltage is chosen on the basis of the size of the load and designer's experience. General observation is that, system processing up to 2000 Wh should be fine at 12 V. System processing from 2000–7000 Wh will function better at 24 V. More than 7000 Wh system should preferably be running at 48 V.

In the present case, as the size is small, an appropriate system voltage will be 12 V

Estimation of battery requirement: As calculated above, the energy to be supplied by the battery (bank) = 240 Wh at 12 V

Required charge capacity = 240 Wh/12 V = 20 Ah

Assuming depth of discharge of the battery as: 70%

Usable battery storage required = 20/0.7 = 28.6 Ah

The available commercial battery capacities are 25 Ah, 30Ah, 40 Ah, 45 Ah, 50 Ah, 100 Ah etc.

Let us use available battery unit of 30 Ah, 12 V

This rounding off will give us some extra capacity (30 Ah instead of 28.6 Ah)

Therefore, a single 30 Ah and 12V battery (with zero autonomy) may be used. Thus, $(\text{Ah})_{\text{daily}} = 30$ Ah

Consideration of battery autonomy: More batteries will be required if we want some autonomy during completely cloudy condition. The autonomy is defined as the number of days the battery is able to supply the load for those number of days when there is no sunshine (that means when no power is generated by PV panels). Thus depending on the required number of days of autonomy, the battery bank size should be increased. If total daily required Ah is $(\text{Ah})_{\text{daily}}$ and n is the number of days of autonomy, then total required Ah capacity of battery (including autonomy period) is given by:

$$\text{Total required Ah} = (\text{Ah})_{\text{daily}} + n \times (\text{Ah})_{\text{daily}} \tag{6.43}$$

Considering one day autonomy, $n = 1$;

Required Ah of the battery including autonomy, = 30 + 1 × 30 = 60 Ah

Now, instead of one battery we would require 2 batteries of 12 V and 30 Ah. These two batteries are to be connected in parallel as system voltage is 12 V. Alternatively, we can use a single battery of 12 V and 60 Ah.

Sizing of the PV module: As calculated above, the energy supplied by the battery (bank), $E_B = E_L = 240$ Wh at 12 V

Assuming battery efficiency as 90%, the energy received by the battery = 240/0.9 = 266.66 Wh

Thus, the energy supplied by the charge controller to the battery, $E_C = 266.66$ Wh

Assuming charge controller efficiency as 95%, the energy supplied to the charge controller by PV panel, $E_S = 266.66/0.95 = 280.69$ Wh

Thus 280.69 Wh energy should be supplied by solar panel every day.

At this point, a degradation factor, to account for degradation due to dust settlement, high operating temperature etc. may be considered. Thus PV panel with generating capacity of higher than 280.69 Wh may be required. However, in this example we are not considering the degradation in performance of solar PV panel.

To charge the battery, the PV panel needs to supply the energy to the battery at 12 V. Therefore, total Ah generated by PV panels should be 280.69/12 = 23.39 Ah

Considering fixed array for three tilts: namely, (latitude – 15°), latitude and (latitude + 15°), maximum annual average daily peak sun hours (assuming 1000 W/m^2 irradiance) is seen to be 6.18 hours for array tilted at altitude. That means the array tilted at latitude will collect maximum annual energy. Therefore, we choose PV panel tilted at latitude.

After deciding the tilt angle of PV panel let us now focus on the size of the array. To size the array, the peak sun hours of shortest day are needed. The shortest peak sun hours are found to be 4.20 hours in the month of July (from Table 6.4). That means a production rate of 23.39/4.2 = 5.57 A is required in the worst condition.

Let us use 80 W_p module for which voltage and current at peak power point are given as, $V_m = 17.6$ V and $I_m = 4.55$ A. Since one module can produces 4.55 A, we require 5.57/4.55 = 1.22 or on rounding off 2 panels will be required. These panels should be connected in parallel.

Example 6.8

Design a solar PV system for a rooftop mounted system for the loads, whose details are given in Table 6.5. Minimum sunshine hours may be assumed as 5 hrs.
Given:

Solar PV panel to be used are: $W_p = 80$ W, $V_m = 17.6$ V, $I_m = 4.55$ A
Operating factor = 0.8
Battery efficiency = 85%
Inverter efficiency = 95%
Charge controller efficiency = 95%
Days of autonomy = 1
Use PV module: “BP380” from **BP Solar,** whose data are given below:
Peak power = 80 W_p
Voltage at peak power (V_{pp}) = 17.6 V
Current at peak power ((I_{pp}) = 4.55 A
Assume operating factor of 0.8

Table 6.5 Rooftop mounted solar PV system load details

Load	Rating (Watts)	Number	Power (Watts)	Hours/day	Wh
CFL	15	5	75	4	300
Fan	75	4	300	3	900
TV	100	1	100	3	300
Computer	250	1	250	2	500
Refrigerator	150	1	150	12	1800
Total	-	-	875	-	3800

Solution

The energy flow diagram is shown in Fig. 6.49.

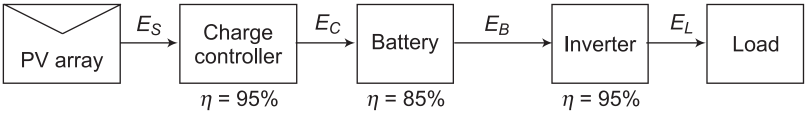


Figure 6.49 Energy flow diagram

Estimation of load requirement: Load is estimated in Table 6.5 in terms of Wattage requirement and energy requirement on daily basis. As estimated in Table 6.5, the Wattage requirement is 875 W and energy requirement is, E_L = 3800 Wh.

Determining the rating of inverter:

Power handling capacity of inverter = 875 W

Since all loads are AC, the inverter output voltage = 220 V, (50 Hz)

The inverter output energy (supplied to the load, on daily basis), E_L = 3800 Wh

Inverter efficiency = 95%

The inverter input energy E_B = 3800/0.95 = 4000 Wh

Deciding the system voltage: Please refer to discussion on this topic in the preceding example. In the present case, as the size of the system is medium, an appropriate system voltage will be 24 V

Sizing of battery (bank): As calculated above, the energy to be supplied by the battery (bank) E_B = 4000 Wh at 24 V

Required charge capacity = 4000 Wh / 24 V = 166.66 Ah

Assuming depth of discharge of the battery as: 70%

Usable battery storage required = 166.66/0.7 = 238.1 Ah

The available commercial battery capacities are 25 Ah, 30Ah, 40 Ah, 45 Ah, 50 Ah, 100 Ah, 120 Ah, etc.

Let us use available battery unit of 120 Ah, 12 V

Number of batteries required = 238.1/120 = 1.98 ≈ 2

This rounding off will give us some extra capacity (240 Ah instead of 238.1 Ah)

Thus the available daily stored ampere-hour, $(Ah)_{daily} = 240$ Ah

These 2 batteries are to be connected in parallel to add up Ah. But these 240 Ah will be available at 12 V only. This battery bank needs to supply 240 Ah at 24 V. Therefore, two 12 V batteries should be connected in series to get 24 V. Two such series need to be connected in parallel. Therefore, in total 4 number of 120 Ah, 12 V batteries are needed (with zero period of autonomy).

Consideration of battery autonomy: For 1 day of autonomy, $n = 1$, the required Ah may be calculated from Eq. (6.3):

$$\begin{aligned}\text{Total required Ah} &= (\text{Ah})_{\text{daily}} + n \times (\text{Ah})_{\text{daily}} \\ &= 240 + 1 \times 240 \\ &= 480 \text{ Ah}\end{aligned}$$

Now, instead of 4 we would require 8 batteries of 12 V and 120 Ah. The battery bank connections are shown in Fig. 6.50.

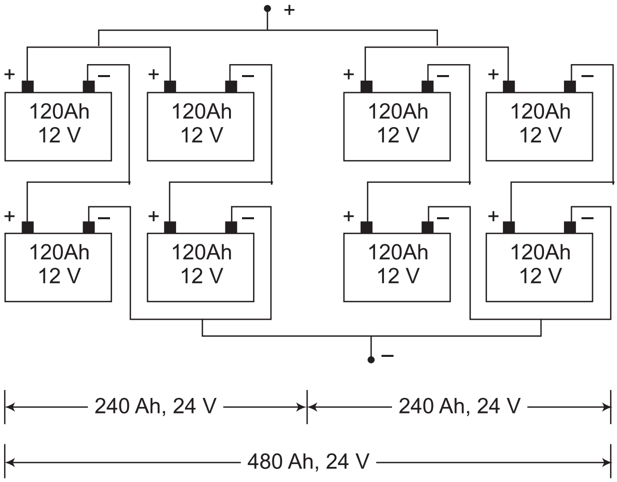


Figure 6.50 Battery bank, 480 Ah, 24 V

Determining the rating of charge controller: As calculated above, the daily energy supplied by the battery bank to the inverter = 4000 Wh

The battery efficiency is 85%.

Therefore, the energy supplied to the battery bank $E_C = 4000/0.85 = 4705.8$ Wh

This is in fact the output energy of charge controller.

Sizing of the PV module: The energy supplied by the charge controller to the battery, $E_C = 4705.8$ Wh

Assuming charge controller efficiency as 95%, the energy supplied to the charge controller by PV panel, $E_S = 4705.8/0.95 = 4953.47$ Wh

At this point, a degradation factor, to account for degradation of PV panel due to dust settlement, high operating temperature etc. may be considered. In this example, this is given as 0.8.

Thus net energy rating of the PV panel = 4953.47/0.8 = 6191.8 Wh

This 6191.8 Wh energy need to be supplied at 24 V. Therefore, total Ah generated by PV panels should be 6191.8/24 = 258 Ah

Minimum sunshine hours are given as 5 hrs. That means a production rate of 258/5 = 51.6 A is required in the worst condition.

Let us use 80 W_p module for which the current at peak power point is I_m = 4.55 A. Since one module can produces 4.55 A, we require 51.6/4.55 = 11.3 or on rounding off 12 modules. These modules should be connected in parallel. As nominal voltage of PV panel is 12 V but the system voltage is 24 V. Therefore, to generate 24 V we have to connect 2 modules in series and 12 such series connections in parallel as shown in Fig. 6.51. Thus a total of 24 modules need to be employed.

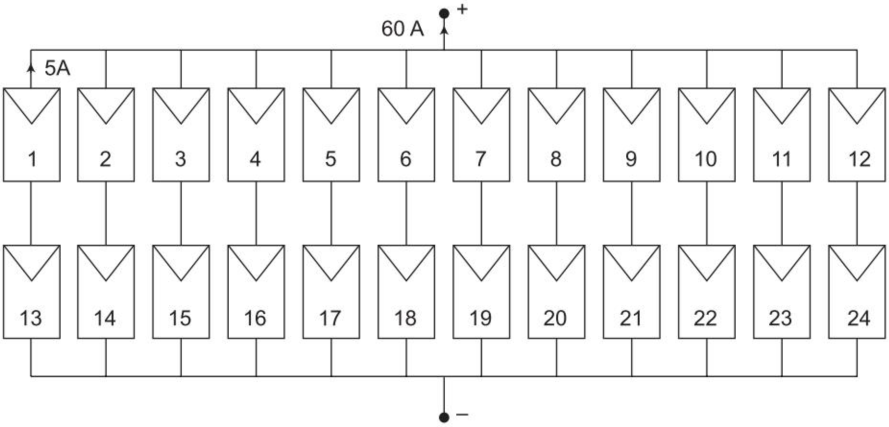


Figure 6.51 Series parallel connections of modules

Wire sizing: Normally, the voltage drop in the line connecting the modules to battery should not be more than 5% of the line voltage. Similarly, the voltage drop in the line connecting battery and the load should not be more than 5% of the line voltage.

6.11 SOLAR PV APPLICATIONS

6.11.1 Grid Interactive PV Power Generation

The first large sized (1 MW_p) grid interactive PV plant was installed in Lugo, in California, USA. The second and largest (6.5 MW_p) plant was installed in Carissa Plains, California, USA. Also some other large sized plants are operating in various countries and many others are proposed in Italy, Switzerland, Germany, Austria, Spain and Japan.

Presently, the biggest solar PV plant of 579 MW capacity, solar star project, is located at Antelope valley, Los Angeles County, California. This is followed by a 550 MW Desert Sunlight Star at Riverside County, and 550 MW Topaz Solar farm at San Louis, Obispo County, California.

In India, a 221 MW solar PV plant at Chankara, Gujarat is the biggest plant. Another 750 MW plant is underway at Rewa, MP.

A large number of small rooftop grid interactive systems are successfully being operated in various parts of the world.

6.11.2 Water Pumping

Pumping of water for the purpose of drinking or for minor irrigation, during sunshine hours, is very successful application of stand-alone PV system without storage. Water pumping appears to be most suited for Solar PV applications as water demand increases during dry days when plenty of sunshine is available. There would be less need of water during rainy season when the availability of solar energy is also low. SPV water pumping systems have been successfully used in many parts of the world in the range of few hundred W_p to 5 $kW_{p.}$ An SPV water pumping system is expected to deliver a minimum of 15,000 liters per day for 200 W_p panel and 1, 70,000 liters per day for 2,250 W_p panel from suction of 7 meters and / or a total head of 10 meters on a clear sunny day. Three types of motors have generally been used: (i) permanent magnet dc motor (in low capacity pumping systems), (ii) brush-less dc motors and (iii) variable voltage and variable frequency ac motors, with appropriate electronic control and conversion system. An SPV water pumping system for a fishing farm is shown in Fig. 6.53.

Figure 6.52 A 221 MW Solar Park at Charanka Village, Distt. Patan, Gujarat, India

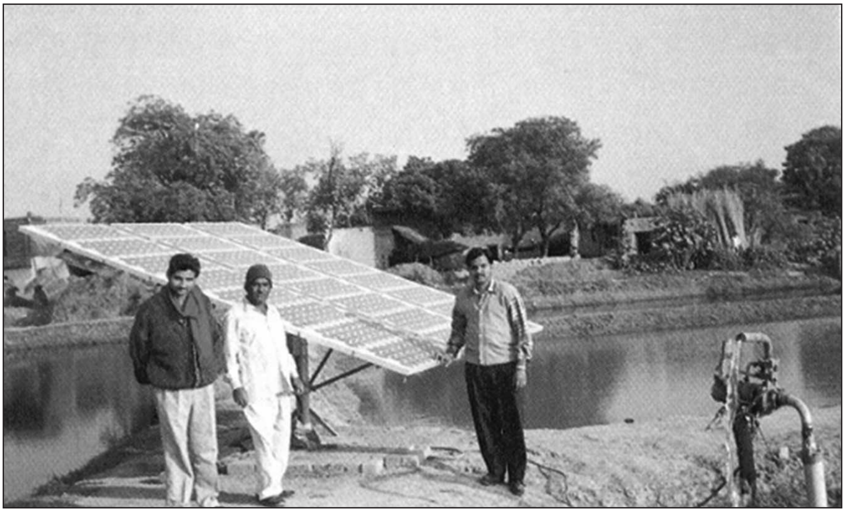


Figure 6.53 An SPV water pumping system for fishing form

Source: MNES Annual report

6.11.3 Lighting

Next to water pumping, lighting is the second most important and extensive application of stand-alone solar PV system. As lighting is required when sun is not available battery storage is essential. Energy efficient compact fluorescent lamps (CFL) or low-pressure sodium vapour lamps (LPSVL) are used at 25–35 kHz frequencies, as SPV is an expensive power source. Pole mounted out-door lighting, shown in Fig. 6.54, is designed for 3–6 hours an evening. A typical system has two 35 W_{FP} modules connected in parallel, an 11W (900 lumens) CFL, a 90 or 120 Ah, 12 V storage battery and associated electronics including inverter, battery charger and timer to switch on and off the light. The approximate cost of one pole mounted streetlight is Rs 30,000.

Figure 6.54 Pole mounted SPV lighting

Source: MNES Annual report

A portable SPV lantern, shown in Fig. 6.55, is usually designed to operate for 2–6 hours. A typical system consists of 10 W_p module, a 5–7 W CFL, a 7Ah, 12 V battery and associated electronics and hardware. The cost of portable solar lantern varies from Rs 4000 to Rs 5000.

Figure 6.55 Solar lantern

Source: Tata BP Solar product

6.11.4 Medical Refrigeration

Many life-saving medical supplies, particularly vaccines, require refrigeration during storage and transportation in order to remain effective. For life saving vaccines the World Health Organization (WHO) has laid down ground rules to maintain the cold chain from point of their manufacture to their application. In many developing countries where such life-saving vaccines are in great demand, electricity is not available to operate conventional refrigerators. WHO has specified technical details for PV based refrigerators using solar energy for such applications. This has resulted in success of WHO sponsored immunization program in these countries. The volume of refrigerator chamber varies from 20-100 liters with freezer volume ranging from 10–35 liters. The PV module size ranges from 100 W_p to over 600 $W_{p,}$ with 12 V / 24 V battery, of 150 to over 600 Ah capacities. An SPV powered portable medical refrigerator is shown in Fig. 6.56.

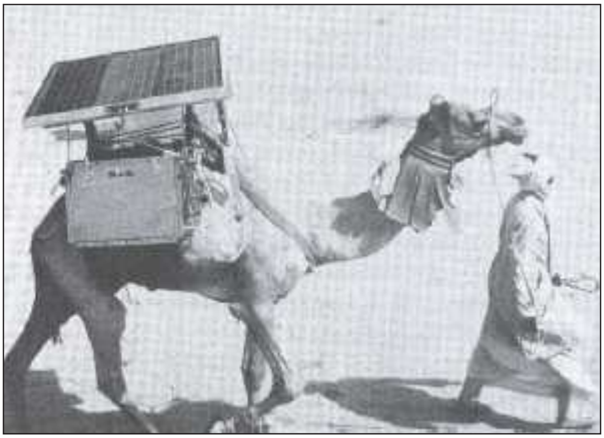


Figure 6.56 An SPV powered portable medical refrigerator

6.11.5 Village Power

Solar PV power can be used to meet low energy demands of many remote, small, isolated and generally unapproachable villages in most developing countries. Two approaches have generally been used:

(i) Individual SPV system for every household
(ii) A centralized SPV plant to meet combined load demand of the whole village

Both approaches have been extensively tried out in most parts of the world, particularly in developing countries. Whereas centralized village PV power system require large scale integrated planning and execution, individual village household system may be available off-the-shelf. In many Asian and African countries, PV kits are available to cater to the needs of the later types.

6.11.6 Telecommunication and Signaling

Solar PV power is ideally suited for telecommunication applications such as, local telephone exchange, radio and TV broadcasting, microwave and other forms of electronic communication links. This is because, in most telecommunication applications, storage batteries are already in use and the electrical systems are basically dc. An SPV for satellite earth station is shown in Fig. 6.57.

Figure 6.57 SPV for satellite earth station

In hilly and mountainous terrain, radio and TV signals may not reach as they get blocked or reflected back due to undulating terrain. At these locations, either low power transmitters (LPT) or very low power transmitters (VLPT) are installed to receive and retransmit the signal for local population. As these locations are generally remote and normal grid supply is not available, these are powered by solar photovoltaic electricity. Each VLPT is designed to operate completely unattended. It consists of a 10 W transmitter with daily mean energy consumption of less than 4 kWh. Usually a 1.7 kW_p SPV system with battery storage, enough to last for 6 days in cloudy season is provided.

On highways, SPV power is being used for lighted road signs, highway telephone booths etc. even in many industrialized nations. Indian Railways are now using standalone SPV system for applications such as: semaphore signaling, automatic radio controlled level crossing audio-visual alarms, etc. These applications are highly cost effective in comparison to kerosene light used earlier.

REVIEW QUESTIONS

1. Which is the most expensive component in a solar PV system?

2. What are major advantages and disadvantages of a solar PV system? **(UPTU Lucknow 2003-04)**

3. What are the advantages and disadvantages of direct energy conversion system over the conventional power generation system? **(UPTU Lucknow 2003-04)**

4. Describe the principle of solar photovoltaic energy conversion. **(UPTU Lucknow 2003-04)**

5. What are direct and indirect gap materials?

6. Explain the mechanism of photoconduction in a PV cell.

7. Explain the I-V characteristics of a solar cell and define fill factor. What is the significance of fill factor?

8. Explain, how the variation of insolation and temperature affects the I-V characteristics of a solar cell?

9. Explain various factors contributing to losses and hence reduction of efficiency of a solar cell.

10. What do you understand by energy payback period?

11. Explain various types of solar cells based on material thickness and the type of junction structure.

12. Explain the main features of different types of solar cells based on the active material used in their fabrication.

13. What do you understand by cell mismatch in a solar module and what are its implications?

14. What is the effect of partial or complete shadowing of a cell in a module?

15. Illustrate the concept of load mismatch in an SPV-load system.

16. What is the importance of MPPT in an SPV system? Explain various strategies used for operation of an MPPT.

17. With the help of block diagrams explain the operations of stand-alone and grid interactive SPV systems.

18. Distinguish between an abrupt and graded *PN* junction.

19. Explain depletion region and barrier voltage.

20. How are electron-hole pairs generated when solar radiation is directed on a semiconductor material?

21. Draw and explain an equivalent circuit of a practical solar PV cell.

22. Describe the classification of solar cells based on the type of active material used.

23 . Explain with suitable diagrams, the working of various types of solar photovoltaic power plant. **(UPTU Lucknow 2007-08)**

PROBLEMS

1. In an *N*-type silicon, the effective density of states in conduction band is 1×10^{22} cm^{-3}. What level of donor concentration is required to move the Fermi level close to conduction band by 0.2 eV? Assume room temperature as 0°C.

(*Ans.* 4.19×10^{18} cm^{-3})

2. The band gap for GaAs is 1.43 eV. Calculate the optimum wavelength of light for photovoltaic generation in a GaAs cell.

(*Ans.* 0.867 μm)

3. Calculate the open circuit voltage of a silicon solar cell at 47 °C if short circuit and reverse saturation currents are given as 2A and 10 nA respectively.

(*Ans.* 0.5275 V)

4. Solve the problem given in Example 6.4 by considering a load that intersects the PV characteristics at (26V, 2A), other data remaining the same.

(*Ans.* 8,560.7 hrs)

5. A photovoltaic system is installed for supplying water for minor irrigation needs at a remote place in a developing country. The water is pumped through a bore well from a depth of 25 m. The PV array consists of 24 modules. Each module has 36 multicrystalline silicon solar cells arranged in 9 × 4 matrix. The cell size is 125 mm × 125 mm and cell efficiency is 12 per cent. The combined motor and pump efficiency is 50 per cent. Calculate the water discharge rate at noon when global radiation incident normally to the panel is 800 W/m^2. Assume density of fresh water as 996 kg/m^3.

(*Ans.* 2.653 liters/s)

6. Design a PV water pumping system for daily requirement of 6000 liters of water from a depth of 32 m (elevation = 10 m, standing water level = 20 m, drawdown = 2 m). Use following data:

Solar PV module used : "BP380" from BP Solar

Peak power = 80 W$_p$

Voltage at peak power (V_m) = 17.6 V

Current at peak power (I_m) = 4.55 A

Operating factor = 0.75

(Due to various reasons, a solar panel does not operate at its rated peak power)

Mismatch factor = 0.85

(This factor arises due to operation at a point other than maximum power, if MPPT is used, this factor may be assumed to be unity)

Mono block (Pump + motor) efficiency = 30%

Water density = 1000 kg/m^2

Sunshine hours = 4 h/day (peak of 1000 W/m^2 equivalent)

7. Design a pole mounted street lighting with 9 W CFL (DC) for a place near New Delhi with 2 days of battery autonomy period. The solar insolation data for New Delhi are given in Table 6.4.

8. Design a solar PV system for a rooftop mounted system for the loads, whose details are given in Table below. Minimum sunshine hours may be assumed as 5 hrs.

Given:

Solar PV panel to be used are: $W_p = 80$ W, $V_m = 17.6$ V, $I_m = 4.55$ A

Operating factor = 0.75

Battery efficiency = 90%

Inverter efficiency = 95%

Charge controller efficiency = 95%

Days of autonomy = 2

Use PV module: "BP380" from BP Solar, whose data are given below:

Peak power = 80 W_p

Voltage at peak power (V_{pp}) = 17.6 V

Current at peak power ((I_{pp}) = 4.55 A

Assume operating factor of 0.75

Load	Rating (Watts)	Number	Power (Watts)	Hours/day	Wh
CFL	9	3	27	3	81
Fan	60	1	60	4	240
TV	100	1	100	3	300
Computer	250	1	250	2	500
Total	-	-	**437**	-	**1121**

OBJECTIVE TYPE QUESTIONS

1. A solar cell is basically:
- (a) a voltage source, controlled by flux of radiation
- (b) a current source, controlled by flux of radiation
- (c) an uncontrolled current source
- (d) an uncontrolled voltage source

2. The efficiency of a commercial solar cell lies in range:
- (a) 0–10%
- (b) 10–20%
- (c) 20–30%
- (d) 50–60%

3. Typical open circuit voltage of a solar cell is:
- (a) 12 V
- (b) 6 V
- (c) 3 V
- (d) 0.5 V

4. Which of the following statement is not true about solar cell?
- (a) It has no moving part.
- (b) It is reliable and almost maintenance free.

(c) It is modular in design.
(d) It is cheap and efficient.

5. The charge carrier available in a semiconductor material:
(a) free electrons and holes
(b) only electrons
(c) only holes
(d) positively charged ions

6. The Fermi level in an intrinsic type semiconductor material:
(a) is close to conduction band and away from valance band
(b) is close to valance band and away from conduction band
(c) lies in the middle of energy gap
(d) lies within the valance band

7. The energy level of donor ions are:
(a) very close to conduction band
(b) very close to valance band
(c) lies in the middle of energy gap
(d) lies within the conduction band

8. The energy associated with a photon is:
(a) directly proportional to wavelength
(b) inversely proportional to frequency
(c) directly proportional to intensity of radiation
(d) inversely proportional to wavelength

9. What is responsible for movement of carriers after creation of an electron-hole pair due to radiation?
(a) Diffusion process
(b) Drift process
(c) Built in electric field across the junction
(d) External voltage

10. The short circuit current of a solar cell is:
(a) inversely proportional to radiation intensity
(b) directly proportional to radiation intensity
(c) constant and not affected by radiation
(d) changes logarithmically with radiation

11. At maximum power point of the solar cell:
(a) current is maximum
(b) voltage is maximum
(c) both voltage and current are maximum
(d) the product of voltage and current are maximum

12. The photons having energy less than the energy gap:
(a) are absorbed and converted to heat
(b) are not absorbed by the semiconductor material as it behaves as transparent to them
(c) work jointly to produce electron-hole pair
(d) are reflected from semiconductor material surface

13. Energy payback period of a single crystal silicon cell:
(a) 6 months to 1 year
(b) 1 to 3 years
(c) 10 to 20 years
(d) 3 to 5 years

14. In a homogeneous *pn* junction:
(a) the width of *p* and *n* layers are equal and constant throughout
(b) the impurity levels on both sides of the junction are same
(c) same semiconductor material is used on both sides of the junction
(d) different semiconductor material on both sides of the junction but same level of doping

15. In a series string of mismatched solar cell:
(a) full voltage and current capability can be attained and losses are less
(b) losses are less
(c) full current capability cannot be attained and losses are more
(d) full voltage capability cannot be attained and losses are more

16. If no load is connected to solar PV system:
(a) it will stop absorbing light
(b) it will dissipate energy in the panel and increase its temperature
(c) its voltage will go on increasing till its breakdown
(d) it will start reflecting the light

17. An MPPT is basically :
(a) a dc-dc switching regulator (b) an ac–dc converter
(c) a dc–ac inverter (d) an amplifier

18. A grid interactive solar system:
(a) always supplies power to the grid
(b) supplies power to as well as receives power from the grid as required
(c) always receives power from the grid
(d) works only when the grid fails

19. At a temperature of 0 K, silicon behaves as a (an):
(a) superconductor (b) normal conductor
(c) insulator (d) semiconductor

20. When a photon having sufficient energy is directed to direct band gap material:
(a) it is absorbed by the material easily.
(b) it is absorbed by the material with difficulty.
(c) it is not absorbed and reflected back.
(d) it just passes through the material.

21. In an intrinsic semiconductor material, when temperature is increased, Fermi function:
(a) shifts up without changing its shape
(b) shifts down without changing its shape
(c) its shape does change and it does not shift up or down
(d) its shape changes and it does not shift up or down

22. If band gap of solar cell material decreases, then:
(a) its short circuit current increases (b) its short circuit current decreases
(c) its open circuit voltage increases (d) its open circuit voltage decreases

23. If band gap of solar cell material increases, then:
(a) its open circuit voltage increases.
(b) its open circuit voltage decrease
(c) its open circuit voltage remains unchanged
(d) its reverse saturation current increases

24. The use of MPPT:
(a) increases the solar energy received on the module.
(b) sets the operating point at maximum voltage
(c) sets the operating voltage at maximum current
(d) sets the operating voltage and current for maximum power output

25. In deep discharge batteries, the allowed DoD is:
(a) 5% (b) 20%
(c) 40% (d) 80%

CHAPTER 7

Wind Energy

Learning Objectives

In this chapter you will be able to:

- ➤ Define basic terms and definitions
- ➤ Know how the winds originate
- ➤ Understand the nature of winds and estimation of wind energy generation potential at a site
- ➤ Explore the methods to extract energy from winds using various types of devices
- ➤ Explain the detailed theory involved in harnessing of wind energy
- ➤ Identify means and methods of storing the energy generated from wind
- ➤ Describe complete electrical energy generation system from wind energy
- ➤ Analyse the effect of wind energy generation and use on environment
- ➤ Appraise the current status of wind energy in India

7.1 INTRODUCTION

Wind energy is the kinetic energy associated with movement of large masses of air. These motions result from uneven heating of atmosphere by the sun, creating temperature, density and pressure differences. It is estimated that 1 per cent of all solar radiation falling on the face of the earth is converted into kinetic energy of the atmosphere, 30 per cent of which occur in the lowest 1000 m of elevation. It is thus an indirect form of solar energy. In contrast to diurnal availability of direct solar radiation, wind energy can be available continuously throughout 24-hour day for much longer periods, though it can vary to a great extent including no-wind periods. It is a clean, cheap, and eco-friendly renewable source. Main disadvantages are: it is a dispersed, erratic and location-specific source. Wind energy is harnessed as mechanical energy with the help of wind turbine. The mechanical energy thus obtained can either be used as such to operate farm appliances, water pumping, etc., or converted to electric power and used locally or fed to a grid. A generator coupled to wind turbine is known as *aero-generator*. Very slow winds are useless, having no possibility of power generation. On the other hand very strong stormy winds cannot be utilized due to safety of turbine. Moderate to high-speed winds, typically from 5 m/s to about 25 m/s are considered favourable for most wind turbines. The global potential in winds for large-scale grid-connected power generation has been estimated as 12,300 TWh/year or 1.4 TW_e continuous flow of power ($1T = 10^{12}$) [46]. Favourable winds for small-scale applications such as wind pumps, battery chargers, heaters, etc., are estimated to be available on about 50 per cent of earth's surface that means small-scale wind turbines can be practical in many parts of the world.

The idea of harnessing winds is not new. It was one of the first natural energy sources to be used by mankind. There are indications that windmills were used in Babylon and China around 2000 to 1700 B.C. to pump water and grind grains. Egyptians used wind power to sail ships in the Nile some 5000 years ago. It has traditionally been used worldwide for ship propulsion until the start of industrial era. In Persia and Afghanistan windmills were used around 7th century A.D. for grinding grains. Europeans imported the technology from the east and were probably the first to introduce the horizontal axis windmill around 12th century, and by 1750, Holland had 8,000 windmills and England had 10,000. Their use, however, declined after the introduction of James Watt's steam engine in late 18th century and further declined in 20th century as a result of availability of cheap, reliable fossil fuels and hydropower. The electric power generation through wind was first proposed in Denmark in 1890 and many aero-generators were built in Europe and elsewhere.

The interest in wind energy has renewed after the oil crisis of 1973. Most modern, large-scale wind energy systems were built after 1980 using modern engineering designs, materials and incorporating microelectronics monitoring and control. Several demonstration and commercial plants of different sizes, from few kW to few MW are in operation in different parts of the world. Improved turbine designs and plant utilization have contributed to reduction of large-scale wind energy generation cost from Rs 17.00 per kWh in 1980 to about Rs 3.75 per kWh at present, at favourable locations [47]. With modern blade materials the expected life of wind turbine has exceeded 20 years. The installation cost has come down to a level comparable to that of a conventional thermal plant, i.e. about Rs. 4.5 crore/MW [47]. The energy payback period of a wind turbine is about one year. Due to these reasons, wind energy is gaining increasing acceptance and competing with conventional power sources. It is the fastest growing energy source among all renewables in recent years. United Kingdom is building 15 huge offshore wind forms, to provide most of the added electricity England will need in the coming two decades. The global installed capacity by end of year 2014 has reached 371 GW. In year 2014, wind energy installation has crossed 50 GW mark for the first time. More than 51 GW of new wind power capacity was brought on line, a sharp rise in comparison to 2013, when global installations were just over 35.6 GW [45]. The current status of wind energy is discussed in Section 1.15.2.

Globally, wind energy has become a mainstream energy source and an important player in the world's energy markets, and it now contributes to the energy mix in more than 70 countries across the globe.

Major factors that have led to accelerated development of the wind power are as follows:

(i) Availability of high-strength fiber composites for constructing large low-cost rotor blades
(ii) Falling prices of power electronics
(iii) Variable speed operation of electrical generators to capture maximum energy
(iv) Improved plant operation, pushing the availability up to 95 per cent
(v) Economy of scale, as the turbines and plants are getting larger in size
(vi) Accumulated field experience (the learning curve effect) improving the capacity factor
(vii) Short energy payback (or energy recovery) period of about one year

7.2 ORIGIN OF WINDS

The origin of winds may be traced basically to uneven heating of earth surface due to sun. This may lead to circulation of widespread winds on global basis, producing planetary winds or may have a limited influence in a smaller area to cause local winds.

7.2.1 Global (or Planetary) Winds

Two major forces determine the speed and direction of wind on global basis.

(i) Primary force for global winds is developed due to differential heating of earth at equator and Polar Regions. In the tropical regions there is net gain of heat due to solar radiation, whereas in the Polar Regions there is net loss of heat. This means that the earth's atmosphere has to circulate to transport heat from tropics towards the poles. On a global scale, these atmospheric currents work as an immense energy transfer medium. Ocean currents act similarly, and are responsible for about 30 per cent of this global heat transfer.

(ii) Spinning of earth about its axis produces Coriolis force, which is responsible for deviation of air currents towards west.

Between 30°N and 30°S, heated air at the equator rises and is replaced by cooler air coming from north and south. This is known as Hadley circulation. Due to Coriolis force these winds deviate towards west. These air currents are also known as trade winds because of their use in sailing ships for trades in the past. There is little wind near the equator (±5° around it), as the air slowly rises upwards rather than moving westward. Between 30°N (/S) and 70°N (/S) predominantly western winds are found. These winds form a wavelike circulation, transferring cold air southward and warm air northward (in northern hemisphere and vice versa in southern hemisphere). This pattern is called Rossby circulation. This is shown in Fig. 7.1.

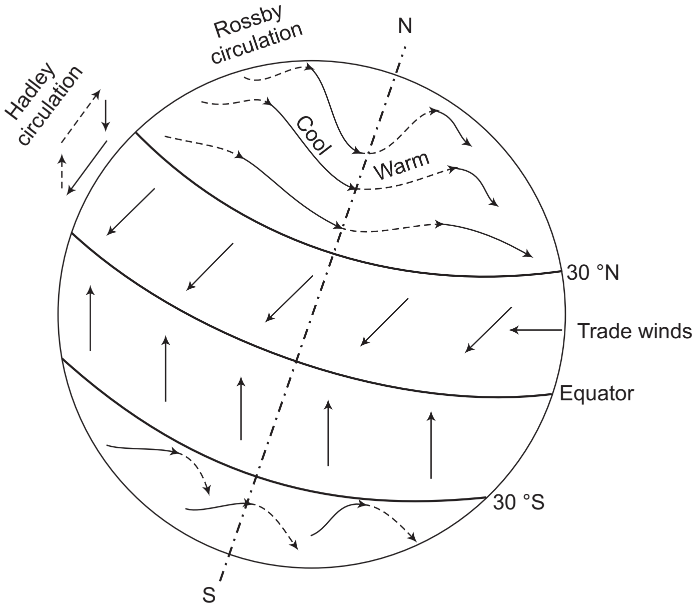


Figure 7.1 Global circulation of wind

7.2.2 Local Winds

Localized uneven heating is responsible for local winds. Local winds are produced due to two mechanisms:

(i) The first is differential heating of land surface and water bodies due to solar radiation. During the day, solar energy is readily converted to sensible thermal energy on the land surface and thus quickly increases its temperature. Whereas, on water bodies it is partly consumed in evaporating water and only partly absorbed to cause an increase in temperature. The land mass thus becomes hotter than water, which causes differential heating of air above them. As a result, cool and heavier air blow from water towards land. At night, the direction of wind is reversed as the land mass cools to sky more rapidly than the water. This is the mechanism of shore breeze.

(ii) The second mechanism of local winds is differential heating of slope on the hillsides and that of low lands. The slope heats up during the day and cools down during night more rapidly than the low land. This causes the heated air to rise along the slope during the day and relatively cool air to flow down at night.

7.2.3 Factors Affecting the Distribution of Wind Energy on the Surface of Earth

Several factors are responsible for distribution of wind energy on the surface of earth. Some factors work globally while others have limited local influence. Both global and local factors influence the availability of wind energy at a particular site. The extent of influence of each factor varies from site to site.

(i) On planetary level, great mountain massifs influence the circulation of air currents.

(ii) Surface roughness or friction, owing to the resistance that different elements of the earth's surface offer to air circulation affects the nature of wind. Hills, trees, buildings and similar obstructions impair streamline airflow. Turbulence results and the wind velocity in a horizontal direction get markedly reduced. Frictional effect is less on smooth area such as sea or large open area and more in rough urban area with tall buildings or trees etc. Therefore, wind speed is quite high at seashore.

(iii) Climatic disturbances such as downdraught from thunderclouds and precipitation, etc., also affect the local winds.

(iv) Wind speed also increases while passing through narrow mountain gaps, where it gets channeled.

7.3 NATURE OF WINDS

To be able to understand and predict the performance of wind turbines it is essential to have some knowledge of the behavior and structure of wind. This is also required for proper design of supporting structure to carry the imposed load safely and at an economically viable cost. The behavior and structure of the wind varies from site to site depending on the general climate of the region, the physical geometry of the locality, the surface condition of the terrain around the site and various other factors.

Rapid fluctuations in the wind velocity over a wide range of frequencies and amplitudes, due to turbulence caused by mechanical mixing of lower layers of atmosphere by surface roughness are commonly known as *gusts*.

The Beaufort scale, a wind speed classification, gives a description of the effect of the wind. It was initially designed for sailors and described the sea state, but has been modified to include wind effects on land. It is a useful guide to wind speed. The description of wind based on Beaufort number is given in Table 7.1.

Table 7.1 Description of wind based on Beaufort scale

Beaufort number	Wind speed		Observable effects	Wind Description
	m/s	km/h		
0	0.0–0.4	0.0–1.6	Smoke rises vertically	Calm
1	0.4–1.8	1.6–6	Smoke drifts but vanes unaffected	Light
2	1.8–3.6	6–13	Leaves move slightly but vanes unaffected	Light
3	3.6–5.8	13–21	Leaves in motion, flags begin to extend	Light
4	5.8–8.5	21–31	Small branches move, dust raised, pages of book loosen	Moderate
5	8.5–11	31–40	Small trees sway, wind noticeable	Fresh
6	11–14	40–51	Large branches sway, telephone lines whistle	Strong
7	14–17	51–63	Whole tree in motion	Strong
8	17–21	63–76	Twigs break off, walking difficult	Gale
9	21–25	76–88	Slight structural (e.g. chimneys) damage	Gale
10	25–29	88–103	Trees uprooted, much structural damage	Strong gale
11	29–34	103–121	Widespread damage	Strong gale
12	>34	>121	Disastrous conditions, countryside devastated, only occurs in tropical cyclones	Hurricane

7.3.1 Wind Data

All countries have national meteorological services that record and publish weather related data including wind speed and direction. Wind speed is measured by anemometer and wind direction is measured by wind vane attached to a direction indicator. Anemometers work on one of the following principles.

(i) The oldest and simplest anemometer is a swinging plate hung vertically and hinged along its top edge. Wind speed is indicated by the angle of deflection of the plate with respect to vertical.

(ii) Cup anemometer consists of three or four cups mounted symmetrically about a vertical axis. The speed of rotation indicates wind speed.

(iii) Wind speed can also be recorded by measuring the wind pressure on a flat plate.

(iv) Hot wire anemometer measures the wind speed by recording cooling effect of the wind on hot wire. The heat is produced by passing an electric current through the wire.

(v) An anemometer can also be based on sonic effect. Sound travels through still air at a known speed. However, if the air is moving, the speed decreases or increases accordingly.

(vi) The other more novel techniques include the laser anemometer, the ultrasonic anemometer and the SODAR Doppler anemometer.

Figure 7.2 shows the typical anemograph of wind speed recorded at three heights, 10 m, 50 m and 150 m during strong winds. These records demonstrate the main characteristics of the flow in the region near ground. Main conclusions may be drawn as:

(i) Wind speed increases with height.
(ii) Wind speed is fluctuating with time, i.e. turbulences are present at the site.
(iii) The turbulence is spread over a broad range of frequencies.

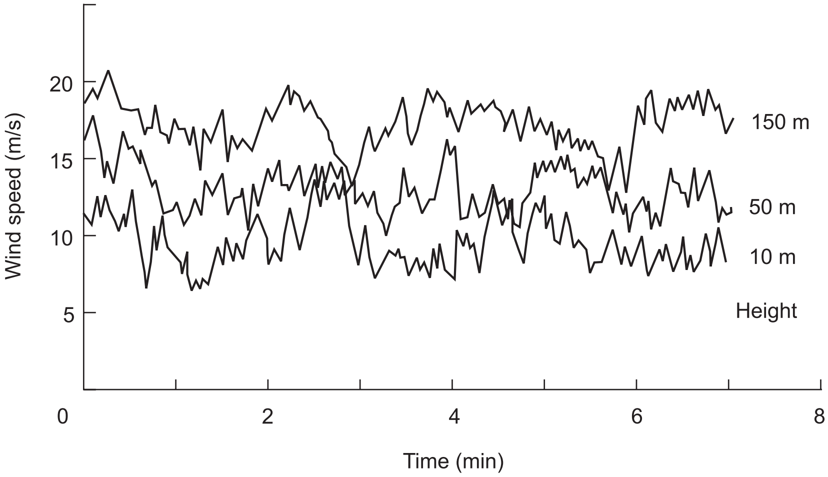


Figure 7.2 Wind speed recording

According to World Meteorological Organization (WMO) recommendation, wind speed measurement should be made at an effective height of 10 m above the ground. The frequency of measurement depends on the purpose for which the data is going to be used. For some applications, such as the estimation of the highest probable gust or the evaluation of turbulence intensity at a site, measurements at few seconds interval are required as wind speed varies on a time scale of seconds or less. For the purpose of energy studies, mean wind speed is used, which is generally based on different averaging periods from 10 min to 1 h in different countries. An elegant method of describing average wind speed, duration and direction on a single graph is shown in Fig. 7.3. It is known as wind rose. It depicts the compass bearing from which the wind comes (all 16 directions) along with average wind speed and duration in a year. The lengths of bars represent the percentage of duration.

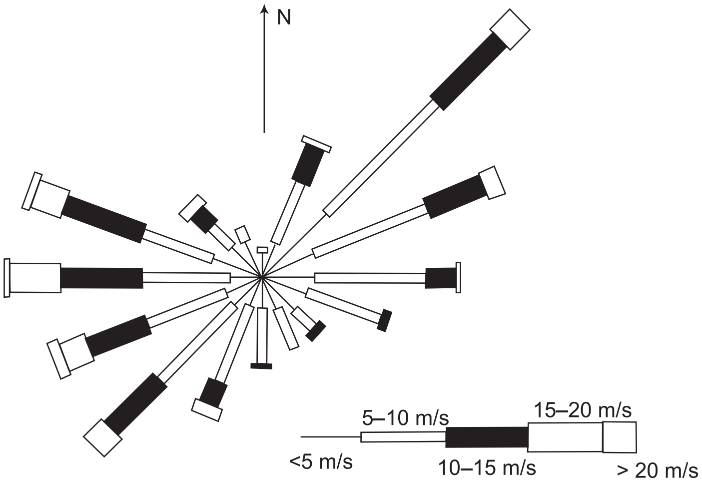


Figure 7.3 A typical wind rose

7.3.2 Variation of Wind Speed with Height

At the earth surface wind speed is always zero. It increases with height above the ground. The wind near the earth surface is retarded by surface roughness. The rate of change of wind speed with height is called wind *shear*. The lower layers of the air retard those above them, resulting in change in mean wind speed with height, until the shear forces are reduced to zero. This height is called the *gradient height* and is typically of about 2000 m, above the gradient height, known as *free atmosphere*, changes in wind speed are not affected by ground conditions. The layer of air from ground to gradient height is known as *planetary boundary layer*. The planetary boundary layer mainly consists of (i) *surface layer*, which extends from the height of local obstructions to a height of approximately 100 m and (ii) *Ekman layer*, which starts from 100 m and extends up to gradient height as shown in Fig. 7.4. In the surface layer the variation of shear stress can be neglected and mean wind speed with height can be represented by Prandtl logarithmic law model:

$$u_z = V \ln\left(\frac{z-d}{z_o}\right) \tag{7.1}$$

where, V is characteristic speed, d is zero plane displacement, its magnitude is a little less than the height of local obstructions, z_o is roughness length, $(z_o + d)$ is the height of local obstructions.

As seen in the diagram, near the line of local obstructions the average wind speed does not follow Eq. (7.1), (i.e. the dotted line) but deviates from it and becomes highly erratic. It is very important then to place the wind turbine well above the height of local obstructions so that the turbine disk receives a strong uniform wind flux across its area without erratic fluctuations.

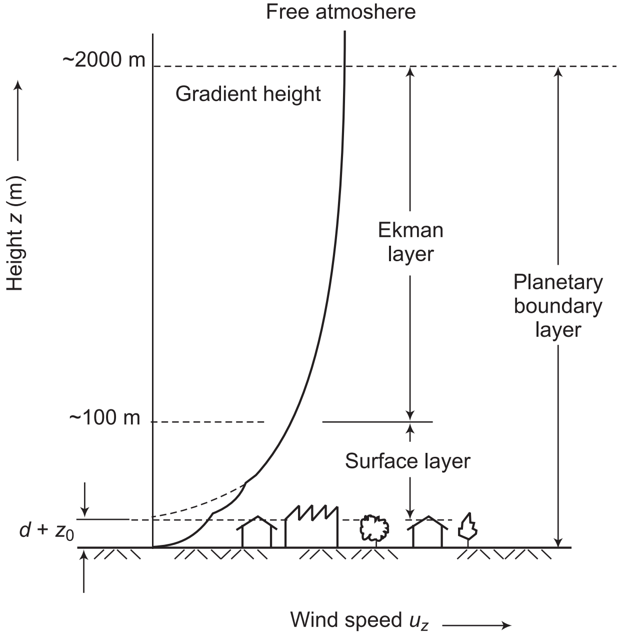


Figure 7.4 Wind speed variation with height

As stated earlier, the standard wind speed measurements are often taken at a height of 10 m from ground but wind turbines often operate at a height above this. A simple empirical power law model can be used to estimate wind speed u_z at a height z relative to that available at standard reference height H.

$$u_z = u_H \left(\frac{z}{H}\right)^{\alpha} \tag{7.2}$$

where u_H is mean wind speed at reference height H (usually 10 m), α depends on surface roughness and the range of height being covered. Great care should be taken in using this formula, especially for $z > 50$ m. Good sites should have low values of α. Range of values of α for varying ground roughness is given in Table 7.2.

Table 7.2 Range of values of α for varying ground roughness

Description of land	Range of value of α
Smooth land with very few obstacles (e.g. sea coast, desert, snow)	0.10–0.13
Moderately rough (e.g. agricultural fields with very few trees, grasslands, rural areas)	0.13–0.20
Land with uniformly distributed obstacles 10–15 m high (e.g. forest, small towns, agricultural fields with tree plantations)	0.20–0.28
Land with big non-uniform obstacles (e.g. big cities, plateaus)	0.28–0.40

7.3.3 Estimation of Wind Energy at a Site

1. Power in Wind

If u_o is the speed of free wind in unperturbed state, the volume of air column passing through an area A per unit time is given by Au_o. If ρ is the density of air, the air mass flow rate, through area A, is given as, ρAu_o. Power (P_o) available in wind, is equal to kinetic energy rate associated with the mass of moving air, i.e.:

$$P_o = \frac{1}{2}(\rho\, A\, u_o)u_o^2$$

or

$$P_o = \frac{1}{2}(\rho A)\, u_o^3 \tag{7.3}$$

Power available in wind per unit area:

$$\frac{P_o}{A} = \frac{1}{2}\,\rho\, u_o^3 \tag{7.4}$$

This indicates that power available in wind is proportional to the cube of wind speed. The air density ρ varies in direct proportion with air pressure and inverse proportion with temperature as:

$$\rho = \frac{P}{RT} \tag{7.5}$$

where P is air pressure in Pa, T is air temperature in kelvin and R is the gas constant, (= 287 J/kg K). At the standard value of air pressure, 1.0132×10^5 Pa (i.e. 1 atmosphere), and at 15 °C, the value of air density,

$$\rho = \frac{1.0132 \times 10^5}{287 \times 288} = 1.226 \text{ J/kg-K/m}^3$$

Assuming the above value of wind density, ρ at 15 °C and at sea level, the power available in moderate wind of 10 m/s is 613 W/m^2.

2. Presentation of Wind Data

Wind data available at a site is presented on annual basis. One method of presenting wind speed data is to produce a histogram of the number of hours each year that the wind speed is within certain band. An example is shown in Fig. 7.5.

Rather than reporting the total time the wind is within certain band, sometimes the data is normalized by dividing the total number of hours in a year (i.e. 8760). The result is a probability vs wind speed histogram, as shown in Fig. 7.6.

To assess the energy generation potential, the hourly mean wind speed data of Fig. 7.5 are recast into number of hours in the year for which the speed equals or exceeds the specified value, as shown in Fig. 7.7. Naturally, the largest coordinate on Y-axis is the number of hours in a year (i.e. 8760), when the wind speed exceeds or equal to zero.

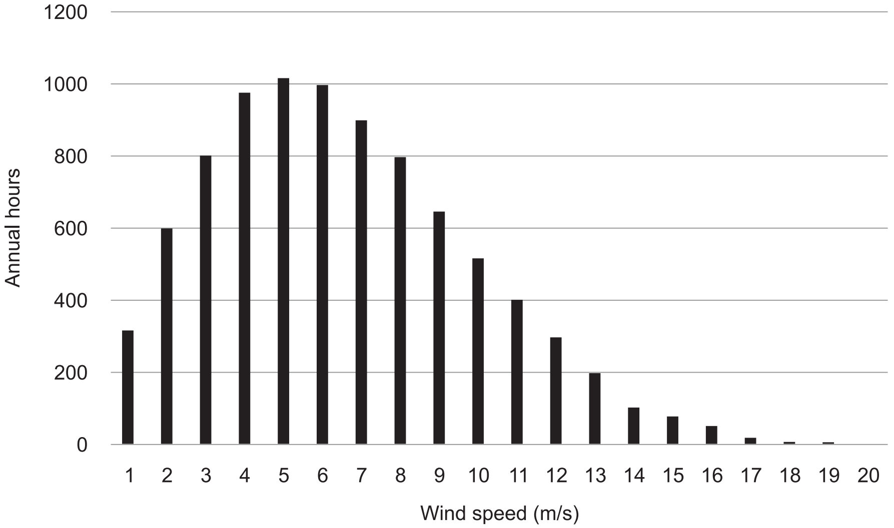


Figure 7.5 Wind speed frequency distribution

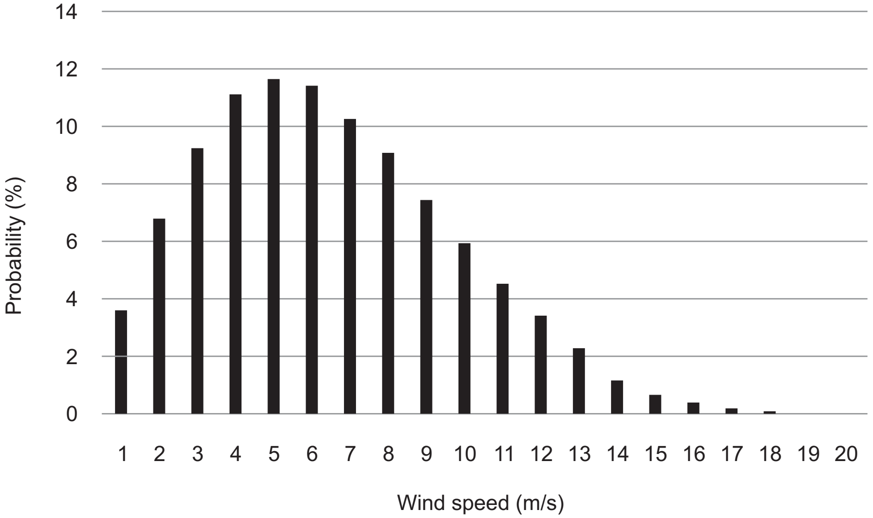


Figure 7.6 Normalized speed frequency diagram

Wind power generation at a particular site depends on the characteristics of the site as well as that of wind machine. The site characteristics are shown in Fig. 7.7. As evident from Eq.(7.4), the power contained in wind is proportional to cube of wind speed. Accordingly, the speed may be replaced by power on X-axis to obtain power-duration curve (GABCD), as shown in Fig. 7.9.

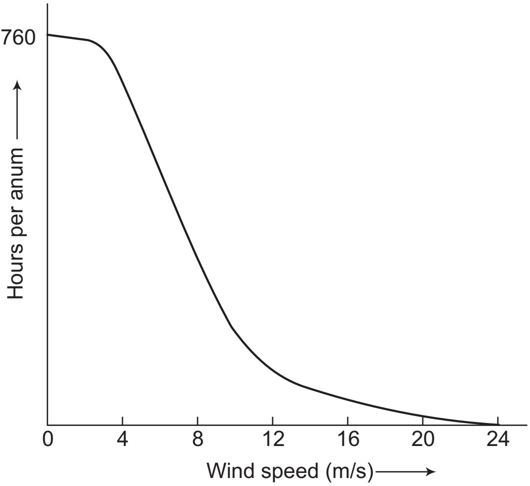


Figure 7.7 Wind speed-duration curve

The wind turbine characteristics will be discussed in detail in Section 7.8.7. Every wind turbine-generator has a specific cut-in speed, where it starts generating power, a rated speed and a furling speed where it stops generation, as shown in Fig. 7.8.

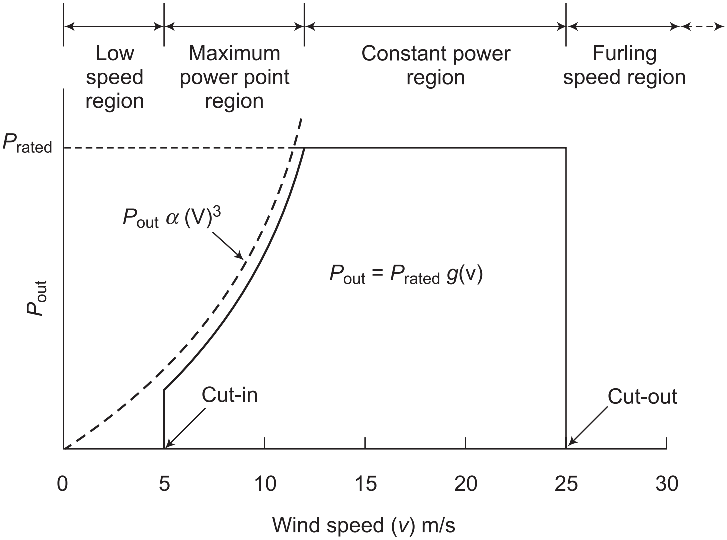


Figure 7.8 Power versus wind speed characteristics

Finally, the wind turbine-generator characteristics, as weighted by the site's wind speed-duration curve (Fig. 7.7), yield the output power-duration characteristics as shown in Fig. 7.9. *A*′, *B*′ and *C*′ are power outputs corresponding to cut-in speed, rated (or design) speed and cut-out speeds respectively. The area within *GAF* could not be tapped as the wind speed therein is less than cut-in speed. Also, the area within *CDOE* remained untapped because the wind speed is greater than furling speed. Segment BC represents the portion where the wind speed is greater than rated speed. Accordingly, power generation is kept constant at rated capacity and therefore, the energy represented by the area *BCB″* also could not be harnessed. Thus, the hatched area under the output power-duration curve (i.e. *ABB″EF*) measures the actual annual energy output of a particular wind machine at a given site. It may be noted that area under rectangle *GHB′O* represents the energy that would be generated if the wind generator ran at full capacity and generated rated power all through the year.

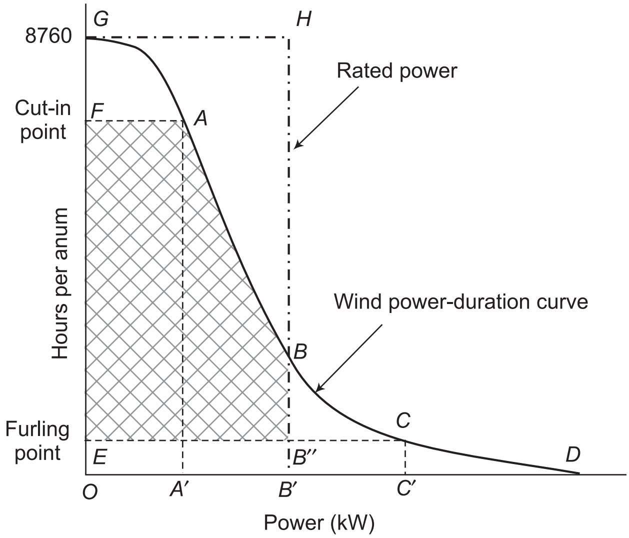


Figure 7.9 The output power-duration characteristics of a wind generator at a given site

3. Wind Data Statistics

It is convenient to work with an equation rather than discrete data. Most wind data is modeled analytically by assuming that it follows a Weibull probability distribution function, as shown in Fig. 7.10. If $f(v)$ is the probability of the wind being at speed v, then the Weibull distribution is given by:

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left\{-\left(\frac{v}{c}\right)^{k}\right\} \tag{7.6}$$

The parameters k and c are called the scale and shape parameters, respectively, and are chosen to fit the data. c has dimensions of velocity, and k is dimensionless. The parameters c and k of a wind regime at a site are determined from the annual mean wind speed averaged over few years, based on measurements at the site.

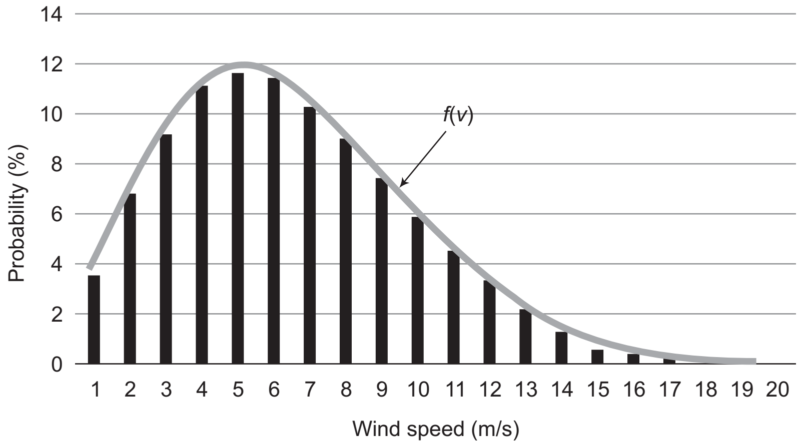


Figure 7.10 Weibull distribution

7.3.4 Capacity Factor

Because of variable nature of wind speed, the wind power plants cannot operate steadily at full power, 24-hours a day, 365 days a year. At times the wind speed may even be insufficient to drive the turbine. A wind turbine generally runs 65-80 per cent of the time in a year with variation in output power. Therefore, instead of power capacity, the annual energy output is more important as the revenue is generated on the basis of energy produced.

Capacity factor is defined as the ratio of the actual annual output energy, to the energy that would be generated if it is operated at rated power throughout the year.

$$\text{Capacity Factor (CF)} = \frac{\text{annual energy output}}{\text{rated power} \times \text{time in a year}}$$

$$= \frac{\text{average power output during a year}}{\text{rated power output}}$$

$$= \frac{\text{area enclosed by } ABB''EF}{\text{area enclosed by } GHB'O}$$

The analytical expression for CF may be derived as follows:

As seen in Fig. 7.8, the power output of wind turbine is a function $g(v)$ of wind speed and expressed as:

$$P_{\text{out}} = P_{\text{rated}}\, g(v) \tag{7.7}$$

Taking into account the Weibull distribution of speed, the average power output P_{avg} of a wind turbine is given as by,

$$P_{\text{avg}} = P_{\text{rated}} \int f(v) g(v) dv \tag{7.8}$$

Equation (7.8) depicts the power output of a wind turbine at a given speed and frequency at which that speed is obtained, summed over all possible speeds. The capacity factor can now be given as,

$$CF = \frac{P_{\text{avg}}}{P_{\text{rated}}} = \int f(v)\, g(v)\, dv \tag{7.9}$$

The sites where CF is less than 12 per cent are not considered suitable for wind power generation.

7.4 WIND TURBINE SITING

The power available in wind increases rapidly with wind speed. Therefore main consideration for locating a wind power generation plant is the availability of strong and persistent wind. A suitable site should preferably have some of the following features:

1. No tall obstructions for some distance (about 3 km) in the upwind direction (i.e. the direction of incoming wind) and also as low a roughness as possible in the same direction
2. A wide and open view, i.e. open plain, open shoreline or offshore locations
3. Top of smooth well-rounded hill with gentle slopes (about 1:3 or less) on a flat plain
4. An island in a lake or the sea
5. A narrow, mountain gap through which wind is channeled
6. The site should be reasonably close to power grid
7. The soil conditions must be such that building of foundations of the turbines and transport of road construction material loaded on heavy trucks must be feasible
8. If there are already wind turbines in the area, their production results are an excellent guide to local wind conditions.

7.5 MAJOR APPLICATIONS OF WIND POWER

Wind turbines have been built in power output range from a kilowatt to few MW to suit wide range of applications. Major applications may be grouped in three categories.

1. Applications Requiring Mechanical Power

(i) *Wind pumps*: Low power turbines are used for producing mechanical power for pumping water in remote areas. These are also known as wind pumps. Simple and reliable traditional reciprocating pumps or centrifugal pumps are used. These wind pumps are used to supply water for livestock, small-scale irrigation, low head pumping for aquatic breeding and domestic water supply. Mechanical power is also used to operate farm appliances.

(ii) *Heating*: The direct dissipation of mechanical power produces heat with 100 per cent efficiency using paddlewheel and other turbulent fluid systems. The available hot water is used as such or employed for space heating.

(iii) *Sea transport:* The old square-rigged sailing ships were inefficient as they were operated by drag forces (to be discussed later). Modern racing yachts, with a subsurface keel, harness lift forces and are much more efficient and can sail faster than the wind. Large cargo ships requiring power in MW range, driven by improved efficient sails are now being designed. Also wind turbines are installed onboard to power propellers in ferries operating on short routes.

2. As Off Grid Electrical Power Source

(i) Machines of low power with a rotor diameter of about 3 m and 40–1000 W rating can generate sufficient electrical energy for space heating and cooling of homes, water heating, battery charging, and for operating domestic appliances such as fan, light and small tools.

(ii) Applications for somewhat more powerful turbines of about 50 kW are: producing electrical power for navigation signal (e.g. lighthouse), remote communication, weather stations and offshore oil drilling platforms.

(iii) Intermediate power range, roughly 100 to 250 kW aero-generators can supply power to isolated populations, farm cooperatives, commercial refrigeration, desalination and to other small industries. The generator may operate in stand-alone mode or may be connected to a mini-grid system.

(iv) For lifting water to a hill, aero-generator is installed on the top of hill and electrical energy is transmitted to a pump fixed at a lower level. Same principle is utilized to store excess generated power using pumped storage system, to be utilized later during no wind periods.

3. As Grid Connected Electrical Power Source

Large aero-generators in the range of few hundred kW to few MW are planned for supplying power to a utility grid. Large arrays of aero-generators, known as *wind farms* are being deployed in open plains or offshore in shallow water for this purpose.

7.6 BASICS OF FLUID MECHANICS

7.6.1 Important Terms and Definitions

Figure 7.11, shows the position of rotor blade and various forces acting over it along with various components of speed, for the purpose of illustration and indicating the correlation among these factors.

Blade Element Incremental cross-section of the rotor blade as shown in Fig. 7.11(a)

Chord Width of the blade or distance from one edge (fore) of the blade to the other (aft) (i.e. length of blade element as shown in Fig. 7.11 (b))

Wind Velocity, u_o Velocity of free air in the neighbourhood of wind turbine (at a distance where the disturbances due to rotation of turbine does not reach)

Incident Wind Velocity, u_1 Velocity of air passing through the rotor, i.e. the velocity at which the wind strikes the blade, which is slightly less than u_o

Blade Element Linear Velocity, v Linear circumferential velocity of the blade element due to rotation of blade

Relative Wind Velocity, v_r Velocity of air relative to the blade element as both the air and blade elements move

Angular Speed, ω Angular speed of rotor in rad/s

Angle of Attack (or Angle of Incidence), α Angle between central line of the blade element and relative wind velocity v_r as shown in Fig. 7.11 (c)

Blade Setting Angle (or Pitch Angle), γ Angle between central line of the blade element and direction of linear motion of the blade element or angle between relative wind velocity v_r and normal to the plane of blade

Drag Force, ΔF_D Incremental force acting on the blade element in the direction of relative velocity of wind

Lift Force, ΔF_L Incremental force acting on the blade element in a direction perpendicular to the relative velocity of wind

Axial Force, ΔF_A Incremental force acting on the blade element along the axis of rotation of blade

Tangential Force, ΔF_T Incremental force acting on the blade element tangential to circular path of rotation

Solidity Solidity is defined as the ratio of the projected area of the rotor blades on the rotor plane to the swept area of the rotor

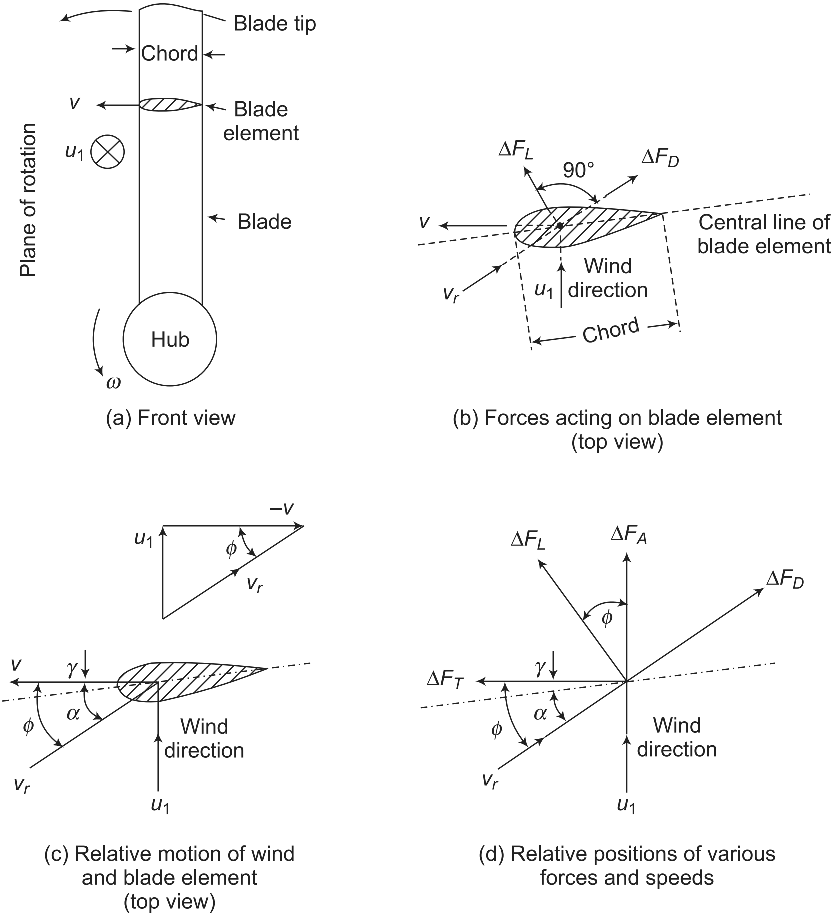
Thus solidity = $nC/\pi D$, where n is the number of blades, C is average breadth of a blade and D is the diameter of the rotor

Details and the relative positions of the above quantities are illustrated in Fig. 7.11. The incremental axial and tangential forces acting on the blade element are given by:

$$\Delta F_A = \Delta F_L \cos\phi + \Delta F_D \sin\phi$$

$$\Delta F_T = \Delta F_L \sin\phi - \Delta F_D \cos\phi$$

where, $\phi = \alpha + \gamma$.



(a) Front view

(b) Forces acting on blade element (top view)

(c) Relative motion of wind and blade element (top view)

(d) Relative positions of various forces and speeds

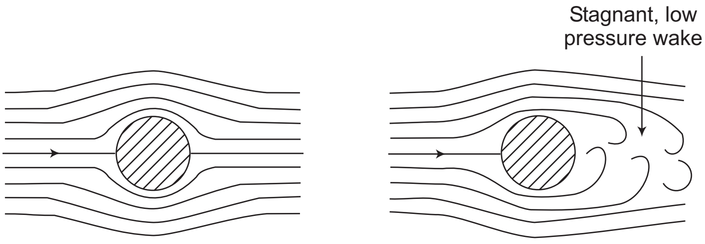
Figure 7.11 Blade element velocities and forces

7.6.2 Elementary Fluid Flow Concepts

The nature of flow around a body at a given velocity depends upon the relative magnitudes of the inertia and the viscous forces. The ratio of these forces is known as *Reynolds number*.

In a very slow moving (creeping) fluid, there is no relative motion at the body wall, and the drag on the body may be directly attributed to viscous, frictional shear stresses set up in the fluid. The flow remains attached to the surface of the body as shown in Fig. 7.12(a).

In practical situations, when the viscosity is low and the velocity is relatively high, the drag force that exists is due primarily to an unsymmetrical pressure distribution, fore and aft. This is caused by the fact that the fluid does not follow the boundary of the body, but separates from it leaving to a low pressure, stagnant fluid in the wake as shown in Fig. 7.12(b). On the upstream side, where the flow remains attached, the pressure is high, because the flow has been slowed down and pushed aside by the body obstructing its path.



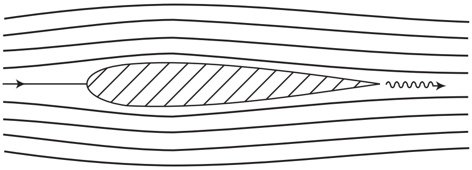
(a) Creeping flow past a cylinder (b) Separated flow past a cylinder

Figure 7.12 Attached and separated flow past a cylinder

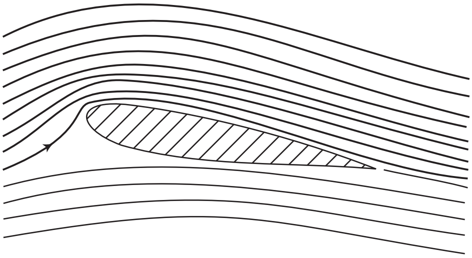
An airfoil is a streamlined body tapered gently in the aft region and has sharp trailing edge. For an airfoil the flow remains attached to the body throughout. Because the trailing edge is sharp, the separation leaves no low-pressure wake. The drag is very low, largely due to skin friction only, rather than the pressure difference. The drag does not depend on the frontal area but on the surface area and surface finish. This situation is shown in Fig. 7.13(a).

Consider an airfoil at a small angle of incidence α to oncoming flow as shown in Fig. 7.13(b). The flow remains attached and drag is small. The particles above the airfoil travel faster causing static pressure there to reduce whereas, those beneath it move slowly causing the static pressure to increase in this region. This produces a normal force on the airfoil, known as *lift force*.

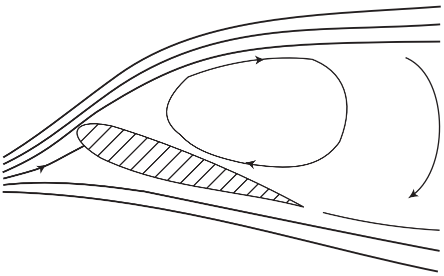
When the incidence angle α is increased beyond a certain critical value (10 to 16°, depending on the Reynolds number), the separation of the boundary layer on the upper surface takes place as shown in Fig. 7.13(c). This causes a wake to form above the airfoil, reducing the lift and increasing the drag substantially.



(a) Flow past an airfoil at $\alpha = 0$



(b) Flow past an airfoil at small α



(c) Stalled flow around an airfoil (large α)

Figure 7.13 Fluid flow around an airfoil

This is known as *stalled state* of the airfoil. A well-rounded leading edge and proper thickness of the airfoil improves stalling behaviour of the airfoil.

7.7 WIND TURBINE AERODYNAMICS

7.7.1 Power Extraction from Wind

Wind turbine is used to harness useful mechanical power from wind. The rotor of the turbine collects energy from the whole area swept by the rotor. For the purpose of simple analysis a smooth laminar flow with no perturbations is assumed. A horizontal axis wind turbine, which is most commonly used, is considered. The rotor may be considered as an actuator disk across which there is reduction of pressure as energy is extracted. As air mass flow rate must be same everywhere within the stream tube the speed must decrease as air expands. The stream tube model, also known as *Betz model* of expanding air stream tube is shown in Fig. 7.14. The stream tube area of constant air mass is A_o upstream, which expands to A_1 while passing through rotor and become A_2 downstream. The wind speed is u_o upstream, which reduces to u_1 while passing through the rotor and becomes u_2 downstream. The air mass flow rate remains same throughout the stream tube, therefore;

$$\dot{m} = \rho A_o u_o = \rho A_1 u_1 = \rho A_2 u_2 \tag{7.10}$$

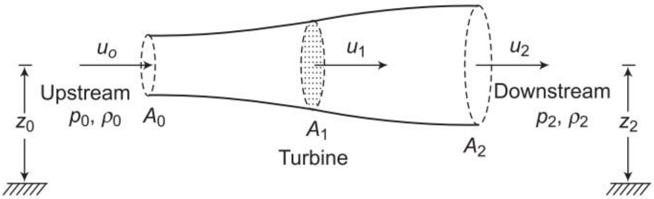
If u_o and u_2 are wind speeds upstream and downstream (before the wind front reforms and regains the atmospheric level) respectively, the force or thrust on the rotor is equal to the reduction in momentum per unit time from the air mass flow rate $\dot{m}$:

$$F = \dot{m} u_o - \dot{m} u_2 \tag{7.11}$$

This force is applied by the air at uniform airflow speed of u_1, passing through actuator disk (turbine), the power extracted by the turbine is:

$$P_T = F u_1 = \dot{m}(u_o - u_2) u_1 \tag{7.12}$$

(a) Unperturbed wind stream tube in absence of turbine



(b) Wind stream tube in presence of turbine

Figure 7.14 Betz model of expanding air stream tube

The power extracted from wind is also equal to loss in K.E. per unit time, thus:

$$P_W = \frac{1}{2}\dot{m}\,(u_o^2 - u_2^2) \tag{7.13}$$

Equating (7.12) and (7.13) we have,

$$u_1 = \frac{u_o + u_2}{2} \tag{7.14}$$

As an extreme case, considering u_2 to be zero (which is not practical as downstream air must have some kinetic energy to leave the turbine region), $u_1 = u_o/2$. Thus according to this linear momentum theory, the air speed through the actuator disk cannot be less than half the speed of upstream air.

An *interference factor*, 'a' is defined as fractional wind speed decrease at the turbine thus:

$$a = (u_o - u_1)/u_o \tag{7.15}$$

or $$u_1 = (1 - a)\,u_o$$

or $$a = (u_o - u_2)/(2u_o) \tag{7.16}$$

'*a*' is also known as *induction* or *perturbation* factor.

Using Eqs (7.10), (7.12), (7.14) and (7.15), power extracted by the turbine may be written as:

$$P_T = 4a\,(1-a)^2\left(\frac{1}{2}\,\rho\,A_1\,u_o^3\right) \tag{7.17}$$

Comparing with Eq. (7.3):

$$P_T = C_P\,P_o \tag{7.18}$$

where, C_P is the fraction of available power in the wind that can be extracted and is known as *power coefficient*. C_P is given as:

$$C_P = 4a(1 - a)^2 \tag{7.19}$$

The variation of power coefficient, C_P with interference factor '*a*' is shown graphically in Fig. 7.15. Physical significance of the curve is discussed below:

When no load is coupled to the turbine, the blades just freewheel. There is no reduction of wind speed at the turbine, therefore, $u_1 = u_o$ and the value of '*a*' is zero. The turbine does not generate any power and $C_P = 0$. The air just passes through the turbine without any reduction of speed.

Now as load is applied, power is extracted, so C_P increases as u_1 decreases. Maximum value of C_P (i.e. $C_{P\,\max} = 16/27 = 0.593$) occurs at '*a*' = 1/3. At this condition:

$$u_1 = \frac{2}{3}\,u_o \quad \text{and } u_1 = \frac{1}{3}\,u_o$$

That means, at maximum power extraction condition the upstream wind speed is reduced to two third at the turbine and further reduced to one third downstream. The criterion for maximum power extraction, i.e. $C_{P\,\max} = 16/27$ is called *Betz criterion*. This applies to an ideal case. For a commercial wind turbine, however, maximum power coefficient is less than ideal value.

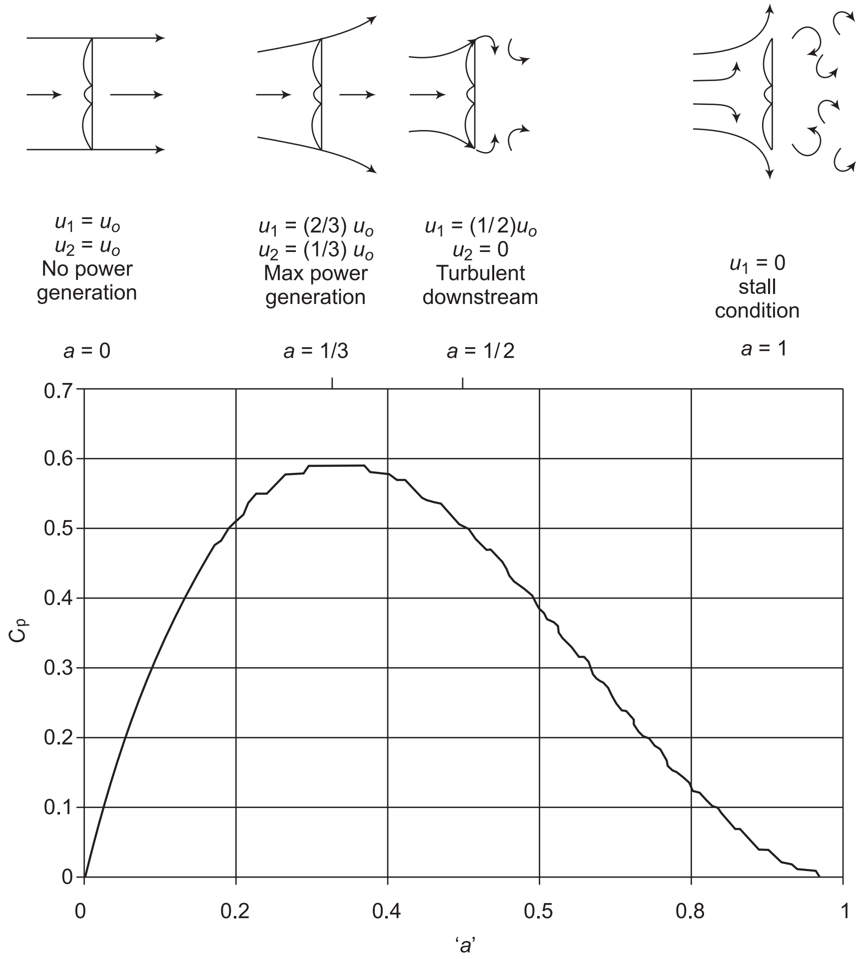


Figure 7.15 C_p versus '*a*'

When $u_2 = 0$, 'a' = 0.5 the simple model breaks down as no wind is predicted to be leaving downstream. In practice, this is equivalent to onset of turbulence downstream. Power extraction decreases due to mismatch of rotational frequency and wind speed and partial stalling begins. The turbine blades will still be turning, causing extensive turbulence in the air stream, leading to more losses. When the wind speed at the turbine is reduced to zero (i.e. $u_1 = 0$), 'a' becomes unity and no power is extracted. This state is known as (complete) *stall state* of blades.

Betz Criterion

In practice all of the kinetic energy in the wind cannot be converted to shaft power since the air must be able to flow away from the rotor area. The Betz criterion derived using the principles of conservation of momentum and conservation of energy suggests a maximum possible turbine efficiency, (or power coefficient) of 59 per cent. In practice power coefficients of 20–30 per cent are more common.

7.7.2 Axial Thrust on Turbine, F_A

With no energy extraction, Bernoulli's equation for upstream and downstream, (refer Fig. 7.14) may be written as:

$$p_o / \rho_o + g\, z_o + u_o^2 / 2 = p_2 / \rho_2 + g\, z_2 + u_2^2 / 2$$

As $z_o = z_2$ and variation in air density is negligible compared to other terms, considering ρ as average air density, the static pressure difference across the turbine may be written as:

$$\Delta p = p_o - p_2 = (u_o^2 - u_2^2)\ \rho / 2$$

Maximum value of static pressure difference occurs when u_2 approaches zero (which will be the situation for a solid disk). Thus:

$$\Delta p_{\max} = \rho\, u_o^2 / 2 \text{ and maximum thrust on the disk is:}$$

$$F_{A\,max} = A_1\ \rho\, u_o^2 / 2 \tag{7.20}$$

On a horizontal machine, this thrust acts along the turbine axis and therefore known as axial thrust F_A.

This axial thrust must be equal to loss of momentum of the air stream as given in Eq. (7.11), i.e.:

$$F_A = \dot{m}\, u_o - \dot{m}\, u_2$$

Using Eqs (7.3), (7.14) and (7.15), we can write:

$$F_A = 4a(1 - a)\ (A_1\ \rho\, u_o^2 / 2\ ) \tag{7.21}$$

or $$F_A = C_F\, F_{A\,\max} \tag{7.22}$$

where $$C_F = 4a(1 - a) \tag{7.23}$$

Maximum axial thrust occurs when $C_F = 1$, which is achieved when 'a' = 0.5, equivalent to $u_2 = 0$. Maximum power extraction by the Betz criterion occurs when 'a' = 1/3, corresponding to $C_F = 8/9$.

7.7.3 Torque Developed by the Turbine, T

Maximum conceivable torque T_M on an ideal turbine rotor would occur if maximum circumferential force acts at the tip of the blade with rotor radius r. Thus:

$$T_M = F_{cir\,\max}\, r \tag{7.24}$$

$$T_M = \frac{P_o}{u_o}\, r \tag{7.25}$$

Now, if the tip speed ratio λ is defined as:

$$\lambda = \frac{\text{speed of tip of the rotor blade}}{\text{speed of oncoming air}} = \frac{r\omega}{u_o} \tag{7.26}$$

then, T_{M} can be written as:

$$T_M = \frac{P_o\, \lambda}{\omega} \tag{7.27}$$

For a practical machine, where circumferential force is not concentrated at the tip but spread throughout the length of the blade, less shaft torque will be produced than what is given by Eq. (7.27), thus, the shaft torque, T_{sh} is given as:

$$T_{sh} = C_T\, T_M \tag{7.28}$$

where, C_T is known as torque coefficient.

As the product of shaft torque and angular speed equals power developed by the turbine:

$$T_{sh}\, \omega = P_T$$

or

$$C_T\, T_M\, \omega = C_P\, P_o$$

Substituting for T_M from Eq. (7.27), we get:

$$C_T\, P_o\, \lambda = C_P\, P_o$$

or

$$C_T = \frac{C_P}{\lambda} \tag{7.29}$$

Both C_T and C_P are functions of tip speed ratio, λ. As per Betz criterion, maximum value of C_P can be 0.593, therefore,

$$C_{T\,\max} = \frac{C_{P\,\max}}{\lambda} \tag{7.30}$$

Thus, machines with higher speeds have low value of $C_{T\max}$ or low starting torque.

7.7.4 Dynamic Matching for Maximum Power Extraction

As per Betz criterion, a turbine can theoretically extract a maximum of 59 per cent of the available power in wind. However, this criterion tells nothing about dynamic rotational state of the turbine required to reach this maximum power condition. This aspect will be explored here.

1. Tip Speed Ratio

For constant wind speed the power extraction by a turbine will decrease if:

(i) the blades are so close together, or rotating so rapidly that a blade moves into the turbulence created by a preceding blade; or

(ii) the blades are so far apart or rotating so slowly that much of the air passes through the cross section of the device without interacting with the blades.

Thus for a particular wind speed there exists an optimum turbine speed to produce maximum output. Therefore, to obtain optimum efficiency, it is important to match the rotational frequency of the turbine to the corresponding wind speed.

Let t_b is the time taken by a blade to move into the position previously occupied by the preceding blade and t_w is the time for the disturbed wind moving past that position and normal air stream becoming re-established. For '*n*' bladed turbine rotating at angular velocity of ω:

$$t_b = \frac{2\pi}{n\,\omega}$$

A disturbance at the turbine disk created by a blade into which the following blade moves will last for a time:

$$t_w = d/u_o$$

where, d is the length of the wind strongly perturbed by the rotating blades.

Maximum power extraction occurs when $t_w \approx t_b$ at the blade tips, where the blades sweep maximum incremental area. Thus:

$$\frac{d}{u_o} \approx \frac{2\pi}{n\omega}$$

Multiplying both side by r, radius of the rotor disk and rearranging the terms:

$$\frac{r\omega}{u_o} \approx \frac{2\pi r}{nd} \tag{7.31}$$

The term on L.H.S. of this equation has earlier been defined as tip speed ratio, as per Eq. (7.26). Thus, the tip speed ratio at optimum power extraction:

$$\lambda_o \approx \frac{2\pi}{n}\left(\frac{r}{d}\right) \tag{7.32}$$

Practical observations indicate that $d \approx (½)\, r$ and therefore,

$$\lambda_o \approx \frac{4\pi}{n} \tag{7.33}$$

Thus for a two bladed turbine, maximum power extraction ($C_{P\,\max}$) occurs at $\lambda_o \approx 2\pi$ and that for four bladed turbine at $\lambda_o \approx \pi$.

The relationship between C_P and λ for various types of rotors (to be discussed in Section 7.7) is shown graphically in Fig. 7.16. Maximum practically obtainable value of power coefficient is approximately 0.5. A wind turbine, achieving a value of power coefficient as 0.4 or above is considered to have good performance.

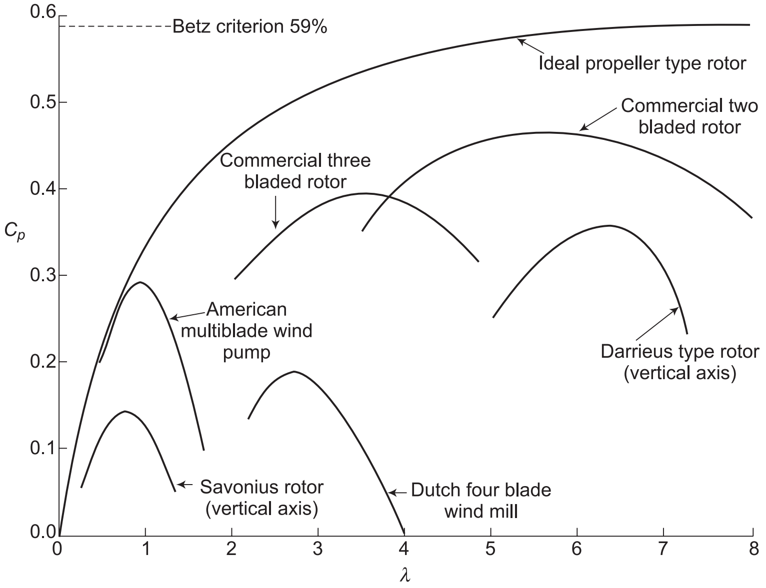


Figure 7.16 Power coefficient, C_P versus tip speed ratio λ

The TSR is also related to number of blades in a rotor. The TSR increases as the number of blades decreases as shown in Table 7.3.

Table 7.3 TSR vs number of blades

Tip speed ratio (TSR)	Number of blades
1	6–20
2	4–12
3	3–8
4	3–5
5–8	2–4
8–15	1–2

2. Blade Setting Angle, γ (or Blade Pitch Angle)

The output of a turbine is also greatly influenced by blade pitch angle, γ. The effect of blade pitch on $C_P - \lambda$ characteristics is illustrated in Fig. 7.17. Blade pitch control is a very effective way of controlling the output power, speed or torque.

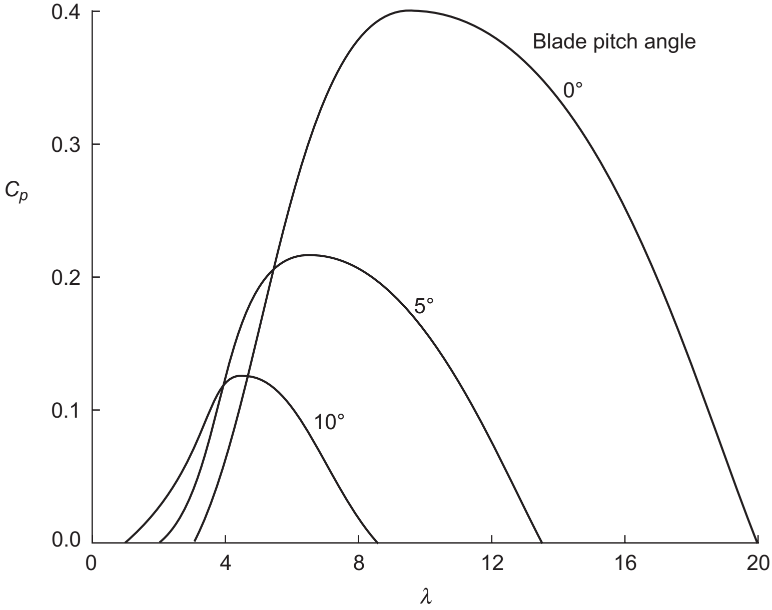


Figure 7.17 $C_P - \lambda$ curves for different pitch angle settings

Example 7.1

A propeller type wind turbine has following data:

Speed of free wind at a height of 10 m = 12 m/s
Air density = 1.226 kg/m^3
$\alpha = 0.14$
Height of tower = 100 m

Diameter of rotor = 80 m
Wind velocity at the turbine reduces by 20%
Generator efficiency = 85%

Find:

(i) Total power available in wind
(ii) Power extracted by the turbine
(iii) Electrical power generated
(iv) Axial thrust on the turbine
(v) Maximum axial thrust on the turbine

Solution:

From given data:

$u_H = 12$ m/s, $H = 10$ m, $z = 100$ m
$\rho = 1.226$ kg/m^3, $\alpha = 0.14$
$D = 80$ m $A_1 = 5026.55$ m^2
$u_1 = 0.8\, u_o$, $\eta_{\text{Gen}} = 0.85$

From Eq. (7.2),

$$u_z = u_H \left(\frac{z}{H}\right)^{\alpha} \quad 12 \times \left(\frac{100}{10}\right)^{0.14} = 16.565 \text{ m/s} = u_o$$

and $$u_1 = 0.8\, u_o = 0.8 \times 16.565 = 13.252 \text{ m/s}$$

(i) From Eq. (7.4),

$$\frac{P_o}{A} = \frac{1}{2} \rho\, u_o^3$$

$$P_o = P_o = 5026.55 \times \frac{1}{2} \times 1.226 \times 16.565^3 = 14 \text{ MW}$$

(iii) From Eq. (7.15),
The interference factor, $a = (u_o - u_1)/u_o = (16.565 - 0.8 \times 16.565)/16.565 = 0.2$
From Eq. (7.19),
The power coefficient $C_P = 4\, a\, (1 - a)^2 = 4 \times 0.2\, (1 - 0.2)^2 = 0.512$
From Eq. (7.18),
Power extracted by the turbine $P_T = C_P\, P_o = 0.512 \times 14 = 7.168$ MW

(iii) Electrical power generated = 0.85 × 7.168 = 6.09 MW

(iv) From Eq. (7.21),
Axial thrust on the turbine,

$$F_A = 4a(1 - a)\,(A_1\, \rho u_o^2/2) = 4 \times 0.2 \times (1 - 0.2) \times (5026.55 \times 1.226 \times 16.565^2/2)$$

$$= 5.4 \times 10^5 \text{ N}$$

(v) Maximum axial thrust occurs when $a = 0.5$ and $C_F = 1$

$$F_{A\,\max} = (A_1\, \rho u_o^2/2) = 5026.55 \times 1.226 \times 16.565^2/2$$

$$= 8.455 \times 10^5 \text{ N}$$

Example 7.2

Following data were measured for a HAWT:

Speed of wind = 20 m/s at 1 atm and 27 °C
Diameter of rotor = 80 m
Speed of rotor = 40 rpm

Calculate the torque produced at the shaft for maximum output of the turbine.

Solution

Given: $u_o = 20$ m/s, $P = 1$ atm $= 1.01325 \times 10^5$ Pa, $T = 273 + 27 = 300$ K

Radius of rotor $r = 40$ m

Speed of rotor $\omega = 40$ rpm $= (2\pi) \times (40/60) = 4.1888$ rad/sec

$$\rho = P/(RT) = 1.01325 \times 10^5 / (287 \times 300) = 1.177 \text{ kg/m}^3$$

Area of rotor $A = \pi r^2 = 5026.548$ m^2

For maximum output $a = 1/3$, $C_{P\,\max} = 0.593$

Tip speed ratio $\lambda = 40 \times 4.1888/20 = 8.378$

From Eq. (7.3),

$$P_o = \frac{1}{2}(\rho A)u_o^3 = 23.665 \text{ MW}$$

$$T_M = \frac{P_o}{u_o} r = 23.665 \times 40/20 = 47.3\text{w}3 \times 10^6 \text{ Nm}$$

$$C_{T\max} = \frac{C_{P\max}}{\lambda} = 0.593/8.378 = 0.07078$$

Torque produced at the shaft at maximum output,

$$T_{\text{sh max}} = 47.33 \times 10^6 \times 0.07078 = 3.35 \times 10^6 \text{ Nm}$$

Example 7.3

A HAWT is installed at a location having free wind velocity of 15 m/s. The 80 m diameter rotor has three blades attached to hub. Find the rotational speed of the turbine for optimal energy extraction.

Solution

Given:

Rotor diameter = 80 m, $r = 40$ m

$$u_o = 15 \text{ m/s}, n = 3$$

From Eq. (7.33), tip speed ratio for optimum output, $\lambda_o \approx \dfrac{4\pi}{n} = 4.188$

From Eq. (7.26), tip speed ratio is given by,

$$\lambda_o = \frac{r\omega}{u_o}$$

$$4.188 = \frac{40 \times \omega}{15}$$

or $\omega = 1.57$

If N is rotor speed in rpm, $\omega = 2\pi N/60$

$$N = 15 \text{ rpm}$$

Therefore, for optimum energy extraction rotor speed should be maintained at 15 rpm.

Example 7.4

Calculate the rotor radius for a wind turbine operating at wind speed of 6 m/s to pump water at a rate of 4 m^3/h with a lift of 5 m. Also calculate the angular velocity of the rotor.

Use following data:

Water density ρ_w = 1000 kg/m^3, g = 9.8 m/s^2, water pump efficiency = 50%, efficiency of rotor to pump = 80%, power coefficient, C_p = 0.3, tip speed ratio, λ = 1.0, air density, ρ = 1.2 kg/m^3

Solution

Hydraulic power required to pump water = $\dot{m}gh = \dfrac{4\times1000}{60\times60}\times9.8\times5$ = 54.44 W

Mechanical power required to be developed at rotor = $\dfrac{54.44}{0.5\times0.8}$ = 136.1 W

From Eq. (7.3),

Power available in wind,

$$P_o = \frac{1}{2}(\rho A)u_o^3 = \frac{1}{2}\rho\pi r^2 \times u_o^3 = \frac{1}{2}\times1.2\times\pi r^2\times6^3$$

From Eq. (7.18), power extracted by the rotor, $P_T = C_P\, P_o$

$$136.1 = 0.3 \times \frac{1}{2}\times1.2\times\pi r^2\times6^3$$

$$r = 1.055 \text{ m}$$

From Eq.(7.26),

Tip speed ratio, $\lambda = \dfrac{r\omega}{u_o}$

$$1.0 = \frac{1.055\times\omega}{6}$$

$$\omega = 5.684 \text{ rad/s}$$

$$= 54.\ 278 \text{ rpm}$$

Example 7.5

An aero-generator generates an output of 1200 W at wind speed of 5 m/s at one atmospheric pressure and a temperature of 20 °C. What will be the output, if the same aero-generator is installed on the top of a hill where the temperature is 10 °C, pressure is 0.85 atmospheric and wind speed is 6 m/s?

Solution

1 atm pressure = 1.01325×10^5 Pa

The air density is given as, $\rho = \dfrac{P}{RT} = \dfrac{1.01325 \times 10^5}{287 \times 293}$ = 1.2049 kg/m^3

Power generated by wind turbine,

$$\begin{aligned} P_T &= C_P \times (½) \times \rho \times A \times u_o^3 \\ 1200 &= C_P \times (½) \times 1.2049 \times A \times 5^3 \\ C_P A &= 15.935 \end{aligned}$$

Now, at the top of the hill,

The atmospheric pressure at the top of the hill = $0.85 \times 1.01325 \times 10^5$ Pa
= 0.86126×10^5 Pa

The air density $\rho = \dfrac{P}{RT} = \dfrac{0.86125 \times 10^5}{287 \times 283}$ = 1.06038

The wind speed at the top of the hill, u_o = 6 m/s

Power generated by wind turbine,

$$\begin{aligned} P_T &= (C_P \times A) \times (½) \times \rho \times u_o^{\,3} \\ &= (15.935) \times (½) \times 1.06038 \times 6^3 \\ &= 1824.89 \text{ W} \end{aligned}$$

7.8 WIND TURBINE TYPES AND THEIR CONSTRUCTION

Wind turbines are broadly classified into two categories. When the axis of rotation is parallel to the air stream (i.e. horizontal), the turbine is said to be a Horizontal Axis Wind Turbine (HAWT), and when it is perpendicular to the air stream (i.e. vertical), it is said to be a Vertical Axis Wind Turbine (VAWT). The size of the rotor and its speed depends on rating of the turbine. Some of the features of HAWT estimated at wind speed of 12 m/s and C_P = 30 per cent are given in Table 7.4.

Table 7.4 Typical wind turbine characteristics

SN	Features	Class										
		Small		Medium			Large			Very large		
1.	Rated Power, kW	10	25	50	100	150	250	500	1000	2000	3000	4000
2.	Rotor diameter, m	6.4	10	14	20	25	32	49	64	90	110	130
3.	Rotor RPM	200	150	100	67	55	43	29	19	15	13	11

7.8.1 Horizontal Axis Wind Turbine (HAWT)

HAWTs have emerged as the most successful type of turbines. These are being used for commercial energy generation in many parts of the world. Their theoretical basis is well researched and sufficient field experience is available with them.

1. Main Components

The constructional details of most common, three-blade rotor, horizontal axis wind turbine are shown in Fig. 7.18. Main parts are as follows:

(a) Turbine Blades Turbine blades are made of high-density wood or glass fiber and epoxy composites. They have airfoil type cross-section. The blades are slightly twisted from the outer tip to the root to reduce the tendency to stall. In addition to centrifugal force and fatigue due to continuous vibrations there are many extraneous forces arising from wind turbulence, gust, gravitational forces and directional changes in the wind, etc. All these factors are to be taken care off at the designing stage. Diameter of a typical, MW range, modern rotor may be of the order of 100 m.

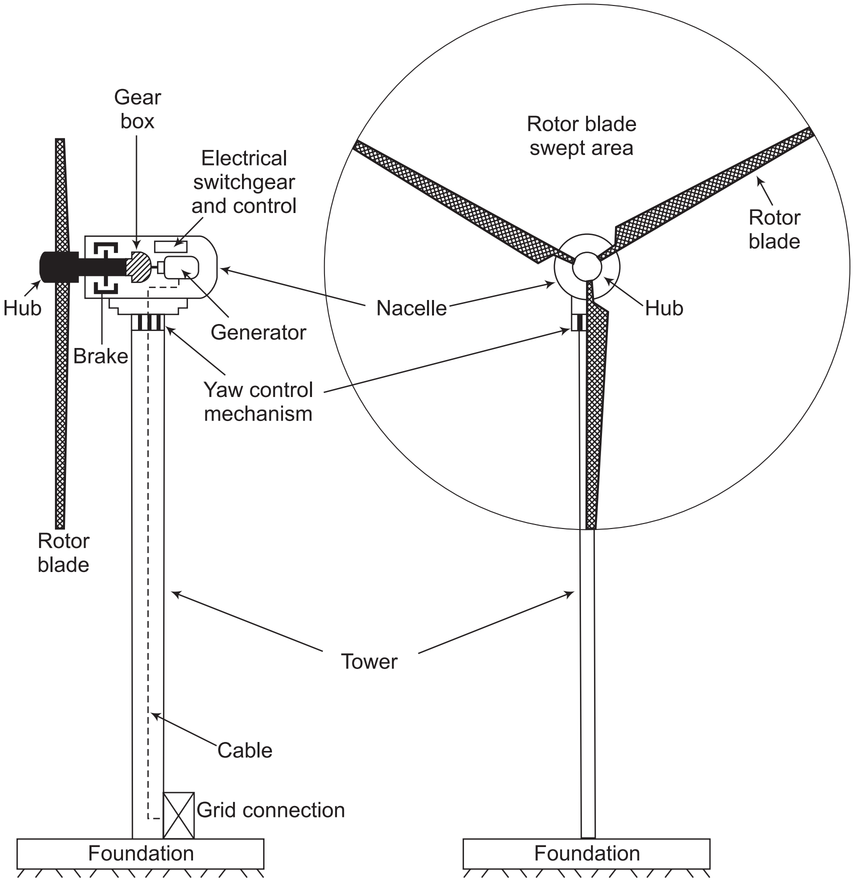


Figure 7.18 Horizontal axis wind turbine

Modern wind turbines have two or three blades. Two/three blade rotor HAWT are also known as *propeller type* wind turbines owing to their similarity with propellers of old aero planes. However, the rotor rpm in case of wind turbine is very low as compared to that for propellers. The relative merits and demerits of two and three blade rotors are as follows:

(i) Compared to two-blade design, the three-blade machine has smoother power output and balanced gyroscopic force.

(ii) There is no need to teeter (to be discussed later in this section) the rotor, allowing the use of simple rigid hub. The blades may be cross-linked for greater rigidity.

(iii) Adding third blade increases the power output by about 5 per cent only, while the weight and cost of rotor increases by 50 per cent, thus giving a diminished rate of return for additional 50 per cent weight and cost.

(iv) The two-blade rotor is also simpler to erect, since it can be assembled on ground and lifted to the shaft without complicated maneuvers during the lift.

Three blades are more common in Europe and other developing countries including India. The American practice, however, is in favour of two blades.

(b) Hub The central solid portion of the rotor wheel is known as hub. All blades ate attached to the hub. Mechanism for pitch angle control is also provided inside the hub.

(c) Nacelle The term nacelle is derived from the name for housing containing the engines of an aircraft. The rotor is attached to nacelle, mounted at the top of a tower. It contains rotor brakes, gearbox, generator and electrical switchgear and control. Brakes are used to stop the rotor when power generation is not desired. Gearbox steps up the shaft rpm to suit the generator. Protection and control functions are provided by switchgear and control block. The generated electrical power is conducted to ground terminals through a cable.

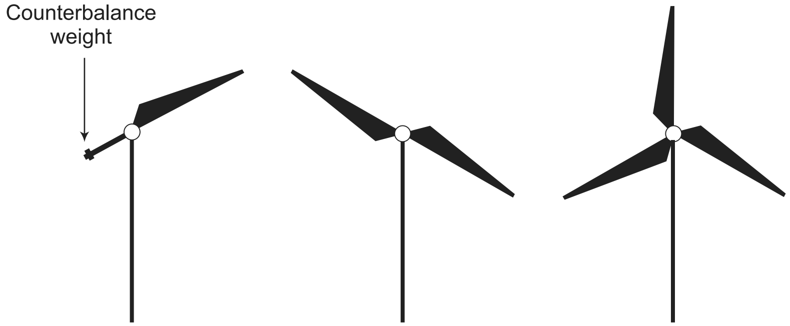
(d) Yaw Control Mechanism The mechanism to adjust the nacelle around vertical axis to keep it facing the wind is provided at the base of nacelle.

(e) Tower Tower supports nacelle and rotor. For medium and large sized turbines, the tower is slightly taller than the rotor diameter. In case of small sized turbine, the tower is much larger than the rotor diameter as the air is erratic at lower heights. Both steel and concrete towers are being used. The construction can be either tubular or lattice type.

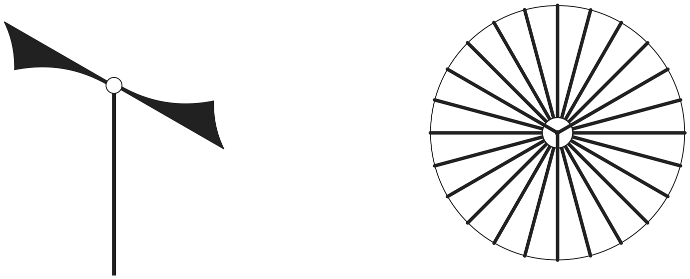
The tower vibrations and resulting fatigue cycles under wind speed fluctuations are avoided by careful design. This requires avoidance of all resonance frequencies of tower, the rotor and the nacelle from the wind fluctuation frequencies.

2. Types of Rotors

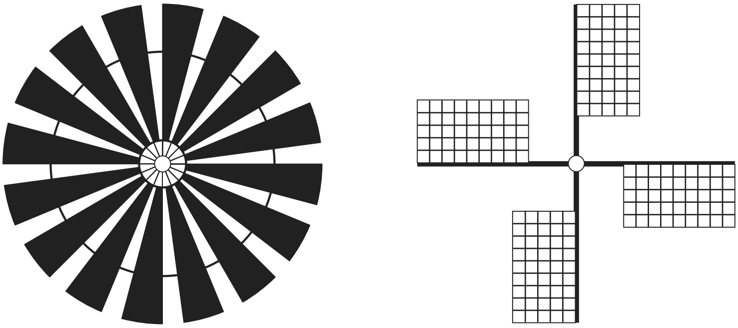
Depending on the number of blades, wind speed and nature of applications, rotors have been developed in various types of shapes and sizes. These are shown in Fig. 7.19. The types of rotors shown in (a) to (e) are relatively high-speed ones, suitable for applications such as electrical power generation. Large HAWTs have been manufactured with two and three blades. A single-blade rotor, with a balancing counterweight is economical, has simple controls but it is noisier and produces unbalanced forces. It is used for low-power applications. Those given in Fig. 7.19 (f) and (g) are low-speed rotors and most suited for water lifting applications, which require high starting torque. They can capture power even from very slow winds.



(a) Single-blade rotor (b) Two-blade rotor (c) Three-blade rotor



(d) Sailwing rotor (e) Chalk multi-blade rotor



(f) Americal Multibladed rotor (g) Dutch type rotor

Figure 7.19 Various types of rotors for HAWT

3. Teetering of Rotor

As wind speed rises with height, the axial force on blade when it attains the upper position is significantly higher as compared to that when it is at lower position. For one and two blade rotors this causes cyclic (sinusoidal) load on a rigid hub leading to fatigue. This is greatly relieved by providing a teeter hinge (a pivot within the hub) that allows a see-saw motion to take place out of the plane of rotation (i.e. vertical plane). The rotor leans backwards to accommodate the extra force as shown in Fig. 7.20. This also reduces blade loads near the root by approximately 40 per cent. The use of third blade has approximately same effect as a teeter hinge on the hub moments since the polar symmetry of the rotor averages out the applied sinusoidal loads. Therefore, teetering is not required when the number of blades is three or more.

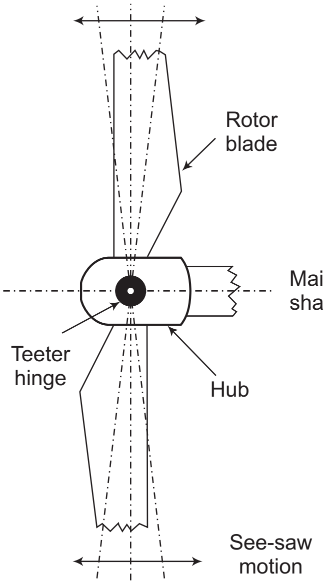
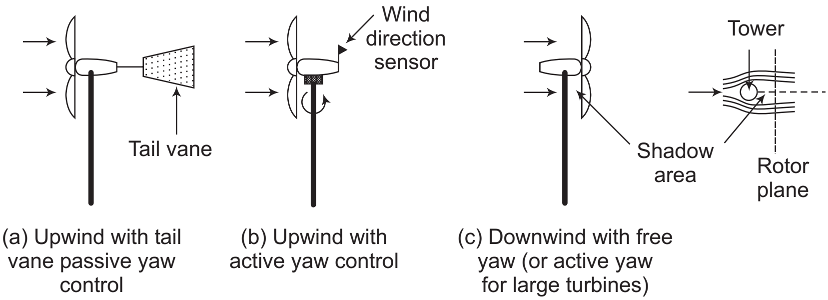


Figure 7.20 A teetered hub

4. Upwind and Downwind Machines

In upwind machine, rotor is located upwind (in front) of the tower whereas in downwind machine, the rotor is located downwind of (behind) the tower as shown in Fig. 7.21. Both types have certain benefits. Downwind machine allows the use of free yaw system (in low rating machines). It also allows the blades to deflect away from the tower when loaded. However, it suffers from **wind shadow** effects of the tower on the blades as they pass through tower's wake, in a region of separated flow. For a high solidity tower with limited rotor overhang, the wind speed might be effectively reduced to zero causing severe impulsive load of periodic nature. This may be very dangerous as it may excite any natural mode of the systems if that lies near a rotor harmonics.



(a) Upwind with tail vane passive yaw control
(b) Upwind with active yaw control
(c) Downwind with free yaw (or active yaw for large turbines)

Figure 7.21 Yaw control in upwind and downwind machines

Upwind machine on the other hand produces higher power as it eliminates the tower shadow on the blades. This also results in lower noise, low blade fatigue and smoother power output.

5. Yaw Control System

Adjusting the nacelle about vertical axis to bring the rotor facing the wind is known as *yaw control*. The yaw control system continuously orients the rotor in the direction of wind. For localities with prevailing wind in one direction only, the rotor can be in a fixed orientation. Such a machine is said to be *yaw fixed*. Most wind turbines however, are *yaw active*. In small wind turbines, a tail vane is used for passive yaw control. In large turbines however, an active yaw control with power steering and wind direction sensor is used to maintain the orientation.

6. Pitch Control System

Pitch of a blade is controlled by rotating it from its root, where it is connected to the hub as shown in Fig. 7.22. Pitch control mechanism is provided through the hub using hydraulic jack in the nacelle. The control system continuously adjusts the pitch to obtain optimal performance. In modern machines, pitch control is incorporated by controlling only outer 20 per cent length of the blade (i.e. tip), keeping remaining part of the blade as fixed.

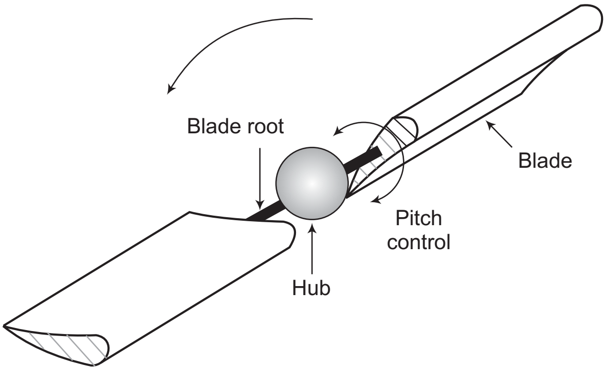


Figure 7.22 Pitch control

7.8.2 Vertical Axis Wind Turbine (VAWT)

VAWTs are in the development stage and many models are undergoing field trial. Main attractions of a VAWT are:

(i) it can accept wind from any direction, eliminating the need of yaw control.
(ii) gearbox, generator etc. are located at the ground, thus eliminating the heavy nacelle at the top of the tower. This simplifies the design and installation of the whole structure, including tower.
(iii) the inspection and maintenance also gets easier and
(iv) it also reduces the overall cost.

1. Main Components

The constructional details of a vertical axis wind turbine (Darrieus type rotor) are shown in Fig. 7.23. The details of main components are as follows:

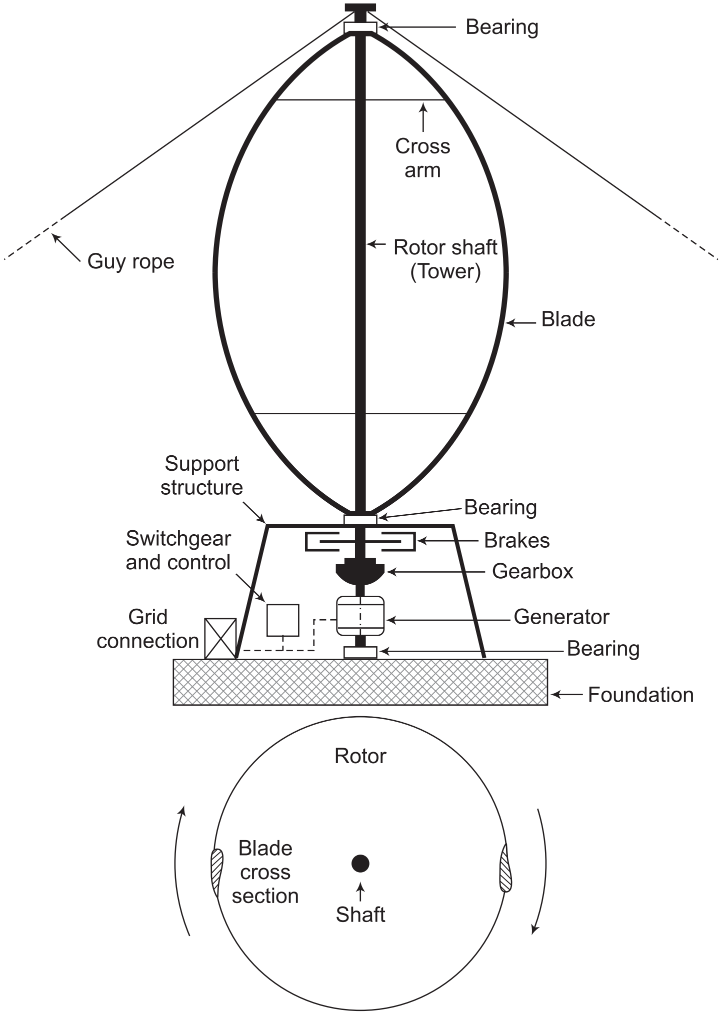


Figure 7.23 Vertical axis wind (Darrieus) turbine

(a) Tower (or Rotor Shaft) The tower is a hollow vertical rotor shaft, which rotates freely about vertical axis between top and bottom bearings. It is installed above a support structure. In the absence of any load at the top, a very strong tower is not required, which greatly simplifies its design. The upper part of the tower is supported by guy ropes. The height of the tower of a large turbine is around 100 m.

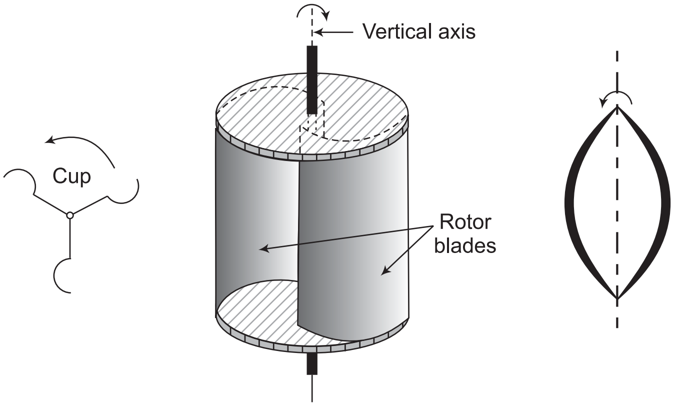
(b) Blades It has two or three thin, curved blades shaped like an eggbeater in profile, with blades curved in a form that minimizes the bending stress caused by

centrifugal forces-the so-called ‘Troposkien’ profile. The blades have airfoil cross-section with constant chord length. The pitch of the blades cannot be changed. The diameter of the rotor is slightly less than the tower height. The first large (3.8 MW), Darrieus type, Canadian machine has rotor height as 94 m and diameter as 65 m with a chord of 2.4 m.

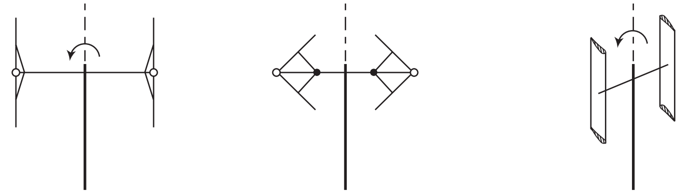
(c) Support Structure Support structure is provided at the ground to support the weight of the rotor. Gearbox, generator, brakes, electrical switchgear and controls are housed within this structure.

2. Types of Rotors

Various types or rotors for VAWTs are shown in Fig. 7.24. The simplest being three or four cups structure attached symmetrically to a vertical shaft. Drag force on concave surface of the cup facing the wind is more than that on convex surface. As a result, the structure starts rotating. Some lift force also helps rotation. However, it cannot carry a load and is, therefore, not used as power source. Main characteristic of this rotor is that its rotational frequency is linearly related to wind speed. Therefore, it is used as a transducer for measuring the wind speed and the apparatus is known as cup anemometer.



(a) Cup type rotor (b) Savonious rotor (c) Derrieus rotor



Operating position

Fully reefed or furled position

Blade pitch controllable

(d) Musgrove rotor (e) Evans rotor

Figure 7.24 Various types or rotors for VAWT

The Savonius or S-rotor consists of two half cylinders attached to a vertical axis and facing in opposite directions to form a two-vaned rotor. It has high starting torque, low speed and low efficiency. It can extract power even from very slow wind, making it working most of the time. These are used for low power applications. High starting torque particularly makes it suitable for pumping applications, using positive displacement pumps.

Darrieus rotor is used for large-scale power generation. Power coefficient is considerably better than S-rotor. It runs at a large tip-speed ratio. The aerodynamic force on the blade reverses in every revolution causing fatigue. This along with centrifugal force complicates the design of the blade. One of the drawbacks of this rotor is that it is usually not self-starting. Movement may be initiated by using electrical generator as motor. As the pitch of the blade cannot change, the rotor frequency and thus the output power cannot be controlled. Rotor frequency increases with wind speed and power output keeps on increasing till the blades stall. Hence at high wind speed it becomes difficult to control the output. For better performance and safety of the blades, gearbox and generator, etc., it is desirable to limit the output to a level much below its maximum possible value.

Musgrove suggested H shaped rotor where blades with fixed pitch are attached vertically to a horizontal cross arm. Power control is achieved by controlled folding of blades. Inclining the blades to the vertical provides an effective means of altering the blades angle of attack and hence controlling the power output.

Evans rotor, also known as Gyromill is an improvement over H shaped rotor. Here, the rotor geometry remains fixed (blades remain straight), but the blades are hinged on a vertical axis and the blade pitch is varied cyclically (as the blade rotates about vertical axis) to regulate the power output. But the need to vary the pitch cyclically through every rotor revolution introduces considerable mechanical complexity. However, this enables it to self-start.

7.8.3 Lift and Drag Type Machines

Wind turbines make use of either lift force or drag force predominantly to cause motion and accordingly known as lift or drag type machines. In lift devices the ratio of lift to drag forces may be as high as 30:1. For the drag design, the wind literally pushes the blades out of the way. Drag devices are less efficient and turn slower than wind. They produce high torque and thus are suitable for pumping applications. At high wind speeds they spill wind instead of producing more energy. Thus they do not benefit from high energy density available in wind.

The lift blade design employs the same principle that enables aeroplanes, kites and birds to fly. The blade is essentially an airfoil, or wing. When air flows past the blade, a wind speed and pressure differential is created between the upper and lower blade surfaces. The pressure at the lower surface is greater and thus acts to “lift” the blade. When blades are attached to a central axis, like a wind turbine rotor, the lift is translated into rotational motion. Lift-powered wind turbines have much higher rotational speeds than drag types and, therefore, well suited for generating electricity. Lift devices are more efficient and turn faster than wind. They are able to benefit from high power densities available in strong winds. The ratio of power extracted from wind by a lift device to that of a drag device is usually greater than 3:1 for the same swept area. Lift-type rotors often use tapered and/or twisted blades to reduce bending strains and improve the stalling performance. The types and characteristics of various types of rotors are given in Table 7.5.

Table 7.5 Characteristics of various types of rotors

S.N.	Rotor type	Tip speed ratio	RPM	Torque	Typical load
1.	Propeller (1–3 blade) (Lift)	6–20	High	Low	Electric Power generation
2.	Sailwing (Lift)	4	Moderate	Moderate	Electric Power generation or pump
3.	Chalk multi-blade (Lift)	3–4	Moderate	Moderate	Electric Power generation or pump
4.	American multi-blade (Drag)	1	Low	High	Pump
5.	Dutch type (Drag)	2–3	Low	High	Pump
6.	Savonious (Drag)	1	Low	High	Pump
7.	Darrieus (Lift)	5–6	High	Low	Electric Power generation
8.	Musgrove and Evan (Lift)	3–4	Moderate	Moderate	Electric Power generation or pump

7.8.4 Effect of Solidity

High solidity rotors use drag force and turn slower. Solidity of Savonious rotor is unity and that of American multi-blade rotor it is typically 0.7. Low solidity rotors, on the other hand, use lift force. Lift devices usually have solidity in the range of 0.01 to 0.1. They have slender airfoil blades. When solidity is less than 0.1, the device will usually not start up without first being rotated to generate lift.

7.8.5 Horizontal Axis versus Vertical Axis Turbines

Most wind turbines, used at present are of horizontal axis type. They have been well researched and have gone through extensive field trial. As a result, well-established technology is available for HAWTs. Some advantages of VAWT have recently generated considerable interest in this type of turbine. These are: (i) it can accept wind from any direction without adjustment, which avoids the cost and complexity of yaw orientation system, (ii) gearing and generators, etc., are located at ground level, which simplifies the design of tower, the installation and subsequent inspection and maintenance and (iii) also they are less costly as compared to HAWTs.

The principal disadvantages of VAWTs are: (i) many vertical axis machines have suffered from fatigue arising from numerous natural resonances in the structure, (ii) rotational torque from the wind varies periodically within each cycle, and thus unwanted power periodicities appear at the output, (iii) it normally requires guy ropes attached to the top for support, which could limit its applications particularly for offshore sites, (iv) it is noisier than HAWT, (v) as wind speed increases significantly with height, for the same tower height HAWT captures more power than VAWT and (vi) the technology is under development stage and far less is known about them as compared to HAWTs.

7.8.6 Speed Control Strategies for Wind Turbine

Various options are available for speed control of a turbine. The particular control strategy depends on the size of the turbine. Small machines use simple, low cost methods while large machines use more sophisticated methods incorporating pitch control along with power electronic circuit. These methods may be grouped in the following categories:

(i) No speed control at all. Various components of the entire system are designed to withstand extreme speed under gusty wind.
(ii) Yaw and tilt control, in which the rotor axis is shifted out of wind direction, either by yaw control or by tilting the rotor plane with respect to normal vertical plane when the wind exceeds the design limit.
(iii) Pitch control, in which the pitch of the rotor blades is controlled to regulate the speed.
(iv) Stall control, in which the blades are shifted to a position such that they stall when wind speed exceeds the safe limit.

7.8.7 Wind Turbine Operation and Power versus Wind Speed Characteristics

The power-speed characteristics of a wind turbine have four separate regions as shown in Fig. 7.25.

(a) Low Speed Region (Zero to Cut-in Speed) In this region, the turbine is kept in braked position till minimum wind speed (about 5 m/s), known as cut-in speed becomes available. Below this speed the operation of the turbine is not efficient.

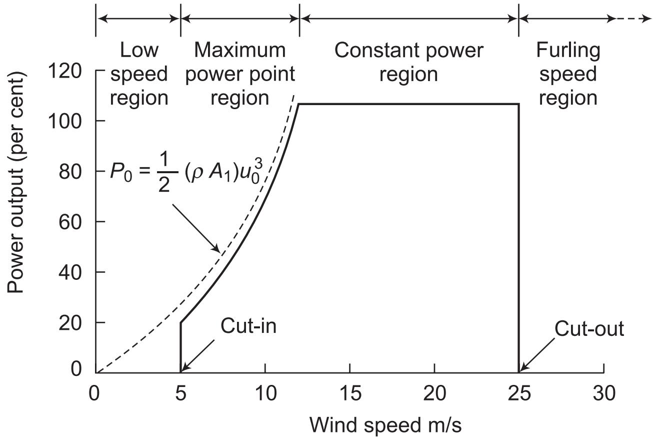


Figure 7.25 Power versus wind speed characteristics

(b) Maximum Power Coefficient Region In this region, rotor speed is varied with wind speed so as to operate it at constant tip-speed ratio, corresponding to maximum power coefficient, $C_{P\,\max}$. In this range the nature of characteristics is close to that of maximum power available in the wind as given by Eq.(7.4). The turbine is operated at maximum power output point using pitch control.

(c) Constant Power Region (Constant Turbine Speed Region) During high-speed winds (above 12 m/s), the rotor speed is limited to upper permissible value based on the design limits of system components. In this region the power coefficient is lower than $C_{P\,\max}$. Large machines use pitch control to maintain turbine speed as constant. Such a machine is known as *pitch regulated*. Classical European machines use fixed blades (constant pitch) and the blade twist and thickness are so designed as to crudely maintain the speed as constant. Such a machine is known as *stall regulated*. This is a simple system requiring only passive technique, as there are no moving blade surfaces or complicated hardware. However, power capture is somewhat less due to rounding of power curve.

In case of fixed blades rotor, the flow over the blade stalls. The stall performance depends on the twist of blade tip from the root and thickness of blade sections. The lift and drag coefficients change so as to flatten out the peak of the power curve. Thus the power output of the wind turbine is limited as shown in Fig. 7.26. Stall regulation can be used without much problem up to about 25 m diameter rotor. Above this size severe vibration problems, associated with the stalled flow in high wind speeds, have been encountered. Thus large HAWTs always have variable pitch control.

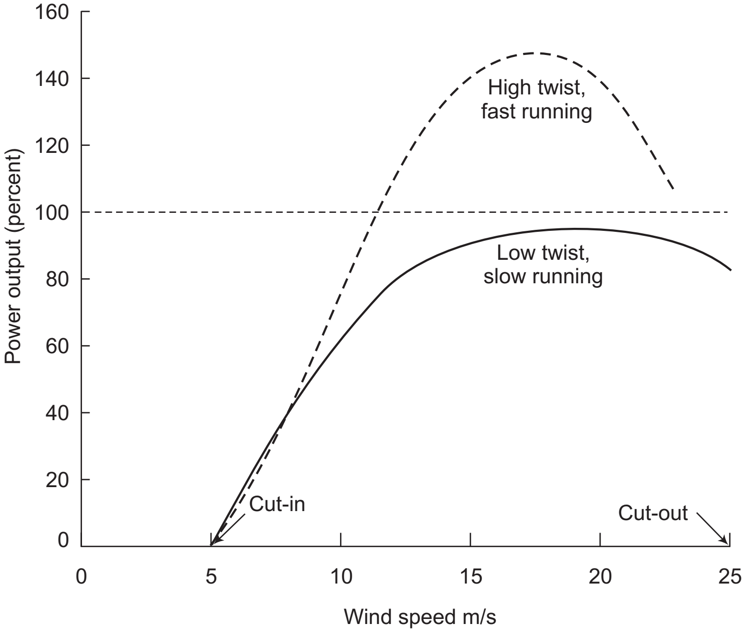


Figure 7.26 Power versus wind speed characteristics with stall regulation

At still higher wind speeds, such as gusts, constant speed operation is maintained by employing additional means such as some kind of braking (e.g. eddy current braking).

(d) Furling Speed Region (Cut-out Speed and Above) Beyond certain maximum value of wind speed (around 25 m/s) rotor is shut down and power generation is stopped to protect the blades, generator and other components of the system.

7.9 WIND ENERGY CONVERSION SYSTEMS (WECS)

A wind energy conversion system converts wind energy into some form of electrical energy. In particular, medium and large scale WECS are designed to operate in parallel with a public or local ac grid. This is known as *grid-connected system*. A small system, isolated from grid, feeding only to local load is known as *autonomous*, remote, decentralized, stand alone or isolated power system. A general block diagram of a grid connected WECS is shown in Fig. 7.27. The turbine shaft speed is stepped up with the help of gears, with fixed gear ratio, to suit the electrical generator and fine-tuning of speed is incorporated by pitch control. This block acts as drive for the generator. Use of variable gear ratio has been considered in the past and was found to add more problems than benefits. DC, synchronous or induction generators are used for mechanical to electrical power conversion depending on the design of the system. The interface conditions the generated power to grid quality power. It may consist of power electronic converter, transformer and filter, etc. The control unit monitors and controls the interaction among various blocks. It derives the reference voltage and frequency signals from the grid and receives wind speed, wind direction, wind turbine speed, etc., processes them and accordingly controls various blocks for optimal energy balance.

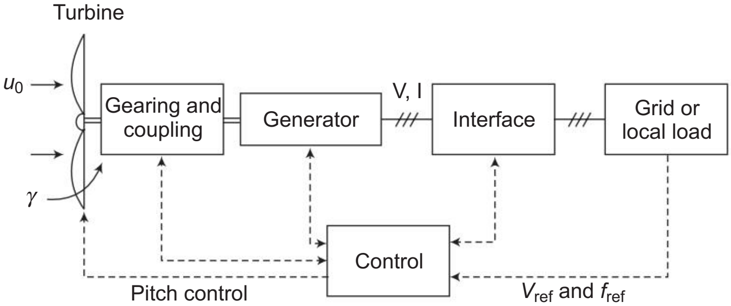


Figure 7.27 General block diagram of a WECS

Main features of various types of generators and their suitability in wind power generation are discussed below:

(a) DC Generator Conventional dc generators are no more favored due to their high cost, weight and maintenance problems due to commutator. However, permanent magnet (brush less and commutator less) dc machines are considered in small rating (below hundred kW) isolated systems.

(b) Synchronous Generator Synchronous generators produce high quality output and are universally used for power generation in conventional plants. However, they have very rigid requirement of maintaining constant shaft speed and any deviation from synchronous value immediately reflects in the generated frequency. Also precise rotor speed control is required for synchronization. Due to this reason a synchronous machine is not well suited to wind power generation. Requirement of dc current to excite rotor field, which needs sliding carbon brushes on the slip rings also poses limitations on its use. The need of dc field current and brushes can be eliminated by using reluctance rotor. The reliability is greatly improved while reducing the cost. The machine rating, however, is limited to tens of kW. Synchronization of a wind driven generator with the power grid also poses problems especially during gusty winds. Main advantage is that it generates both active as well as reactive powers.

(c) Induction Generator Primary advantages of induction machine are the rugged, brush less construction, no need of separate dc field power and tolerance of slight variation of shaft speed (±10 per cent) as these variations are absorbed in the slip. Compared to dc and synchronous machines they have low capital cost, low maintenance and better transient performance. For these reasons induction generators are extensively used in wind and micro-hydroelectric plants. The machine is available from very low to several megawatt ratings.

The induction machine requires ac excitation current, which is mainly reactive. In case of grid-connected system, the excitation current is drawn from the grid and therefore, the network must be capable of supplying this reactive power. The voltage and frequency are determined by the grid. In a stand-alone system the induction generator is self-excited by shunt capacitors.

Based on the generator drive, two schemes have been developed for the operation of WECS: (i) fixed speed drive scheme and (ii) variable speed drive scheme.

7.9.1 Fixed Speed Drive Scheme

In this scheme, constant speed is maintained at the shaft of generator by pitch control. A synchronous or induction generator is used to generate electrical energy. Induction generator is gaining more acceptability due to its ability to absorb small variations in shaft speed. Two types of fixed speed drive schemes are possible:

(a) One Fixed Speed Drive Shaft speed is held fixed for the whole range of wind speed. The major disadvantage of one fixed speed drive is that it never captures the wind energy at peak value of power coefficient C_P. Wind energy is wasted when wind speed is higher or lower than the optimal value, corresponding to $C_{P\,\max}$. Because of low annual energy yield, the use of one fixed-speed drive is limited to small machines.

(b) Two Fixed Speed Drive Two fixed speed drive, increases the energy capture, reduces the electrical losses and reduces the gear noise. The speed setting is changed by changing the gear ratio. The two operating speeds are selected to optimize the annual energy production with expected annual wind speed distribution at the site. The power production from a typical WECS using two fixed-speed drive is shown in Fig. 7.28. In this particular example, the gear ratio is changed at wind speed of 10 m/s.

The induction generator is designed to operate at two speeds. This is achieved by either (i) having two stator windings with different number of poles or (ii) using single winding with pole changing arrangement by connecting the winding coils in series and/or parallel. In separate winding machines, matching with system requirement is easy and change of speed setting is made without losing the control of the machine. However, separate windings are difficult to accommodate. While in pole changing method, the poles are either P or 2P, the only possible speed ratio is 2:1. Also a dead time is to be allowed for coils reconnection during every speed transition.

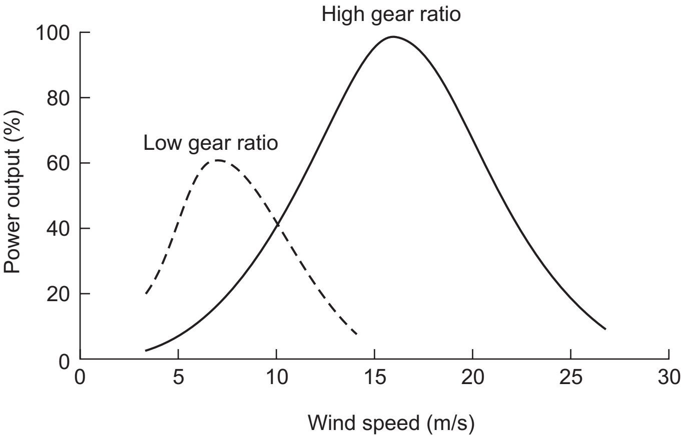


Figure 7.28 Power output vs wind speed for two fixed speed drives

7.9.2 Variable Speed Drive Scheme

Recent advancement in power electronics has paved the way for variable speed drive system. In this scheme, rotor speed is allowed to vary optimally with the wind speed to capture maximum power. As a result it can capture about one third more power per year as compared to fixed speed drive system. Following types of variable speed drive systems are possible:

(a) Variable Speed Drive Using Power Electronics Modern variable speed drive schemes make use of power electronic converters for power conditioning. The variable voltage and variable frequency output available from a generator (synchronous or self-excited induction generator) is first rectified to dc and then converted to fixed frequency and fixed voltage ac using inverter. The harmonics are filtered out to get grid quality output before connecting to the grid. The rectifier, inverter, filter and transformer constitute the main parts of the interface.

Apart from higher energy yield, use of power electronics offers remotely adjustable and controllable quality of power. This has two major benefits not available in other systems: (i) Opportunity for remote control. This makes it attractive for offshore applications. (ii) Fine tuning for superior grid connection, to make it better suited for meeting the demand of weak grids.

Use of power electronics adds to the cost, electrical noise and losses of the system. However, the cost and benefit trade is generally positive for large machines.

(b) Scherbius Variable Speed Drive Scherbius drive makes use of wound rotor induction machine. The stator is connected to the grid and rotor is connected to variable frequency source via slip rings, as shown in Fig. 7.29. The speed is controlled by controlling the frequency of the external voltage injected into the rotor. It offers lower cost and eliminates the power quality disadvantages. However, sliding contacts at the slip rings lead to increased maintenance and the range of speed control is generally limited to 2:1.

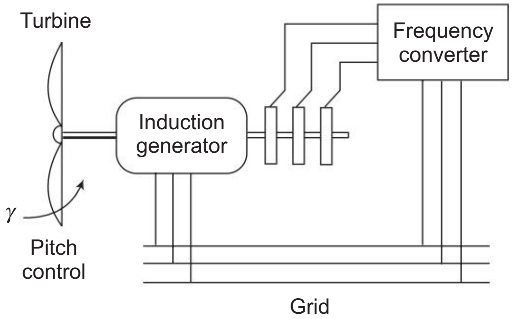


Figure 7.29 Scherbius variable speed drive

(c) Variable Speed Direct Drive In this scheme, the generator is directly coupled to the turbine shaft without gear and operates at turbine speed. Also it does not make use of power electronics. Main benefits are: (i) lower nacelle weight, (ii) reduced noise and vibration, (iii) lower power loss and (iv) less frequent servicing requirement at the nacelle, which is particularly very attractive for offshore installations. For small sized turbines, where the rotor speed is high, direct coupling to the generator is possible without much difficulty. Large rotors turn slowly and direct coupling requires large number of poles on electrical machines, which impose design limitations. To circumvent such limitations, the permanent magnet synchronous machines with large number of poles are being considered. Another possible solution is the use of axial gap induction machines, where large number of poles can be designed with less difficulty compared to conventional radial gap induction machines. These systems are still under development stage and various alternatives are being tried.

7.10 WIND–DIESEL HYBRID SYSTEM

There are many remote and isolated areas in the world where utility power grid has no access due to techno-economic reasons. Power to such places is supplied by small locally installed diesel generator unit. In such places wind electricity may be very economical if favourable wind is available. Unfortunately, wind is a highly fluctuating power source and the raw output at the terminals of a wind turbine is incompatible with the demand of a normal domestic or commercial user. In such places isolated wind turbines can be installed in conjunction with diesel generating units for backup.

This hybrid system, popularly known as wind–diesel system, is shown in Fig. 7.30. For economic viability, the savings in fuel cost should cover the additional investment cost due to wind generator, controller, dump load, storage unit, converter and other auxiliary equipment.

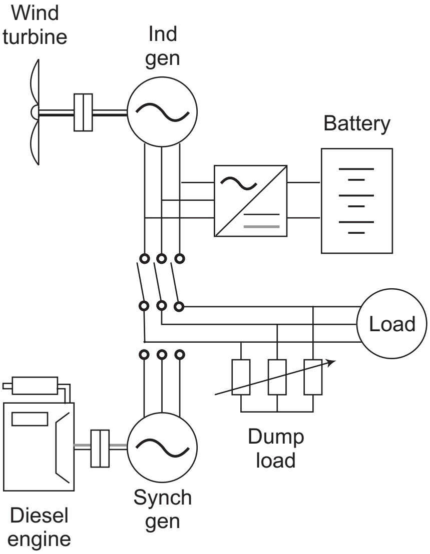


Figure 7.30 Wind–diesel hybrid system

Two types of operational schedule is possible for diesel unit:

1. Continuous Diesel Unit Operation

The simplest way to incorporate the wind turbine into the standard diesel powered system, without increasing the risk of loss of load, is to operate wind turbine in parallel with a continuously running diesel generator. In this mode, wind power acts as negative load, reducing the average load of the diesel unit. The diesel generator can be allowed to operate at very low loading or even at negative load. This system performs well without the need of any supervisory control.

2. Intermittent Diesel Unit Operation

In this mode diesel unit is switched off during periods when the output of wind turbine is sufficiently high to meet the demand without any backup. The saving in fuel is more in this case. However, due to variation in wind power, which is much more significant than that of the load, frequent starts/stops of diesel unit may be required. Frequent startups hasten the wear of diesel engine and starter. Also owing to inertia, comparatively lengthy time interval is necessary to start and stop the unit. The system may collapse during diesel generator startup if wind power drops within startup interval. Some kind of energy storage (battery, flywheel or pumped storage) may reduce diesel start/stop operations within the acceptable rate of system cycling. However, this also increases the cost of the system.

In some hybrids, batteries meet the daily load fluctuations, and the diesel generator takes care of the long-term fluctuations. For example the diesel generator is used in the worst-case weather conditions, such as extended windless days or weeks.

7.11 EFFECTS OF WIND SPEED AND GRID CONDITION (SYSTEM INTEGRATION)

Wind energy is an intermittent source of power. There are variations in wind speed and therefore the power output on a yearly, seasonal, daily and hourly scale. A utility has to serve the varying load of its customers by the power available from various power plants. As wind power is a varying power source, which cannot really be dispatched, conventional power plants or storage facilities have to deal with these variations. (The wind and solar PV power are treated as non-dispatchable for not being available on demand.) This means that output variations in wind power can give rise to extra cost due to extra power changes or start/stop of conventional units.

If the penetration of wind power into the grid is continuously increased, it might reach to a level where economics of the total power production is affected in a negative way. This will limit the penetration of wind power into the grid. The optimum penetration depends on specific circumstances and characteristics of the utility system. In most cases wind power penetration level less than 10 per cent of the total electricity production will cause no severe problem and will not cause any economic disadvantage. For higher penetration, total electricity production system is to be re-optimized. This may require integration of some more peak load units or storage capacity plants. Also the distance of the wind resource from the grid poses another limiting factor as it influences the economics of wind power. A distance of less than 50 km is generally considered as economically feasible.

7.12 WIND ENERGY STORAGE

A major problem with wind power is intermittency. It does not garner higher prices from the purchaser because it is not schedulable. Higher prices may be obtained if it is available on demand. This can be made possible if provision of energy storage is available. For example, if the wind is blowing hardest at 11 O’clock at night, a wind farm operator could store the energy generated from the wind and release it at 11 O’clock the next morning when the demand for power starts spiking up.

In place of a generator, a compressor is used in the nacelle. The highly compressed air is sent down the tower into underground storage such as caves or depleted gas wells through pipelines. The pressurized air can be released when needed to power an electricity generator, even if wind is not spinning the turbine. “Mechanology”, a compressor research and development firm, has designed a compressor and has tested a prototype wind energy storage system. The company plans to build its large-scale version now.

For wind turbines with power outputs up to about 20 kW, direct current generators can be used to charge batteries directly. For higher rating, ac generators can be used with rectifiers. The energy can be recovered when battery is discharged. The dc output can also be used in an electrolyzer which produces hydrogen and oxygen from ordinary water. The hydrogen and oxygen thus produced can be stored in tanks. Electrical energy can later be produced using fuel cells.

A wind power plant can also be integrated with pumped storage plant. The excess power generated can be utilized to store water at a higher reservoir. The stored energy can be later recovered by running the pumped storage plant as a normal hydro plant.

The excess wind energy can also be stored as thermal energy (e.g. hot water) and may be utilized later for space heating, heating of green house or crop drying.

7.13 ENVIRONMENTAL ASPECTS

In general, the use of energy in any form, affects the environment in one-way or the other at different levels. Wind energy is no exception. Although, these effects are of far less consequence as compared to that related to other sources of energy.

In terms of causing stress on water resources, wind energy is one of the most benign sources of energy. A major advantage of wind generation relative to any thermal based generation (nuclear, geothermal, fossil fuel and solar thermal) is that it does not need cooling water.

Main environmental concerns are discussed below:

1. Indirect Energy Use and Emissions

Energy is required to produce materials used to construct the wind turbine and in its installation. This energy is paid back in a period of few months to about a year, what is known as energy payback period. Some pollution (emission of CO_2, etc.) is caused due to use of energy during construction. But in total the so-called indirect CO_2 emission over the total operating life of the wind generator is very low (about 1 per cent of the system using coal).

2. Bird Life

Large wind turbines pose a threat to bird life as a result of collision with tower or blades. Their resting and breeding patterns are also affected.

3. Noise

The disturbance caused by the noise produced by wind turbine is one of the important factors that prevent its siting close to inhabited areas. The acoustic noise is composed of (a) mechanical noise due to movement of mechanical parts in the nacelle (mainly gear and also other equipment), which can be reduced by good design and acoustic insulation and (b) aerodynamic noise (swishing sound from the rotating blades), which is a function of wind speed and which cannot be avoided. Some of this noise is of infra sound, at frequencies below the audible range. This infrasound may cause houses and other structures to vibrate. Analysis shows that for turbines with rotor diameters up to 20 m the mechanical component dominates, whereas for larger rotor diameters the aerodynamic component is predominant.

The sound level of a 500 kW machine rotating at 18 revolutions per minute at the hub is typically 102 dBA, which reduces down to 60 dBA at a distance of 50 m and declines very rapidly afterwards. A sound level of 35 dBA (noise limit for residential areas in many countries) is reached only after a distance of 500 m.

4. Visual Impact

Wind turbines are massive structures quite visible over a wide area in most locations. Visual impact of wind turbine is qualitative in nature. In a study, it was found that public appreciation of a landscape decreases as more and more wind turbines are installed. A special case of visual impact is the effect of shadow of the turbine, particularly of the rotor blades. The rotational frequency plays an important role in determining the disturbance level. Offshore wind farms being away from inhabited areas do not in general create same severity of visual intrusion.

5. Telecommunication Interference

Wind turbines present an obstacle for incident electromagnetic waves (i.e. TV or microwave signals). These waves can be reflected, scattered and dithered. Thus they interfere with telecommunication links and badly affect the quality of radio and TV reception. The effect can be mitigated by use of cable system or by installing powerful antennas.

6. Safety

Accidents with wind turbines are rare but they do happen, as in other industrial activities. For example, a detached blade or its fragment may be thrown a considerable distance and can harm people and property. However, most wind turbines are located in isolated areas, which make it less likely to cause any damage. The International Electrical Committee (IEC) has taken the initiative to produce an international standard on safety.

7. Effects on Ecosystem

Large-scale use of wind generation can reduce wind speed and cause stress to ecosystem. Lakes that are downhill from the wind turbines might become warmer because of reduced evaporation from their surface. Soil moisture might also increase. Nevertheless there impacts may not be of great consequence except in certain sensitive areas.

7.14 WIND ENERGY PROGRAM IN INDIA

Wind energy program was initiated in India in 1983–84. The program has been managed and implemented by Ministry of New and Renewable Energy Sources, Government of India. The Ministry's wind power program covers survey and assessment of wind resources, facilitation of implementation of demonstration and private sector projects through various fiscal and promotional policies. A total capacity of 22,465 MW has been established up to December, 2014 in the country. India is the fifth largest wind power producer in the world, after China, USA, Germany, and Spain.

The Wind Resource Assessment (WRA) Program is an ongoing activity and is being coordinated by the National Institute of Wind Energy (NIWE), Chennai in association with State Nodal Agencies. WRA has so far been covered in 29 states and 3 Union Territories involving establishment of 794 dedicated wind-monitoring stations. Out of the total stations established so far, 237 stations have shown potential for commercial wind power installations and 109 stations are presently in operation. Under the project entitled "Estimation and Validation of Wind Power Potential at 100 m level in 7 States", 74 nos. of 100 m level Wind Monitoring Stations have so far been commissioned and data collection is under progress.

As per the Indian Wind Atlas, the on-shore wind power potential has been estimated as 49,130 MW at 50 m height. On a conservative consideration, a fraction of 2 per cent land availability for all states except Himalayan states, North-eastern states and Andaman & Nicobar Islands has been assumed for potential estimation. In Himalayan states, North-Eastern states and Andaman & Nicobar Islands, it is assumed as 0.5 per cent. However, the potential would change as per the actual land availability in each state. The wind potential has also been extrapolated at 80 m height and has been found to be 1, 02,788 MW. However, this needs to be validated with field measurements. The state wise potential as well as installed capacity is given in Table 7.6.

Table 7.6 State wise wind power as on 31.03.2015 [48]

S.N.	State (Sites)	Estimated potential, MW		Installed capacity MW
		50 m	80 m	
1.	Andhra Pradesh	5394	14497	1031.4
2.	Gujarat	10609	35071	3645.4
3.	Karnataka	8591	13593	2636.4
4.	Kerala	790	837	35.1
5.	Madhya Pradesh	920	2931	879.7
6.	Maharashtra	5439	5961	4450.8
7.	Rajasthan	5005	5050	3307.2
8.	Tamil Nadu	5374	14152	7,455.2
9.	West Bengal	22	22	3.8
10.	Others	6,986	10,644	2.5
Total		49,130	1,02,788	23,447.5

Source: MNRES Annual Report, 2014–15

Wind electric generators of unit sizes between 225 kW and 2.50 MW have been deployed across the country. Wind turbines are being manufactured by 20 manufacturers in the country with 58 models ranging from unit size from 250–2650 KW, mainly through joint ventures or under licensed production agreements. Nine new models were introduced during the year and few models were discontinued due to request of manufacturers. A few foreign companies have also set up their subsidiaries in India, while some companies are now manufacturing wind turbines without any foreign collaboration. The current annual production capacity of domestic wind turbine industry is around 9500 MW. The technology is continuously upgraded, keeping in view global developments in this area. The distribution of wind power density in the country is shown in Fig. 7.31. A view of wind form at Jogimatti, Karanataka is given in Fig. 7.32.

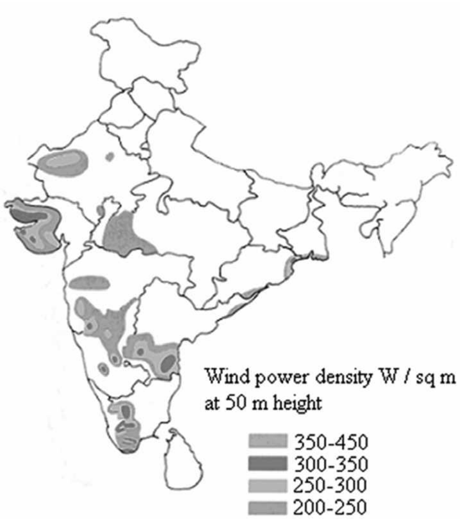


Figure 7.31 Wind map of India

Source: MNES Annual report

Figure 7.32 A 8.4 MW commercial wind farm at Jogimatti (Karnataka)

Source: MNES Annual report

Research and Development activities are being undertaken through research institutions, national laboratories, universities and industry for the development of cost effective technologies and systems to improve the quality of power generation from wind. R & D activities are coordinated through the National Institute of Wind Energy (NIWE), Chennai.

REVIEW QUESTIONS

1. What range of wind speed is considered favorable for wind power generation?
2. What factors led to accelerated development of wind power?
3. With the help of a diagram indicate the circulation of global winds. What are the forces responsible for determining the speed and direction of global winds?
4. Explain the mechanism of production of local winds.
5. What are the factors responsible for distribution of wind energy on the surface of earth?
6. What do you understand by gust?
7. What principles may be used for measurement of wind speed? What is the standard height for measurement of wind speed?
8. What are the advantages of presenting the wind data in the form of a wind rose?
9. With the help of a diagram, explain the nature of variation of wind speed with height from the ground. Explain the terms: wind shear, gradient height, free atmosphere, planetary boundary, surface layer and Ekman layer.
10. What are the most favorable sites for installing of wind turbines?
11. Explain the major applications of wind power.
12. With the help of a diagram, explain the terms: free and relative wind velocities, drag and lift forces, solidity, pitch angle and chord.
13. What do you understand by attached and separated flow? With the help of diagram show attached and stalled flow. What are the main features of stalled flow? How is the stalled performance improved?
14. Derive an expression for energy available in the wind.
15. Using Betz model of a wind turbine, derive the expression for power extracted from wind. What is the maximum theoretical power that can be extracted and under what condition?
16. Derive the expression for maximum axial thrust experienced by a wind turbine and also find the condition for such operation.
17. Explain the variation of power output of a wind turbine with tip speed of the rotor.
18. Sketch the diagram of a HAWT and explain the functions of its main components.
19. Explain various designs of blades of HAWTs and their relative features.
20. What do you understand by teetering of rotor? In what cases it is required?
21. What do you understand by upwind and downwind machines, yaw active and yaw fixed machines?
22. Sketch the diagram of a VAWT and explain the functions of its main components.
23. Explain various designs of blades of VAWTs and their relative features.

24. What are the relative features of drag and lift type machines?

25. What are the effects of solidity on the performance of a wind turbine?

26. Comment on the relative features of HAWT and VAWT.

27. With the help of a diagram, discuss the power versus wind speed characteristics of a wind turbine.

28. Discuss the relative performances of a pitch regulated and stall regulated wind turbine.

29. With the help of block diagram explain the functions of various blocks of a WECS.

30. Evaluate the suitability of various types of generators for wind power generation.

31. Discuss various types of drive schemes used in wind turbines.

32. Explain the main features of wind-diesel hybrid generating systems. Also point out various types of operational scheduling for diesel unit.

33. Comment on the environmental impacts of wind energy.

PROBLEMS

1. Following data were recorded for a two blade HAWT:

Average free wind speed at a standard height of 10 m = 8 m/s

$\alpha = 0.13$

Air density = 1.226 kg/m^3

Hub height from the ground = 80 m

Rotor diameter = 60 m

Downstream wind velocity is half that of upstream wind.

Find:

(i) Power available in the wind
(ii) Power extracted by the turbine
(iii) Axial force on the turbine
(iv) Axial force on the turbine under the condition when,
    (a) maximum power is extracted and
    (b) no power is extracted and the blade stalls completely.

(*Ans.* 1.995 MW, 1.1219 MW, 1.427×10^5 N, 1.693×10^5 N, zero)

2. A HAWT has following data:

Speed of wind =10 m/s at 1 atm and 15 °C

Diameter of rotor = 120 m

Speed of rotor = 40 rpm

Calculate the maximum possible torque produced at the shaft.

(*Ans.* 0.98 N)

3. A two blade HAWT is installed at a location with free wind velocity of 20 m/s. The rotor diameter is 30 m. What rotational speed should be maintained to produce maximum output? (*Ans.* 80 rpm)

4. Calculate the rotor radius for a wind turbine operating at wind speed of 7 m/s to pump water at a rate of 5 m^3/h with a lift of 6 m. Also calculate the angular velocity of the rotor.

Use following data:

Water density $\rho_w = 1000$ kg/m^3, $g = 9.8$ m/s^2, water pump efficiency = 45%, efficiency of rotor to pump = 80%, power coefficient, $C_p = 0.25$, tip speed ratio, $\lambda = 1.1$, air density, $\rho = 1.2$ kg/m^3.

(*Ans.* 1.4035 m, 52.39 rpm)

5. An aero-generator, installed at sea shore generates an output of 1200 W at wind speed of 6 m/s at a temperature of 27 °C. What will be the output, if the same aero-generator is installed on the top of a hill where the temperature is 15 °C, pressure is 0.85 atmospheric and wind speed is 8 m/s? (*Ans.* 2518.48 W)

OBJECTIVE TYPE QUESTIONS

1. The range of wind speed suitable for wind power generator is:
(a) 0 to 5 m/s (b) 5 to 25 m/s
(c) 25 m/s to 50 m/s (d) 50 m/s to 75 m/s

2. Favorable winds for small scale applications exists:
(a) everywhere on earth surface (b) on 75% of earth surface
(c) on 50% of earth surface (d) on 25% of earth surface

3. Compared to conventional sources of power such as thermal plant, the cost of wind power is:
(a) 100 times (b) 10 times
(c) comparable (d) 1/10 times

4. The energy payback period of wind generation is:
(a) 1 year (b) 2 years
(c) 3 years (d) 4 years

5. There is little wind in:
(a) north pole region (b) south pole region
(c) tropical region (d) ±5° around equator

6. When solar radiation falls on earth surface, temperature of:
(a) land mass rises faster than water mass
(b) land mass rises slower than water mass
(c) land mass and water mass rises uniformly
(d) only land mass increases and water remains at fixed temperature

7. A wind turbine extracts maximum power from wind, when the downstream wind speed reduces to:
(a) one-third that of upstream wind (b) half that of upstream wind
(c) two-third that of upstream wind (d) zero

8. Stalled flow occurs when the value of incident angle is:
(a) 0 degree
(b) 180 degree
(c) in range from 0 to 16 degree (approximately)
(d) beyond 16 degree

9. If the speed of wind stream remain unchanged while passing through the rotor,:
(a) a large power will be generated (b) zero power will be generated
(c) the flow is known as stalled flow (d) the speed of rotor will be very high

10. As per Betz criterion, the maximum energy extractable by an ideal wind turbine is:
(a) 29% of that available in wind (b) 39% of that available in wind
(c) 49% of that available in wind (d) 59% of that available in wind

11. Maximum axial thrust occurs when interference factor 'a' is:
(a) 0 (b) 0.33
(c) 0.5 (d) 1.0

12. A two blade wind turbine produces maximum power when the tip speed ratio is equal to:
(a) π (b) 2π
(c) 3π (d) 0.593

13. The wind turbine rotor having low value of solidity:
(a) runs slower (b) runs faster
(c) produce high torque (d) have low efficiency

14. Stall regulation is used with turbines:
(a) having diameter less than 25 m (b) having diameter more than 25 m
(c) having rotor of large solidity (d) having rotor with pitch control

15. Grid connected wind generator usually have maximum penetration of:
(a) 10 to 20% (b) 20 to 30%
(c) 30 to 40% (d) 40 to 50%

16. As per the size of installed capacity of wind power generation in the world, India ranks:
(a) fifth (b) second
(c) third (d) fourth

17. Potential sites for wind generation are those having average energy densities of:
(a) 25–50 W/m^2 (b) 50–100 W/m^2
(c) 100–200 W/m^2 (d) 200 W/m^2 or more

18. If the velocity of wind is doubled, the power out be:
(a) reduced to half (b) doubled
(c) increase by 8 times (d) increase by 6 times

19. A place where many wind turbines are installed together to produce electricity is called:
(a) wind farm (b) propeller collection
(c) wind station (d) wind turbine group

20. Wind blows because of:
(a) difference in temperature (b) difference in latitude
(c) difference in longitude (d) difference in surface roughness

21. Why do wind turbines using aerodynamic lift produce more energy for a given swept area than wind turbines using aerodynamic drag?
(a) The lift force pushes the rotor blade in the direction of wind.
(b) The lifting force is roughly perpendicular to local flow fields.
(c) Lift produces more torque.
(d) Drag services capture more energy because of greater friction on blade surfaces.

22. Windmill works on the principle of:
(a) rotation (b) momentum
(c) gravitation (d) collision

23. The wind speed increases with height because of:
(a) enhancement of drag effect on the earth surface
(b) reduction of drag effect of the earth surface

(c) reduction in lift effect of the air
(d) reduction in the gravitational force

24. Cut-in velocity in a wind power machine is:
(a) the maximum wind speed at which a wind turbine is designed to come into operation
(b) the minimum wind speed at which a wind turbine is designed to come into operation
(c) the wind speed at which the wind turbine stops functioning
(d) the velocity of the rotor

25. During day time the surface wind flows:
(a) from sea to land (b) from land to sea
(c) on sea only (d) on land surface only

26. The air density at standard condition at sea level is about:
(a) 1.855 kg/m^3 (b) 2.555 kg/m^3
(c) 1.226 kg/m^3 (d) 3.267 kg/m^3

27. Wind energy conversion devices based on drag:
(a) move faster than wind
(b) move slower than wind
(c) move with velocity equal to that of wind
(d) do not depend on wind velocity

28. Yawing system in a wind energy conversion system is used to:
(a) control wind speed (b) stop the wind rotor
(c) control the electricity generation (d) keep the rotor in wind direction

29. In a horizontal axis wind turbine, the gear box is located:
(a) at the ground in the control room (b) at the bottom of the tower
(c) at the top of the tower (d) inside and in the middle of the tower

CHAPTER

8

Biomass Energy

Learning Objectives

In this chapter you will be able to:

- Know about the origin of biomass energy
- Recognize the importance of biomass as a useful source of renewable energy
- Describe technologies for conversion of raw biomass into useful forms of energy
- Explore the use of energy farming as sustainable source of energy

8.1 INTRODUCTION

Biomass is a general term for living material – plants, animals, fungi, bacteria. Taken together, the Earth's biomass represents an enormous store of energy. It has been estimated that just one eighth of the total biomass produced annually would provide all of humanity's current demand for energy. And, since biomass can be re-grown, it is potentially a renewable resource.

The energy obtained from biomass is known as biomass energy. Animals feed on plants and plants grow through photosynthesis process using solar energy. Thus, photosynthesis process is primarily responsible for generation of biomass energy. A small portion of the solar radiation is captured and stored in the plants during photosynthesis process. Therefore, it is an indirect form of solar energy. The average efficiency of photosynthetic conversion of solar energy into biomass energy is estimated to be 0.5–1.0 per cent.

To use biomass energy, the initial biomass may be transformed by chemical or biological processes to produce more convenient intermediate bio-fuels such as methane, producer gas, ethanol and charcoal etc. On combustion it reacts with oxygen to release heat, but the elements of the material should be available for recycling in natural ecological or agricultural processes. Thus the use of industrial bio-fuels, when linked carefully to natural ecological cycle, may be nonpolluting and sustainable. For the biomass to be considered as renewable, growth must at least keep pace with its use. It is disastrous that forest and firewood consumption is significantly outpacing their growth in ever-increasing areas of the world. It is estimated that the biomass, which is 90 per cent in trees, is equivalent to the current proven extractable fossil fuel reserves in the world. The dry matter mass of biological material cycling in biosphere is about 250×10^9 tons/year. The associated energy bound in photosynthesis is 2×10^{21} J/year (equivalent to continuous flow of 0.7×10^{14} W) [49].

Although fossil fuels have their origin in ancient biomass, they are not considered biomass by the generally accepted definition because they contain carbon that has been "out" of the carbon cycle for a very long time. Their combustion therefore disturbs the carbon dioxide content in the atmosphere.

Biomass, mainly in the form of wood, is mankind's oldest form of energy. It has traditionally been used both in domestic as well as industrial activities, basically by direct combustion. As industrial activities increased, the growing demand for energy depleted biomass natural reserves. The development of new, more concentrated and more convenient sources of energy has led to its replacement to a large extent by other sources. However, it still plays a significant role in the supply of primary energy in many countries of the world. Though biomass energy share in primary energy supply for the industrialized countries is not more than 3 per cent, a number of developing countries still use a substantial amount of it mostly in the form of noncommercial energy.

Main advantages of biomass energy are:

- it is a renewable source;
- the energy storage is its in-built feature;
- it is indigenous source requiring little or no foreign exchange;

- the forestry and agricultural industries that supply feed stocks also provide substantial economic development opportunities in rural areas;
- the pollutant emissions from combustion of biomass are usually lower than those from fossil fuels;
- commercial use of biomass may avoid or reduce the problems of waste disposal in other industries, particularly municipal solid waste in urban centers;
- use of biogas plants apart from supplying clean gas, also leads to improved sanitation, better hygienic conditions in rural areas as the harmful decaying biomass gets stabilized;
- the nitrogen-rich bio-digested slurry and sludge from biogas plant serves as a very good soil conditioner and improves the fertility of the soil;
- varying capacity can be installed; any capacity can be operated, even at lower loads;
- no seasonality.

Its main disadvantages are:

- it is a dispersed and land intensive source,
- it is often of low energy density and
- it is also labor intensive and the cost of collecting large quantities for commercial application is significant. Most current commercial applications of biomass energy use material that has been collected for other reasons, such as timber and food processing residues and urban waste.
- capacity is determined by availability of biomass and not suitable for varying loads
- not feasible to set up at all locations

8.2 PHOTOSYNTHESIS PROCESS

Solar radiation incident on green plants and other photosynthetic organisms performs two basic functions: (i) temperature control for chemical reactions to proceed and (ii) photosynthesis process. The fundamental conversion process in green plants is *photosynthesis*, which is the process of combining CO_2 from the atmosphere with water plus light energy to produce oxygen and carbohydrates (sugars, starches, celluloses and hemicelluloses). They are ultimate source of most of our foods and other necessities of daily life such as cloths (in the form of cotton), furniture (in the form of wood) etc.

$$x\mathrm{CO}_2 + y\mathrm{H}_2\mathrm{O} + \text{light energy} \xrightarrow{\text{Photosynthesis}} xO_2 + C_x(\mathrm{H}_2\mathrm{O})_y \tag{8.1}$$

The generalized symbol $C_x(H_2O)_y$ is used to indicate the carbohydrates. The products of this reaction are about 5 eV per C atom higher in energy than the initial material. Photosynthesis is a complex process. It involves several successive stages, but the overall basic reaction is the formation of hexose (glucose, fructose, etc.) as represented by:

$$6\mathrm{CO}_2 + 6\mathrm{H}_2\mathrm{O} + \text{light energy} \xrightarrow{\text{Photosynthesis}} 6\mathrm{O}_2 + \mathrm{C}_6\mathrm{H}_{12}\mathrm{O}_6 \tag{8.2}$$

More complex hydrocarbons (sucrose, starch, cellulose, etc.) are formed by a chain of these simple structures. The reverse of this process is called respiration, in which CO_2, H_2O and energy are produced using carbohydrate and oxygen. The energy produced in the plants by respiration is used in several processes such as to draw moisture and nutrients through its roots. In green plants, both photosynthesis and respiration occur during the day and only respiration at night. This is symbolically shown in Fig. 8.1. There is a net overall gain of energy in the process, as the rate of energy loss in respiration is much less as compared to rate of energy gain during photosynthesis process. The process also results in net gain of oxygen and fixation of carbon in the form of biomass. The net energy absorbed from solar radiation during photosynthesis can be measured from its combustion:

$$x\,\mathrm{CO_2} + y\,\mathrm{H_2O} + \Delta Q \quad \overset{\text{Photosynthesis}}{\underset{\text{Combustion}}{\rightleftarrows}} \quad x\,O_2 + C_x\,(\mathrm{H_2O})_y \tag{8.3}$$

ΔQ is enthalpy change of the combustion process, equal to the energy absorbed from photons of solar radiation, less the energy of respiration during growth. The value of ΔQ is 4.8 eV per carbon atom, 470 kJ per mole of carbon or 16 MJ/kg of dry carbohydrate material. It is to be noted that the combustion requires the temperature of approximately 400 °C, whereas respiration occurs at 20 °C through catalytic enzyme reactions.

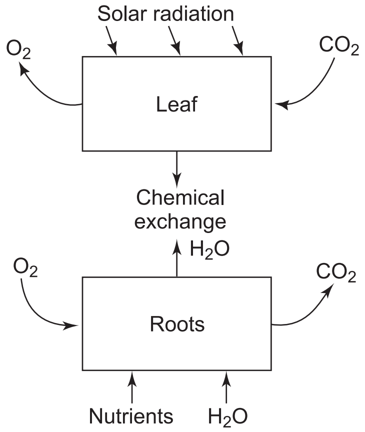


Figure 8.1 Photo synthesis and respiration processes in a plant

The uptake of CO_2 by a plant leaf is a function of many factors, especially temperature, CO_2 concentration and the intensity and wavelength distribution of light. Solar radiation incident on a leaf is reflected, transmitted and absorbed. Part of the absorbed radiation (< 5 per cent) provides the energy stored in the photosynthesis and produces oxygen and carbohydrate; the remainder is absorbed in the plant as sensible heat raising its temperature, or as latent heat for water evaporation. Absorption is usually most marked in the blue and red regions.

8.3 USABLE FORMS OF BIOMASS, THEIR COMPOSITION AND FUEL PROPERTIES

Biomass is organic material that reacts with oxygen in combustion and natural metabolic process to release heat. Sometimes, it is used as such in its original form but more often it is transformed into modern energy forms such as liquid and gaseous fuels, electricity, and process heat to provide energy services needed by rural and urban populations and also by industry. Some of its forms available to users are discussed below:

1. Fuel Wood (Virgin Wood)

Wood is the most obvious and oldest source of biomass energy. This was the main source of energy used by mankind for centuries. Direct combustion is the simplest way to obtain heat energy. Its energy density is 16–20 MJ/kg. It can also be converted to more useful forms such as charcoal or producer gas.

About half of the world population depends on fuel wood or other biomass such as cow dung, crop residue etc. for cooking and other domestic uses. Because of inefficient use of fuel wood in conventional household stove (Chulhas), only 5 per cent heat is utilized. The remainder is lost due to wind, incomplete combustion, radiation losses and other losses resulting from mismatch of fire and pot size. Considerable energy is also wasted in evaporation from uncovered pot and from use of wet fuel. Smoke, which is in fact unburnt tar and carbon, is a health hazard. There is little control over the rate at which wood is burnt. Improved household stoves (Chulhas) and use of pressure cooker is being encouraged for better fuel utilization.

2. Charcoal

Charcoal is a clean (smokeless), dry, solid fuel of black color. It has 75–80 per cent carbon content and has energy density of about 30 MJ/kg. It is obtained by carbonization process of woody biomass to achieve higher energy density per unit mass, thus making it more economical to transport. It can be used as fuel in domestic environment as it burns without smoke. In the industrial sector it is used in specialized applications where specific fuel characteristics are required, such as high carbon and low sulphur content. Chemical grade charcoal has many uses in laboratory and industrial chemical processes. It is also used for making high quality steel. It is in common use in many developing countries such as Brazil.

3. Fuel Pellets and Briquettes

Crop residues such as straw, rice husk etc. and waste wood are pressed to form lumps, known as fuel pellets or briquettes and used as solid fuel. The purpose is to reduce moisture content and increase the energy density of biomass making it more feasible for long distance transportation.

4. Bio-diesel

Some vegetable oils, edible as well as non-edible can be used (after some chemical processing) in pure form or its blend with petroleum diesel as fuel in a compression–ignition (diesel) engine. Bio-diesel is simple to use, biodegradable, nontoxic, and essentially free of sulfur and aromatics. In fact Rudolf Diesel, inventor of diesel engine initially designed his engine to use peanut oil and demonstrated its first working prototype on 10th August 1893. He believed that the utilization of biomass fuel was the real future of his engine. In remembrance of this event, August 10 has been declared as "International Bio-diesel day".

The raw vegetable oil is upgraded as bio-diesel through a chemical process called trans-esterification whereby the glycerin is separated from the animal fat or vegetable oil. The process leaves behind two products—methyl (or ethyl) esters (the chemical name for bio-diesel) and glycerin (a valuable byproduct usually sold to be used in soaps and other products). Bio-diesel can be produced from vegetable oils, animal fats or recycled restaurant greases.

Fuel-grade bio-diesel must be produced to strict industry specifications (such as ASTM D6751) in order to insure proper performance. Bio-diesel that meets the prescribed specifications and is legally registered with the Environmental Protection Agency is a legal motor fuel for sale and distribution. Raw vegetable oil cannot meet bio-diesel fuel specifications, it is not registered with the EPA, and it is not a legal motor fuel. Bio-diesel refers to the pure fuel before blending with diesel fuel. Bio-diesel blends are denoted as, "BXX" with "XX" representing the percentage of bio-diesel contained in the blend (i.e., B20 is 20 per cent bio-diesel and 80 per cent petroleum diesel, B100 is pure biodiesel).

Jatropha and Karanj are the most promising bio-diesel resources. Some plants (e.g. Euphorbia lathyris) produce latex, which can be processed to obtain hydrocarbons, which have molecular weights very close to petroleum. It also produces sugar as a byproduct. However, the technology is at research stage and its economic viability has not been assessed yet.

5. Bio-ethanol

Ethanol (C_2H_5OH) is a colorless liquid biofuel. Its boiling point is 78 °C and energy density is 26.9 MJ/kg. It can be derived from wet biomass containing sugars (e.g. sugarcane, sugarbeet, sweet sorghum, etc.), starches (grains, tubers such as potato, cassava, etc.) or cellulose (woody matter). Main constituents of woody matter are: lignin (fibrous part) and cellulose (juicy part). Ethanol is largely produced from sugar cane (from maize in USA due to surplus production). Commercial ethanol is used in specially designed IC engines with 25 per cent mileage penalty compared to conventional vehicles. Blend of up to 22 per cent anhydrous ethanol with gasoline, requires no engine modification and incurs no mileage penalty. It is being used by a large number of automobiles in the world. Brazil, the biggest producer of sugar cane, presently produces around 23.4 billion litres/year (2014) of ethanol representing 25 per cent of the world's total ethanol used as fuel. Major bio-ethanol programs are also being developed in USA, Zimbabwe and Malawi etc.

6. Biogas

Organic wastes from plants, animals and humans contain enough energy to contribute significantly to energy supply in many areas, particularly the rural regions of developing countries. Aquatic biomass can also be used. Biogas is produced in a biogas fermenter or digester. Nitrogen rich sludge (fertilizer) is also produced as a byproduct with improved sanitation as an added bonus. If raw material is cow manure, the output biogas will contain about 50–60 per cent CH_4, 30–40 per cent CO_2, 5–10 per cent H_2, 0.5–0.7 per cent N_2 with trace amounts of O_2 and H_2S. Its energy density is about 23 MJ/m^3. It is used for cooking, lighting (using mantle lamps), heating and operating small IC engines, etc. It is unlikely to be used for mobile vehicles on large scale because of low pressure and high inert fraction. Use of biogas is widespread in rural China and India. Two third of China's rural families use biogas as their primary fuel.

7. Producer Gas

Woody matter such as crop residue, wood chips, bagasse (fibrous residue of sugar cane after juice extraction), rice husk, coconut shell, etc., can be transformed to producer gas (also known as synthesis gas, syn gas, wood gas, and water gas or blue gas) by a method known as *thermal gasification* of solid fuel. The composition of gas produced depends upon the type of biomass and the design of gasifier. For wood chips as input the typical gas composition is 19 per cent CO, 18 per cent H_2, 1 per cent CH_4, 11 per cent CO_2 and the rest N_2. It has a typical energy density of 4–8 MJ/m^3 (5–10 MJ/kg). This can be used to fuel IC engines (diesel, dual fuel mode engines) for irrigation pumps, motor vehicles, and small-scale power generation or to produce process heat.

The commercial diesel engine has to be modified to a duel-fuel mode engine. The air intake manifold is modified to suck (air + producer gas) mixture. Limited quantity of diesel is required to initiate the ignition. The engine is started with diesel fuel only and subsequently the quantity of diesel is reduced as producer gas is mixed with air. About 85–87 per cent diesel replacement can be obtained.

8.4 BIOMASS RESOURCES

Biomass resources for energy production encompass a wide spectrum of materials ranging from silviculture (forest), agriculture (field), aquaculture (fresh and sea water) and industrial and social activities that produce organic wastes residues (food processing, urban refuse, etc.). When plants are cultivated especially for the purpose of energy, it is known as *energy farming*.

1. Forests

Forests; natural as well as cultivated, serve as a source of fuel wood, charcoal and producer gas. Forest waste and residues from forest processing industries can be utilized at the mill itself. Forest resource is consumed, not just for firewood but also for sawn timber, papermaking and other industrial purposes. Some fast growing energy intensive trees such as *eucalyptus*, *poplar*, *pine* are specially cultivated for the purpose of energy.

Some plants produce seeds (or nuts) to yield vegetable oil on pressing. This serves as a liquid bio-fuel (bio-diesel). There are two categories of oil-producing plants: (a) wild plants, e.g. *Jojoba* (a shrub, producing nuts), *Karanj* (a tree generally used on roadsides in India, produces seeds), etc., which takes care of themselves and

(b) agricultural crops, e.g. *Jatropha curcas* (Ratanjyot, produces seeds) etc., which require common agricultural techniques. There are more than 300 different species of oil bearing trees; most of them are wild and do not require much care and effort. These plants are quite hardy, require little water, can resist severe drought and pest, can survive in hot and cold climates and can grow on most soil types. In India, the experience with a wild, oil-bearing tree, *Karanj (Pongamia pinnata)* has been encouraging. It is estimated that the plantation of Jatropha on 30 million-hectares would produce equivalent bio-fuel that can completely replace the current use of fossil fuels in the country [50].

2. Agricultural Residues

Crop residues such as straw, rice husk, coconut shell, groundnut shell, sugarcane bagasse etc., are gasified to obtain producer gas. Alternatively, these are converted to fuel pellets or briquettes and used as solid fuel.

3. Energy Crops

Certain cultivated plants produce raw material for bio-fuels. The greatest potential for energy farming occurs in tropical countries, especially those with adequate rainfall and soil condition.

(a) Sugar Plants *Sugarcane* is a major raw material source for bio-ethanol. Various products from sugarcane are shown in Fig. 8.2. Alcohol represents only 30 per cent of the total sugar cane energy. About 35 per cent is available in bagasse and another 35 per cent in leaves and tops of the sugarcane plant.

Sweet sorghum also supplies raw material for ethanol production, especially during off-season supply for the sugar mills.

Sugar beet supplies raw material for ethanol production.

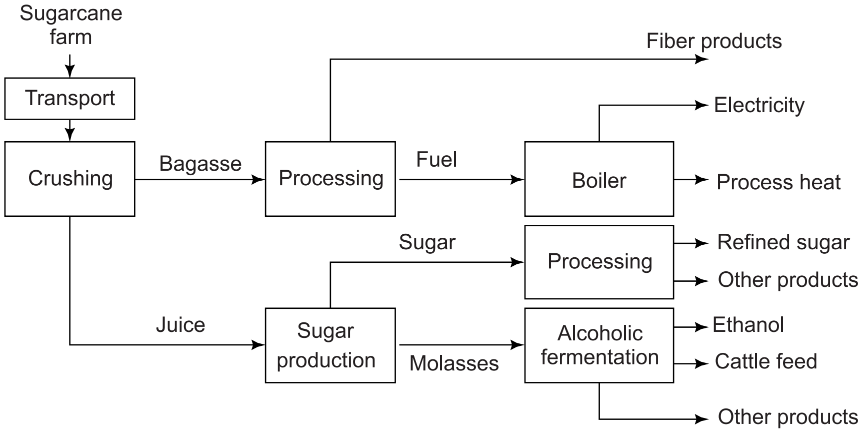


Figure 8.2 Sugarcane industry products

(b) Starch Plants *Jerusalem artichoke* provides raw material for bio-ethanol. It is a tubular plant and can be grown on marginal lands and relatively poor soil. It is able to withstand adverse conditions such as cold and draught conditions.

Cassava is also a tubular plant. It is seen as complementary to sugarcane as it can be cultivated in areas with acidic infertile soils, whereas cane requires more amenable soil. It also provides raw material (starch) for bio-ethanol. Potato, sweet potato, etc. also fall in the same category.

Grains, such as maize, barley, rice and wheat provide starch, which can be converted to ethanol.

(c) Oil Producing Plants In a short-term diesel engine test, over 40 different plant derived oils have been evaluated including *sunflower, rapeseed, palm oil, castor oil, soybean, groundnut and cottonseed*. The benefits to be derived from a plant oil fuel industry are:

- Most of these plants are very adaptable and hardy.
- Because of the relatively simple technology involved in oil extraction and filtering, the oil can be produced right on the farm.
- The leftover biomass after the extraction of oil, known as cake, can be used to produce biogas in a biogas plant and sludge produced thereof can be used as a quality fertilizer.
- The by-products from the oil press can often be used as a high protein animal feed.
- Most of these plants require low cost and low input.
- Plant oils are safe to handle and store.
- Marginal and wasteland can be used for its cultivation.
- It will increase the employment opportunities in rural areas and boost its economy.

4. Aquatic Plants

Some water plants grow faster than land based plants and provide raw materials for producing biogas or ethanol. These are *water hyacinth, kelp, seaweed and algae*, etc.

5. Urban Waste

Urban waste is of two types: (a) Municipal Solid Waste (MSW or garbage) and (b) sewage (liquid waste). Energy from MSW can be obtained from direct combustion (incineration) or as landfill gas. Sewage can be used to produce biogas after some processing.

8.5 BIOMASS CONVERSION TECHNOLOGIES

There are many different ways of extracting energy from biomass. These energy conversion technologies may be grouped into four basic types: (i) physical method, (ii) incineration (direct combustion), (iii) thermo-chemical method and (iv) biochemical method. The general outlines of these technologies are briefly described here.

8.5.1 Physical Method

The simplest form of physical conversion of biomass is through compression of combustible material. Its density is increased by reducing the volume using compression through the processes called 'briquetting' and 'pelletization'.

Fuel oils can be extracted from plant products by expelling them. Also light hydrocarbons may be obtained from certain plants in the same way as production of rubber.

(a) Pelletizaton Pelletization is a process in which waste wood is pulverized, dried and forced under pressure through an extrusion device. The extracted mass is in the form of pellets (rod; 5 to 10-mm dia and 12-mm long), facilitating its use in steam power plants and gasification system. Pelletization reduces the moisture to about 7 to 10 percent and increases the heat value of the biomass

(b) Briquettng Biomass briquettes are made from woody matter (e.g. agricultural waste, sawdust, etc.). They serve as replacement for fossil fuels such as oil or coal, and can be used to heat boilers in manufacturing plants. Burning a wood briquette is far more efficient than burning firewood. Moisture content of a briquette can be as low as 4 per cent, whereas in green firewood it may be as high as 65 per cent.

Briquetting is brought about by compression and squeezing out moisture and breaking down the elasticity of the wood and bark. If elasticity is not sufficiently removed, the compressed wood will regain its pre-compression volume. Densification is carried out by compression under a die at high temperature and pressure. It is a process similar to forming a wood pellet but on a larger scale. There are no binders involved in this process. The natural lignin in the wood binds the particles of wood together to form a solid piece.

Sawdust briquettes have developed over time with two distinct types: those with holes through the centre, and those which are solid. A solid briquette is formed using a piston press, which sandwiches the layers of sawdust together. The one with a hole is produced using a screw press. The hole is formed due to screw thread passing through the centre. The screw press briquettes are more homogeneous, have better crushing strength and better storage properties with extraordinary combustion properties due to large surface area per unit weight.

(c) Expelling Agro Products Concentrated vegetable oils may be obtained from certain agro products and may be used as fuel in diesel engines. However, difficulties arise with direct use of plant oil due to high viscosity and combustion deposits. Therefore, these oils are upgraded by a chemical method known as trans-esterification to overcome these difficulties. Categories of certain materials with examples are as follows:

- Seeds: Sunflower, rapeseed, soya beans, etc.
- Nuts: oil palm, coconut copra, jojoba nuts, etc.
- Fruits: olive, etc.
- Leaves: eucalyptus, etc.

(d) Fuel Extraction Occasionally, milky latex is obtained from freshly cut plants. The material is called exudates and is obtained by cutting (tapping) the stems or

trunks of the living plants (a technique similar to that, used in rubber production). Some plants are not amenable to tapping and in such cases the whole plant (usually a shrub) is crushed to obtain the product. For example, Euphorbia lathyris plant is crushed to extract hydrocarbons of less molecular weight than rubber. The extract may be used as petroleum substitute.

8.5.2 Incineration

Incineration means direct combustion of biomass for immediate useful heat. The heat (usually in the form of steam) produced are either used to generate electricity or provide the heat for industrial process, space heating, cooking or district heating.

Furnaces and boilers have been developed for large scale burning of various types of biomass such as wood, waste wood, black liquid from pulp industry, food industry waste, and MSW. The moisture content in the biomass and wide range of composition tends to decrease the efficiency of conversion. However the economic advantage of cogeneration makes it attractive for adoption.

8.5.3 Thermo-Chemical

The basic thermo-chemical process to convert biomass into more valuable and/or convenient product is known as *pyrolysis*. Biomass is heated either in absence of oxygen or by partial combustion of some of the biomass in restricted air or oxygen supply. Pyrolysis can process all forms of organic materials including rubber and plastics, which cannot be handled by other methods. The products are three types of fuels, usually: a gas mixture (H_2, CO, CO_2, CH_4 and N_2), oil like liquid (water soluble phase including acetic acid, acetone, methanol and non-aqueous phase including oil and tar) and a nearly pure carbon char. The distribution of these products depends upon the type of feedstock, the temperature and pressure during the process and its duration and the heating rate.

High temperature pyrolysis (~1000 °C) maximizes the gaseous product. The process is known as *gasification*. Low temperature pyrolysis (up to 600 °C) maximizes the char output. The process has been used for centuries for production of charcoal. The process is known as *carbonization*. Liquid product is obtained through catalytic *liquefaction* process. Liquefaction is a relatively low temperature (250–450 °C), high-pressure (270 atm) thermo-chemical conversion of wet biomass, usually with high hydrogen partial pressure and also a catalyst to enhance the rate of reaction and/or to improve the selectivity of the process.

8.5.4 Biochemical

The process makes use of metabolic action of microbial organism on biomass to produce liquid and gaseous fuel. Two major biochemical processes are explained below:

(a) Ethanol Fermentation Alcoholic Fermentation is the decomposition in absence of air of simple hexose sugars (sugars containing six carbon atoms per molecule, i.e. $C_6H_{12}O_6$) in aqueous solution by action of enzyme (a natural catalyst) present in yeast, in acidic conditions (p^H value 4 to 5).

Thus:

$$C_6H_{12}O_6 \xrightarrow[\text{Ferementation}]{32\ ^\circ\text{C}} 2C_2H_5OH + 2CO_2$$

The products are ethanol and carbon dioxide.

(b) Anaerobic Fermentation (Anaerobic Digestion) This process converts decaying wet biomass and animal wastes into biogas through decomposition process by the action of anaerobic bacteria (bacteria that live and grow in absence of oxygen). Carbon present in biomass may be ultimately divided between fully oxidized CO_2 and fully reduced CH_4. Thus:

$$\text{Decaying wet biomass} \xrightarrow[\text{Anaerobic Fermentation}]{20-55\ ^\circ\text{C}} \text{Biogas (largely } CH_4 \text{ \& } CO_2)$$

The biomass material in the form of water slurry is digested by the bacteria anaerobically for several days in an airtight container. The reactions are slightly exothermic and small amount of heat (equivalent to 1.5 MJ per kg dry digestible material) is also generated that helps in maintaining favorable temperature. The process may be expedited at somewhat higher temperature. The most useful biomass materials appear to be animal manure, algae, kelp, hyacinth, plant residues and other organic waste materials with high moisture content.

The energy available from various biomass resources using various conversion technologies is listed in Table 8.1.

Table 8.1 Energy available from various biomass resources

S.N.	Biomass source	Biofuel produced	Conversion technology	Available energy (MJ/kg)
1.	Wood chips, saw mill dust, forest residues etc.	(Direct heat)	Incineration	16-20
2.	"	Gas Oil Char	Pyrolysis	40 (Nitrogen removed) 40 20
3.	Grain crops	Straw	Incineration	14–16
4.	Sugarcane residue	Bagasse	"	5–8 (fresh cane)
5.	Urban refuse	(Direct heat)	"	5–16 (dry input)
6.	Sugarcane juice	Ethanol	Fermentation	3–6 (fresh cane)
7.	Animal waste	Biogas	Anaerobic digestion	4–8 (dry input)
8.	Municipal sewage	"	"	2–4 (dry input)

8.6 URBAN WASTE TO ENERGY CONVERSION

8.6.1 MSW Incineration Plant

Municipal solid waste is the solid waste generated by households, commercial and institutional operations and some industries. Disposal of MSW is a major problem in big cities where large quantities of waste is to be disposed of, far away from the city centers. The emerging solution is to use this waste biomass as an energy resource in a waste-to-energy conversion plant near city center. The energy thus generated is used within city itself and only a relatively small residue of used biomass (ash etc.) is disposed away in landfills. Through incineration or gasification, electrical energy may be generated along with thermal energy for process heat.

The composition of urban waste depends on the style and standard of living of the people. A general national profile of waste in USA is given in Table 8.2. The energy content of domestic refuse differs significantly from area to area. Generally it lies in range 4.2 to 14 MJ/kg.

Table 8.2 A typical composition of urban waste in USA

S.N.	Waste material	Percentage
1.	Paper and paper board	39.2
2.	Food and yard waste	21
3.	Glass	6.2
4.	Metals	7.6
5.	Plastics, rubber	9.1
6.	Wood	7.1
7.	Others (including hazardous wastes, e.g. chemicals, lead, insecticides, household cleaning chemicals, etc.)	9.8

A block diagram of MSW-to-energy incineration plant showing the sequence of various steps is shown in Fig. 8.3. The dry biomass is shredded to pieces of about 2.5 cm diameter. An air stream segregates refuse derived fuel (RDF), which is lighter from heavier metal and glass pieces. The heavier part is reclaimed and recycled. About 30 per cent of US waste stream is recycled. The RDF thus obtained is burnt in the furnace at about 1000 °C to produce steam in the boiler. Combustion process may be assisted by required amount of auxiliary fuel when RDF does not burn properly by itself. The superheated steam obtained from boiler is used in a steam turbine coupled with an alternator to produce electrical output in the same way as in a conventional thermal plant. The flue gases are discharged to atmosphere through stack after removal of pollutants such as particulate matter, SO_x and NO_x, etc. Heat recovery steam generator extracts maximum possible heat from flue gases to form thermal output. The ash is removed and disposed of to landfills.

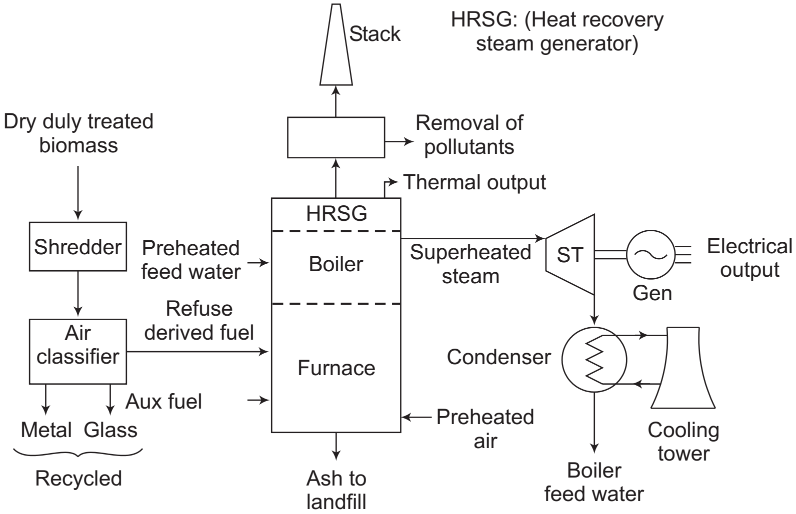


Figure 8.3 MSW to energy incineration plant

Strong concerns exist about the pollutants emitted during combustion. Because of various materials contained in the waste stream, pollutants in the flue gases include derivatives of sulphur, chlorine, fluorine, nitrogen, chlorinated hydrocarbons and heavy metals. One particular important group of pollutants, polychlorinated dibenzo-*p* dioxins (PCDD) and the dibenzofurans (PCDF) are possibly among the most acutely carcinogenic compounds known so far. It has been proven to cause cancer in animals and is linked with a variety of other health problems, including genetic defects. PCDD/PCDF are formed either in the combustion chamber or after combustion when the gases cool in the exhaust stack. Disagreement continues over establishing safe levels of dioxins emission from any incinerator. It has been discovered at various levels at every incinerator tested so far. The residual ash, which has high metal concentration, is also of concern. The ash is usually disposed of in landfills; the leachate (garbage juice; liquid that results when water percolates through the landfill) must be well contained to prevent groundwater contamination. The typical metal concentrations found in fly ash and bottom ash of an incinerator are listed in Table 8.3.

Table 8.3 Typical metal concentrations in fly ash and bottom ash of an incinerator

S.N.	Elements	Fly ash (mg/kg or ppm)	Bottom ash (mg/kg or ppm)
1.	Calcium	54,500	50,500
2.	Cadmium	470	100
3.	Lead	5200	900
4.	Aluminum	70,000	33,000
5.	Iron	17,000	132,000

Financially, many incineration plants are breaking even with the income from the sale of process steam and electricity and tipping at the facility on each truck.

8.6.2 Sewage to Energy Conversion

Sewage produced by human settlements also has some energy potential as indicated in Table 8.1. It can also be anaerobically digested (after some processing) to produce methane in the same way as with animal manure. The gas produced can be used to heat the digester. Though the gas production is not much and may not be sufficient for heating, but it can reduce the conventional fuel requirement.

8.7 BIOMASS GASIFICATION

The word gasification (or thermal gasification) implies converting solid fuel into a gaseous fuel by thermo-chemical method without leaving any solid carbonaceous residue. Gasification is an established technology, the first commercial application of which dates back to 1830. During World War II, biomass gasification system appeared all over the world to power vehicles to keep basic transport system running. Gasifier is the equipment that converts biomass into producer gas. Most common raw materials are: wood chips and other wastes from wood industry, coconut shells, straw etc. Biomass that has high ash content such as rice husk etc. can also be handled though with some difficulty.

Gasification involves partial combustion (oxidation in restricted quantity of air/oxidant) and reduction operations of biomass. In a typical combustion process generally oxygen is surplus, while in gasification process fuel is surplus. The combustion products, mainly carbon dioxide, water vapour, nitrogen, carbon monoxide and hydrogen pass through the glowing layer of charcoal for the reduction process to occur. During this stage both carbon dioxide and water vapour, oxidize the char to form CO, H_2 and CH_4. Following are the typical reactions, which occur during gasification:

$$C + O_2 \rightarrow CO_2 \qquad \text{(Combustion, 240 kJ/mole)} \qquad (8.1)$$

The moisture available in the biomass is converted to steam and generally no extra moisture is required. Thus the product of combustion of pyrolysis gases results in CO_2 and H_2O (steam), which further react with char:

$$C + CO_2 \rightarrow 2CO \qquad \text{(Boudouard reaction, –164.9 kJ/mole)} \qquad (8.2)$$

$$C + H_2O \rightarrow CO + H_2 \qquad \text{(Water gas reaction, –122.6 kJ/mole)} \qquad (8.3)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \text{(Water shift reaction, 40.2 kJ/mole)} \qquad (8.4)$$

$$C + 2H_2 \rightarrow CH_4 \qquad \text{(Methane reaction, 83.3 kJ/mole)} \qquad (8.4)$$

The composition of the gas produced depends on the degree of equilibrium attained among various reactions.

Gasifiers are broadly classified into: (i) fixed bed gasifier and (ii) fluidized bed gasifier. The fixed bed gasifiers are further classified as: (a) downdraft, (b) updraft and (c) cross draft types, depending upon the direction of airflow.

8.7.1 Downdraft Type

Downdraft type is best suited for a variety of biomass. Its design forces the raw products to pass through a high temperature zone so that most of the unburnt pyrolysis products (especially tars) can be cracked into gaseous hydrocarbons, thus producing a relatively clean gas. A recently developed open top downdraft type gasifier is shown in Fig. 8.4 [51].

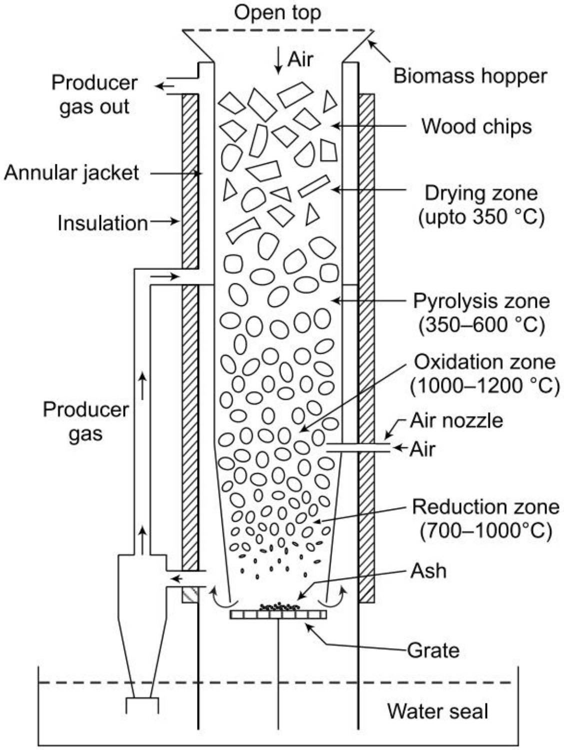


Figure 8.4 Downdraft biomass gasification plant

In steady state operation, heat from the combustion zone (oxidation zone), near the air nozzle is transferred upwards by radiation, conduction and convection causing wood chips to pyrolyse and lose 70–80 per cent of their weight. These pyrolysed gases burn with air to form CO, CO_2, H_2 and H_2O, thereby raises the temperature to 1000–1200 °C. The product gases from combustion zone further undergo reduction reaction with char to generate combustible products like CO, H_2 and CH_4. Generally about 40–70 per cent air is drawn through open top depending on the pressure drop conditions due to size of wood chips and gas flow rate. This flow of air opposite to flame front helps in maintaining homogeneous air/gas flow across the bed. Combining the open top with air nozzle towards the bottom of the reactor helps in stabilizing the combustion zone by consuming the uncovered char left and also by preventing the movement of the flame front to the top. As a consequence, the high temperature zone spreads above the air nozzle by radiation and conduction, aided by airflow from the top. The tar thus is eliminated in the best possible way by creating a high temperature-oxidizing atmosphere in the reactor itself. The gas produced is withdrawn from an exit at the bottom and reintroduced in the annular jacket for heat recovery. The hot gas, which enters the annular jacket around 500 °C, transfers some heat to the wood chips inside–improving the thermal efficiency of the system in addition to drying the wood in this zone. The inner wall temperature reaches more than 350 °C after a few hours of operation. This aspect enables the use of wood chips with moisture content as high as 25 per cent. The regenerative heating due to the transfer of heat from hot gas to the biomass moving downwards also increases its residence time in high temperature zone. This leads to better tar cracking.

The raw producer gas thus obtained can be used as such for thermal applications. However, for use in IC engines, further processing is required. Admission of hot gas into an engine results in loss of power and hence, the gas has to be cooled. Raw gas contains varying amounts of dust (ash and char) particles, moisture and tar. Dust and tar are detrimental to the life of engine. Hence the gas has to be cooled and cleaned before admitting to the engine. The upper limit of allowable tar is about 50 mg/m^3 and that for particulate (size less than 10 μm) content is about 50 mg/m^3. The gas may be cooled to ambient temperature by direct injection of cooling water from a spray tower. A sand bed filter may be deployed to remove the particulate collected by the cooling water. Periodic washing of this sand bed is adequate to keep the operation smooth. For filtering of the gas, sand bed filter with specific particle size distribution is used. The filter is divided into coarse (sand particle size 0.5 to 2 mm) and fine sections (particle size 0.2 to 0.6 mm). The size of the filter area is so chosen that the gas velocities through the filter bed do not exceed 0.1 m/s. This low velocity coupled with tortuous path causes the removal of large part of the dust from the gas. Some part of the tar also gets deposited in the filter circuit, particularly when the moisture carried over from the cooler causes slight wetting of the sand bed.

8.7.2 Updraft Type

Updraft type gasifier (also called counter flow gasifier) is the simplest as well as first type of gasifier developed. This type of gasifier is easy to build and operate. The air enters below the combustion zone and the gas is drawn off at the top. The updraft gasifier achieves highest efficiency as the hot gas passes through the fuel bed and then leaves the gasifier at low temperature. The gas produced has practically no ash but contains tar and water vapor because of passing of gas through unburnt fuel. Hence updraft gasifier is suitable for tar free feedstock (fuels like charcoal, etc.). It is most unsuitable for high volatile fuels. The zones of various reactions are shown in Fig. 8.5.

8.7.3 Crossdraft Type

Crossdraft type gasifier is shown in Fig. 8.6. Air enters the gasifier through a water-cooled nozzle mounted on one side of the firebox. It operates at a very high temperature and confines its combustion and reduction zone near the air nozzle. Because of short path length for gasification reactions, this type of gas producer responds most rapidly for change in gas production. The high exit temperature of the gas and low CO_2 reduction results in poor quality of gas and low efficiency. Therefore, this type of gasifier is not in common use.

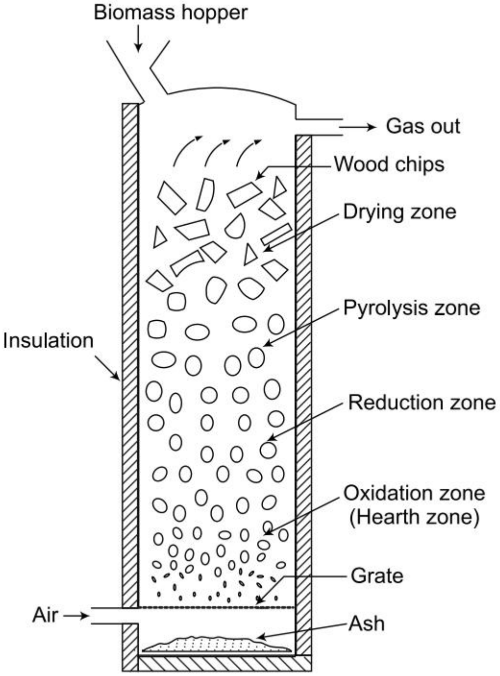


Figure 8.5 Updraft biomass gasification plant

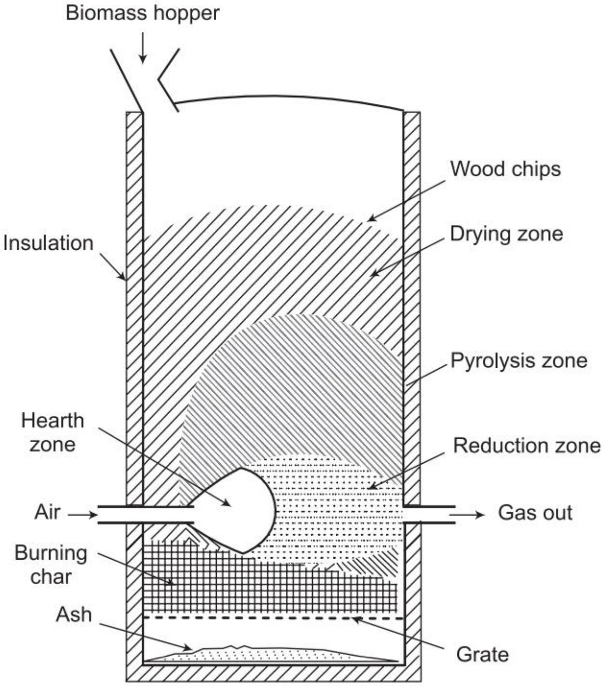


Figure 8.6 Crossdraft biomass gasification plant

8.7.4 Fluidized Bed Type

A fluidized bed gasifier takes the advantage of excellent mixing characteristics and high reaction rates of gas-solid mixture. A simple fluidized bed gasifier is a chamber with a bed of inert particles such as sand or lime stone supported by distributor plate as shown in Fig. 8.7. Pressurized air is passed through distributor plate. The velocity of the air is progressively increased till the upward drag of air on bed particles supports the entire weight of the bed. The bed is then said to be incipiently fluidized, and it exhibits fluid like properties above this velocity, called minimum fluidization velocity. This moving mass of solid is called a fluidized bed. The turbulence of the bed increases with velocity, above minimum fluidization velocity.

The fluidized bed is initially heated externally close to the operating temperature. The bed material, usually sand absorbs and stores the heat while the turbulence and mixing of the bed keeps the temperature very uniform throughout the bed. When biomass fuel is introduced into the fluidized bed, the high heat and mass-transfer characteristics permits the rapid energy conversion at particularly isothermal condition. The high surface area available in fluidized bed and constantly moving mass results in good conversion efficiency and lower operating temperature compared to fixed beds. The fluidized bed design produces a gas with low tar content but high value of particulate. The high exit temperature complicates efficient energy recovery.

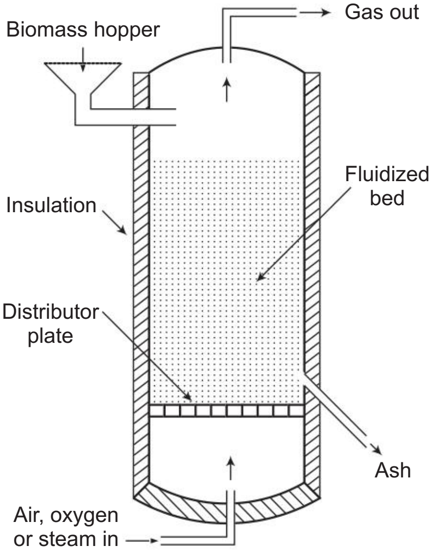


Figure 8.7 Fluidized bed biomass gasification plant

8.8 BIOMASS LIQUEFACTION

Liquefaction of biomass mainly takes place through two routes: (i) liquefaction through pyrolysis process without any gasification medium and (ii) liquefaction through methanol synthesis with gasification medium.

The former process has been explained in Section 8.5.3 under “pyrolysis” process. Pyrolysis liquids can be used directly as heating oil. They have high water content. The low p^H of pyrolysis liquids which arise from organic acids makes the liquid highly corrosive. The liquid also contains particulate char. The high heating value of pyrolysis liquid ranges from 17 to 20 MJ/kg and has liquid densities of about 1280 kg/m^3

Liquefaction through gasification medium involves the production of methanol from mixture of H_2 and CO (producer gas). The reaction takes place at 330 °C and 150 atm pressure.

$$2H_2 + CO \rightarrow CH_3OH$$

The H_2 and CO required for this process is produced by gasifying biomass fuel. Gasification often produces less H_2: CO ratio than 2:1 required for methanol synthesis. The gas mixture is often reacted with steam in presence of catalyst to promote a shift to increase hydrogen content.

$$CO + H_2O \rightarrow H_2 + CO_2$$

CO_2 and H_2S present in producer gas are removed prior to methanol reactor. Yields of methanol from woody biomass are expected to be in the range 480–568 litres/tons. Methanol can be used as liquid fuel in petrol engines with energy density of 23 MJ/kg.

8.9 BIOMASS TO ETHANOL PRODUCTION

Ethanol is manufactured by action of microorganisms on carbohydrates. The process is known as alcoholic fermentation. Carbohydrates (also known as saccharides) can be divided into three major classes in order of increasing complexity.

(a) Monosaccharides These are simple hydrocarbons, which cannot be hydrolyzed into simpler compounds. Most common monosaccharides are glucose ($C_6H_{12}O_6$) and fructose ($C_6H_{12}O_6$). More precisely glucose and fructose can be represented by formulae $HCO - (HCOH)_4 - CH_2OH$ and $CH_2OH - CO - (HCOH)_3 - CH_2OH$ respectively. Glucose occurs naturally in sweet fruits (e.g. ripe grapes), honey, etc.

(b) Oligosaccharides Oligosaccharides yield few but definite numbers (2–10) of monosaccharide molecules on hydrolysis. For example, disaccharide (such as sucrose, maltose, etc., both having formula $C_{12}H_{22}O_{11}$) produces two monosaccharide molecules on hydrolysis. Sucrose (common sugar) occurs naturally in sugar cane and beetroot. Maltose (malt sugar) is derived from starch.

(c) Polysaccharides These are high molecular mass carbohydrates, which yield large number of monosaccharides molecules on hydrolysis. Examples are starch and cellulose, both having general formula $(C_6H_{10}O_5)_n$. Large numbers (few hundreds to few thousands) of glucose units are joined together in a complex chain. Starch occurs naturally in all plants, particularly in seeds. The main sources are maize, barley, rice, wheat, potato, cassava and sorghum, etc. Cellulose is main constituent of cell walls of the plants. Wood contains 45–50 per cent while cotton contains 90–95 per cent cellulose.

In general monosaccharides and oligosaccharides are crystalline solids, soluble in water and sweet in taste. These are collectively known as sugars. Polysaccharides on the other hand are amorphous, insoluble in water and tasteless and are known as non-sugars.

The hexose (glucose and/or fructose) required for ethanol fermentation is derived from: (a) sucrose (b) starch or (c) cellulose. The preparation is explained below:

(a) From Sucrose Sucrose is most common disaccharide and is manufactured from sugar cane or beetroot. Usually commercial sucrose is removed from the cane juice, and the remaining molasses, which has low commercial value, is used for ethanol production. The molasses itself has about 55 per cent sugar content and serves as very good raw material for ethanol production. On hydrolysis with dilute acids or enzyme it gives equal amounts of glucose and fructose.

$$C_{12}H_{22}O_{11}\text{ (Sucrose)} \xrightarrow{\text{Hydrolysis}} C_6H_{12}O_6\text{ (Glucose)} + C_6H_{12}O_6\text{ (Fructose)}$$

(b) From Starch On hydrolysis with dilute H_2SO_4 or enzyme, starch breaks down to maltose and finally to glucose.

$$2(C_6H_{10}O_5)_n\text{ (Starch)} + nH_2O \rightarrow nC_{12}H_{22}O_{11}\text{ (Maltose)} + nH_2O$$
$$\rightarrow 2nC_6H_{12}O_6\text{ (Glucose)}$$

(c) From Cellulose Cellulose is not hydrolyzed so easily as starch, but on heating with dilute sulphuric acid under pressure yield glucose (i.e. at 393K and pressure (2–3 atm).

$$(C_6H_{10}O_5)_n\text{ (Cellulose)} + nH_2O \rightarrow nC_6H_{12}O_6\text{ (Glucose)}$$

Sucrose materials are readily available in fermentable form, require least expensive preparation, but are generally most expensive to obtain. Starch bearing materials are often cheaper, but require processing to solubilize and convert starch to sugars. Cellulosic materials are the most readily available raw materials, as cellulose is the most abundantly available organic compound in the world, but they require the most extensive and costly preparation. Finally, ethanol is obtained from fermentation of hexose sugars.

$$C_6H_{12}O_6\text{ (hexose)} \xrightarrow[\text{Ferementation}]{32\ ^\circ\text{C}} 2C_2H_5OH\text{ (ethanol)} + 2CO_2$$

The ethanol yield from various types of raw materials is given in Table 8.4.

Table 8.4 Ethanol yield from hydrocarbon rich plants

S.N.	Raw material	Litres of Ethanol per ton of crop (l/t)	Ethanol yield per hectare per year (l/ha)
1.	Sugarcane	60–80	3500–7000
2.	Sugar beet	90–100	3800–4800
3.	Sweet sorghum	80–90	2500–3500
4.	Maize	360–400	1500–3000

5.	Wheat	370–420	800–2000
6.	Barley	310–350	700–1300
7.	Potato	100–120	2200–3300
8.	Sweet potato	140–170	1600–3100
9.	Cassava	175–190	2200–2300
10.	Jerusalem artichoke	80–100	2700–5400
11.	Softwood		
	Hydrolytic agent: Dilute acids	190–220	1800–3100
	Conc. acids	230–270	2200–3800
12.	Hardwood		
	Hydrolytic agent: Dilute acids	160–180	1500–2500
	Conc. acids	190–220	1800–3000
13.	Straw		
	Hydrolytic agent: Dilute acids	140–160	200–500
	Conc. acids	160–180	300–600

Fermentation of simple sugars to ethanol in absence of air can be carried out either in batches or continuously. This is a slow reaction and after 36 hours, 94 per cent sugar is utilized. The most common microorganism, the yeast, Saccharomyces cerevisiae is poisoned by ethanol concentration greater than 10 per cent so the fermentation process ceases when the resulting liquid (known as beer) contains about 10–12 per cent ethanol (by volume).

The concentration of ethanol is increased to 95 per cent (by volume) by successive fractional distillation. The product is known as pure commercial alcohol and used as fuel in IC engines or other thermal applications. The remaining 5 per cent water cannot be removed by simple distillation and special procedure (azeotropic distillation: co-distillation with solvent such as benzene) is used to reduce water content to get 99.7 per cent pure ethanol. This is known as absolute or anhydrous ethanol. This anhydrous ethanol is used for blending with gasoline. This second distillation process is energy intensive process and accounts for about 40–60 per cent of the total plant energy requirements. Various steps involved in production of ethanol from the three types of biomass resources are shown in Fig. 8.8.

Ethanol fermentation process produces considerable quantities of carbon dioxide, which can be easily recovered, compressed and used as an additive in the beverage and food industries. It can also be made into dry ice and used for refrigeration process.

The fermentation yeast and other insoluble components of raw fermented products are rejected from the still as stillage (slops and vinasse). When starch is used as a feedstock, this has a high protein contents, and can be used as livestock feed after evaporation and drying. The stillage from sugar fermentation is of low value and a major waste problem.

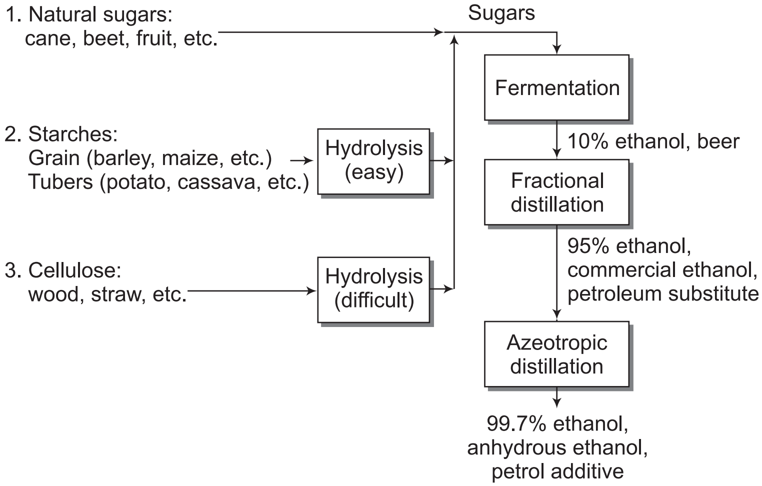


Figure 8.8 Ethanol production from various types of biomass

Use of Ethanol as Fuel

Hydrous ethanol (95 per cent by volume) or commercial ethanol is used as fuel in specially designed IC engines with 25 per cent mileage penalty compared to conventional vehicles. Up to 22 per cent blend of anhydrous ethanol (99.7 per cent, by volume) with petrol requiring no engine modification and incurring no mileage penalty is being used by a large number of automobiles in the world. The blended petrol is known as gasohol (in USA), proalcol (in Brazil) and carburol (in France). Note that water does not mix with petrol. In conventional vehicles it is often present as sludge in petrol storage tank without causing difficulty. However, it cannot be tolerated for gasohol storage tank. Therefore, anhydrous ethanol is required for the purpose of blending of petrol. The ethanol additive has antiknock properties and is preferred to the more commonly used tetraethyl lead, which produces serious air pollution. The excellent combustion properties of ethanol enables an engine to produce up to 20 per cent more power as compared to that with petrol.

8.10 BIOGAS PRODUCTION FROM WASTE BIOMASS

Biomass, if left to decompose in open air, is acted upon by aerobic bacteria (bacteria that require oxygen for their survival and growth) to produce mainly CO_2, NH_3, etc. Thus total carbon component completely get oxidized to produce CO_2 and no fuel is produced. Some part of nitrogen is also lost in the form of ammonia.

Biogas is produced from wet biomass with about 90–95 per cent water content by the action of anaerobic bacteria (bacteria that live and grow in absence of oxygen). Part of carbon is oxidized and another part reduced to produce CO_2 and CH_4. These bacteria live and grow without oxygen. They derive the needed oxygen by decomposing the biomass. The process is favored by wet, warm and dark conditions. The airtight equipment used for conversion is known as *biogas plant* or digester, which is constructed and controlled to favor methane production. The conversion process is known as *anaerobic fermentation* (or biodigestion). Nutrients such as soluble nitrogen compounds remain available in solution and provide excellent fertilizer and humus. The energy available from the combustion of biogas is 60–90 per cent of the input dry matter heat of combustion. Thus the energy conversion efficiency of the process is 60–90 per cent.

The biochemical processes proceed in three stages, as shown in Fig. 8.9:

(a) *Stage I:* First of all the original organic matter containing complex compounds e.g. carbohydrate, protein, fats etc. is broken through the influence of water (known as hydrolysis) to simple water soluble compounds. The polymers (large molecules) are reduced to monomers (basic molecules).

The process takes about a day at 25 °C in an active digester.

(b*) Stage II*: The micro-organisms of anaerobic and facultative (that can live and grow with or without oxygen) groups, together known as acid formers produce mainly acetic and propionic acids. This stage also takes about one day at 25 °C. Much of CO_2 is released in this stage.

(c) *Stage III*: Anaerobic bacteria, also known as methane formers slowly digest the products available from second stage to produce methane, carbon dioxide, small amount of hydrogen and trace amount of other gases. The process takes about two weeks' time to complete at 25 °C. This third stage, i.e. methane formation stage is carried out strictly by the action of anaerobic bacteria.

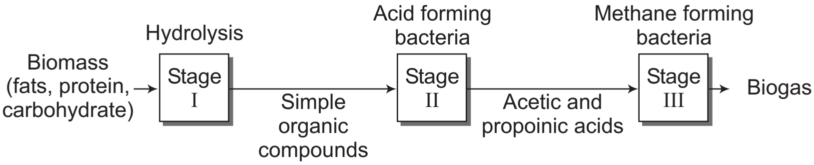


Figure 8.9 Various stages of anaerobic digestion process

The theoretical methane and carbon dioxide composition in the biogas produced from the above three main organic materials are given in Table 8.5.

Table 8.5 Biogas production and its composition from three main organic matters

S.N.	Substance	Biogas produced in litre/ kg of dry substance	Methane content (%)	Carbon dioxide content (%)
1.	Fat	1200	67	33
2.	Protein	700	70	30
3.	Carbohydrate	800	50	50

8.10.1 Fuel Properties of Biogas

Energy density:

(i) With 40% CO_2 : 22.35 to 24.22 MJ/m^3
(ii) without CO_2 : 33.53 to 35.39 MJ/m^3

Octane rating:

(i) with 40% CO_2 : 110

(ii) without CO_2 : 130

Ignition temperature : 650 °C

Air to methane ratio (by volume) for complete combustion : 10 to 1

Explosive limits to air (by volume) : 5 to 10

8.10.2 Utilization of Biogas in IC Engines

As methane is the major constituent of biogas, it can be used in all natural gas fuelled IC engines. However, raw biogas contains corrosive constituents that can significantly shorten the useful life of the engine. This is particularly true when the engine is operated intermittently. During shutdown, the last few strokes of the engine piston intakes unburnt biogas. The various acidic components (for example hydrogen sulfide) present corrode the surfaces of the cylinder walls, the piston rings, valve seats and spark plug. These acids leak by the corroded rings into the oil sump where they are pumped throughout the engine. The contaminated oil is particularly corrosive for copper and lead alloy components. As this corrosive process progresses, the engine become more difficult to start until it eventually fails completely.

Thus, the gas quality demands for IC engines are strict so the raw biogas from a digester or a landfill has to be upgraded. A gas scrubbing system will probably need to be installed, to remove hydrogen sulfide from the biogas.

Alternatively, Sterling engines with their external combustion can be used to produce mechanical power. Sterling engines can burn any quality of gas that is combustible, but they are still new to the market place.

8.10.3 Advantages of Anaerobic Digestion

Anaerobic digestion has the following advantages:

1. Discarded waste material is utilized to produce energy. In practice energy is often available where none would otherwise have been obtained.
2. In the normal course the waste material can best be used either as fuel after drying or as fertilizer after composting. If used through anaerobic digestion process, both benefits are obtained: (a) fuel, in the form of biogas (better fuel than dried biomass) and (b) fertilizer, in the form of sludge/digested slurry (better fertilizer than composted biomass).
3. In anaerobic digestion about 70–75 per cent of original biomass weight is conserved, while in open compost pit (aerobic digestion) 50 per cent or more is lost. Similarly, almost all the nitrogen content in cattle dung is conserved in a biogas unit, while a substantial part of it is lost in composting. Thus the anaerobically produced manure (digested slurry and sludge) is better in terms of both quantity and quality as compared to ordinary manure.
4. Energy requirements of some industries (e.g. dairy, etc.) can be met from anaerobic digestion of the waste generated within these industries.
5. Waste is converted to less offensive and stable slurry and most (but not all) of the disease causing organisms are killed. As the process digest night soil and animal manure, it has potential to considerably reduce the pathogens.

The cycle of reinfection is broken and considerable improvement in public health results. Mosquitoes and flies do not breed in digested slurry. In fact, in municipal waste digestion plants, main aim is to stabilize the waste rather than to produce gas and in many cases only a part of gas produced is utilized.

In fact these digesters were initially conceived in China as a means of stabilizing the sewage of rural communities, thereby reducing the incidence of disease caused by parasites and pathogens (bacteria that cause disease). However, they have subsequently been optimized for the production of biogas.

6. Since the system is enclosed the odors are contained. Digested slurry is odourless.

8.10.4 Classification of Biogas Plants

Biogas plants are mainly classified as: (i) batch type and (ii) continuous type. Continuous type plants are further classified into (a) floating drum (constant pressure) type and (b) fixed dome type (constant volume) type.

Batch type plant is charged at 50–60 days interval. Once charged, it starts supplying the gas after 8–10 days and continues to do so for about 40–50 days till the process of digestion is completed. Afterwards it is emptied and recharged. A battery of digesters are charged and emptied one by one in a synchronous manner to maintain regular supply of gas through common gasholder. The outline of such an arrangement is shown in Fig. 8.10. The installation and operation of such plants are capital and labor intensive and are not economical unless operated on large scale. Such plants are installed in European countries. These plants do not suit to conditions in Indian rural areas.

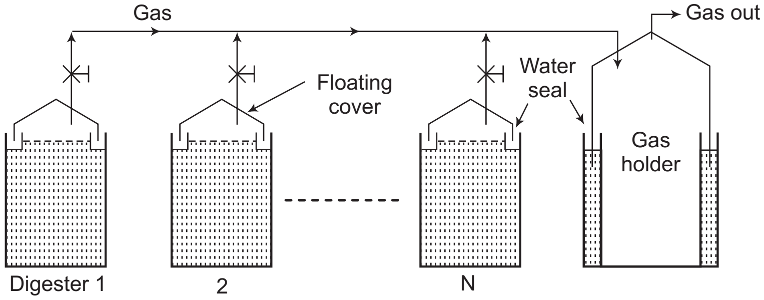


Figure 8.10 Biogas batch plant system

Main features of continuous type plant are shown in Fig. 8.11. The plant is fed daily (and not intermittently) with certain quantity of biomass. The gas produced is stored in the plant or in a separate gasholder and remains available for use as required. The biomass while slowly passing through the digester is completely digested and the digested slurry is rejected through an outlet. The period during which the biomass remains in the digester is known as *retention period*, which depends mainly on the type of biomass and operating temperature. The plant operates continuously and stopped only for maintenance or for removal of sludge (undigested biomass residue). A thin dry layer often formed at the top of slurry is known as scum. The scum tends to prevent the escape of gas from slurry. The scum layer is broken by slowly stirring the slurry. This also helps in digestion process due to better mixing. Such plants are convenient for individual owners as feeding pattern matches with daily waste generation and do not require its storage. These types of plants are very popular in India and China.

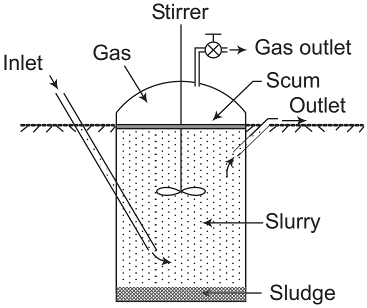


Figure 8.11 Basic features of a continuous type biogas plant

8.10.5 Operational Parameters of Biogas Plant

The operation of biogas plant or digestion process is affected by a number of factors, which are to be optimized to obtain best results:

(a) Temperature Methane forming bacteria work best in temperature ranges 20–55 °C. Digestion at higher temperature proceeds more rapidly than at lower temperature, with gas yield rates doubling at about every 5 °C increase in temperature. In cold climate regions the digester has to be heated to about 35 °C, in most cases by using part of the biogas produced. Sometimes solar thermal collectors are used for heating. The gas production decreases sharply below 20 °C and almost stops at 10 °C. It is to be noted that raising the temperature accelerates the gas production; however its methane content gets relatively reduced.

(b) Pressure A minimum pressure of 6–10 cm of water column, i.e. 1.2 bar (abs) is considered ideal for proper functioning of plant and it should never be allowed to exceed 40–50 cm of water column. Excess pressure inhibits release of gas from slurry. It also leads to leakage in masonry through micro pores. Even normal gas taps and pipe joints start leaking due to excess pressure.

Also there is no advantage in maintaining negative pressure (vacuum) either, which is a costly and energy consuming option. Any leakage of air (oxygen) into the plant during negative pressure condition completely inhibits the growth of methane formers, as these are strictly anaerobic. Addition of oxygen also results in an explosive mixture raising safety concern. Hence the plant should be completely leak proof.

(c) Solid to Moisture Ratio in the Biomass Water is essential for survival and activity of microorganisms, hydrolysis process and activity of extra cellular enzymes.

This helps in (i) better mixing of various constituents of the biomass, (ii) movement of bacteria and (iii) faster digestion rate. However, when water content is too high, the mean slurry temperature and hence gas production drops. If water content is too low, acids accumulate and hinder fermentation process. The optimum total solid concentration is 7 to 9 per cent. Hence for various input materials the optimum ratio of solid to moisture should be adjusted by mixing extra water, for best results. Raw cow dung contains about 80–82 per cent moisture (by weight). It is usually mixed with equal amount of water to reduce solid content to 9–10 per cent.

In some designs the amount of water in the digester is kept to its minimum value, which is just sufficient to keep raw material wet for its active fermentation. This prevents the floatation of plant material on water. Total solids may be 25–30 per cent with no free water. This process is called *dry fermentation*. In this plant the problem of floatation and scum formation may not arise, but the accumulation of acids and entrapment of gas in plant material is likely to occur. The problem of p^H regulation, non-uniform culture and movement of material may pose serious problems. Some of these problems may be less severe when dry fermentation is carried out in batch fermentation plants.

(d) p^H Value In the initial acid forming stage of the digestion process p^H value may be around 6 or less. However, during methane formation stage, p^H value of 6.5 to 7.5 is maintained, as methane-forming bacteria are very sensitive to acidity. Too much and sudden deviation from this value is likely to cause imbalance in bacteria population affecting the production of gas.

(e) Feeding Rate If the digester is fed with too much raw material at a time, acids will accumulate and digestion process may stop. Also faster feeding rate will not help increase the gas production. At higher feeding rate the retention period will be less and undigested slurry may come out. Therefore, uniform feeding rate should be maintained. For example, for desired retention period of 50 days, an amount equal to 1/50 of the volume of the digester should be fed daily.

(f) Carbon to Nitrogen (C/N) Ratio and Other Nutrients in Biomass A digester is culture of bacteria feeding upon organic wastes. For optimal growth and activity of bacteria, it is essential that required nutrients are available in correct chemical form and concentration. Carbon (in carbohydrate) and nitrogen (in proteins, nitrates etc.) are the main nutrients for anaerobic bacteria. While carbon supplies energy, nitrogen is needed for building up the cell structure (i.e. growth). The fact that anaerobic bacteria use carbon 25 to 30 times faster than nitrogen necessitates the optimum C: N ratio as 30:1 for maximum microbiological activity. Deviation from this ratio slows down the digestion process. Various organic wastes used for biogas production markedly differ in their C: N ratio as shown in Table 8.6. Small amount of phosphorus (2 per cent of dry input, by weight) is also required for proper microbiological activity. Proper balance of nutrient is maintained by supplementing required amount of selected raw materials, to make up the deficiency of particular nutrient, e.g. night soil for phosphorus and chopped leguminous plants (plants producing seeds in pod) for nitrogen, etc.

Table 8.6 C/N ratio of various input biomass materials of biogas plant

S.N.	Raw material	C/N ratio	S.N.	Raw material	C/N ratio
1.	Cow dung	25	11.	Wheat straw	150
2.	Poultry droppings	5.2	12.	Corn stalks	60
3.	Night soil	8.0	13.	Raw sawdust	511
4.	Farmyard manure	14	14.	Sea weeds	19
5.	Human urine	0.8	15.	Raw domestic garbage	25
6.	Sugar cane tops	500	16.	Bread	20
7.	Grass clipping/hay	19	17.	Potato tops	25
8.	Ripe leaves	203	18.	Kitchen veg. scraps	16
9.	Cut straw	48	19.	Rags	12
10.	Flax waste	58	20.	Household dirt	41

(g) Seeding of Biomass with Bacteria To start and accelerate fermentation process, small amount of digested slurry, which contains methane-forming bacteria, is added to the freshly charged plant. This is known as seeding. If the biomass is animal manure, it already contains acid and methane fermenters and seeding in not necessary. However, their number is not large. Also methane fermenters reproduce and multiply slowly. Seeding helps to accelerate the starting of digestion process.

(h) Mixing or Stirring Mixing has three important effects: (a) maintains uniformity in substrate concentration, temperature and other environmental factors, (b) minimizes the formation of scum at the surface and (c) prevents the deposition of solids at the bottom. The masses that float at the top in the form of scum and that deposit at the bottom are not easily available to bacteria for biodigestion. Stirring brings these masses to the reach of bacteria thus helping in proper functioning of the plant.

(i) Retention Time Retention time is the time duration for which the slurry remains in the plant or the time that is available for biodigestion. It is determined by the volume of digester divided by the volume of slurry added per day. Retention time is optimized to achieve a 70-80 per cent complete digestion. The biodegradability period depends on the temperature and the type of biomass. Table 8.7 shows biodegradability periods of various digester feeds at 35 °C. In India biogas plants are designed for retention period of 30, 40, and 50 days depending on the region.

Table 8.7 Required retention time of various feed materials at 35 °C

S.N.	Raw material	Required retention time (days)
1.	Cow dung	50
2.	Poultry droppings	20
3.	Night soil	30
4.	Rice straw	33
5.	Sugar cane tops	43
6.	Water hyacinth	46

(j) Effect of Toxic Substances High concentration of ammonia, antibiotics, pesticides, detergents, heavy metals like chromium, copper, nickel, zinc etc. are toxic to bacteria responsible for biodigestion. Low C: N ratio in slurry leads to high concentration of ammonia. Antibiotics given to animals in feed or injected to them will have its trace in the manure produced. Traces of pesticides and disinfectants may be present in farm products. Synthetic materials are also toxic to bacteria. Heavy metals are mostly present in industrial wastes. Maximum allowable concentrations of some of the harmful materials are summarized in Table 8.8. Also the digested slurry, if allowed to remain in the digester beyond a certain time, becomes toxic to microorganisms.

Table 8.8 Maximum allowable concentrations of toxic materials

S. N.	Toxic material	Allowable concentration (mg/litre)	S. N.	Toxic material	Allowable concentration (mg/litre)
1.	Copper	100	7.	Magnesium	1,500
2.	Chromium	200	8.	Ammonia	3,000
3.	Nickel	200-500	9.	Sulphate	5,000
4.	Sodium	5,500	10.	Sodium chloride	40,000
5.	Potassium	4,500	11.	Cyanide	Below 25
6.	Calcium	4,500	12.	Detergent compd.	40 ppm

8.10.6 Availability of Raw Materials and Gas Yield

Most of the organic matters containing proteins, fats and carbohydrates (except mineral oils and lignin) can be microbiologically transformed into biogas. These are: (a) animal wastes based resources, such as: animal and human excreta, slaughter house waste etc., (b) land based resources such as: crop wastes, byproducts of agro based industries, urban solid wastes and (c) water based resources such as: algae, sea weed, water hyacinth, etc. The availability and gas yield from some of these resources is given in Table 8.9.

Table 8.9 Raw material availability and gas yield

S.N.	Raw material	Production rate	Gas yield (m^3 per kg of dry matter)
1.	Cow dung	10–15 kg/day/head	0.34
	Poultry manure	0.06 kg/day/head	0.46–0.56
	Sheep manure	0.75 kg/day/head	0.37–0.61
	Night soil	0.75 kg/day/head	0.38
	Rice husk	1–1.3 tons/ha/year	5.67
	Algae	40 tons/ha/year	0.32
	Water hyacinth	60 tons/ha/year	0.42

Some Facts about Biogas Plant

Only 70 per cent of the cow dung produced can be collected, as 30 per cent is lost in fields during grazing. Solid matter content in cow dung is about 18 per cent. Equal amount of water is to be mixed to reduce solid mater to 9%. Biogas required for cooking is about 0.227 m^3/person/day. Gas required for lighting a 100 C.P. (candle power) mantle lamp is 0.126 m^3/hour. A biogas plant producing 2 m^3 gas/day could replace a fuel equivalent of 26 kg of LPG (nearly two standard cylinders) per month. The density of slurry is about 1090 kg/m^3.

The required gasholder capacity is an important planning parameter. If the gasholder is insufficient, part of gas produced will be lost and the remaining volume of the gas will not be enough at the time of demand. If the gasholder is much too large, construction cost will be unnecessarily high. The gasholder must therefore be made large enough to accept the entire volume of the gas consumed at a time. It must also be able to accept all the gas produced between consumption times. It must be able to compensate for daily fluctuations in the gas production. These fluctuations range from 75–125 per cent.

Example 8.1

Calculate the volume of a cow dung based biogas plant required for cooking needs of a family of five adults and lighting need with two 100 C.P. lamps for three hours daily. Also calculate the required number of cows to feed the plant. Assume standard values of data where required.

Solution

Gas required for cooking for the family = $5 \times 0.227 = 1.135$ m^3/day

Gas required for lighting = $0.126 \times 2 \times 3 = 0.756$ m^3/day

Total daily gas requirement of the family = $1.135 + 0.756 = 1.891$ m^3

Let 'n' be the number of cows.

Cow dung produced = $10\,n$ kg/day

Collectable cow dung (70%) = $7\,n$ kg/day

Weight of dry solid mass (18%) in cow dung = $0.18 \times 7\,n$ kg/day

Gas production per day (from Table 8.9) = $0.34 \times 0.18 \times 7\,n$ m^3

At equilibrium state the production and consumption of gas must match,

Thus, Gas production = gas required

$$0.34 \times 0.18 \times 7\,n = 1.891$$

$$n = 4.41 \approx 5$$

Thus five cows are required to feed the plant.

Daily feeding of cow dung = $7 \times 5 = 35$ kg

This will be mixed with equal quantity of water to make the slurry.

Thus daily feed of slurry = $35 + 35 = 70$ kg = $70/1090$ m^3 = 0.0642 m^3

(Assuming slurry density = 1090 kg/m^3)

For 50 days retention time, volume of slurry in the digester = $50 \times 0.0642 = 3.21$ m^3

As about 90% volume is occupied by the slurry, the required volume of the digester

$$= 3.21/0.9 = 3.56 \text{ m}^3$$

Example 8.2

A school in a remote place has following energy requirements.

- Ten lamps each of 100 CP that operate for 4 hours daily
- Six computers, each 250 W that operate for 6 hours daily by a dual fuel engine driven generator.
- 2 hp water pump driven by dual fuel engine for two hours daily.

Calculate the size of biogas plant and the number of cows required to feed the plant. Assume the standard values of data where required.

Solution

One 100 CP lamp consumes 0.126 m^3/h biogas

Gas required for daily lighting = $10 \times 0.126 \times 4 = 5.04$ m^3/day

Electrical energy required by 6 computers per day = $6 \times 250 \times 6 \times 60 \times 60 = 32.4$ MJ

Assuming the conversion efficiency of generator to be 80% and the thermal efficiency of engine to be 25%, the thermal input to the engine to generate 32.4 MJ electrical energy = $32.4/(0.25 \times 0.80) = 162$ MJ

Mechanical energy required per day for water pumping = $2 \times 746 \times 2 \times 60 \times 60$
= 10.74 MJ

Assuming the thermal efficiency of engine to be 25%, the required thermal input
= $10.74/0.25 = 42.96$ MJ

Total thermal input required by the engine per day = $162 + 42.96 = 204.96$ MJ

Assuming heating value of biogas to be 23 MJ/m^3, the required volume of biogas per day for the engine = $204.96/23 = 8.911$ m^3

Therefore, total daily requirement of biogas = $5.04 + 8.911 = 13.951$ m^3

Let 'n' be the number of cows.

Collectable cow dung per day = $7n$ kg/day

Weight of solid mass (18%) in the cow dung = $7\,n \times 0.18 = 1.26\,n$ kg/day

Assuming gas yield of 0.34 m^3/kg of dry mass, the gas produced per day
= $1.26\,n \times 0.34 = 0.4284 \times n$ m^3/day

At equilibrium state the production and consumption of gas must match,
Thus: daily biogas production = daily gas required

$$0.4284 \times n = 13.951$$

$$n = 32.56 = 33$$

Thus 33 cows are required to feed the plant.

Daily feeding of cow dung into the plant = $7 \times 33 = 231$ kg

This will be mixed with equal quantity of water to make the slurry. Thus the daily slurry produced = $231 + 231 = 462$ kg

Assuming slurry density to be 1090 kg/m^3, the volume of slurry added per day
= $462/1090 = 0.42385$ m^3/day

For 50 day retention time, the total volume of the slurry in the digester = 50×0.42385
= 21.19 m^3

As only 90% of the digester volume is occupied by the slurry, the net volume of the digester = $21.19/0.9 = 23.55$ m^3

Example 8.3

A plant produces 1200 litres of biogas daily. Calculate the size of gasholder and gasholder capacity for a biogas plant that feeds a constant load during following periods daily. (Assume uniform consumption of gas)

- From 0600 to 0800 hours (2 hrs)
- From 1200 to 1400 hours (2 hrs)
- From 1900 to 2100 hours (2 hrs)

Solution

Gas is produced uniformly for 24 hours, gas production rate = 1200/24 = 50 litres/hr

Gas is consumed uniformly in 6 hours, gas consumption rate = 1200/6 = 200 litres/h

Gas holder size required to supply gas for 2 hrs during which the production is also continuing V_G (1) = (200 – 50) × 2 = 300 litres

The largest period of gas accumulation without its consumption is from 2100 to 0600 hours (9 hrs), the necessary gas holder size V_G (2) = 50 × 9 = 450 litres

V_G (2) is the maximum relevant gasholder size required.

With a safety margin of 25%, the required gas holder size = 1.25 × 450 = 562.5 litres

The gas holder size required = **562.5 litres**

The required gas holder capacity = 562.5/1200 = 0.468 = **46.8%**

Example 8.4

Calculate the volume of the fixed dome type biogas digester for the output of the two cows. Also calculate the thermal power available from biogas. Use following data:

Retention time = 40 days

Dry matter produced = 2 kg/day/cow

Biogas yield = 0.22 m^3/kg of dry matter

Percentage of dry matter in cow dung = 18%

Density of slurry = 1090 kg/m^3

Burner efficiency = 60%

Heating value of biogas = 23 MJ/m^3

Solution

Dry matter produced by two cows = 2 × 2 = 4 kg/day

As dry matter content in cow dung is only 18%, cow dung produced = 4/0.18
= 22.22 kg/day

Equal quantity of water is added to make the slurry. The amount of slurry produced per day = 22.22 + 22.22 = 44.44 kg/day

Slurry volume produced per day = 44.44/1090 = 0.04077 m^3/day

With retention time of 40 days, total slurry in the digester = 40 × 0.04077 = 1.6308 m^3

As about 10% digester area is occupied by the gas, the net digester size = 1.6308/0.9
= 1.812 m^3

Gas produced = 4 × 0.22 = 0.88 m^3/day

Thermal energy available = 0.88 × 23 × 0.6 = 12.144 MJ/day

Continuous thermal power available = $12.144 \times 10^6/(24 \times 60 \times 60) = 140.55$ W

Example 8.5

A group of 10 families in a village plans to install a KVIC biogas plant for energy needs of cooking, bathing and lighting. Calculate the volume of gasholder and digester of the plant and number of cattle required. Use following data:

Total number of persons = 45

Mass of wet cow dung produced/cattle/day = 10 kg

Heat energy required for cooking daily food = 1758 kJ/person/day

Heat energy required for breakfast, snacks etc. may be assumed to be half that required for cooking.

Room temperature is 25 °C

Assume that 20 litres of water at 45 °C is required for bathing per person

Assume that 3 lamps of 40 W are used for 4 hours daily by each family for the purpose of lighting

The efficiency of lamp may be assumed as 40%

Gas burner efficiency may be assumed as 60%

Heating value (L.C.V) of biogas = 17500 kJ/m^3

Gas yield of cow dung = 0.34 m^3/kg of dry matter

Density of slurry = 1090 kg/m^3

Retention period = 40 days

Solution

(i) Heat energy required for cooking $E_1 = 45 \times 1758 = 79{,}110$ kJ/day

(ii) Heat energy required for breakfast, snacks, etc. $E_2 = 0.5 \times 79110$
$= 39{,}555$ kJ/day

(iii) Heat energy required for bathing purpose $= 20 \times 4.2 \times (45 - 25)$
$= 1680$ kJ/day/person

Total heat energy required for bathing $E_3 = 45 \times 1680 = 75600$ kJ/day

Gas burner efficiency = 60%

Total thermal energy to be supplied for cooking (food + breakfast) and bathing $= (E_1 + E_2 + E_3)/0.6 = (79110 + 39555 + 75600)/0.6$
$= 3{,}23{,}775$ kJ/day

Biogas required = 3,23,775/17,500 = 18.5 m^3/day

(iv) The energy required for 3 lamps (40 W), each in 10 families 4 hours per day $= 3 \times 40 \times 10 \times 4 \times 3600/1000$ kJ/day = 17280 kJ/day

As the efficiency of lamps is 40%, net energy required $E_4 = 17280/0.4$
$= 43200$ kJ/day

Thus, gas required for lighting = 43200/17500 = 2.468 m^3/day

Hence total gas requirement of 10 families = 18.5 + 2.468 = 20.97 m^3/day

Considering 20% incidental requirement, net gas required = 25 m^3/day

(v) Gas yield of cow dung = 0.34 m^3/kg of dry matter

Required dry matter to produce 25 m^3 of biogas = 25/0.34 = 73.53 kg of dry matter

Considering 18% of solid matter in cow dung, the required wet dung
= 73.53/0.18 = 408.5 kg/day

(vi) Let us assume that one cattle produces 10 kg of wet dung, but 30% is lost during grazing. Thus net collectable dung obtained from one cattle = 7 kg
Number of cattle required to produce 408.5 kg of dung per day
= 408.5/7 = 58.36 ≈ 59

(vii) Daily gas production of the plant = 25 m^3/day
Fraction of gas to be stored in gas holder of KVIC plant = 0.6
Required volume of the gas holder = 0.6 × 25 = 15 m^3

(viii) Daily feed of wet dung in the plant = 408.5 kg/day
Daily feed of slurry = dung + water = 408.8 + 408.5 = 817 kg/day

$$= 817/1090 = 0.7495 \text{ m}^3/\text{day}$$

As retention period is 40 days, volume of digester = 40 × 0.7495 m^3
= 29.98 m^3 = 30 m^3

8.10.7 Floating Drum (Constant Pressure) Type Biogas Plants

Numerous models of floating drum type biogas plants are developed in various countries. Most representative of this type is the KVIC model (Khadi Village Industries Commission), developed in India, shown in Fig. 8.12.

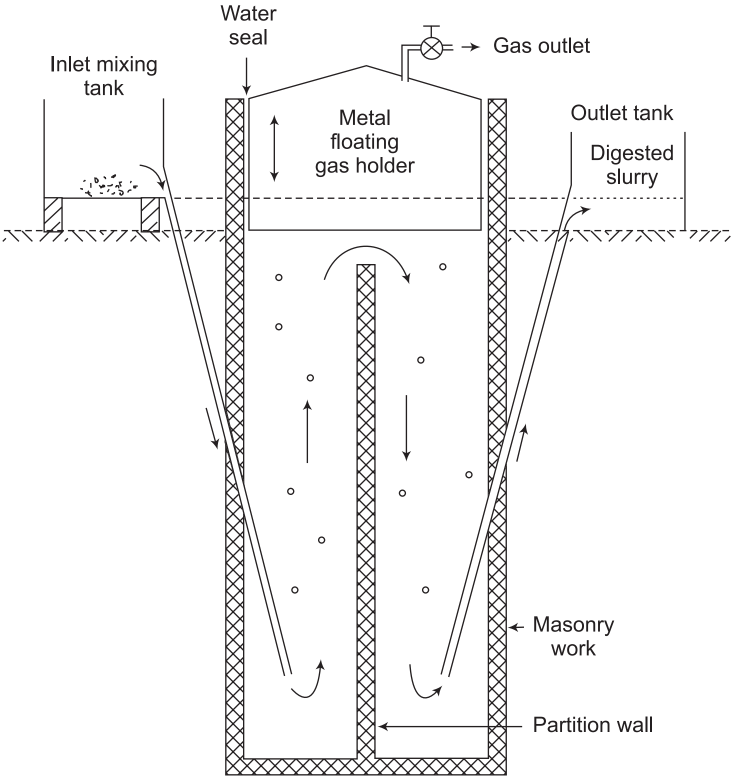


Figure 8.12 Floating drum type biogas plant

It has an inverted mild steel drum to work as gasholder. This is the most expensive component of the plant. The drum floats either direct on fermentation slurry or in a water jacket of its own. Most Indian plants now have a pair of central guide pipes. The gasholder is free to rise or fall depending on the production and use of gas. It is also free to rotate on its axis. Gasholder rotation will also be useful as a device to break the scum in the digester. A flexible hosepipe is attached at the top of the gasholder for gas dispersion. The gas passes through a moisture trap before supplying to the utility/house.

The digester is a deep circular pit or a well, built of bricks, mortar and plaster, with a partition wall. The bifurcation of digestion chamber through partitioning wall provides optimum conditions for growth of acid formers and methane formers as the requirement of p^H values for these bacteria are different. Therefore, this plant operates very well with good biogas yield. The underground structure helps minimize the heat loss from the plant and the cylindrical shape has better structural strength.

8.10.8 Fixed Dome (Constant Volume) Type Biogas Plants

This plant is more economical as only masonry work is required. Gas pressure in the dome varies depending on the production/consumption rate. By construction a dome structure is very strong for outside pressures but a weak one for inner pressures. As gas pressure is exerted from inside out, the dome structure may fail if proper care is not taken in its construction. The dome is constructed underground to maintain pressure over it. Skilled masonry workmanship is required for construction of dome. In case of any leakages/cracks the plant may fail. A typical family size Chinese model (Janata Model) is shown in Fig. 8.13. Many variations of this basic design are developed to reduce the cost by making use of different materials to suit local conditions.

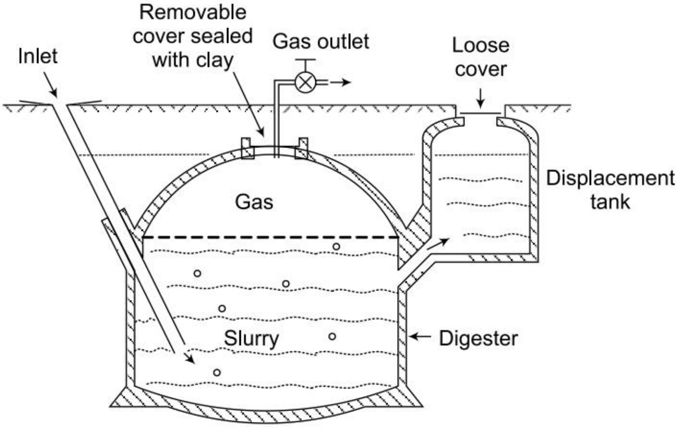


Figure 8.13 Fixed dome type biogas plant

The slurry enters from inlet and the digested slurry is collected in a displacement tank. Stirring is required if raw material is crop residue. There is no bifurcation in the digester chamber and therefore the gas production is somewhat less as compared to floating point design. The gas produced is stored in the dome and displaces the liquids in inlet and outlet, often leading to gas pressure as high as 100 cm of water. The gas occupies about 10 per cent of the volume of the digester. As complete plant is constructed underground, the temperature tends to remain constant and is often considerably higher than ambient temperature in winter.

Many variations of the above two basic models are developed keeping in view the portability, ease of installation and maintenance, local availability of material and cost, etc. Some of them are: plastic bag reactor, prefabricated steel/bamboo/plastic reactors (both are portable models) and horizontal type reactors, etc.

8.10.9 Comparison of Floating Drum and Fixed Dome Type Plants

The relative merits and demerits of the two basic designs of biogas plants are summarized in Table 8.10.

Table 8.10 Relative merits and demerits of floating drum and fixed dome biogas plants

S.N.	Feature	Floating drum	Fixed dome
1.	Cost	More (due to steel drum)	Less
2.	Corrosion	Yes (likely in steel drum)	No
3.	Maintenance	More • drum requires painting, once or twice a year) • flexible gas pipe requires replacement	Less • no steel part is used. • gas pipe is a fixed G.I. pipe.
4.	Thermal Insulation	Bad (heat loss due to steel drum)	Good (temperature will be constant due to complete underground construction)
5.	Scum troubles	Less likely (as solids are constantly submerged)	More likely
6.	Gas production per unit volume of digester	High (due to bifurcation, both acid and methane formers find better environment for growth)	Low
7.	Scum braking	By rotation of drum (no stirrer required)	External stirrer is required
8.	Leakage	Less likely	More likely
9.	Danger of mixing with oxygen due to leakage/cracks	No	More likely
10.	Gas pressure	Constant	Variable
11.	Masonry workmanship	Average skill	Specialized, skilled masonry work required
12.	Repairing of defects in gas holder	Easy	Difficult
13.	Choice of feed material	Can process dung and night soil slurry. Other organic materials can clog the inlet pipe	It can be easily adapted/modified for use of other materials along with dung slurry

8.10.10 Variations of Basic Biogas Models

A number of variants of the basic floating drum type and dome type biogas plant are evolved to suit the local conditions, choice of material, cost, ease of erection, and maintenance.

1. Taper Digester with Floating Gas Holder Model (Nepal)

This design, also known as Nepal design is shown in Fig. 8.14. This is suitable for shallow water table regions. The digester diameter below the gasholder is increased so that the total depth can be reduced. In most Indian designs, a hosepipe is attached at the top of the gasholder to take out gas for use. This flexible hose-pipe is exposed to outdoor environment and subject to deterioration and leakage. This problem is avoided in Nepal design by having a fixed underground pipe that runs vertically through the gasholder with open end at the top for entry of the gas. Other features, including bifurcation of gas digester are same as in a KVIL design.

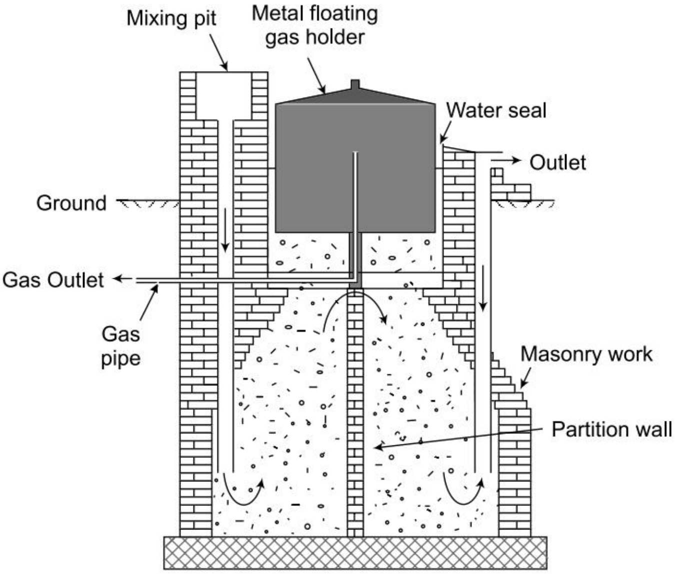


Figure 8.14 Taper digester with floating gas holder (Nepal)

2. Pragati Biogas Model

The digester of Pragati model has hemispherical (dome) shape with sloping bottom slab to reduce the earth and digester wall work leading to reduction of cost. The cost of Pragati plant is 20 per cent less than the cost of KVIC plant. Dome shape construction is carried out up to collar base, where a central guide frame is provided. The digester wall above guide frame is constructed in cylindrical shape. The partition wall is also constructed in the digester. The guide frame, which is made of angle iron and steel pipe, is embedded in the digester wall at the top of spherical portion of the digester. The central guide pipe holds gas holder which is also made of M. S. sheet and angle iron. The basic features of Pragati model is shown in Fig. 8.15.

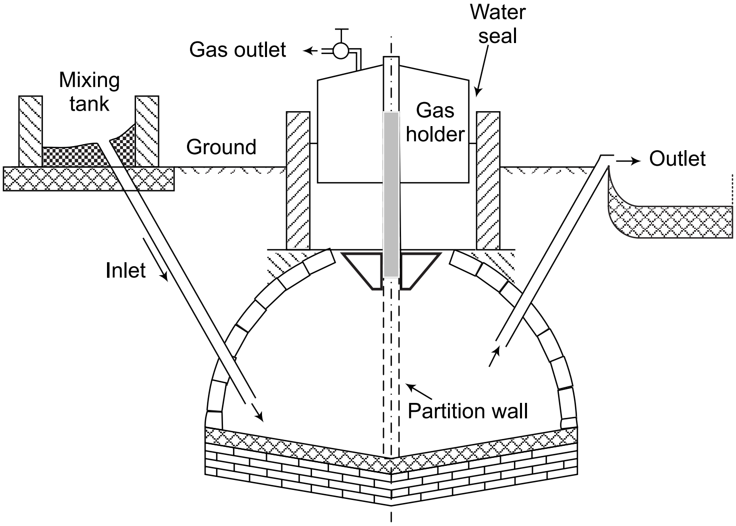


Figure 8.15 Pragati biogas plant

3. Ganesh Model of Biogas Model

It is basically a KVIC model with digester constructed with angle iron frame and bamboo wrapped with polythene sheet instead of a masonry structure. The gas holder and guide frame are same as that used in KVIC model. The cost is about 70 per cent of KVIC plant besides being easy to construct.

4. Jwala Biogas Model [53]

It was developed by AMM Murugappa, Chetiar Research Centre, Tamil Nadu, India. The Jwala design mainly consists of a digester (or fermenter tank) and a balloon type gasholder. The masonry part of the plant is similar to KVIC design. The outlet connection for gas as well as for stirrer is incorporated with the digester.

The expensive mild steel drum for a gas holder is replaced by a geodesic balloon made of a low density polythene (LDPE) or PVC sheet with a supportive wooden frame (or dome). The gasholder does not have any upward or downward movement. The gasholder balloon is placed inside a water seal and tied with hooks at the bottom. The LDPE or PVC sheet balloon requires the dome support to hold it in the water seal and to prevent it from flying off under gas pressure. The details of the plant are shown in Fig. 8.16.

The Jwala model is considerably cheaper because no costly materials are involved in its construction. The gasholder can be constructed locally and easily dismantled and transported. It does not require regular maintenance nor highly skilled personnel for construction.

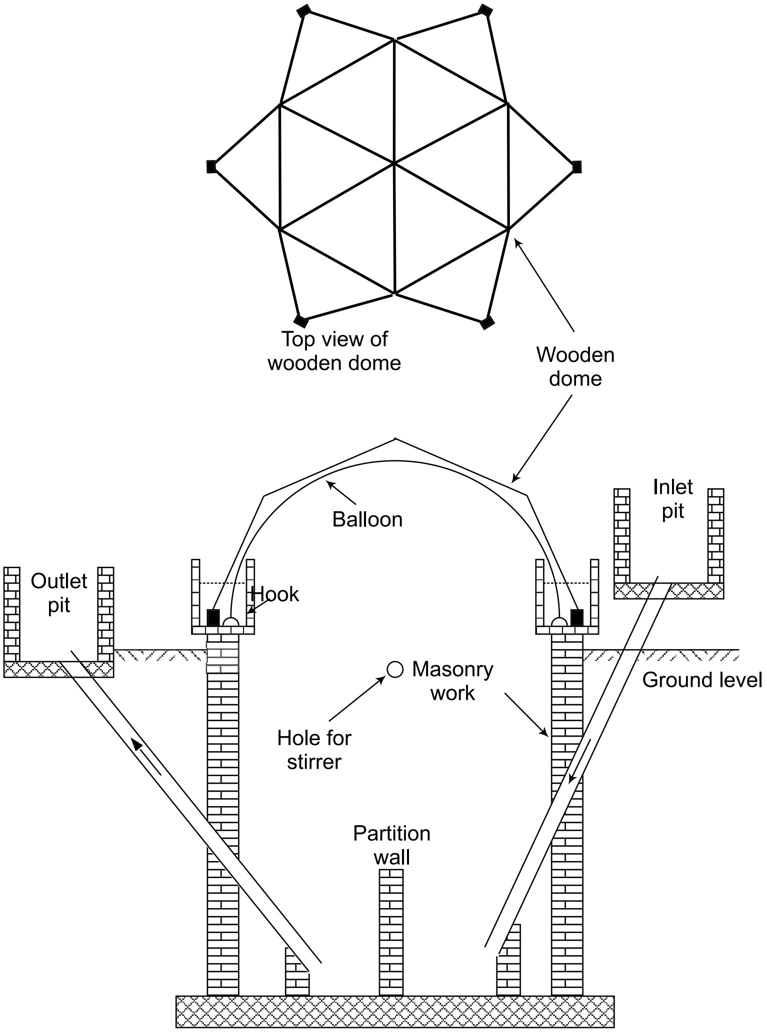


Figure 8.16 Jwala model

5. Ferro-cement Biogas Plant

Ferro-cement is a form of reinforced concrete made of wire mesh, sand, water and cement. Both gasholder and digester is made from this composite material. The digester of small plants (below 6 m^3) is prefabricated in a single piece. In case of big plants the periphery is divided into 4–6 segments which are casted at a central place over a prepared masonry or wooden mould. These precast segments are then transported and erected at the site. The plant follows the KVIC model design specifications.

6. Floating Drum Fibreglass Reinforced Polyester Plant

Fibre Reinforced Plastic (FRP) has been used in place of metal in the floating drum gasholder. It employs one of the less expensive of moulds, resulting in lower cost of the plant. The major advantage of FRP is its good resistance to corrosion, which saves the recurring expenditure on painting the drum.

7. ARTI Model of Floating Drum Type Biogas Plant

The Indian Appropriate Rural Technology Institute (ARTI) has developed a small biogas digester that uses starchy or sugary wastes as feedstock, including waste flour, vegetable residues, waste food, fruit peelings, rotten fruit, oil cake, rhizomes of banana, canna (a plant similar to a lily but rich in starch), and non-edible seeds.

The ARTI design is fabricated from cut-down high-density polythene (HDPE) water tanks. A heat gun can be used to make joints and standard HDPE fittings can be used. The standard ARTI biogas plant uses two tanks, with volumes of typically around 0.75 to 1 m^3. The larger diameter tank serves as fermenter. The smaller diameter tank, inverted and placed over the fermenter, serves as a gasholder. The gasholder can move up and down inside the bigger tank.

It is the fermenter which holds the mixture of decomposing feedstock and water. For best results the feedstock should be blended so that it is smooth. The starter mix can be cattle dung blended in water or some waste flour. An inlet (shown as white pipe) is provided for adding feedstock, and an overflow (shown as grey pipe) for removing the digested residue. The ARTI biogas digester should be set up in a sunny place close to the kitchen, so a short section of pipe can take the biogas to the kitchen. A photograph of such a plant is shown in Fig. 8.17.

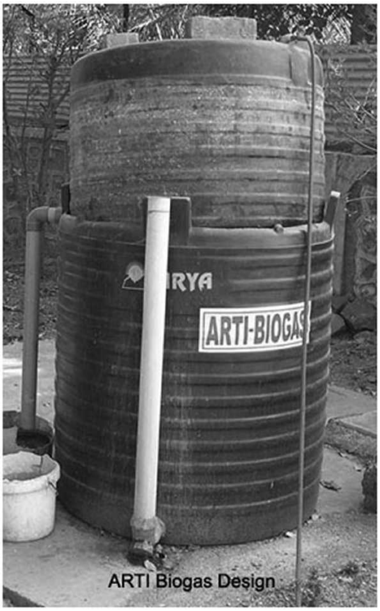


Figure 8.17 ARTI biogas plant

8. Deenbandhu Biogas Plant

This is a modified version of fixed dome plant, developed in 1984 by Action for Food Production (AFPRO), New Delhi, a voluntary organization. The cost of the plant is almost half of the KVIC model. The cost reduction is achieved by minimizing the surface area through joining the segments of two spheres of different diameters at their bases. While the base diameter to rise of arch has been kept as 1:5 for bottom sphere segment, the top dome is a hemisphere. This structure acts as a digester as well as gas storage. The digester is made underground in order to always maintain it under pressure and minimize heat loss.

The gas holding capacity is around 33 per cent of daily gas production. The gas outlet pipe is flushed with the ceiling. The gas collects at the top of the digester and exerts pressure on the slurry which is pushed into the displacement chamber. As the gas is drawn out from the outlet for use, the slurry again enters the digester. The brick masonry dome requires skilled workman ship and quality material to ensure leak proof construction. Main features of the plant are shown in Fig. 8.18.

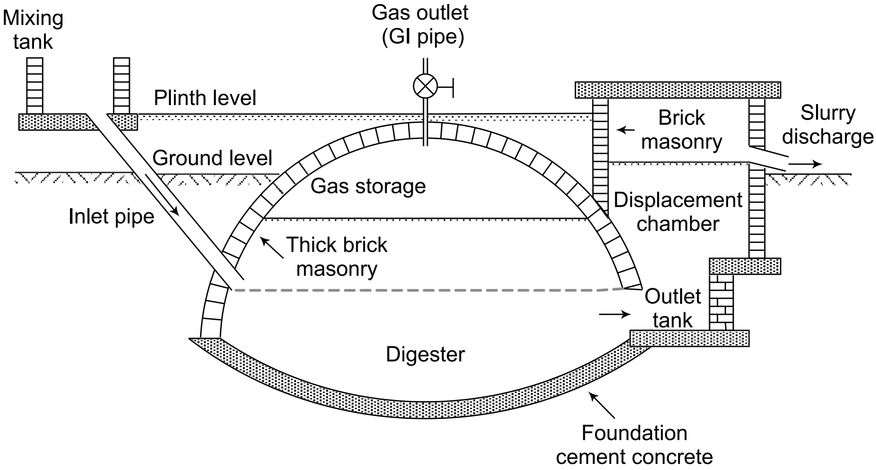


Figure 8.18 Deenbandhu biogas plant

9. CAMATEC Model

This model, shown in Fig. 8.19, was developed at Centre for Agricultural Mechanization and Rural Technology, Arusha, Tanzania. It has a simplified structure of a hemispherical dome shell based on a rigid foundation ring only and a calculated joint of fraction, the so-called weak/strong ring.

The weak/strong ring improves the gas-tightness of fixed-dome plants. It was first introduced in Tanzania and showed promising results. The weak ring separates the lower part of the hemispherical digester, (filled with digesting substrate), from the upper part (where the gas is stored). Vertical cracks, moving upwards from the bottom of the digester, are diverted in this ring of lean mortar into horizontal cracks. These cracks remain in the slurry area where they are of no harm to the gas-tightness. The strong ring is a reinforcement of the bottom of the gasholder; it could also be seen as a foundation of the gasholder. It is an additional device to prevent cracks from entering the gasholder. Weak and strong rings have been successfully combined in the CAMARTEC design material and construction.

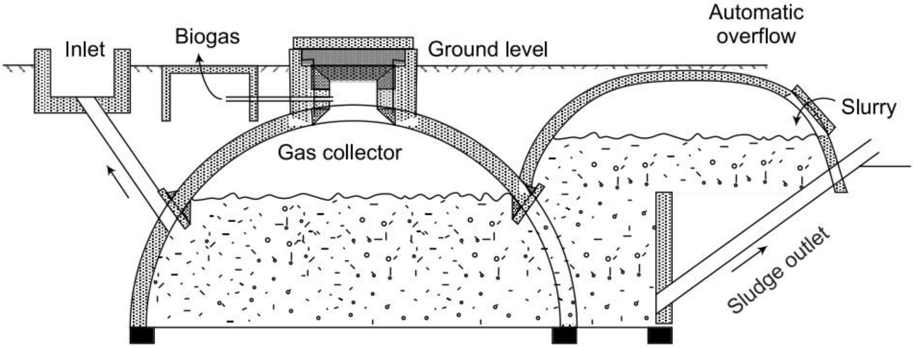


Figure 8.19 CAMATEC biogas plant

10. Bag/Tube/Flexi/Balloon Biogas Plant

The flexi biogas plant in general consists of plastic or rubber digester bag, in the upper part of which the gas is stored. The digester/gasholder bag is placed on a sand base and supported by steel cage. The model is particularly useful for hilly areas where the cost of transportation of construction material like brick, cement etc. is prohibitive. The schematic diagram of balloon plant is shown in Fig. 8.20. Integral with the bag are feed inlet and outlet pipes and a gas pipe. When the gas space is full, the plant works like a fixed dome plant. Alternatively the gas can be stored in a separate bag.

The advantages of balloon digesters include low cost, ease of transportation and installation, low construction depth (important for shallow water table), high digester temperature, uncomplicated cleaning, emptying and maintenance and shorter retention time. The main disadvantages are: short service life (about 5 years, due to degradation because of exposure to UV radiation) and vulnerability to damage.

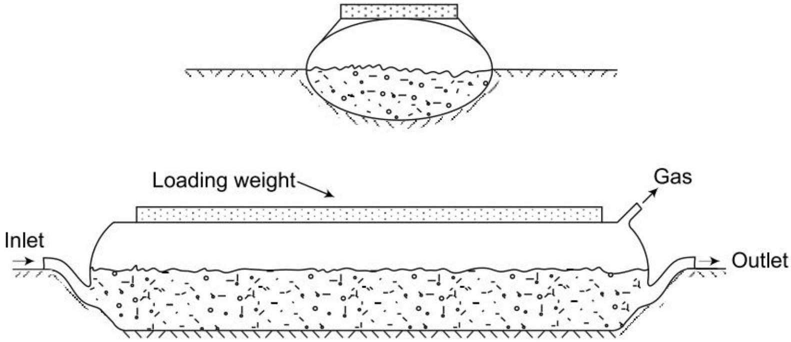


Figure 8.20 Flexible bag type biogas plant

8.10.11 General Maintenance Problems of Biogas Plants and their Remedies

(a) Handling of digested slurry: It may be a major problem if sufficient open space or compost pits are not available to get the slurry dry. For domestic plant a 200-litre capacity oil drum can be used to carry this affluent to the fields.

(b) Low gas production rate: The methane forming bacteria are very sensitive to temperature. During winter, as the temperature falls, the gas production rate also reduces. Following methods may be used to enhance rate of gas production.

  i. Using solar thermal heater to add hot water in the inlet slurry, but the water temperature should not exceed 60 °C as higher temperature will kill the methane forming bacteria.
  ii. Circulation of solar-heated hot water through pipes in the digester
  iii. Greenhouse effect may be used to trap solar radiation for heating.
  iv. Covering the biogas plant by straw bags during night hours
  v. Manual or auto stirring of digester slurry
  vi. Addition of some nutrients for bacteria

(c) Some problems arise due to the following:

  i. Increased loading rate
  ii. Not mixing sufficient water in the cattle dung

Due to these reasons, the flow of slurry from inlet towards outlet is very slow or may even stop. This may cause accumulation of volatile fatty acids leading to decrease of p^H value and ultimately failure of the plant. Also due to lack of water in the slurry, it is not possible to stir the digester content of high solid concentration.

(d) Some persons add urea fertilizer in large quantities, leading to reduction of bacterial activity due to toxicity.

(e) Leakage of gas from gasholder, especially in case of Janata plant is a major and common problem. Leakage should be checked and leakage points are marked and repaired. During repairing operation there should be no gas inside the gasholder and the stopcock should remain open till the repaired points get dry.

8.10.12 Starting a Biogas Plant

At the time of starting, if the digester is fed with cattle dung/night soil, it is not necessary to inoculate it because it contains necessary bacteria although not in sufficient number. These bacteria get activated under favorable environment and subsequently gas production starts. However, if the slurry obtained from another working biogas plant is mixed, the gas production starts earlier.

If the digester is operated on agricultural/forest residues then it is necessary to inoculate it with slurry from cattle dung fed biogas plant, otherwise gas formation will not start.

8.10.13 Landfill Reactors

Sanitary land filling is a method of controlled solid waste disposal. Biodegradable urban wastes are compacted and used to generate substantial amount of biogas. Nowadays "secure" landfills are used to prevent ground water contamination as a result of leaching of garbage. The location is first lined with both clay and synthetic liner (plastic) that will trap leachate. The site will also have a leachate collection system to collect and recycle it to accelerate decomposition process or dispose it at sewage treatment facility. Both dry as well as high moisture content in the waste hinder biogas production. The optimum moisture content is about 60 per cent (dry basis). When a landfill is filled and ready for closure, a plastic liner is placed over the top and then it is covered with soil. The biodegradable part, which constitutes about 70 per cent in MSW, is slowly digested anaerobically to produce biogas. During decomposition process, the temperature in the upper portion of landfill may go as high as 60 °C.

The gas collection system consists of wells comprising vertical pipes of 80 to 120 mm diameter with holes on the cylindrical body. These perforated or plastic pipes are driven in the landfill, surrounded by gravel and the area around the pipes is sealed with concrete at the surface. Knockout drums are installed in the pipeline for removal of water. A typical landfill site has 20–40 wells and the collection pipe system, which is connected to manifolds for gas disbursement.

About 225 m^3 of gas can be recovered from one ton of refuse. A well-managed 40-hectare landfill with waste height between 100–125 m can yield 135 m^3 of gas per minute continuously for about 15–20 years. A landfill site near Bedford, U.K. has a void volume of 10 million m^3 and covering 100-km^2 land area. The site receives 1000 t of urban waste per day. The Fresh Kills landfill near New York City is world's largest city dump. It is the tallest mountain on the east coast.

8.11 ENERGY FARMING

Production of plant material for their fuel value by capturing solar radiation is known as energy farming. Plants are convenient solar energy storage devices, from which the accumulated energy can be released, at will. "Energy forming" or "energy plantation" by design is managed and operated to provide substantial amounts of usable fuel continuously throughout the year at the cost competitive with other fuels.

An energy crop is planted and harvested periodically. The harvesting period varies greatly depending on the type of crop. Harvesting may be multiple times per year, for example 6 per year in case of Sudangrass, or once per year, as with sugar beets, sorghum and switch grass, or once in 5–7 years, as with certain trees such as hybrid poplar or willow. The cycle of planting and harvesting over a relatively short interval of time insures the sustainability of the resource.

Energy crops contain significant quantities of one or more of the four energy rich components: oils, sugars, starches and lignocelluloses (fibers). An outstanding and established example of energy farming is the sugarcane industry. Sugarcane crops are used for food (sugar) and energy (in the form of ethanol and baggasse). Fast growing hybrid poplar and eucalyptus trees are other example of energy farming. They grow very quickly (as much as 4 metres per year), require little water, use less land and are quite hardy.

Energy crops are divided into (i) wood energy crop and (ii) herbaceous energy crops. Woody crops are harvested on a rotation of 5–7 years and often referred to as short rotation woody crops (SRWC). Hardwoods are more promising than soft wood because of their higher productivity potential, lower cost and the ability to re-sprout from stumps. Promising hardwoods include hybrid poplar, willow and black locust. Herbaceous energy crops include both annual crops and perennial crops. The examples of annual crops are corn, sweet sorghum, etc. and that of perennial crops are switch grass, Indian grass, etc.

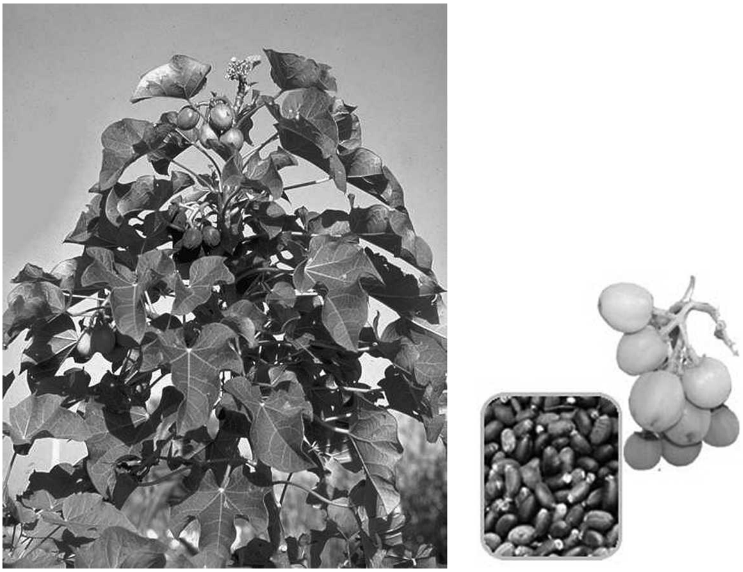
The potential of production of bio-diesel through plantation of certain plants is attracting the attention, the world over. For example, Jojoba (*Simmondsia Chinensis*), Jatropha Curcas and Karanj (*Pongamia Pinnata*) are being planted in a big way and their commercial viability is being assessed. The fuel yield depends on geography, climate and the type of soil. Typical details are of these plants are given below.

Jojoba is a shrub, about 1–2 m tall. It is well suited to semiarid desert regions and can live between 100 to 200 years. The female plant produces flowers in the spring that are pollinated when wind carries pollen produced by male plants. The pollinated flowers then harden into capsules containing 1–3 peanut sized seeds rich in a unique liquid wax commonly called "jojoba oil". On pressing, it produces about 45–65 per cent oil. This oil is toxic and not edible. This is used as hair conditioner, as massage oil, in pharmaceutical applications and recently as bio-diesel. All seeds on a jojoba shrub do not mature at the same time, and more than one harvest may be necessary. Jojoba generally does not produce an economically useful yield until the fourth or fifth year after planting. It produces 1–2 tons of seeds per hectare. Thus the fuel produced is about 3400 litres/ha. The plant and the seeds are shown in Fig. 8.21. Jojoba grows best in sandy or decomposed granite or rocky soils and slowest in heavy clay soils such as adobe. Even if the fertility of the soil is marginal, jojoba is still able to produce well without the use of fertilizers. Current jojoba commercial plantations exist in the desert regions of countries worldwide including Argentina, Australia, Chile, Egypt, Israel, Mexico, Peru, and the US.

(a) Plant (b) Seed in husk

Figure 8.21 Jojoba

Jatropha Curcas is a shrub that grows up to 5 m in height. The photograph of the plant, fruit and seeds are shown in Fig. 8.22. The plant, originating in Central America, has been spread to other tropical and subtropical countries as well and is mainly grown in Asia and in Africa. It is resistant to a high degree of aridity. It can be planted even in the desert and therefore, as such does not compete with food crops. *Jatropha curcas* thrives on a mere 250 mm (10 in) of rain a year, and only during its first two years does it need to be watered in the closing days of the dry season. Ploughing and planting are not needed regularly, as this shrub has a life expectancy of approximately forty years. The use of pesticides and other polluting substances are not necessary, due to the pesticidal and fungicidal properties of the plant. While *Jatropha* curcas starts yielding from 9–12 months' time, the effective yield is obtained only after 2–3 years' time. The yield of seed is 6–8 tons/ha. On pressing the seeds produce 31–37 per cent oil. Thus the fuel produced is 2,100–2,800 litres/ha, and is significantly cheaper than crude oil. Jatropha absorbs large amounts of carbon dioxide from the atmosphere and therefore earns carbon credits.



(a) Plant (b) Seed and fruits

Figure 8.22 Jatropha curcas

Karanj (*Pongammia Pinnata*) is another wild tree generally used on highways and along canals to stop soil erosion. The tree is about 15 – 25 m tall. The photograph of the tree and the seeds are shown in Fig. 8.23. Native to humid and subtropical environments, Karanj thrives in areas having an annual rainfall ranging from 500 to 2500 mm. in its natural habitat, the maximum temperature ranges from 27 to 38°C and the minimum 1 to16°C. Mature trees can withstand water logging and slight frost. It can grow on most soil types ranging from stony to sandy to clay, including Verticals. It does not do well on dry sands. It is highly tolerant of salinity. It is common along waterways or seashores, with its roots in fresh or salt water. The natural distribution of Karanj is along coasts and riverbanks in India and Burma. Native to the Asian subcontinent, this species has been introduced to humid tropical lowlands in the Philippines, Malaysia, Australia, the Seychelles, the United States and Indonesia. The seed yield is 25–40 kg per tree. The oil content in the seeds is 30–40 per cent. About 200 plants may be grown per acre. A typical plant produces about 60–90 litres of oil. Thus about 5000 litres of oil can be produced per ha. Seed collection season in India ranges from December to April.

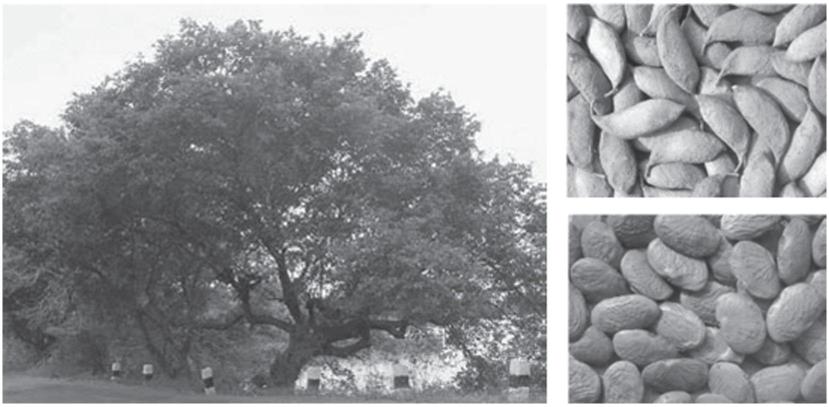

(a) Plant (b) Seeds

Fig. 8.23 Karanj

REVIEW QUESTIONS

1. What is the origin of biomass energy? What is its global potential? What is the average efficiency of photosynthetic conversion of solar energy into biomass?
2. What are main advantages and disadvantages of biomass energy?
3. Explain the process of photosynthesis. How much energy is stored through this process? In what range of frequency spectrum of solar light photosynthesis is most marked?
4. What is the approximate efficiency of fuel wood when used for cooking by conventional methods?
5. What is the heating value of charcoal, how much is the carbon content in it and what are its specific applications?
6. Explain the desirable features of bio-ethanol that makes it suitable as automobile fuel. What grade of bio-ethanol is required for blending with petrol and why?
7. What are the main advantages in use of biogas? What are its main constituents and heating value? In which countries these plants are most popular?
8. Explain the process of gasification of solid bio-fuels? What is the general composition of the gas produced and what is its heating value? What are its main applications?
9. What do you understand by energy farming?
10. What are different biomass energy resources and what is the energy yield from each of them?

11. With the help of block diagram explain the working of an MSW incineration plant. What is the general approximate composition of MSW and what is its heating value? What are the problems in its development?

12. With the help of neat diagram explain the working of a gasifier using woodchip biomass. What further processing is required to use the gas produced in a diesel engine?

13. Explain the process of commercial production of ethanol from biomass.

14. Explain the process of production of biogas from biomass. What are the main advantages of anaerobic digestion of biomass?

15. What are the factors affecting the performance of biogas digester?

16. What raw materials can be used for production of biogas? What is biogas yield of cow dung? How much LPG a biogas plant with gas production of 2 m^3/day can replace in a month?

17. Compare the relative performances of a floating drum and fixed dome type biogas plants.

18. Explain the details of a landfill reactor. What is the optimal moisture content in the MSW and what is the percentage (dry basis) of biodegradable part in the MSW? What is the gas production rate in a landfill?

19. Explain different types of bio-fuels.

20. What is the present status of development of biomass energy resources in India?

PROBLEMS

1. Find the size of cow dung based biogas plant required for a house having following requirements:

- Cooking for two adults and two children
- Lighting for three hours daily, using three gas mantle lamps, each of 100 CP power.

  Also calculate the number of cows required to feed the plant. Assume standard values of data where required.

  (Note: Two children may be considered as equivalent to one adult for cooking energy purpose) (*Ans.* 3.56 m^3, 5)

2. A community biogas plant is used for the following needs of a village having 30 families with 100 adults and 50 children.

- Cooking needs of the people of the village.
- Two lamps of 100 C.P. per family used for 1hr in the evening
- A biogas operated 3 hp engine used for three hours per day to pump drinking water.

  Calculate the size of the digester and the number of the cows required to feed the plant. Assume standard values of data where required. (*Ans.* 49.23 m^3, 69)

3. The consumption pattern of the biogas in a biogas plant is given below:

20 l/h from 0800 to 1200 hrs

40 l/h from 1300 to 1600 hrs

10 l/h from 2000 to 2400 hrs

Determine the size of the gasholder and the required gasholder capacity.

(*Ans.* 112.5 litres, 46.9%)

4. Calculate the volume of a fixed dome type biogas digester for the output of the four cows. Also calculate the thermal power available from biogas. Use following data:

Retention time = 30 days

Dry matter produced = 2 kg/day/cow

Biogas yield = 0.24 m^3/kg of dry matter

Percentage of dry matter in cow dung = 18%

Density of slurry = 1090 kg/m^3

Burner efficiency = 60%

Heating value of biogas = 23 MJ/m^3 (*Ans.* 2.85 m^3, 306.6 W.)

5. A group of 12 families in a village plans to install a KVIC biogas plant for energy needs of cooking, bathing and lighting. Calculate the volume of gasholder and digester of the plant and number of cattle required. Use following data:

Total number of persons = 50

Mass of wet cow dung produced/cattle/day = 10 kg

Heat energy required for cooking daily food = 1758 kJ/person/day

Heat energy required for breakfast, snacks etc. may be assumed to be half of that required for cooking.

Room temperature is 20 °C

Assume that 20 litres of water at 45 °C is required for bathing per person

Assume that 2 lamps of 40 W are used for 3 hours daily by each family for the purpose of lighting

The efficiency of lamp may be assumed as 40%

Gas burner efficiency may be assumed as 60%

Heating value (L.C.V) of biogas = 17500 kJ/m^3

Gas yield of cow dung = 0.34 m^3/kg of dry matter

Density of slurry = 1090 kg/m^3

Retention period = 45 days (***Ans.*** 17.3 m^3, 38.9 m^3, 68)

OBJECTIVE TYPE QUESTIONS

1. Storage of biomass energy is:
(a) very difficult
(b) inbuilt feature
(c) expensive
(d) impossible

2. Biogas is predominantly:
(a) hydrogen
(b) carbon monoxide
(c) carbon dioxide
(d) methane

3. Heating value of producer gas is:
(a) 4–8 MJ/m^3
(b) 14–18 MJ/m^3
(c) 24–28 MJ/m^3
(d) 34–38 MJ/m^3

4. Fluidized bed gasifier produces:
(a) low tar and high particulate
(b) high tar and low particulate
(c) gas at low conversion efficiency
(d) low exit temperature

5. The water content in anhydrous ethanol is:
(a) 20% (b) 10%
(c) 5% (d) 0.7%

6. The percentage of ethanol in blended petrol (gasohol) is:
(a) 20% (b) 30%
(c) 4% (d) 50%

7. Compared to petrol operated engine, an ethanol operated engine:
(a) produces 50% more power
(b) produces 20% more power
(c) produces comparable amount of power
(d) produces 20% less power

8. Increasing the pressure inside biogas plant:
(a) increases the gas production (b) decreases the gas production
(c) has no effect on gas production (d) causes explosion

9. When ambient temperature of biogas plant decreases below 20°C:
(a) the gas production increases
(b) the gas production first increases and then decreases
(c) the gas production decreases
(d) remains unaltered

10. The optimum solid concentration in a biogas is:
(a) 37–39 % (b) 27–29 %
(c) 17–19 % (d) 7–9 %

11. Which material should be added in the feed of biogas plant to increase nitrogen content?
(a) Lignin (b) Carbohydrate
(c) Chopped leguminous plants (d) Night soil

12. Compared to fixed dome model of biogas plant a floating drum type plant is:
(a) more efficient (b) less efficient
(c) equally efficient (d) very cheap

13. In energy farming, the plantation and harvesting is planned and managed so as to:
(a) reduce manual labour (b) insure the sustainability of the resource
(c) insure multiple harvesting per year (d) minimize the cost involved

14. Bio-diesel is:
(a) obtained from fermentation of sugars
(b) obtained from pyrolysis process
(c) exudates of plants
(d) an upgraded vegetable oil

15. Liquefaction of biomass is carried out at:
(a) high temperature and low pressure
(b) relatively low temperature and high pressure
(c) relatively low temperature and normal pressure
(d) room temperature and high pressure

16. Which of the following is a biodegradable waste?
(a) Vegetable and fruit peels (b) Silver foil
(c) Detergent (d) Rubber

17. The process in which waste material is reduced to ashes is called:
(a) biodegradation (b) composting
(c) recycling (d) incineration

18. Which of the following is not a biomass?
(a) Plants and trees (b) Wood
(c) Cattle dung (d) Water

19. Which of the following fuels can be produced by fermenting sugar cane top, sawdust, corn or wood chips?
(a) Alcohol (b) Biogas
(c) Producer gas (d) Bio-diesel

20. A small percentage of the hazardous waste is also generated in the house. Which of the following is a hazardous waste that is generated in the house?
(a) Paper (b) Leftover foodstuff
(c) Old batteries (d) Plastic bags

21. Which of the following does not have energy at all?
(a) Protein (b) Fat
(c) Carbohydrate (d) Vitamin

22. Burning of plastics, especially PVC releases which of the following harmful gases into the atmosphere:
(a) Lithium (b) Dioxins
(c) Methane (d) Nitrogen

23. The optimal p^H value of slurry for biogas production ranges between:
(a) 6.8 and 7.2 (b) 5 and 5.6
(c) 8 and 9.5 (d) 0 and ± 0.5

24. The waste water from distillery can be used to produce which of the following gases commercially?
(a) Carbon dioxide (b) Hydrogen
(c) Oxygen (d) Biogas

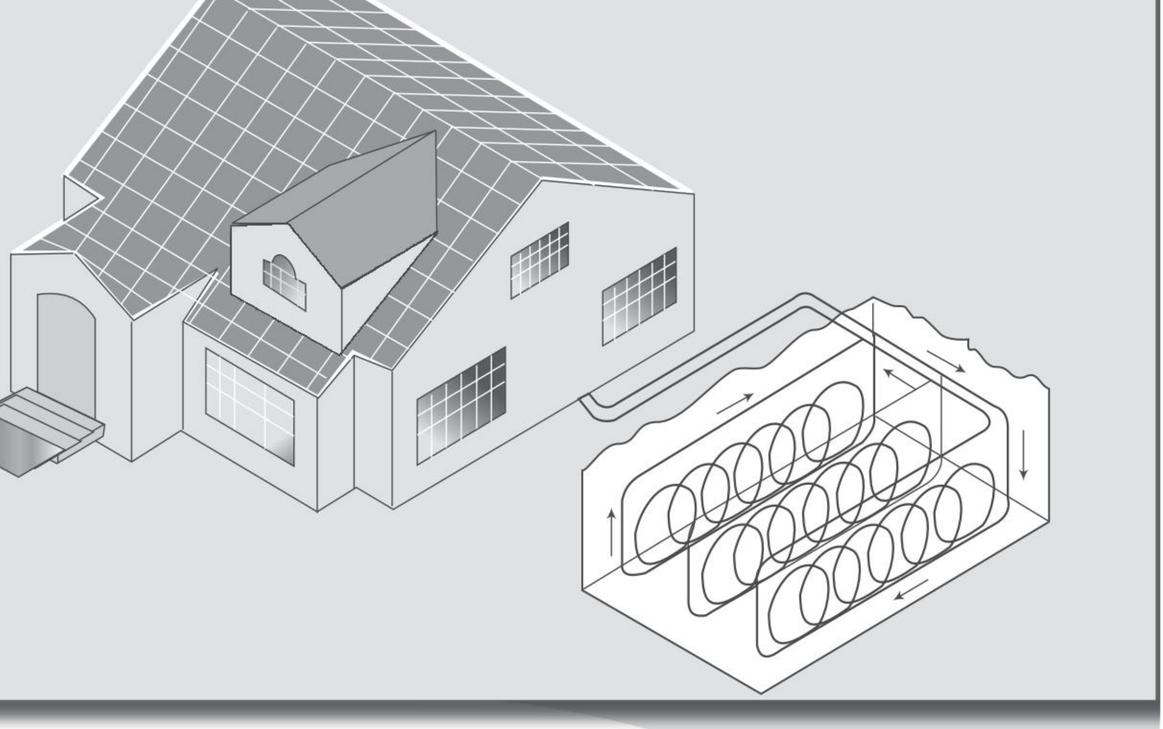
25. Gasification of biomass is which type of conversion process?
(a) Chemical (b) Biochemical
(c) Biological (d) Thermochemical

26. Hydrogen can be generated commercially through:
(a) Aerobic digestion (b) Steam reforming of methane
(c) Incineration (d) Anaerobic digestion

27. Presence of which of the following in the biogas causes corrosive effect?
(a) Hydrogen sulfide (b) Methane
(c) Carbon dioxide (d) Nitrogen

28. The gas generated through biomass gasification is called:
(a) ethane (b) biogas
(c) producer gas (d) carbon dioxide

29. Fuel reforming is a process of:
(a) transforming of fossil fuel into hydrogen
(b) transforming of fossil fuel into carbon monoxide
(c) removing carbon compounds from fossil fuel
(d) removing sulfur compounds from fossil fuel



CHAPTER 9

Geothermal Energy

Learning Objectives

In this chapter you will be able to:

- ➤ Describe nature and distribution of geothermal resources
- ➤ Explain various technologies of harnessing the geothermal energy
- ➤ Classify various types of geothermal resources
- ➤ Analyse and assess the feasibility of geothermal resources
- ➤ Discuss methods and procedures to explore and develop geothermal resources
- ➤ Evaluate environmental aspects of geothermal energy
- ➤ Examine prospects of geothermal energy in India

9.1 INTRODUCTION

Geothermal energy originates from earth's interior in the form of heat. Volcanoes, geysers, hot springs and boiling mud pots are visible evidence of the great reservoirs of heat that lies within earth. Although the amount of thermal energy within the earth is very large, useful geothermal energy is limited to certain sites only, as it is not feasible to access and extract heat from a very deep location. The sites where it is available near the surface and is relatively more concentrated, its extraction and use may be considered feasible. These sites are known as *geothermal fields*. As per US Geological Survey, the entire heat content of the earth's crust up to a depth of 10 km above 15 °C is defined as geothermal resource. As such the geothermal resource is estimated to be more than 2.11×10^{25} J, which is equivalent to 10^9 MTOE (million tons of oil equivalent). This is a huge amount of energy, enough to supply our energy needs at current rates for 3,50,000 years. Thus it is considered an inexhaustible and renewable source. However, it is a low-grade thermal energy form and its economic recovery is not feasible everywhere on the surface of the earth. Practically it is not the size of the resource that limits its use but the availability of technology that can tap the resource in an economic manner.

Low temperature resources, i.e. "geysers" have been used from time immemorial for applications such as therapeutic hot baths, cooking, space and water heating. Most geothermal resources produce low-grade heat at about 50–70 °C, which can be used directly for thermal applications. Occasionally, geothermal heat is available at temperatures above about 90 °C, and so electrical power production from turbines can be contemplated. World's total present (end of year 2012) installed electrical power generating capacity from geothermal resource is about 11,490 MW_e and direct thermal use installed capacity is 50,000 MW_t. Globally, geothermal power is growing steadily at a rate of about 5 per cent per year. The annual growth in energy output over the past five years has been 3.8 per cent for electricity production and around 10 per cent for direct use (including geothermal heat pumps)[9]. The geothermal electrical energy production in El Salvador is 25 per cent of the country's total production. At present the capital cost of a geothermal power plant is about Rs. 150–375 crore (Euro 2–5 million) per MW_e of electric capacity. The geothermal electricity cost is about Rs 3–7.5 (Euro 0.01 to 0.1) per kWh.

Main advantages of geothermal energy are: (i) it is a reliable and cheap source of energy, (ii) it is available 24 hours per day, (iii) its availability is independent of weather, (iv) it has inherent storage feature so no extra storage facility required, (v) geothermal plants require little land area and (vi) feasibility of modular approach represents lot of opportunities for development of relatively quick, cost-effective geothermal projects.

Major disadvantages are: (i) it is site specific – there are not many places where you can build a geothermal power station (ii) generally, energy is available as low grade heat, (iii) continuous extraction of heated ground water may leads to subsidence (setting or slumping) of land, (iv) geothermal fluid also brings with it the dissolved gases and solute (as high as 25 kg/m^3) which leads to air and land pollution, (v) drilling operation leads to noise pollution, (vi) the available thermal energy cannot be distributed easily over long distances (longer than ~30 km) and (vii) corrosive and abrasive geothermal fluid reduces the life of the plant.

9.2 APPLICATIONS

Geothermal energy is useful for a number of applications, although restricted to specific geographical area.

1. Direct Heat Use

Geothermal resources have a great range of temperatures and local peculiarities. In general, although abundant energy is accessible, its thermodynamic quality is low. The source share many similarities with industrial waste heat. The low and moderate temperature hydrothermal fluids can be used as direct heat source for space and water heating, for industrial processes such as drying applications in food, chemical and textile industries, crop drying, washing, for warming fish ponds in aquaculture and for agricultural applications such as soil and space heating of glasshouses. As heat cannot be distributed easily over distances greater than ~30 km concentrated uses near the point of supply are needed. In cold climate it can be used for space heating and hot water supply for public institutions, business district heating for group of buildings. Thus a 100 MW_t plant might serve an urban area of about 20 km × 20 km. Such geothermal schemes have long been established in Iceland and on smaller scale, in New Zealand. About 80 per cent of population of Iceland use geothermal space heating. More than 9000 thermal wells and springs are now in use. These applications are saving the energy equivalent of almost 2 million barrels of oil per year.

2. Electric Power Generation

If temperatures are high enough (> 90 °C), the preferred use of geothermal resource is the generation of electricity, which would either be fed into the utility grid or be used to power the industrial processes on site. It is normally used for base load power generation. The reason is related with the difficulty of control for peak load and with the scaling/corrosion problems, which would occur, if the various vessels and turbines are not kept full of fluid and air is allowed into them. However, this does not apply to dry steam fields. Several important electric power plants are fully established, especially in Italy, New Zealand and the USA. Electricity was first generated from naturally occurring geothermal steam at Larderello, Italy, in 1904. This was followed by commercial plants at Wairakei field in New Zealand in 1958 and “The Geysers” in California in 1960. Electric power is now being produced in several other countries, including Iceland, Japan, the Philippines, Mexico and Russia. The geothermal power installed capacities for electric power production and direct thermal energy use in some countries of the world are listed in Table 9.1.

Table 9.1 Geothermal energy: Electricity generation and direct use at end-2011 [9]

Country	Electricity generation installed capacity (MW$_e$)	Direct use installed capacity (MW$_t$)
Albania	8,123	2.0
Argentina	30	149.9
Australia	1.1	129
Austria	0.9	662
Brazil		360
Bulgaria		98.3
Canada	0.0	1,045
Chile	0.0	9.1
China	24.2	8,898
Costa Rica	166.0	
Croatia		114
Czech Republic	0.0	4.5
Denmark		200
Ecuador		5
El Salvador	2.4	
Ethiopia	7.3	
France	18.3	1,345
Germany	7.3	3,485.4
Greece	0.0	134.6
Guatemala	52	2.3
Hong Kong	24	
Hungary	0.0	654.6
Iceland	665	2,002.9
Indonesia	1,197	
Israel		23.4
Italy	772	1,000
Japan	537.7	2,099.5
Kenya	169	16
Korea (Republic)		105.4
Lithuania		48.1
Mexico	886.6	155.8
Netherlands	0.0	1,410.3
New Zealand	792	393
Nicaragua	82	

(*contd.*)

Table 9.1 (*Contd*)

Norway		1,000
Philippines	1,904	3.3
Poland	0.0	281
Portugal	30	28.1
Romania	0.0	173.6
Russian Federation	82	308.2
Serbia		119
Slovakia		132.2
Spain	0.0	120
Sweden		4,460
Switzerland	0.0	1,060.6
Thailand	0.3	2.5
Turkey	1,14.2	2,080
United Kingdom	0.0	186.6
United States of America	3,101.6	12,611.5
TOTAL WORLD	11,490	50,000

9.3 ORIGIN AND DISTRIBUTION OF GEOTHERMAL ENERGY

Geothermal energy is the heat that originates from the *core* of the earth, where temperatures are about 4000 °C. The heat occurs from a combination of two sources: (i) the original heat produced from the formation of the earth by gravitational collapse and (ii) the heat produced by the radioactive decay of various isotopes. As the thermal conductivity of the rock is very low, it is taking many billions of years for the earth to cool. Average geothermal heat dissipation from land and ocean surface is about 0.06 W/m^2, which is negligible as compared to power dissipation due to other sources e.g. solar energy (~ 1 kW/m^2). The core is surrounded by a region, known as *mantle*, which consists of semi-fluid material called the *magma*. The mantle is finally covered by the outermost layer known as *crust*, which has average thickness of about 30 km. The temperature in the crust increases with depth at a rate of 30 °C/km. The temperature at the base of crust is about 1000 °C and then increases slowly into the core of the earth. A section through the earth is shown in Fig. 9.1.

Though the general distribution of layers is as shown in the Fig. 9.1, at certain locations anomalies exist in composition and structure of these layers. There are regions in which hot molten rock (magma) of the mantle has pushed up through faults and cracks towards the surface. In an active volcano, the magma actually reaches the surface, but more often "hot spots" occur at moderate depths (within 2 to 3 km), where the heat of the magma is being conducted upward through an overlaying rock layer. In fact, the zone of likely geothermal sites corresponds roughly to the regions of seismic and volcanic activities. High enthalpy geothermal fields occur within well-defined belts of geologic activity.

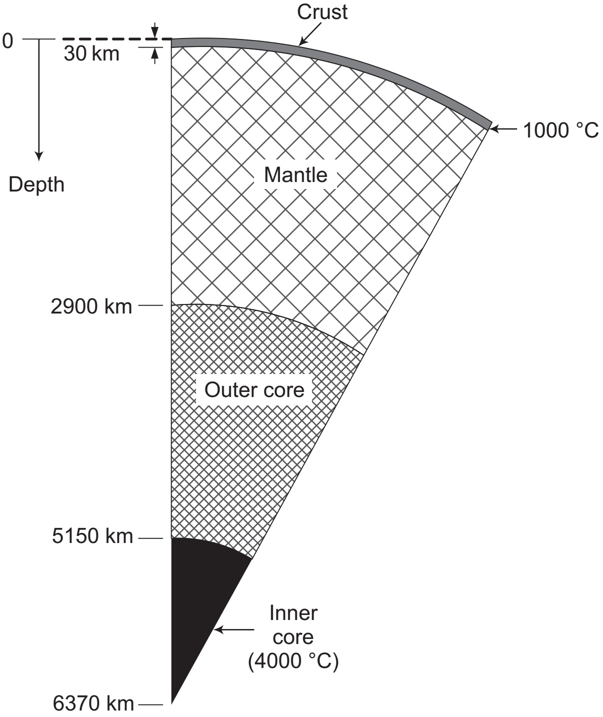


Figure 9.1 Cross section of the earth

The earth's crust consists of tectonic or crustal plates (six major plates and a number of smaller ones) as shown in Fig. 9.2. The geothermal belts are associated with the junctions of major tectonic plates, and are located mainly in the regions of recent volcanic activity or where a thinning of earth's crust has taken place. These plates are in a state of constant relative motion (several centimeters per year). Where they collide or grind, there are very strong forces that can cause earthquakes. It is near the junction of these plates that heat travels most rapidly from the interior via subsurface magma to surface volcanoes. Geothermal energy potential of these regions is great; owing to increased temperature gradients of about 100 °C/km. Moderate increase in temperature gradient to about 50 °C/km occur in localized regions away from plate boundaries, owing to anomalies in crust composition and structure.

Most of the world's geothermal sites today are located near the edges of Pacific plate, the so-called "ring of fire", shown in Fig. 9.2. This belt rings the entire Pacific Ocean, including, New Zealand, Indonesia, Japan, Philippine, Kamchatka, Western North America, Central America, Peru, Chile, Ecuador, and Argentina. An extension also penetrates across Asia into Mediterranean area. Hot crustal material also occurs at mid ocean ridges (e.g. Iceland and the Azores) and interior continental rifts (e.g. the east African rift, Kenya, and Ethiopia). Low enthalpy resources are more abundant and more widely distributed. They are located in many deep sedimentary basins of the world, e.g. certain areas of central and southern Europe, Western Siberia, Western Canada, Gulf Coast of United States as well as the fringe of high enthalpy resources.

As mentioned above, at certain places the tectonic activity or the anomalies in crust composition allow hot or molten rock to approach the earth surface, creating pockets of higher temperature resources at accessible depths. The extraction and practical utilization of this heat requires technology, which depends on the nature of resource.

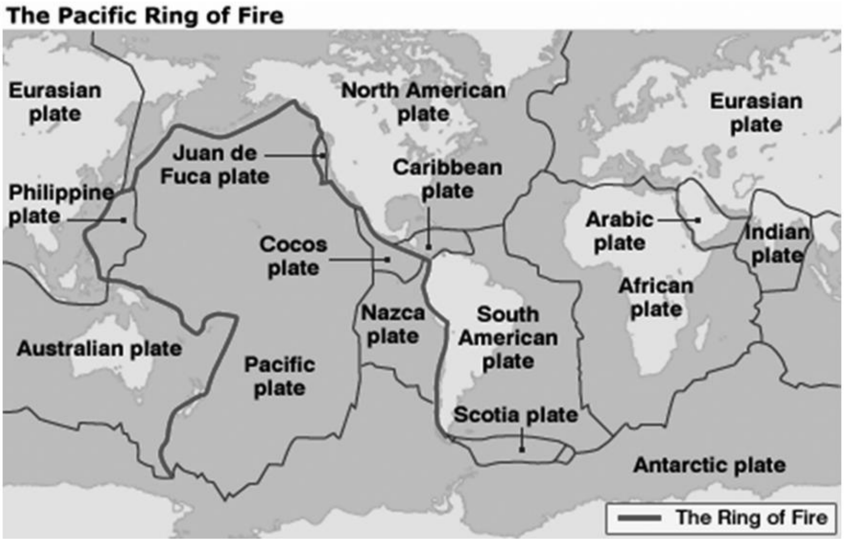


Figure 9.2 Region of seismic and volcanic activities (thick line) and tectonic plate boundaries

9.4 TYPES OF GEOTHERMAL RESOURCES

There are four types of geothermal resources: (i) hydrothermal, (ii) geo-pressured, (iii) hot dry rock (HDR) and (iv) magma. At present the technology for economic recovery of energy is available for hydrothermal resource only. Thus this is the only commercially used resource at present. Other resources are going through development phase and have not become commercial so far.

9.4.1 Hydrothermal Resources

Hydrothermal resources arise when underground water has access to high temperature porous rocks, capped by a layer of solid impervious rock. Thus water is trapped in the underground reservoir (aquifers) and is heated by surrounding rocks. Heat is supplied by magma by upward conduction through solid rocks below the reservoir. Thus it forms a giant underground boiler. Under high pressure, the temperature can reach as high as 350 °C. The hot water often escapes through fissures in the rock, thus forming hot springs or *geysers*. Sometimes steam escapes through cracks in the surface. These are called *fumaroles*. In order to utilize the hydrothermal energy, wells are drilled either to intercept a fissure or, more commonly into the hydrothermal reservoir as shown in Fig. 9.3.

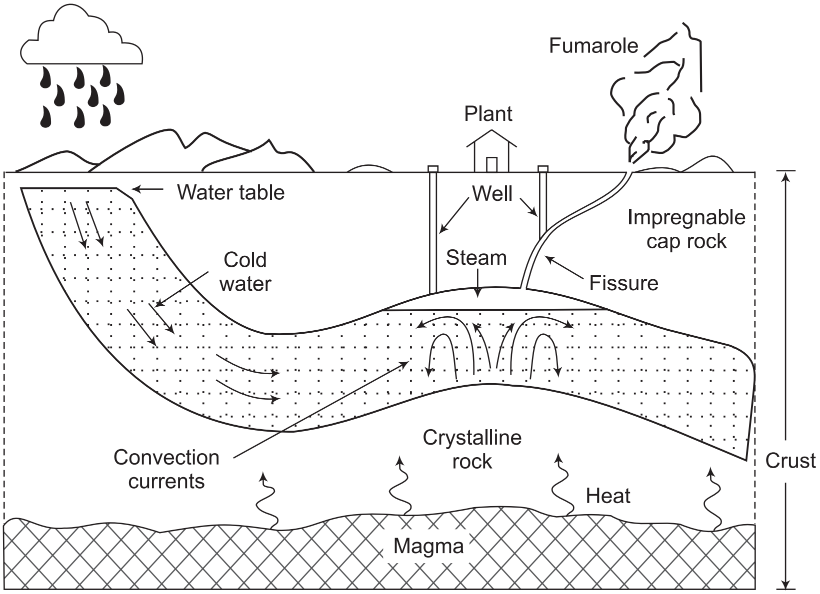


Figure 9.3 General simplified structure of hydrothermal resource

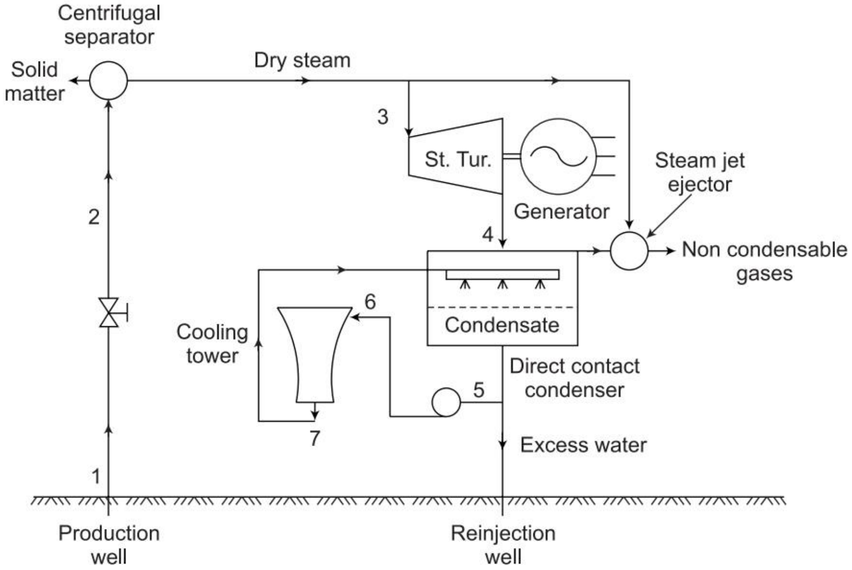
The hydrothermal resources are located at shallow to moderate depths (from approximately 100 m to 4,500 m). Temperatures for hydrothermal reserves used for electricity generation range from 90 °C to 350 °C but roughly two-thirds are estimated to be in the moderate temperature range (150 °C to 200 °C).

For practical purposes, hydrothermal resources are further subdivided into (i) vapour dominated (dry steam fields), (ii) liquid dominated (wet steam fields) and (iii) hot water resource. Vapour dominated fields deliver steam with little or no water and liquid dominated fields produce mixture of steam and hot water or hot water only. The system to utilize the energy depends on the type of resource.

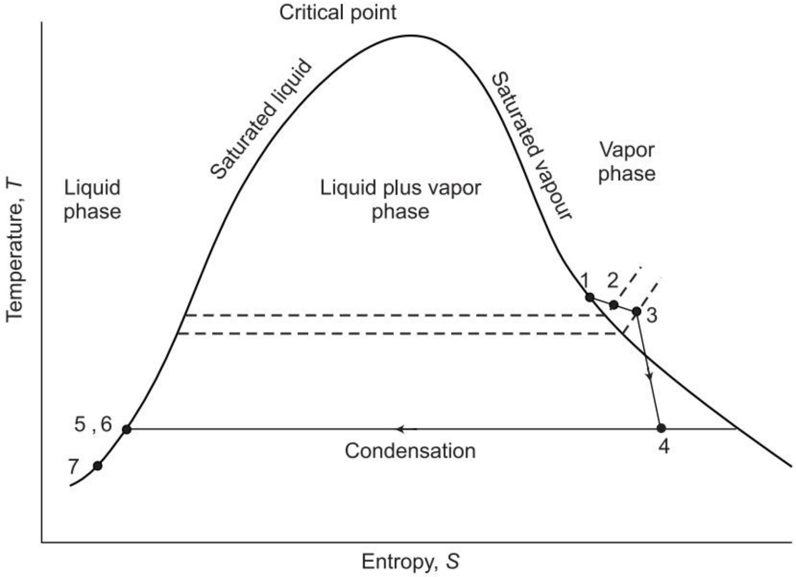
1. Vapour Dominated (Dry Steam) System

Dry steam fields occur when the pressure is not much above the atmospheric pressure and the temperature is high. Water boils underground and generates steam. The most important known dry steam fields are: (a) "The geysers" regions in California, which may be the largest, (b) the Larderello and some smaller areas in Italy and (c) a small field (or fields) at Matsukawa, Japan. Dry steam field at Larderello is especially ideal because its wells produce virtually pure steam with no water.

The layout of vapour-dominated system is shown in Fig. 9.4(a). The operation is explained with the help of T-S diagram given in Fig. 9.4(b). The steam is extracted from the well (1) where it is nearly saturated. The extracted steam is then cleaned in centrifugal separator to remove solid matter. While passing through the well, as well as centrifugal separator the pressure drops, which causes it to slightly super heat. The steam is then supplied to a turbine (3) at temperature of about 165 °C and pressure of about 7.8 atm. (the temperature and pressure in the reservoir are higher) and allowed to expand (4). The exhaust steam of turbine is condensed in direct contact condenser, in which the steam is condensed by direct contact with cooling water. The resulting warm water (5) is circulated and cooled in cooling tower and returned to the condenser (7). The condensation of steam continuously increases the volume of cooling water. Excess water is reinjected at some distance deep into the ground for disposal. The non-condensable gases are removed from the condenser by steam jet ejection.



(a) Layout diagram of vapor dominated system



(b) T–S diagram of vapor dominated system

Figure 9.4 Dry steam hydrothermal system

Major differences as compared to conventional thermal (steam) plants are as follows:

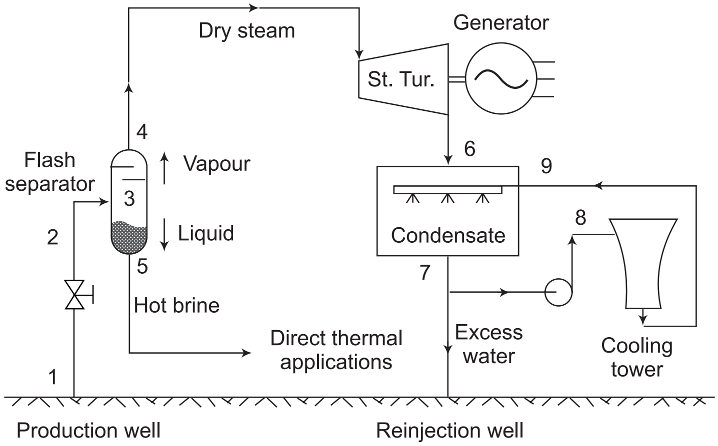
- The temperature and pressure in such plants are much less (about 165 °C and about 7.8 atm) compared to that in conventional thermal plants (where these are about 540 °C and about 160 atm). As a result, the efficiency of this plant is much less; about 15 per cent, compared to 35–40 per cent in case of conventional thermal plants.
- In conventional thermal plants, surface-cooling condenser is used as the condensed steam is to be used as boiler feed water and therefore condensate and cooling water are not allowed to mix. Whereas, in hydrothermal systems, steam is continuously supplied by the resource, which allows more simple and efficient direct contact condensing.
- Hydrothermal systems produce their own cooling water whereas in conventional thermal plants, make up cooling water is required from an external source.
- In case of conventional thermal plants, the steam is not mixed with non-condensable gases. Whereas in hydrothermal system non-condensable gases are also present in the steam. These non-condensable gases need to be removed from the condenser.

2. Liquid Dominated (Wet Steam) System

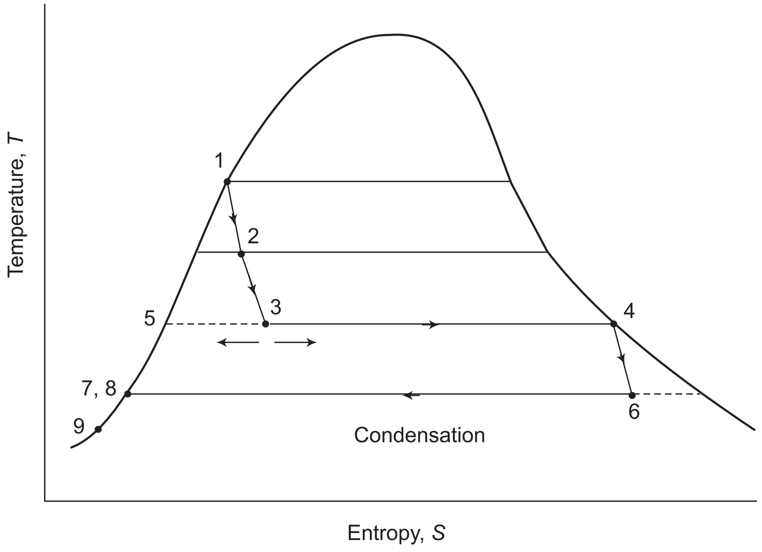
Steam plants are the most cost effective technology, when the resource temperature is above about 175 °C. Therefore, liquid dominated or wet steam fields may further be subdivided into (a) high temperature (above 175 °C), where steam plants can be used and (b) low temperature (below 175 °C) fields where other technologies are used.

(a) Liquid Dominated – High Temperature System In high temperature liquid dominated reservoir, water temperature is above 175 °C; however, it is under high pressure and remains in liquid state. The most extensive development has been in the volcanic Wairakei field in New Zealand, the first of its kind, was built in 1958. In this field the reservoir temperature and pressures are 230 °C and 40 atm respectively and depths are 600 m to 1400 m.

When water is brought to the surface and pressure is reduced, rapid boiling occurs and it “flashes” into steam and hot water. The operation of single flash system is illustrated in Fig. 9.5. The hot water from the well (1) is brought to well head (2) at a lower pressure. Process 1–2 is essentially a constant enthalpy throttling process that results in a two-phase mixture of low quality at 2. This is throttles further in a flash separator (3) to get a two-phase mixture of slightly higher quality. This mixture is now separated into dry saturated steam at 4 and saturated brine at 5. The highly saline hot water (known as brine) can be used for direct heat and then reinjected into the ground. The separated steam at 4 is expanded in a turbine to 6. The maximum initial steam temperature is about 175 °C and the gauge pressure is 3.5 atm. The exhaust steam at 6 is mixed with cooling water in a direct contact condenser and the resulting mixture at 7 is directed to a cooling tower.



(a) Layout diagram

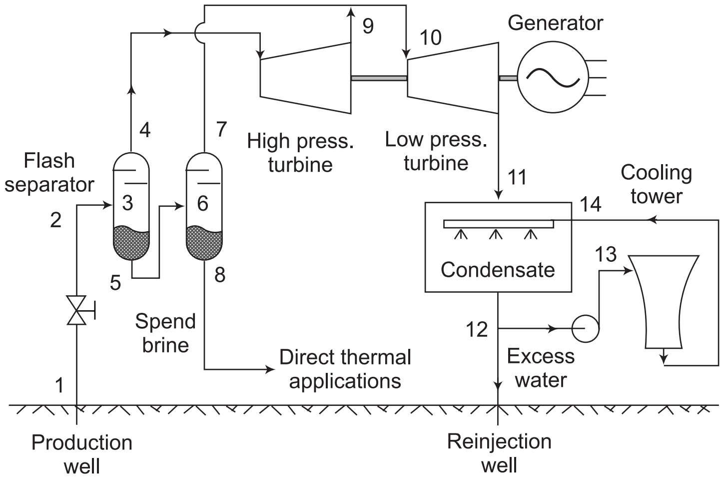


(b) *T–S* diagram

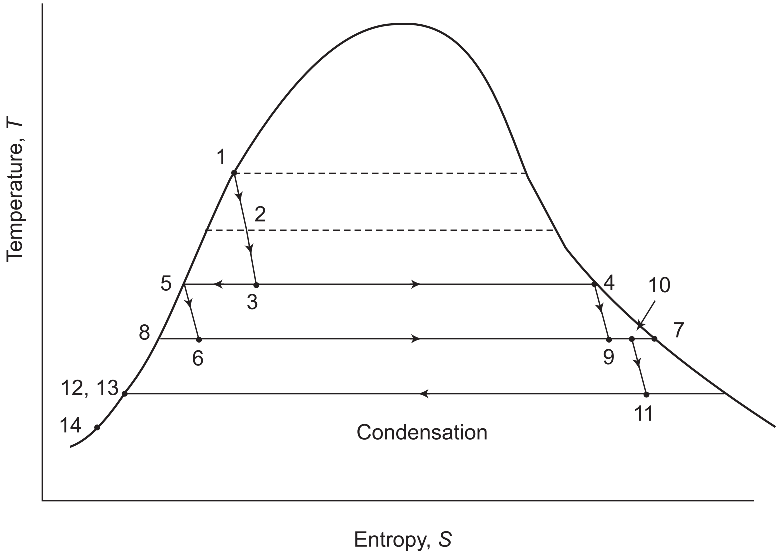
Figure 9.5 Single flash, wet steam high temperature hydrothermal system

In dual flash systems, the steam is flashed a second time from the remaining hot fluid of the first stage, separated and fed into duel inlet turbine or into two separate turbines. The efficiency of such a plant is around 8 per cent. The layout of double flashed systems along with T-S diagrams is shown in Fig. 9.6. The 50 MW_e Hatchobane plant, Kyushu in Japan is a double flash system.

As of 2013, the largest liquid system is Cerro Prieto in Mexico, which generates 750 MWe from temperatures reaching 350 °C (662 °F). The Salton Sea field in Southern California offers the potential of generating 2000 MWe. Such systems are also being implemented in Philippines and other places.



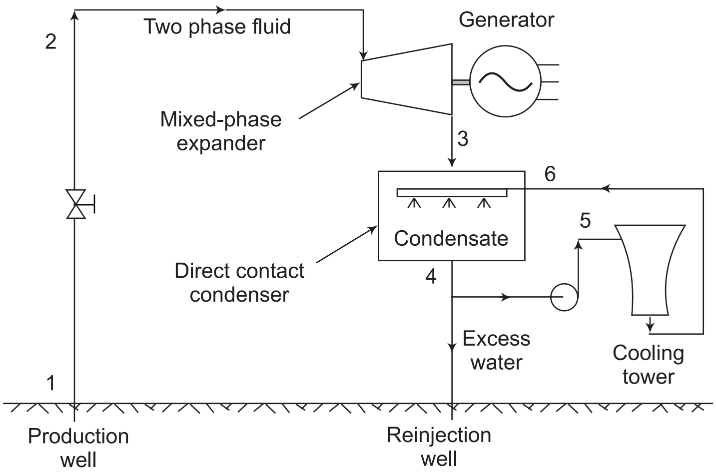
(a) Layout diagram



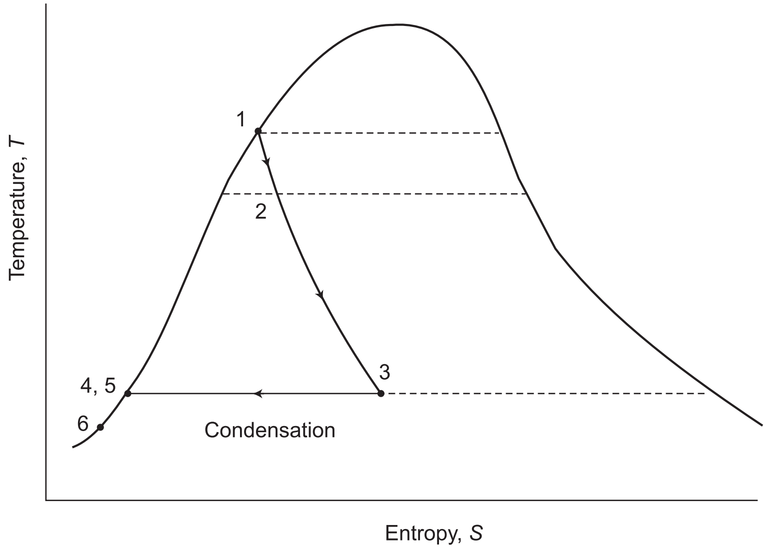
(b) *T–S* diagram

Figure 9.6 Double flash, wet steam high temperature hydrothermal system

A third approach is called **Total Flow Concept**, in which a special mixed phase turbine is used that would utilize both the kinetic energy as well as heat energy of the two-phase (steam–liquid) mixture produced by flashing the geothermal brine. The overall efficiency in such a system should be greater than other methods where only heat content of the brine is utilized. A layout and corresponding T-S diagram of total flow power plant is given in Fig. 9.7. The hot fluid from geothermal well (1) is throttled to get a two-phase mixture of low quality at 2. At this point the two phases are not separated, and the total flow is piped to turbine and allowed to expand to 3. The discharge is condensed to 4 in direct contact condenser. The excess brine is reinjected to ground.



(a) Layout diagram



(b) *T–S* diagram

Figure 9.7 Liquid dominated total flow concept

(b) Liquid Dominated – Low Temperature System These resources are available at moderate temperature range of 90 °C – 175 °C. They are common in extensional terrains, where heating takes place via deep circulation along faults, such as in the

Western US and Turkey. This temperature is not enough for efficient flash steam production and requires pumping. A binary-fluid system is employed, where the heat of geothermal fluid is used to vapourize a volatile organic fluid, such as isobutene (B.P. 10 °C), under pressure in a primary heat exchanger. The geothermal fluid is reinjected after extraction of heat. This vapourized fluid serves as working fluid in a Rankine cycle plant. The exhaust vapour from the turbine is cooled in the regenerative heat exchanger and then condensed in a condenser. The condensed liquid isobutene is returned to primary heat exchanger by way of the regenerative heat exchanger. These binary plants originated in the Soviet Union in late 1960s and predominate in new US plants. The layout of the system is shown in Fig. 9.8. Binary plants have no emissions. The thermal efficiency of such a plant is typically about 10–13 per cent. These plants do not produce any steam condensate and have to rely on external source of cooling water or air-cooling.

Such plants are in use at East Mesa, Mammoth Lake in California and other places in USA, Kawerau, New Zealand and many other places in the world. Presently some 1790 MWe binary power plants are in operation worldwide [52].

Main advantages of binary systems are: (i) they almost avoid corrosion, scaling and environmental problems as the geothermal fluid circulates through a closed-cycle and all the fluid is reinjected and (ii) in many cases, they are capable of higher conversion efficiencies than flash steam plants.

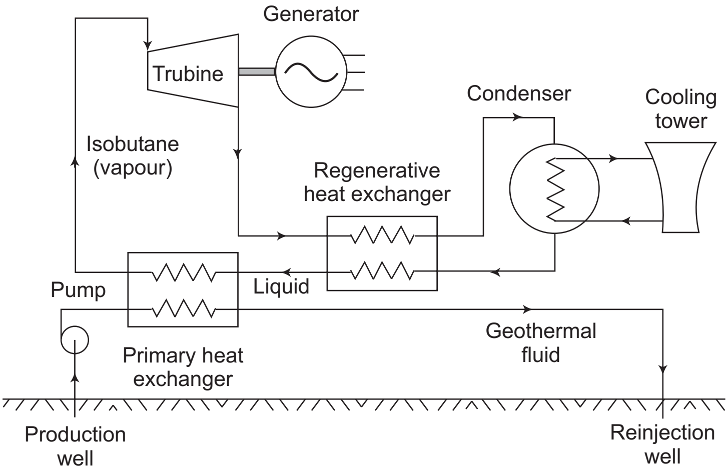


Figure 9.8 Binary fluid hydrothermal system

3. Hot Water System

Hydrothermal reservoirs of low to moderate temperatures (20 °C–150 °C) can be used to provide direct heat for residential and industrial uses. The hot water is brought to the surface where a heat exchanger system transfers its heat to another fluid (liquid or air); although the resource can be used directly if the salt and solid content is low. The geothermal fluid is reinjected into the ground after extraction of heat. The heated fluid transports heat to the place of use. Recent surveys have identified a large potential for direct use geothermal applications. Iceland is the world leader in direct applications. Some 92.5 per cent of its homes are heated with geothermal energy, saving Iceland over $100 million annually in avoided oil imports. Reykjavík, Iceland has the world's biggest district heating system. Once known as the most polluted city in the world, it is now one of the cleanest.

Energy of hot water resource can also be utilized in a hybrid system consisting of geothermal–conventional thermal (fossil fuel or biomass based) system. In this system, hot water resource is used to preheat feed water and / or air for combustion. Geothermal heat replaces some or all of the feed water heaters, depending upon its temperature. A 30 MWe geothermal-wood waste hybrid plant is in operation at Honey Lake, California since 1989.

9.4.2 Geo-pressured Resources

While drilling for oil and gas, hot salty water (brine) reservoirs, at moderately high temperature, (90 °C to 200 °C), and under great pressure are found at a depth of 3 to 6 km. Because of the very high pressure of the water, up to 1350 atm in the deepest layer, these reservoirs are referred to as geo-pressured. A special feature of geo-pressured water is that it also contains a significant amount of dissolved methane gas, usually 1.9 – 3.8 m^3 per m^3 of water. The solubility of methane in water at normal pressure is quite low, but it increases with pressure. When the water is brought to the surface and its pressure reduced, the methane gas is released from the solution. Thus methane can be extracted from brine by simple and economical gravity separation technique. This resource is potentially very promising because three types of energy can be extracted from the wells: (i) thermal energy from the heated fluids, (ii) mechanical (hydraulic) energy from the high pressures involved and (iii) chemical energy from burning of methane gas.

The extent of geo-pressured reserves is not yet well known worldwide, and the only major resource area identified to date is along the Texas and Louisiana coast of the Gulf of Mexico. The belt is about 1200 km in length along the coast and extends up to about 160 km inland and 240 km offshore. The potential of geo-pressured resource of this area has been estimated as 23 to 240 GWe for 30 years. Experimental wells are already in place in Texas and Louisiana. A hybrid geo-pressured conversion unit (1 MWe) was successfully operated in 1990 as a demonstration unit. Studies are underway to identify reservoirs with sufficient volume and permeability to sustain large water flows over long time periods and the extent of dissolved methane gas.

9.4.3 Hot Dry Rock Resources

There are regions underground at temperatures exceeding 200 °C, with little or no water. The rocks are impermeable and/or there is no surface water in the vicinity. Such resources up to a depth of 5 km are estimated to be significant and worthy of development as a source of energy. Hot dry rocks are much more common than hydrothermal reservoirs and more accessible, so their potential is quite high.

The recovery of heat from HDR involves forming a man-made reservoir by drilling deep into the hot rocks and then cracking it to form cavity or fractures. Such a system is known as "Enhanced Geothermal Systems" (EGS), also sometimes called engineered geothermal systems. This can be achieved by (i) detonating high explosive at the bottom of the well, (ii) nuclear explosion or (iii) hydraulic fracturing. Hydraulic fracturing, which is performed by pumping of water at high pressure into the rock formation, is commonly used in oil and gas fields to improve the flow. It appears that the quantity of conventional explosives required would be uneconomically large, nuclear explosives are associated with environmental and safety issues and therefore hydraulic fracturing seems to be more promising.

To recover heat, water is pumped into the cracks from the surface, and withdrawn by another well at a distance. Injection and production wells are joined to form a circulating loop through this man-made reservoir to achieve a steady flow of high temperature water (or water–steam mixture). Electricity can be generated by binary fluid system as shown in Fig. 9.9. When heat is extracted, the rock cools down and new cracks are developed due to temperature gradient. Thus the resource keeps on expanding. The technique was tested at a location near Valles Caldera, USA, where fractures were made at a depth of about 2.76 km. The temperature at the location was 185 °C. Freon (R-114) was used as working fluid for turbine in a binary system. Only 5 per cent of the water introduced was lost in the ground and small proportion of makeup water was required. The largest EGS project in the world is a 25 MW_e demonstration plant currently (year 2015) being developed in the Cooper Basin, Australia – with the potential to generate 5,000–10,000 MW

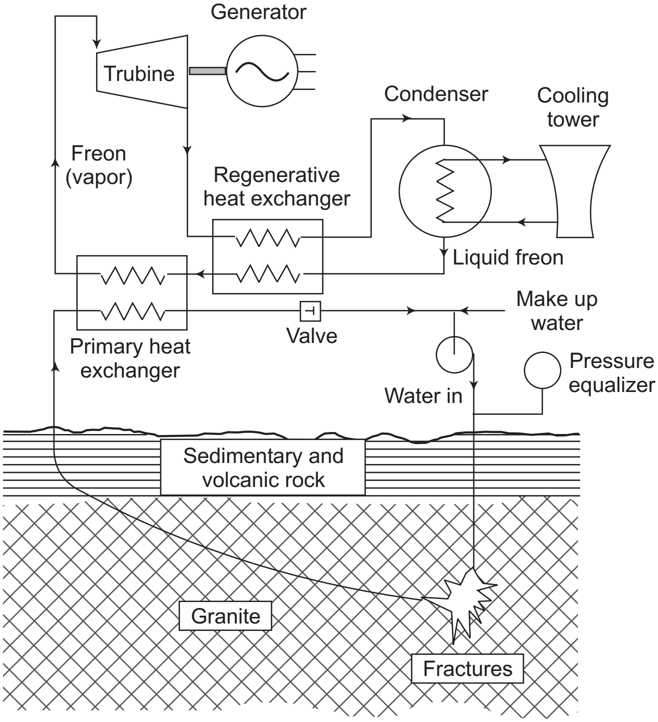


Figure 9.9 Hot dry rock binary fluid system

9.4.4 Magma Resources

At some places, molten or partially molten rock (magma chamber), at temperatures 650 °C to 1,200 °C, occurs at depths 5 km – 10 km. These resources are located, especially in the vicinity of recent volcanic activity (e.g. Hawaii). Very high temperature and large volume make magma a huge potential energy source, the largest of all geothermal resources. However, successful magma drilling technology has not been established yet. Extracting magma energy is expected to be the most difficult of all resource types. Magma technology will require special drilling technology to deal with the interaction of the drill bit with molten rock, the effects of dissolved gases, and mechanisms of heat transport in molten magma. This resource has not been developed as yet.

9.5 ANALYSIS OF GEOTHERMAL RESOURCES

9.5.1 Hot Dry Rock Resource

1. Energy Content

Let us consider a large mass of dry, uniform material (rock) extending from near the earth's surface to deep inside the crust, as shown in Fig. 9.10. As there is no convection and the material is uniform, the temperature, T at any point will increase linearly with depth, h. Thus:

$$T = T_o + \frac{dT}{dh}h = T_o + Gh \tag{9.1}$$

where G is temperature gradient
T_o is surface temperature

Let minimum useful temperature, T_1 occurs at depth h_1 and increases onwards reaching T_2 at maximum depth h_2:

$$T_1 = T_o + Gh_1 \tag{9.2}$$

$$T_2 = T_o + Gh_2 \tag{9.3}$$

$$T_2 - T_1 = T_o + G(h_2 - h_1) \tag{9.4}$$

Average useful temperature of hot dry rock, θ_o:

$$\theta_o = (T_2 - T_1)/2 = G\,(h_2 - h_1)/2 \tag{9.5}$$

Total useful heat (energy) content of the rock to depth h_2

$$E_o = C_r\,\theta_o \tag{9.6}$$

where C_r is the thermal capacity of the rock between depth h_1 and h_2 and may be written as:

$C_r = \rho_r A c_r\,(h_2 - h_1)$, in terms of specific heat capacity, c_r, density, ρ_r area 'A' of the rock.

Therefore, total useful energy of the rock:

$$E_o = \rho_r\,A\,c_r\,G\,(h_2 - h_1)^2/2 \tag{9.7}$$

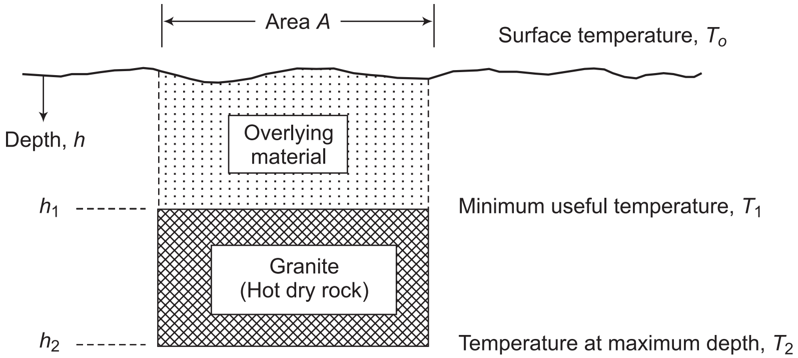


Figure 9.10 Profile of hot dry rock system for calculating the heat content

2. Energy Extraction

Now assume that heat is being extracted uniformly in proportion to the temperature excess over T_1 by circulating water. With heat extraction, the average useful temperature, θ of the hot dry rock starts decreasing from initial value θ_o. The volume flow rate of water is Q and the density and specific heat capacity of water are ρ_w and c_w respectively. The water will be heated in the near perfect heat exchanger through average temperature difference of θ. The rate of energy extraction is given by:

$$Q\,\rho_w\,c_w\,\theta = -C_r\frac{d\theta}{dt} \tag{9.8}$$

$$\frac{d\theta}{\theta} = -\frac{Q\rho_w c_w}{C_r}dt = -\frac{dt}{\tau} \tag{9.9}$$

where the time constant τ is given by:

$$\tau = \frac{C_r}{Q\,\rho_w\,c_w} = \frac{\rho_r\,A\,c_r\,(h_2 - h_1)}{Q\,\rho_w\,c_w} \tag{9.10}$$

The solution of differential Eq. (9.9) may be written as:

$$\theta = \theta_o\,e^{-t/\tau} \tag{9.11}$$

The useful heat (energy) content at average useful temperature, θ of hot dry rock:

$$E = C_r\theta = C_r\,\theta_o\,e^{-t/\tau}$$

$$E = E_o\;e^{-t/\tau} \tag{9.12}$$

and the rate of decrease of thermal energy content:

$$\left|\frac{dE}{dt}\right| = \frac{E_o}{\tau}e^{-t/\tau} \tag{9.13}$$

9.5.2 Hydrothermal Resource (Hot Aquifer)

1. Energy Content

In a hot aquifer resource, thermal energy is available in a layer of hot water, deep beneath the ground level, as shown in Fig. 9.11. Let us assume that the thickness, w of aquifer is much less than the depth, h_2 below ground level and that consequently, the whole water is at temperature T_2. The porosity, p is the fraction of aquifer filled with water. The remaining space is rock of density ρ_r. Assuming the overlying material to be uniform, the temperature, T will increase linearly with depth, h. Thus:

$$T = T_o + \frac{dT}{dh} h = T_o + Gh \tag{9.14}$$

where G is temperature gradient and
T_o is surface temperature

The temperature of aquifer, which is located at depth h_2:

$$T_2 = T_o + \frac{dT}{dh} h_2 = T_o + Gh_2 \tag{9.15}$$

Assuming T_1 as minimum useful temperature, the thermal energy content of aquifer is given as:

$$E_o = C_a(T_2 - T_1) = C_a\theta_0 \tag{9.16}$$

where C_a is thermal capacity of hot aquifer and may be written as:

$$C_a = \{p\, \rho_w\, c_w + (1 - p)\, \rho_r c_r\}\, Aw \tag{9.17}$$

Therefore,

$$E_o = \{p\, \rho_w\, c_w + (1 - p)\rho_r\, c_r\}Aw\theta_0 \tag{9.18}$$

Thermal energy content per unit area of aquifer,

$$E_o/A = \{p\, \rho_w\, c_w + (1 - p)\, \rho_r\, c_r\}\, w\theta_0 \tag{9.19}$$

2. Energy Extraction

Heat is removed by extracting water at a flow rate of Q at temperature θ above T_1 in the near perfect heat exchanger. Therefore,

$$Q\, \rho_w\, c_w\, \theta = -C_a \frac{d\theta}{dt}$$

$$\frac{d\theta}{\theta} = -\frac{Q\rho_w c_w}{C_a} dt = \frac{(Q/A)\rho_w c_w}{\left[p\rho_w c_w + (1-p)\rho_r c_r\right]w} dt = -\frac{dt}{\tau} \tag{9.20}$$

where the time constant τ is given by:

$$\tau = \frac{\{p\rho_w c_w + (1-p)\rho_r c_r\}\, w}{(Q/A)\rho_w c_w} \tag{9.21}$$

The solution of differential Eq. (9.20) may be written as:

$$\theta = \theta_o\, e^{-t/\tau} \tag{9.22}$$

The useful heat (energy) content of hot aquifer at temperature, T:

$$E = C_a\theta = C_a\,\theta_o\,e^{-t/\tau}$$

$$E = E_o e^{-t/\tau} \tag{9.23}$$

and the rate of decrease of thermal energy content:

$$\left|\frac{dE}{dt}\right| = \frac{E_o}{\tau}e^{-t/\tau} \tag{9.24}$$

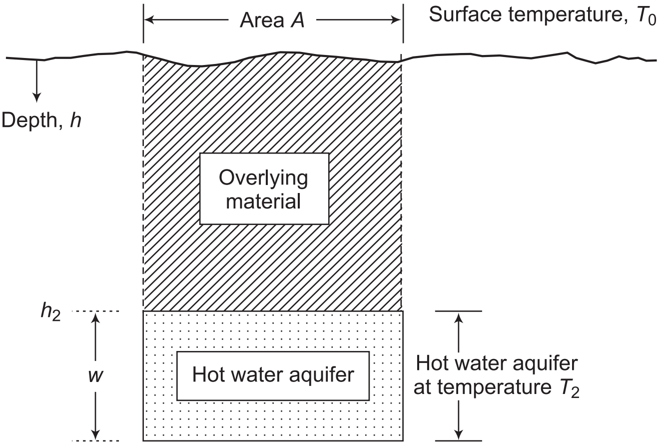


Figure 9.11 Profile of hot aquifer system for calculating the heat content

Example 9.1

A hot dry rock (HDR) resource has a geothermal temperature gradient at 39 K km^{-1}. The minimum useful temperature is 120 K above the surface temperature T_o. Water at flow rate of 0.5 m^3 s^{-1} km^{-2} is used for heat extraction. The density and specific heat capacity for water may be assumed as 1000 kg m^{-3} and 4200 J kg^{-1} K^{-1} respectively. Calculate,

(i) The heat content per square kilometer of HDR to a depth of 10 km, assuming $\rho_r = 2700$ kg m^{-3} and $c_r = 820$ J kg^{-1} K^{-1}.

(ii) Useful average temperature, initially and after 25 years

(iii) Useful heat extraction rate per km^2, initially and after 25 years

Solution

(i) From Eq. (9.3),

$$T_2 = T_o + Gh_2$$

$$T_2 = T_o + 39 \times 10 = T_o + 390$$

From Eq. (9.2),

$$T_1 = T_o + Gh_1$$

$$T_1 - T_o = Gh_1,\ 120 = 39 \times h_1$$

$$h_1 = 3.077 \text{ km},$$

Therefore,

$$h_2 - h_1 = 10 - 3.077 = 6.923 \text{ km}$$

Now, from Eq. (9.7),

$$E_o/A = \rho_r\, cr\, G(h_2 - h_1)^2/2$$
$$= (2700\,\text{kg}\,\text{m}^{-3}) \times (820\,\text{J}\,\text{kg}^{-1}\text{K}^{-1}) \times (39\,\text{K}\,\text{km}^{-1}) \times (1/2) \times (6.923\,\text{km})^2$$
$$= 2.069 \times 10^{18} \text{ J km}^{-2}$$

Heat content per square kilometer = 2.069×10^{18} J km^{-2}

(ii) Initial average useful temperature, θ_o from Eq. (9.5):

$$\theta_o = (T_2 - T_1)/2 = G(h_2 - h_1)/2$$
$$= 39 \times 6.923/2 = 134.99 \text{ K}$$

The time constant may be calculated from Eq. (9.10):

$$\tau = \frac{\rho_r A c_r (h_2 - h_1)}{Q \rho_w c_w} = \frac{\rho_r c_r (h_2 - h_1)}{(Q/A) \rho_w c_w}$$

$$\tau = \frac{(2700 \text{ kg m}^{-3}) \times (820 \text{ J kg}^{-1} \text{ K}^{-1}) \times (6.923 \text{ km})}{(0.5 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}) \times (1000 \text{ kg m}^{-3}) \times (4200 \text{ J kg}^{-1} \text{ k}^{-1})}$$

$$= 7.298 \times 10^9 \text{ s}$$

$$\tau = 231.4 \text{ years}$$

Average useful temperature, θ after 25 years may be calculated from Eq. (9.11):

$$\theta = \theta_o e^{-t/\tau}$$

$$\theta = (134.99 \text{ K}) \times e^{-(25/231.4)}$$

$$\theta = 121 \text{ K}$$

(iii) Heat extraction rate may be calculated from Eq. (9.13):

$$\left|\frac{dE}{dt}\right| = \frac{E_o}{\tau} e^{-t/\tau}$$

Initial heat extraction rate per unit area, ($t = 0$):

$$= \frac{E_o/A}{\tau} = \frac{2.069 \times 10^{18} \text{ J km}^{-2}}{231.4 \text{ years}} = 8.94 \times 10^{15} \text{ MW km}^{-2}$$

Heat extraction rate per unit area after 25 years, ($t = 25$ years):

$$= 8.94 \times 10^{15} \times e^{-(25/231.4)}$$
$$= 8.02 \times 10^{15} \text{ MW km}^{-2}$$

Example 9.2

A 0.6 km thick hot aquifer is located at a depth of 2.5 km and has a porosity of 5 per cent. The density of the under sediments is 3000 kg m^{-3} and its specific heat is 750 J kg^{-1} k^{-1}. The temperature gradient in the overlying material is 35 °C km^{-1}. Assuming the density and specific heat of water as 1000 kg m^{-3} and 4200 J kg^{-1} k^{-1} respectively, Find the:

(i) heat content per square kilometer above 45 °C and the initial temperature of the aquifer, if the average surface temperature is 12 °C

(ii) time constant for useful heat generation with pumped water extraction at a rate of 0.75 $m^3\ s^{-1}\ km^{-2}$

(iii) thermal power extractable per square kilometer initially and after 25 years.

Solution

Given: w = 0.6 km, h_2 = 2.5 km, p = 0.05, ρ_r = 3000 kg m^{-3}, c_r = 750 J $kg^{-1}\ k^{-1}$, ρ_w = 1000 kg m^{-3}, c_w = 4200 J $kg^{-1}\ k^{-1}$, G = 35 °C km^{-1}, T_1 = 45 °C, T_o = 12 °C, Q/A = 0.75 $m^3\ s^{-1}\ km^{-2}$

(i) From Eq. (9.15), initial temperature of the aquifer,

$$T_2 = T_o + Gh_2$$

$$T_2 = 12 + 35 \times 2.5 = 99.5°\text{C}$$

$$\theta = T_2 - T_1 = 95 - 45 = 50°\text{C}$$

From Eq. (9.19), Energy (heat) content per sq. km

$$E_o/A = \{p\,\rho_w\,c_w + (1 - p)\ \theta_r\,c_r\}\ w\ \theta_o$$

$$= \left\{\begin{aligned}&0.05 \times 1000\ \text{kg m}^{-3} \times 4200\ \text{J kg}^{-1}\ \text{K}^{-1} + 0.95 \times 3000\ \text{kg m}^{-3}\\ &\qquad\qquad\qquad \times 750\ \text{J kg}^{-1}\ \text{K}^{-1} \times 0.6\ \text{km} \times 50\ \text{K}\end{aligned}\right\}$$

$$= 7.042 \times 10^{16}\ \text{J km}^{-2}$$

(ii) From (9.21), time constant,

$$\tau = \frac{\{p\,\rho_w\,c_w + (1 - p)\rho_r\,c_r\}\ w}{(Q/A)\,\rho_w\,c_w}$$

$$= \frac{\left\{\begin{aligned}&0.05 \times 1000\ \text{kg m}^{-3} \times 4200\ \text{J kg}^{-1}\ \text{K}^{-1}\\ &\qquad + 0.95 \times 3000\ \text{kg m}^{-3} \times 750\ \text{J kg}^{-1}\ \text{K}^{-1}\end{aligned}\right\} \times 0.6\ \text{km}}{0.75\ \text{m}^3\ \text{s}^{-1}\ \text{km}^{-2} \times 1000\ \text{kg m}^{-3} \times 4200\ \text{J kg}^{-1}\ \text{K}^{-1}}$$

$$\tau = 12.9\ \text{years}$$

(iii) From (9.24), initial extractable thermal power per square kilometer,

$$\left|\frac{d(E/A)}{dt}\right|_{t=0} = \frac{(E_o/A)}{\tau}e^{-t/\tau} = \frac{(E_o/A)}{\tau} = 173.1\ \text{MW km}^{-2}$$

Extractable thermal power per square kilometer after 25 years,

$$\left|\frac{d(E/A)}{dt}\right|_{t=25} = \frac{(E_o/A)}{\tau}e^{-t/\tau} = \frac{(E_o/A)}{\tau}e^{-25/12.9} = 24.925\ \text{MW km}^{-2}$$

9.6 EXPLORATION AND DEVELOPMENT OF GEOTHERMAL RESOURCES

The development of hydrothermal resource begins with exploration, to locate and confirm the existence of a reservoir with economically exploitable temperature, volume and accessibility. Most known reservoirs were discovered from surface manifestations such as hot springs. However, in some geothermal fields, the surface indications provide meager (or misleading) information as to reservoir capacity. Because of high cost of drilling, something needs to be known about energy potential of the reservoir before drilling is undertaken. Efforts are on to develop procedures for forecasting geothermal reservoir performance. The procedures under study include: (i) rate of upward heat flow in the ground, (ii) chemical composition of surface and ground water, (iii) electrical resistivity of the underground at depth, and (iv) seismic measurements.

Exploratory drilling and production testing is then used to establish reservoir properties. If a suitable reservoir is confirmed, field development follows. Deep drilled survey wells commonly reach depths of 6 km, and the technology is available to drill up to 15 km. Drilling technology used for geothermal development is historically derived from the petroleum industry. Geothermal drilling is, however, more difficult and expensive. The temperatures up to 350 °C encountered in geothermal drilling are higher than those in oil (or gas) well drilling and usually hard volcanic rock are to be penetrated. This causes excessive wear of drill bit. The drilling mud used to lubricate and cool the drill bit deteriorates rapidly at temperatures above about 175 °C.

Geothermal fields generally lend themselves to staged development. To begin with, a modestly sized plant can be installed at an early stage of field assessment based on the available information. The operation of this plant would provide more information about the reservoir, which can lead to the installation of future stages.

Geothermal energy is not as renewable as solar or wind energy. Like the energy of the sun, energy within earth is immense and has a lifetime measured in billions of years. However, unlike the use of sunlight, tapping into the local sources of earth's heat can result in temporary decrease in the local amount of the heat available. Though reinjecting the used geothermal fluid can preserve the fluid volume of the reservoir, still the heat content of the reservoir gradually declines. Resources tapped for electricity generation could provide energy for about 50 years or more, if properly managed. Continuous long-term use of geothermal energy would require the periodic construction of new plants at new sites, while previously used reservoir recover. The recovery period of the geothermal resource depends on how it is used. Recent survey indicates a recovery period of 100–200 years for district heating and several hundred years for electricity generation.

Other types of geothermal resources have special requirements in exploration phase. The drilling technology requirements and the cost, increase as the geothermal environment becomes hotter, deeper and more abrasive to drill. Recovery of geo-pressured energy requires high-pressure technology and the use of heavy drilling mud. Hot dry rock requires drilling of deep wells in very hard rocks and creation of small artificial reservoir. Successful magma drilling technology has not been established yet.

9.7 ENVIRONMENTAL CONSIDERATIONS

Hydrothermal (dry steam) resources contain some non-condensable gases, mainly CO_2 and small amounts of H_2S, ammonia, methane, etc., which appear in turbine exhaust. The emission of CO_2 is significantly less than that from any fossil-fuel plant with same output. H_2S is a noxious gas and has a smell of a rotten egg. In the past the non-condensable gases have been released to the atmosphere where the hydrogen sulfide is gradually destroyed by oxidation. However, the products are oxides of sulfur which can themselves be harmful, if accumulate at appreciable concentration. Plans are therefore underway to remove most of the hydrogen sulfide from the gases before they are discharged. Suitable means for mitigation of most of these releases can be adopted. In fact, Lake County dry steam plant (one of "The Geysers" plants, California) is reported to be in compliance with all of the California's air quality regulations. Thus geothermal energy tends to be quite clean.

Geothermal steam may also contain boron, arsenic, mercury and other potentially poisonous elements, which are found in condensate. This can contaminate the ground water and poison fish and other aquatic life, if not disposed of safely. The reinjection of excess condensate deep into the ground solves the problem of its safe disposal.

In wet steam fields, the mineral and salt content of the hot water (brine) can be as high as 20–30 per cent dissolved solids. This poses liquid waste disposal problems. Also withdrawal of large amounts of steam (or water) from hydrothermal resource may result in surface subsidence. These problems can also be dealt with by reinjection of used water deep into the ground. This also increases the useful life of the reservoir. A binary power plant, where geothermal fluid flows through a closed loop and the whole quantity is reinjected into the ground is most benign with almost zero pollutants.

Steam-electric plants of any type discharge much of the heat present in the turbine exhaust to the atmosphere. Because of the low thermal efficiency in case of hydrothermal plants a much larger proportion of heat supplied is discharged to atmosphere as compared to fossil fuel or nuclear plant. Vaporization of water in the cooling tower also results in increased amount of moisture in the atmosphere.

9.8 GEOTHERMAL ENERGY IN INDIA

Though India has been one of the earliest countries to begin geothermal projects way back in the 1970s, but at present there are no operational geothermal plants in India. There is also no installed geothermal electricity generating capacity as of now and only direct uses (e.g. drying) have been detailed.

A systematic collaborative, research, development and demonstration program is undertaken with different organizations, viz., IIT Delhi, National Aeronautic Limited, Bangalore, Geological Survey of India, National Geophysical Research Institute (NGRI), Hyderabad, Oil & Natural Gas Corporation, etc. As a result of various resource assessment studies/surveys, nearly 350 potential hot springs, distributed in seven geothermal provinces, have been identified throughout the country. These springs are perennial and their surface temperatures range from 37 to 90 °C with a cumulative surface discharge of over 1000 l/min. Most of them are low temperature hot water resources and can best be utilized for direct thermal applications. Only some of them can be considered suitable for electrical power generation. The potential for power generation at these sites has been estimated as about 10,600 MW. The use of geothermal energy has already been demonstrated in the country for small-scale power generation and thermal applications. Small direct heat pilot plants have been installed at Puga and Chumathang (in Ladakh, Jammu and Kashmir) and Manikaran (H.P.), etc.

The seven geothermal provinces include, The Himalayas: Sohana: West coast: Cambay: Son–Narmada–Tapi (SONATA): Godavari and Mahanadi. These provinces are associated with major rifts or subduction tectonics and registered high heat flow and high geothermal gradient. The locations of geothermal fields in the country are shown in Fig. 9.12. The heat flow values and thermal gradients at these locations are listed in Table 9.2.

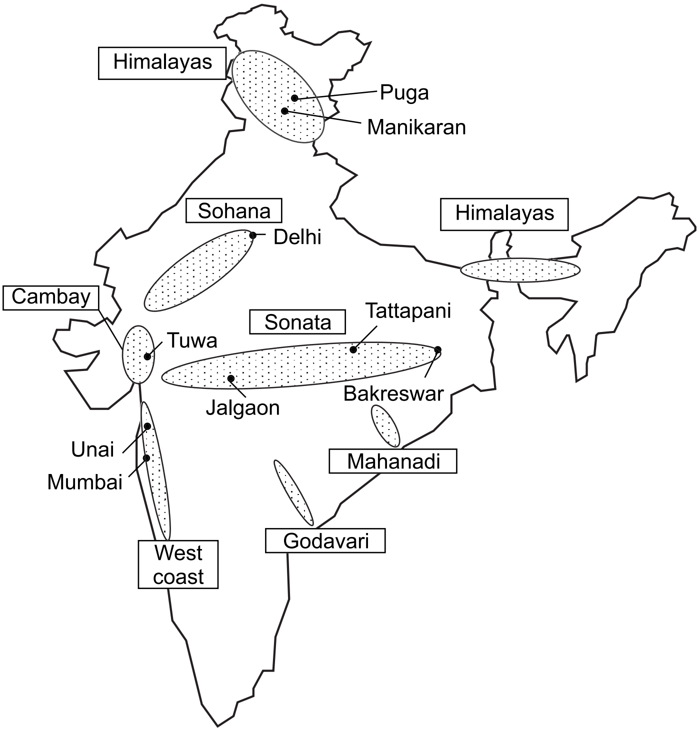


Figure 9.12 Geothermal provinces of India (not to scale)

The geothermal reservoirs suitable for power generation have been located at Tattapani (in Sarguja district), Chhattisgarh and Puga valley of Ladakh, Jammu & Kashmir. Binary cycle system may be used for power generation from these medium enthalpy resources. A study by National Geophysical Research Institute (NGRI), Hyderabad has confirmed the presence of a 260 °C hydrothermal reservoir at a depth of 3 km at Tattapani. The Ministry of New and Renewable Energy Sources is planning to develop this field for power generation. Nation Hydroelectric Power Corporation (NHPC) has been entrusted the job of installing a 300 kW demonstration electric power production plant at a cost of Rs. 4.6 crore. Exploratory study is underway by NGRI, Hyderabad at Sutluj-Spiti, Beas and Parbati valley in Himachal Pradesh, Badrinath-Tapovan in Uttaranchal and Surajkund in Jharkhand to explore potential sites for power generation.

Table 9.2 Geothermal fields in India [53, 54]

S. N.	Geothermal provinces	Main Locations	Estimated reservoir temp. (°C)	Heat flow (mW/m^2)	Thermal gradient (°C/km)
1.	Himalayas	Puga Valley (J&K), Manikaran (H.P.)	260	468	234
2.	Sohana		70		76–96
3.	West coast	Unai (Maharashtra)	102–137	129	59
4.	Cambay	Tuwa (Gujrat)	150–175	93	70
5.	Son–Narmada–Tapi (SONATA)	Jalgaon (Maharashtra), Tattapani (Chhattisgarh), Bakreswar (Bihar)	105–217	120–260	60–90
6.	Godavari		175-215	104	60
7.	Mahanadi		130	200	90

Since majority of these resources are located in rural India, these springs can support small-scale industries in such areas.

REVIEW QUESTIONS

1. What do you understand by geothermal energy? What are geothermal fields?
2. What are the merits and demerits of geothermal energy?
3. What are the major applications of geothermal energy?
4. Comment on the origin and distribution of geothermal energy.
5. Explain various types of geothermal resources.
6. Describe various energy extraction technologies used with hydrothermal resources.
7. Describe various stages of exploration and development of geothermal resources.
8. What are the environmental impacts of geothermal energy?
9. What is the current status of geothermal energy in India?

PROBLEMS

1. A hot dry rock (HRD) resource has a geothermal temperature gradient at 35 K km^{-1}. The minimum useful temperature is 125 K above the surface temperature T_o. Water at flow rate of 1 m^3 s^{-1} km^{-2} is used for heat extraction. The density and specific heat capacity for water may be assumed as 1000 kg m^{-3} and 4200 J kg^{-1} K^{-1} respectively. Calculate,
   (i) The heat content per square kilometer of HRD to a depth of 8 km, assuming $\rho_r = 2700$ kg m$^{-3,}$ and $c_r = 820$ J kg^{-1} K^{-1}.
   (ii) Useful average temperature, initially and after 20 years
   (iii) Useful heat extraction rate per km^2, initially and after 20 years.
   (*Ans.* 7.6×10^{17} J km^{-2}, 77.525 K, 75.46 K, 32.5458 MW / km^{-2}, 31.677 MW / km^{-2})

2. A 0.5 km thick hot aquifer is located at a depth of 3 km and has a porosity of 6 per cent. The density of the under sediments is 3000 kg m^{-3} and its specific heat is 750 J kg^{-1} k^{-1}. The temperature gradient in the overlying material is 40 °C km^{-1}. Assuming the density and specific heat of water as 1000 kg m^{-3} and 4200 J kg^{-1} k^{-1} respectively, Find:
   (i) the heat content per square kilometer above 42 °C and the initial temperature of the aquifer, if the average surface temperature is 10 °C
   (ii) the time constant for useful heat generation with pumped water extraction at a rate of 0.5 m^3 s^{-1} km^{-2}
   (iii) the thermal power extractable per square kilometer initially and after 20 years

(*Ans.* 1.041×10^{17} J km^{-2}, 17.87 yrs., 184.8 MW km^{-2}, 60.35 MW km^{-2})

OBJECTIVE TYPE QUESTIONS

1. Which one of the following statements is not true for geothermal energy system?
   (a) It is a reliable and cheap source of energy
   (b) It is available 24 hours per day
   (c) It has no inherent storage feature, so extra storage facility is required
   (d) The system is modular in nature

2. The world's total present installed electrical power generating capacity from geothermal resource is about:
   (a) 11,490 MW (b) 1000 MW
   (c) 29000 MW (d) 3000 MW

3. World's first geothermal electric power plant is located at:
   (a) Wairakei field in New Zealand (b) Larderello, Italy
   (c) "the Geysers", California (d) El-Salvador

4. The country having maximum (geothermal based) installed capacity for electric as well as thermal power is:
   (a) USA (b) Italy
   (c) Iceland (d) New Zealand

5. The temperature in the crust increases with depth at a rate of about:
   (a) 300 °C/km (b) 10 °C/km
   (c) 1 °C/km (d) 30 °C/km

6. The temperature at the inner core of the earth is about:
   (a) 1000 °C (b) 4000 °C
   (c) 40000 °C (d) 500 °C

7. The zone of likely geothermal sites corresponds roughly to:
   (a) cold, hilly regions (b) hot, flat regions
   (c) tropical regions
   (d) the regions of seismic and volcanic activities

8. Most of the world's geothermal sites today are located:
   (a) in south hemisphere of the globe (b) near the coast of Atlantic ocean
   (c) near the edges of Pacific plate (d) near equator

9. The average thickness of the crust is about:
   (a) 30 km (b) 3 km
   (c) 300 km (d) 1000 km

10. In most hydro-thermal fields, the hot spot occur at a depth of about:
(a) 10 km (b) 10 m
(c) 2 to 3 km (d) 30 km

11. Compared to a conventional steam plant, the temperature and pressure in a geothermal plant are:
(a) comparable (b) much higher
(c) higher (d) lower

12. In geo-pressured resource the pressure can go as high as:
(a) 160 atm (b) 1350 atm
(c) 15000 atm (d) 10 atm

13. Name the country where the world's largest EGS project is currently under development:
(a) Italy (b) USA
(c) New Zealand (d) Australia

14. A geothermal resource tapped for electricity generation could provide energy for about:
(a) 50 years (b) 1000 years
(c) 5 years (d) 1 year

15. Compared to a conventional steam plant, the efficiency of geothermal plant is:
(a) very high (b) higher
(c) comparable (d) lower

16. In geysers, the steam is continuously vented through fissures in the ground. These vents are called:
(a) vent holes (b) pot holes
(c) fumaroles (d) sunspots

17. Petro-thermal systems are composed of hot dry rock with:
(a) no underground water (b) large underground water
(c) petrochemicals (d) dense gases

18. Main disadvantage of geothermal energy is:
(a) large area requirement (b) low efficiency
(c) drilling operation is noisy (d) high cost

19. A potential geothermal source region should have:
(a) high thermal conductivity (b) high thermal gradient
(c) low thermal gradient (d) high electrical resistance

CHAPTER 10

Ocean Energy

Learning Objectives

In this chapter you will be able to:

- ➤ Explore nature and distribution of various types of extractable energy resources in the ocean
- ➤ Discuss the technologies for harnessing of tidal, wave and ocean thermal energies
- ➤ Identify environmental impacts of these technologies

10.1 INTRODUCTION

Oceans cover about 71 per cent of earth's surface. They receive, store and dissipate energy through various physical processes. As per present technological status, recoverable energy in oceans exists mainly in the form of waves, tides and temperature difference (between surface and deep layers). Tides and waves produce mechanical energy whereas temperature difference produces thermal energy. Tidal energy technology is relatively more developed compared to the other two, which are still undergoing evaluation and initial development stages. Main disadvantages common to all of them are: (i) low energy density and (ii) in general the potential occurs remote from the consumption center. Because of the diversity in physical processes involved, exploitation techniques and state of development, these are discussed in three different sections.

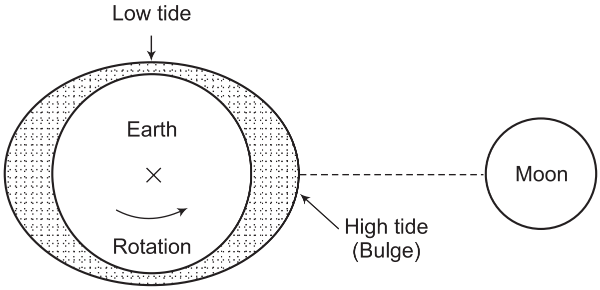
10.2 TIDAL ENERGY

Tidal energy exploits the natural rise and fall of coastal tidal waters caused principally by the interaction of the gravitational fields of the Sun and the Moon. The ocean level difference caused due to tides contains large amount of potential energy. The highest level of tidal water is known as *flood tide* or high tide. The lowest level is known as low tide or *ebb*. The level difference between the high and low tide is known as *tidal range*. The tidal range varies greatly with location. Only sites with large tidal ranges (about 5 m or more) are considered suitable for power generation. Total combined potential at these sites is estimated as 1,20,000 MW [55].

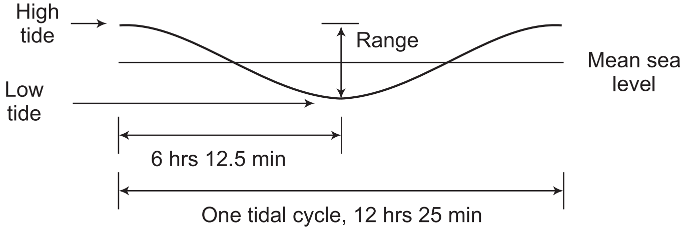
Tidal mills were in use on the coast of Spain, France, UK and China during medieval period, around 1100 AD. They remained in common use for many centuries, but were gradually replaced by more convenient and cheaper sources made available due to industrial revolution. The principle used for harnessing the energy consisted of a pond filled through *sluice* (rapid controlled gates) when tides are high and emptying it during low tides via an undershot waterwheel, producing mechanical power. Still same basic principle with improvements in the design, material and operation techniques is being used to generate electricity, in the same manner as in hydroelectric plant.

10.2.1 Origin and Nature of Tidal Energy

Tides are produced by gravitational attraction of moon and sun acting upon the rotating earth. The moon exerts a larger gravitational force (about 70 per cent of the tide producing force) on the earth, as it is a great deal closer than the sun. Surface water is pulled away from the earth on the side facing the moon, and at the same time the solid earth is pulled away from the water on the opposite side. Thus the ocean height increases both near and far sides of the earth as shown in Fig. 10.1. The solid earth rotates with a period of one day underneath these two bulges. These bulges are swept westward, due to earth's rotation, as deep ocean waves of period 12 hours and 25 minutes. The sun's effect is similar but smaller in magnitude (about 2.2 times less than lunar), and with a period of 12 hours. These are thus semi diurnal changes of ocean level. Due to slight difference of periods, solar tide moves in and out of



(a) Bulge on near and far sides of earth



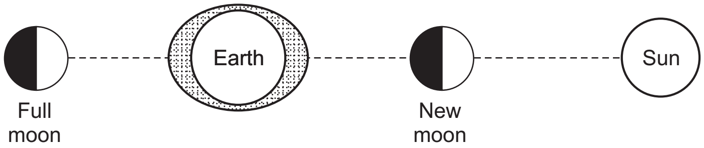
(b) Tidal wave

Figure 10.1 Origin of tides

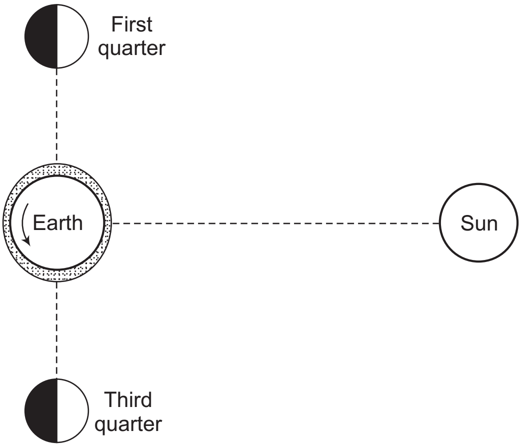
phase with lunar tide. When the sun, earth and moon are aligned (approximately) in conjunction, the lunar and solar tides are in phase, producing net tides of maximum range. These are the *spring tides* occurring twice per lunar month at times of both full and new moon. When sun-earth and moon-earth directions are perpendicular (in quadrature), the solar and lunar tides are out of phase producing net tides of minimum range. These are the *neap tides* that again occur twice per month at times of half-moon (first and third quarter cycle of the moon) as shown in Fig. 10.2.

Superimposed on these short-term variations caused by the sun-moon system there are many other cycles of small magnitudes with periods ranging from days to years. For example (i) long-term (yearly) variations arise from the changes in the distance of earth from the sun during a year, (ii) variations as moon-earth distance oscillates slightly in a period of 27.55 solar days, (iii) variations as the moon's plane of motion moves about 2° in and out of the earth-sun ecliptic plane and also (iv) other variation cycles that last for many years, arising out of complex interactions between the gravitational fields.

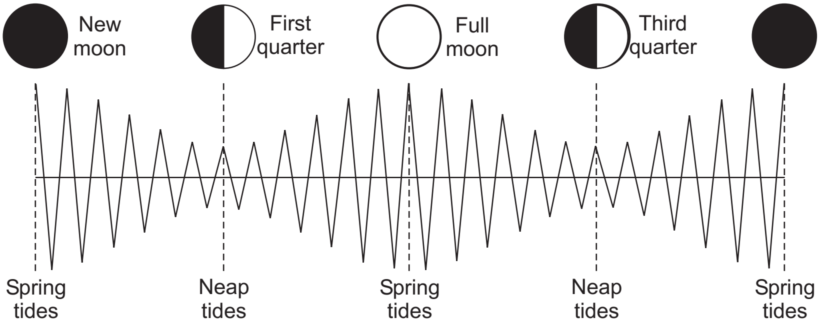
In open oceans, tidal ranges are commonly of the order of 0.6 m to 0.9 m. However, when the ocean tidal waves impinge on continental shelves and coastlines, their ranges can amplify substantially through (i) run up, (ii) funneling and (iii) resonance, depending on the nature of the coastline. Thus tidal range varies from place to place. In some places such as shallow bays and estuaries, the amplification is considerable. Exceptionally high tides with tidal range of about 11 m (or more) occur in the Bay of Fundy on Atlantic coast of Canada near Maine. Despite their complexity, tides at any location can be predicted with high accuracy.



(a) Spring tides



(b) Neap tides



(c) Tidal variations in a lunar month

Figure 10.2 Nature of tides

Ocean tides derive their energy from rotation of earth, slowing it down a bit in the process. However, the slowing down of the earth is very insignificant over human time spans and would not be increased by tidal power development. This will not have any significant effect for billions of years. Therefore, for human purposes, tidal energy can be considered sustainable and renewable energy resource. The total dissipation of energy by water tides in the earth is estimated to be 3000×10^3 MW.

10.2.2 Limitations of Tidal Energy

Main limitations of the tidal energy are: (i) economic recovery of energy from tides is feasible only at those sites where energy is concentrated in the form of tidal range of about 5 m or more and geography provide favorable site for economic construction of a tidal plant, thus it is site specific, (ii) due to mismatch of lunar driven period of 12 hrs 25 min and human (solar) period of 24 hrs, the optimum tidal power generation is not in phase with demand, (iii) changing tidal range in two weeks period produces changing power, (iv) the turbines are required to operate at variable heads, (v) requirement of large water volume flow at low head necessitates parallel operation of many turbines, (vi) tidal plant disrupts marine life at the location and can cause potential harm to ecology, (vii) it requires very large capital cost at most potential installations, and (viii) the location of sites may be distant from the demand centers.

10.2.3 Tidal Energy Technology

Main components of a tidal plant, as shown in Fig. 10.3 are: (i) dam, barrage or dyke: a barrier constructed to hold water, (ii) sluice ways: rapid controlled gates, used to fill basin during high tides or emptying it during low tides and (iii) a special, bulb type power turbine-generator set: steel shell containing an alternator and special Kaplan turbine with variable pitch blades. Tidal power associated with single filling or emptying of a basin may be estimated as follows:

1. Tidal Range Power

Consider water trapped at high tide in a basin of area A, and allowed to run out through a turbine at low tide as shown in Fig. 10.3. Potential energy in the mass of water stored in incremental head *dh* above head *h*:

$$dW = dm.g.h$$

but $$\mathrm{d}m = \rho.A.dh$$

Thus $$dW = \rho.A.g.h.dh$$

Total potential energy of water stored in the basin;

$$W = \int_0^R \rho.\ A.\ g.\ h.\ dh$$

$$W = \frac{1}{2}\rho.\ A.\ g.\ R^2 \quad \text{Joules}$$

where ρ = density of water

g = gravitational constant

R = tidal range

As the time between consecutive high and low tides is 6 hrs 12.5 min (= 22,350 s), this power is to be utilized within this period.

Assuming an average sea water density of 1025 kg/m^3, the average theoretical power generated in one filling or emptying of the basin:

$$P_{av} = \frac{1025 \times 9.80 \times \mathrm{A} \times \mathrm{R}^2}{2 \times 22{,}350}$$

$$P_{av} = 0.225 \times A \times R^2 \quad \text{Watts}$$

Thus tidal power developed is directly proportional to (i) area of basin and (ii) square of the tidal range.

The actual power generation by a practical system would be less than the average theoretical power given in the above expression due to frictional losses of the fluid, conversion efficiency of turbine and generator and due to the fact that the turbine cannot be operated down to zero head and thus full power generation potential cannot be utilized. The turbine has to be stopped when the head reaches a minimum value r, below which the operation becomes uneconomical; the above expressions are modified as:

$$W = \int_r^R \rho.A.g.h.dh \quad \text{Joules}$$

$$W = \frac{1}{2}\rho.A.g.(R^2 - r^2)$$

$$P_{av} = 0.225 \times A \times (R^2 - r^2) \quad \text{Watts}$$

$$P_{av}/A = 0.225 \times (R^2 - r^2) \quad \text{MW/km}^2$$

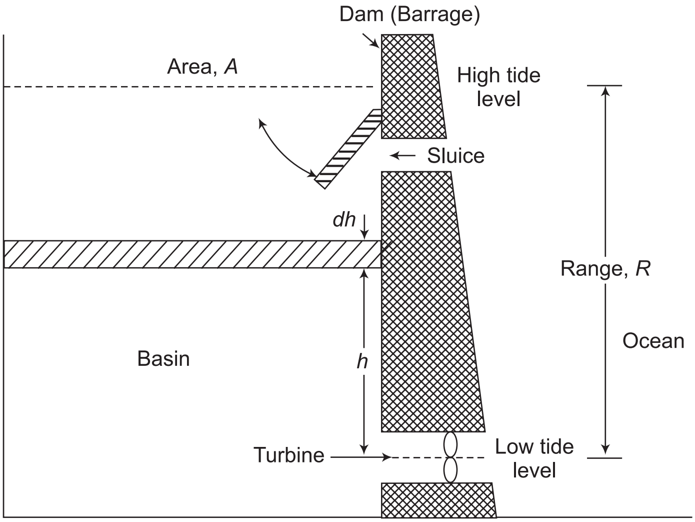


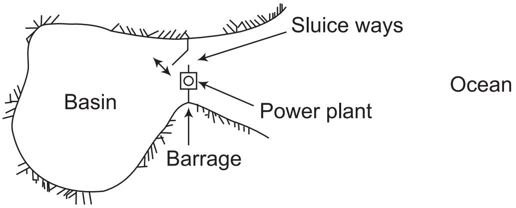
Figure 10.3 Power generation from tides

2. Ocean Tidal Energy Conversion Schemes

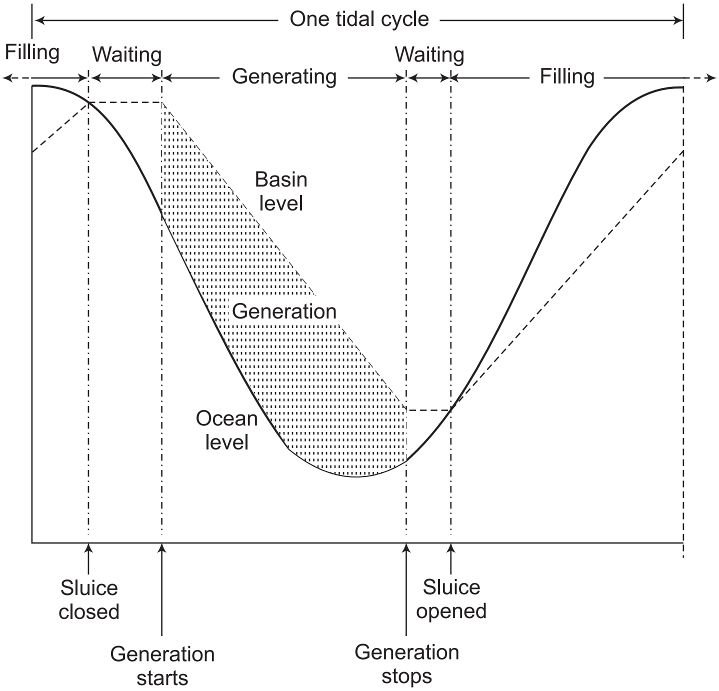
Main tidal energy conversion schemes are: (i) single basin: single effect, (ii) single basin: double effect, (iii) two basin: linked basin (iv) two basin: paired basin and (v) tidal flow (or tidal current) schemes.

(a) Single Basin: Single Effect Scheme Single basin scheme has only one basin as shown in Fig. 10.4. In single effect scheme, power is generated during either filling or emptying the basin. Two types of operation cycles are possible. In *ebb generation cycle*

operation, the sluice way is opened to fill the basin during high tide. Once filled the impounded water is held till the receding cycle creates a suitable head. Water is now allowed to flow through the turbine coupled to generator till the rising tide reduces the head to the minimum operating point. The flow is held till the next generating cycle. The sequence of events is illustrated in Fig. 10.4. This cycle is repeated and power is generated intermittently. In *flood generation cycle* operation, the sequences are altered to generate power during filling operation of the basin. However, the sloping nature of the basin shores usually makes ebb generation the more productive method.



(a) Layout of single basin tidel energy conversion scheme



(b) Sequence of operation

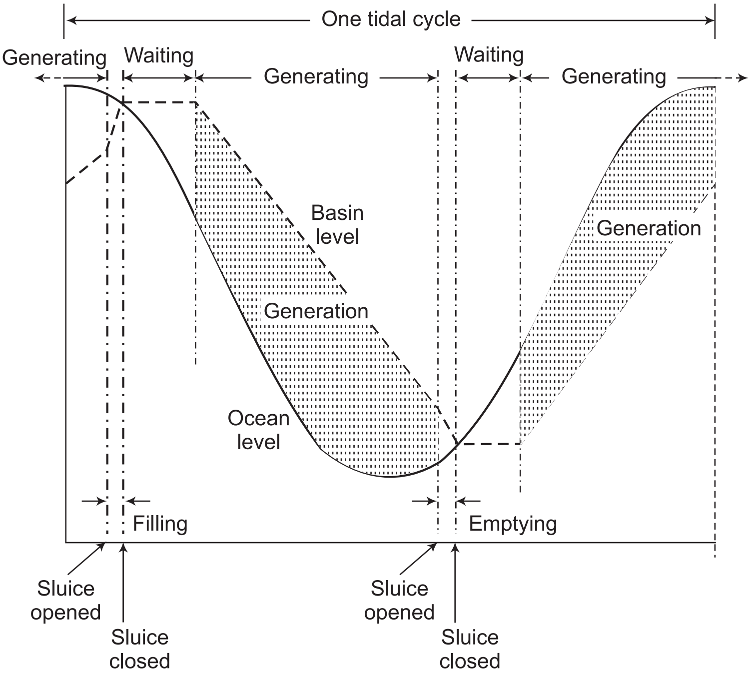
Figure 10.4 Single basin, single effect tidal energy conversion scheme

Increased output can also be obtained by pumping (using turbines as pumps) during high tide to increase the basin level and therefore the generation head. The energy required for pumping must be borrowed and repaid. As the pumping is done against a small head at high tide, whereas the same water is released through the turbine during low tide at a great head, producing a net energy gain.

(b) Single Basin: Double Effect Scheme In single basin, double effect scheme, power is generated on both flood and ebb. Two-way (reversible) hydraulic turbines are used. Pumping may also be used to increase the output. The routine is as follows:

1. inward sluicing to fill the basin
2. holding period
3. ebb generation
4. outward sluicing to empty the basin
5. holding period
6. flood generation

The routine is shown graphically in Fig. 10.5.



(b) Sequence of operation

Figure 10.5 Single basin, double effect tidal energy conversion scheme

(c) Two Basin: Linked Basin Scheme In order to maintain continuity of power supply linked and paired basins schemes are used. Linked basin scheme consists of two basins, one toped up at high tide and the other emptied at low tide. Thus a

permanent head is created between the two basins. Water flows through turbine from high basin to low basin. The layout of such a scheme is shown in Fig. 10.6.

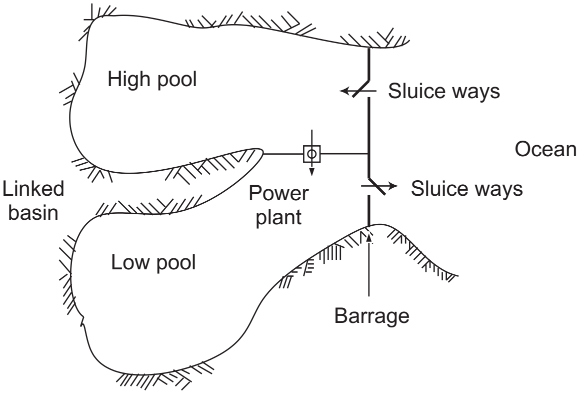


Figure 10.6 Linked basin tidal energy conversion scheme

(d) Two Basin: Paired Basin Scheme A paired basin consists essentially of two single basin schemes. One scheme generates on flood and the other on ebb cycle. The output is almost, but not quite continuous. Two basin schemes are generally found to be economically inferior to single basin schemes.

(e) Tidal Current Schemes In order to explore the possibility of dispensing with the dam, its associated cost and environmental impacts, extraction of energy from tidal currents have been considered. Strong tidal currents (as high as about 5 m/s) are found in shallow seas, particularly where natural constrictions exist, such as around headlands or between islands. The practical devices for tidal flow power will be similar to that used in river flow power systems. The theory of tidal flow power is similar to wind power with the advantage of predictable velocities of high-density fluid. However, in this case the fluid velocities are much less as compared to wind and the operation is carried out in marine environment. The generation will be intermittent and total power available may not be very large. The capital cost per unit of power produced appears to be high. As the **tidal flow power** lags about π/2 behind **tidal range power** from a single basin, the two systems could be complementary.

10.2.4 Present Status

Certain coastal regions experience high tides than others. This is a result of amplification of tides caused by local geographical features such as bays and inlets. In order to produce practical amount of power (electricity) a tidal range of at least 5 m is required. Also the geographic features should permit enclosure of large areas with reasonable short dam or barrage. Few sites are identified for substantial tidal power development as shown in Fig. 10.7. Important sites of the world with substantial estimated potential are: (i) Cook Inlet in Alaska with 57,000 MW potential and 9 m maximum range, (ii) Bay of Fundy with 29,000 MW potential and 11 m maximum range, (iii) White sea with 16,000 MW potential and 7 m maximum range and

(iv) estuary of Severn river, England with 11,000 MW potential (which is about 10 per cent of country's electricity need) and 8 m maximum tidal range.

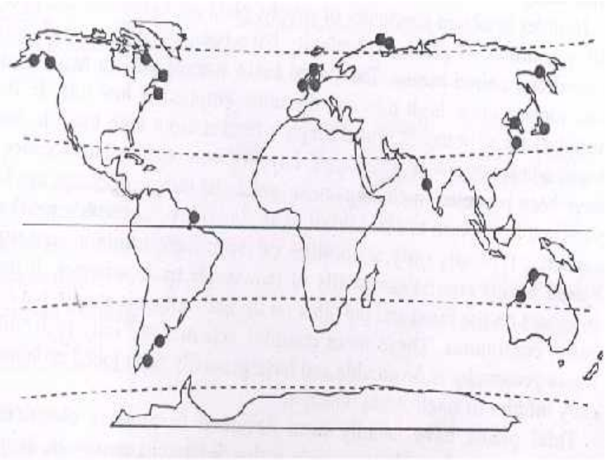


Figure 10.7 Potential sites for tidal power development

The best-known large-scale electricity generating commercial plant is the 240 MW system, at an estuary of La Rance river into the Gulf of St. Malo in Brittany, France. This is a single basin, double effect scheme with pumping, operating since 1966. There are 24 bulb turbines having variable pitch blades, coupled directly to generators, each of 10 MW capacities. The details of existing tidal plants are shown in Table 10.1. None of these countries have progressed to further development. Main barrier to increased use of the tide is the construction cost.

Full-scale prototype tidal-current systems are now being deployed. If these schemes continue to prove successful, commercial systems will follow.

Table 10.1 Existing tidal plants

S.N.	Site	Mean tidal range (m)	Basin area (km^2)	Installed capacity (MWe)	Year of installation
1.	La Rance (France)	8	17	240	1966
2.	Kislaya Guba (near Murmansk, on Barents sea, Russia)	2.4	2	0.4	1968
3.	Jiangxia (China)	7.1	2	3.2	1980
4.	Annapolis (in Nova Scotia, Bay of Fundy, Canada)	6.4	6	17.8	1984

In India, potential sites identified are Gulf of Cambay and Gulf of Kutch in Gujrat with maximum tidal range as11 m and 8 m and average tidal range of 6.77 m and 5.23 m respectively and power generation potentials of 7,000 MW and 1,200 MW (installed capacity) respectively. A potential of 100 MW with maximum tidal range of 5 m and average tidal range as 2.97 m has been estimated at Durgadurani creek of Sundarbans area. Some potential also exists at Belladona creek in West Bengal with mean tidal range of 3.6 m.

In Jan 2011, the state of Gujarat announced plans to install Asia's first commercial-scale tidal current power plant; the state government approved the construction of a 50 MW project in the Gulf of Kutch.

Tidal current technology is in its infancy and going through evaluation and experimental stage. A 5 kW tidal current plant has been operating in Japan since 1990. In 1993 a 10 kW tidal current machine was deployed experimentally in U.K. and is still being assessed.

10.2.5 Environmental Impacts

Tidal energy is a renewable source of energy, which does not result in emission of gases responsible for global warming or acid rain associated with the use of fossil fuels. Changing tidal flows by damming a bay or estuary could, however, result in negative impacts on aquatic and shoreline ecosystem, as well as navigation and recreation. The barrage destroys homes to many birds, fish and other animals.

Studies undertaken so far indicate that the impact at each site is different and depends greatly upon local geography. Very little is understood about how altering the tides can affect incredibly complex aquatic and shoreline ecosystem.

Example 10.1

A single basin type tidal power plant has a basin area of 2 km^2. The tide has an average range of 13 m. Power is generated during ebb cycle only. The turbine stops operating when the head on it falls below 3 m. Calculate the average power generated by the plant in single emptying process of the basin if the turbine generator efficiency is 0.7. Estimate the average annual energy generation of the plant.

Solution

Given Amplitude $R = 13$ m

$r = 3$ m

Basin area, $A = 2$ km^2

Gen-turb. $\eta = 0.7$

Density of sea water may be assumed as, $\rho = 1025$ kg/m^3

$$\text{Average power potential available} = 0.225 \times A\,(R^2 - r^2) \text{ Watts}$$

$$= 0.225 \times 2 \times 10^6 \times (13^2 - 3^2)$$

$$= 72 \text{ MW}$$

$$\text{Average power generated} = 72 \times 0.7$$

$$= 50.4 \text{ MW}$$

$$\text{Energy available in single emptying} = \frac{1}{2}\rho A g\,(R^2 - r^2)$$

$$= \frac{1}{2} \times 1025 \times 2 \times 10^6 \times 9.8 \times (13^2 - 3^2)$$

$$= 1607200 \text{ MJ}$$

one ebb cycle duration = 12 h 25 min = 12.42 h

Number of ebb cycles in a year = $365 \times 24/12.42 = 705.5 \approx 706$

Average annual energy generation = $1607200 \times 706 \times 0.7$ MJ

$$= 1607200 \times 706 \times 0.7/3.6 \text{ kWh}$$

$$= 2.2 \times 10^8 \text{ kWh}$$

Example 10.2

Water is pumped rapidly from the ocean into the basin at high tide to give an increased water level of 1.2 m in a tide power basin. If tidal range is 6 m and the efficiency of pump/generator system is only 50%, find the energy gain due to use of pumping.

Solution

Let *M* be the additional mass of water pumped to raise the water level in the basin by 1.2 m. This whole mass of water may be assumed at center of gravity, i.e. at (½) × 1.2 = 0.6 m above sea level during pumping.

The additional hydraulic energy required for additional water storage
= Mg × [(½) × 1.2]

As efficiency of pump is 50%, the input energy supplied = $\dfrac{\text{Mg} \times (1.2/2)}{0.5} = 1.2 \times \text{Mg}$

This water is released during low tide in the ocean. Due to pumping the available head will increase.

The head increases from 6 m by 1.2 m to reach 7.2 m.

The mass M of water may be assumed at a center of gravity at 6 + (½) × 1.2 = 6.6 m.

Considering 50% of the generator, the extra energy generated = $0.50 \times \text{Mg} \times 6.6$

$$= 3.3 \times \text{Mg}$$

Net energy gain = $(3.3 \times \text{Mg} - 1.2 \times \text{Mg}) = 2.1 \times \text{Mg}$

Net energy gain as %age of input energy = $(2.1 \times \text{Mg}/1.2 \times \text{Mg}) \times 100 = 175\%$

10.3 WAVE ENERGY

Waves are caused by the transfer of energy from surface winds to sea. The rate of energy transfer depends upon the wind speed and the distance over which it interacts with water. The energy flux in waves is more than that available from solar, wind and other renewable sources. The power in the waves is directly proportional to the square of its amplitude and to the period of motion. The energy stored is dissipated through friction at shore and turbulence at rates depending on characteristics of wave and water depth. Larger waves in deep sea loose energy quite slowly and can effectively store it for many days and transmit it over great distances. For instance large waves appearing off Europe might have been initiated in stormy weather in the mid-Atlantic or as far as Caribbean. Wave energy in open oceans is likely to be inaccessible. The resource potential near coastlines is estimated as in excess of 27, 00,000 MW. However, 50,000 MW can be captured with presently available technology. Wave power is usually expressed in kilowatt per m, representing the rate at which energy is transferred across a line of 1m length parallel to the wave front.

Main advantages of wave power are: (i) the availability of large energy fluxes (as will be seen in the next section) and (ii) predictability of wave conditions over periods of days.

Difficulties in the development of wave power are encountered mainly due to following reasons:

(i) Irregularity of wave patterns in amplitude, phase and direction, which makes it difficult to extract power efficiently
(ii) The power extraction system is exposed to occasional extreme stormy conditions. During unusual extreme conditions, once in several years, the wave amplitude may reach as high as 10 times normal value and the associated power about 100 times the normal values. The devastating tsunami near the coast of Indonesia towards the end of December 2004 is the most recent example in hand. Allowing for this is expensive and would reduce normal efficiency of power extraction.
(iii) Peak power of deep-water waves is available in open sea, where it is difficult to construct, operate and maintain a system and transmit power to the shore.
(iv) The slow and irregular motion of wave is required to be coupled to electrical generator requiring high and constant speed motion.

10.3.1 Power in Waves

The characteristics of an ideal deep-water surface wave (water depth more than about half the wavelength) are shown in Fig. 10.8. The wave motion may be expressed mathematically by the following general traveling wave equation:

$$y = a\sin\left(\frac{2\pi}{\lambda}x - \frac{2\pi}{T}t\right) \qquad (10.1)$$

where $y =$ displacement above mean sea level, m

$a =$ amplitude, m

$\lambda =$ wavelength, m

$T =$ period, s

$t =$ time, s

Equation (10.1) can also be written as:

$$y = a\sin(kx - \omega t) \qquad (10.2)$$

where $k = \dfrac{2\pi}{\lambda}$, wave number, and $\omega = \dfrac{2\pi}{T}$, angular frequency, rad/s

As the wave moves in linear direction (along x-axis), every particle of water at the surface undergoes a circular motion of radius 'a' (amplitude of the wave) and angular speed ω. An object suspended in the water will exhibit this type of motion. Viewing the vertical cross section of the water column, the radius of circular motion of water particles continues to decreases with depth and becomes zero at sea bed as shown in Fig. 10.9. Thus, while the wave propagates in x direction, there is no net flow of water.

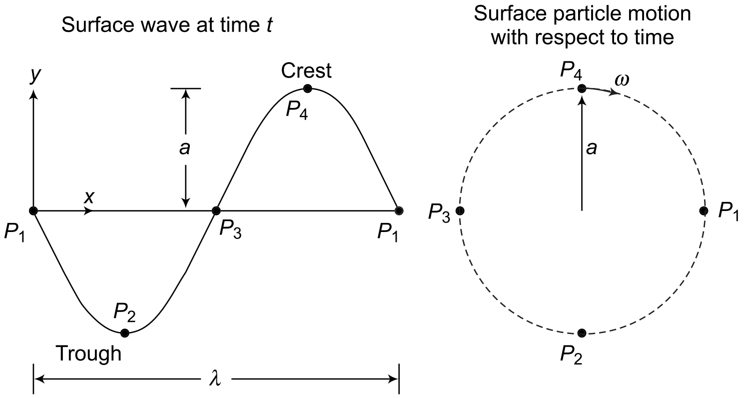


Figure 10.8 Surface wave motion and surface particle motion

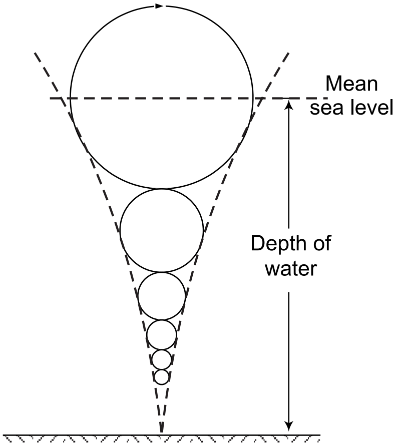


Figure 10.9 Particle motion at various depths in water waves

The wavelength of traveling wave can be shown to be:

$$\lambda = \frac{2\,\pi\, g}{\omega^2} \tag{10.3}$$

The period of motion:

$$T = \frac{2\,\pi}{\omega} = \sqrt{\frac{2\,\pi\,\lambda}{g}} \tag{10.4}$$

or
$$\lambda = 1.5613\; T^2 \tag{10.5}$$

Linear velocity of the particle at the crest of the wave is $a\omega$. The wave velocity (also known as phase velocity) in the direction x is given by:

$$v = \frac{\omega\,\lambda}{2\,\pi} = \frac{\lambda}{T} = \frac{\omega}{k} = \frac{g}{\omega} \tag{10.6}$$

From the above expression it is clear that the wave velocity does not depend on amplitude of the wave.

Now, consider unit width of wave front perpendicular to the direction of motion of wave as shown in Fig. 10.10. Vertical displacement of water particles at any instant (say $t = 0$) is $h = a \sin (kx)$. Element of water mass ($\rho\ dx\ dz$) at distance x and height z, has moved from $-z$ to $+z$ and thus has potential energy of ($\rho\ dx\ dz$) g $2z$. Total potential energy in one wavelength per unit width of wave front is:

$$E_P = \int_{x=0}^{x=\lambda/2} \int_{z=0}^{z=h} (\rho\, dx\, dz)\, g\, 2z \tag{10.7}$$

or $$E_P = \rho g \int_{x=0}^{x=\lambda/2} h^2 dx$$

or $$E_P = \rho g a^2 \int_{x=0}^{x=\lambda/2} \frac{(1 - \cos 2\,k\,x)}{2} dx$$

or $$E_P = \frac{1}{4} \rho g a^2 \lambda$$

Potential energy per unit length and per unit width of wave front (i.e. per unit surface area) is given by:

$$E_P = \frac{1}{4} \rho g a^2 \tag{10.8}$$

In a harmonic motion, average kinetic and potential energy contributions are equal. Thus, kinetic energy per unit area:

$$E_K = \frac{1}{4} \rho g a^2$$

Total energy per unit surface area:

$$E = E_P + E_K$$

$$= \frac{1}{4} \rho g a^2 + \frac{1}{4} \rho g a^2$$

$$E = \frac{1}{2} \rho g a^2 \tag{10.9}$$

The power carried forward per unit width of wave front:

$$P = Eu = \frac{\rho g a^2}{2} \frac{v}{2}$$

where $u = \frac{v}{2}$ is called group velocity of deep-water waves, i.e. the velocity at which the energy in the group of waves is carried forward. Substituting for v from Eq. (10.6),

$$P = \left(\frac{\rho g a^2}{2}\right) \frac{g}{2\omega} = \frac{\rho g a^2}{2} \frac{g}{2} \frac{1}{\omega}$$

Substituting for $\frac{1}{\omega}$ from Eq. (10.3);

$$P = \left(\frac{\rho\, g^2}{8\,\pi}\right) a^2\, T = \left(\frac{\rho\, g\,\sqrt{g}}{4\,\sqrt{2}\,\pi}\right) a^2\,\sqrt{\lambda} \tag{10.10}$$

Thus the power in waves is directly proportional to the square of amplitude and to the period of wave. Therefore the attraction for long periods and large amplitude to wave power engineers is apparent. Annual average wave energy is usually expressed in MWh/m.

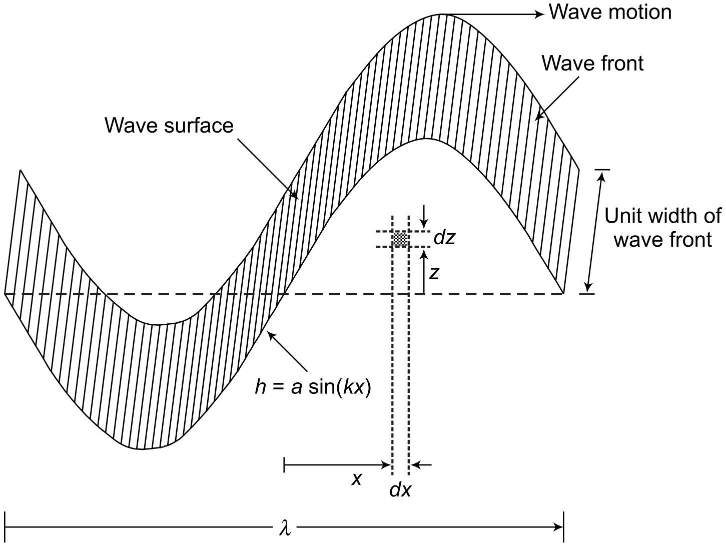


Figure 10.10 Wave surface of one wave length and unit width at any instant of time

Example 10.3

A deep ocean wave of 2 m peak to peak appears at a period of 8 s. Find the wavelength, phase velocity and power associated with the wave. At this power rate, what is the average annual wave energy in MWh/m?

Solution:

Given: Amplitude $a = 2/2 = 1$ m

Period, $T = 8$ s

Density of sea water may be assumed as, $\rho = 1025$ kg/m^3

Angular frequency can be calculated as: $\omega = 2\pi/T = 0.78539$ rad/s

From Eq. (10.3):

$$\frac{2\pi g}{\omega^2} = 99.9238 \text{ m}$$

The phase velocity of the wave can be calculated from Eq. (10.5) as:

$$v = \frac{g}{\omega} = 12.49 \text{ m/s}.$$

Power in wave can be calculated using Eq. (10.9)

$$\frac{\rho g^2}{8\,\pi} a^2 T = \frac{1025 \times 9.81^2}{8\pi} \times 1^2 \times 8 = 31399 \text{ W/m} = 31.399 \text{ kW/m}$$

Average annual wave energy at the site = $31399 \times 24 \times 365 \times 10^{-6}$ = 275 MWh/m

10.3.2 Wave Energy Technology

Energy in the waves is harnessed basically in the form of mechanical energy using wave energy converters, also known as wave devices or wave machines. A wave device may be placed in the ocean in various possible situations and locations. The fluctuating mechanical energy obtained is modified/smoothed out to drive a generator. Wave energy devices may be classified in various ways. Depending upon the location of these devices, it can be classified as (i) off shore or deep-water (water depth of 40 m or more) devices and (ii) shoreline devices. The availability of wave power at deep ocean sites is three to eight times that of adjacent coastal sites. However, the cost of construction/installation, operation and power transmission is quite large. Shoreline devices on the other hand have the advantage of relatively easier maintenance and installation and they do not require deep-water moorings and long underwater cables. Depending upon the position with respect to sea level they are classified as: (i) floating, (ii) submerged and (iii) partly submerged devices. Submerged devices have the benefit of avoiding the worst storm conditions but have increased difficulties of maintenance.

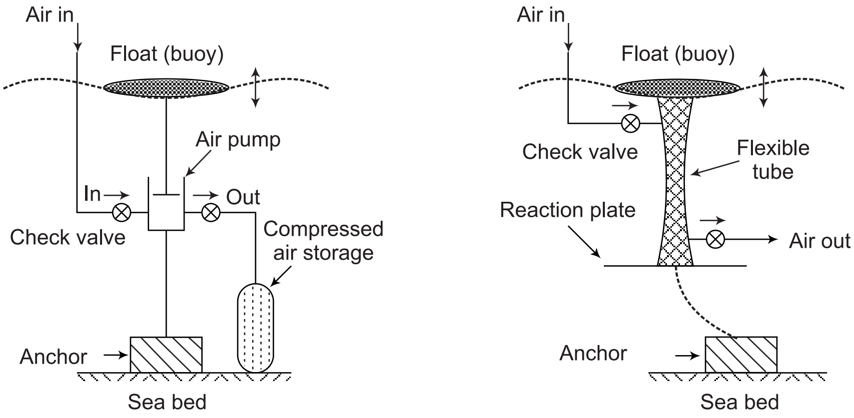
Depending on the actuating motion used in capturing the wave power, these devices are classified as: (i) heaving float type, (ii) pitching type, (iii) heaving and pitching float type, (iv) oscillating water column type and (v) surge devices. For each of these types several designs have been developed and tested with many more still at the design stage. Some designs will be discussed here:

1. Heaving Float Type

A float (buoy) placed on the surface of water heaves up and down with waves due to rise and fall of water level. The resulting vertical motion is used to operate the piston of an air pump through linkage. The pump may be anchored or moored to seabed. Several float-operated air pumps are used to store energy in compressed air storage. The compressed air is used to generate electricity through air turbine coupled to a generator.

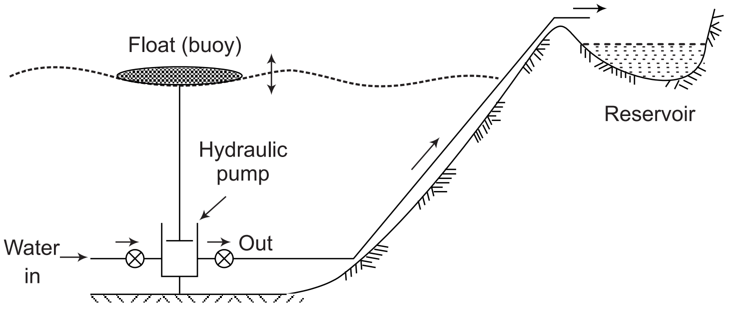
Power may also be extracted from a buoy by means of an internally suspended weight, with high inertia but free to swing. Energy is extracted from differential motion of buoy and pendulum.

In another version, hydraulic pump is operated by the motion of buoy to raise water to an onshore reservoir and passed through a turbo-generator to generate electricity. In a Swedish design a submerged flexible tube attached to buoy is used as air pump. Motion of buoy stretches the tube, decreasing its volume to provide the pumping action. These designs are shown in Fig. 10.11.



(a) Float with air pump

(b) Float with flexible tube air pump



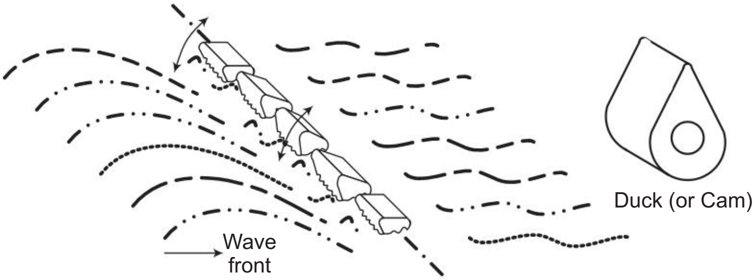
(c) Float with hydraulic pump

Figure 10.11 Heaving float type devices

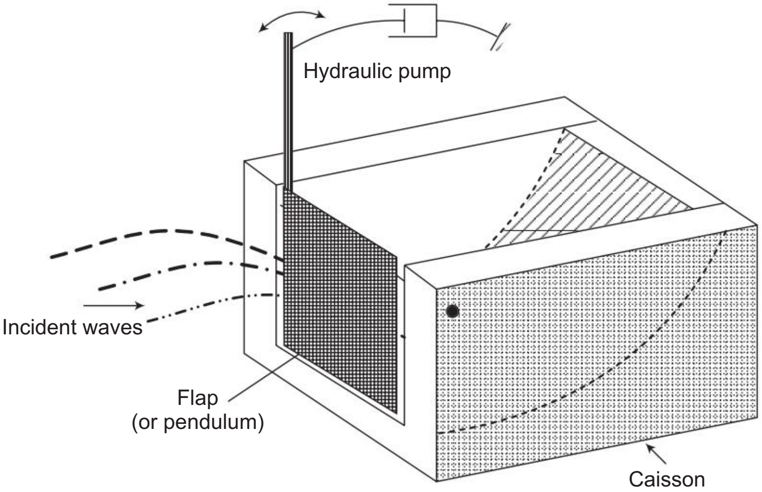
2. Pitching Type

In pitching type devices, the waves strike horizontally on a floating piece or flap causing it to deflect. In one such model several cam shaped floating pieces (known as nodding ducks) are hinged to a common flexible linkage or spine to form nodding duck assembly. A wave entering from left turns the beak of the duck in the direction of motion. The duck swings backward with trough of the wave once the peak has passed over it. It then oscillates about its axis. The shape of the duck is optimized to extract maximum power. The ratchet and wheel mechanism converts the motion of the ducks to common shaft. Power collected by individual duck is thus pooled to drive generator through linkages and gears. Main advantage of this system is that during unusually large wave the duck can flip over and recover again.

In another design, a pendulum flap is hinged over opening of a terminating rectangular box. The action of the waves causes it swing back and forth. This motion is then used to power a hydraulic pump and generator. These designs are shown in Fig. 10.12.



(a) Nodding ducks assembly



(b) Pendular device

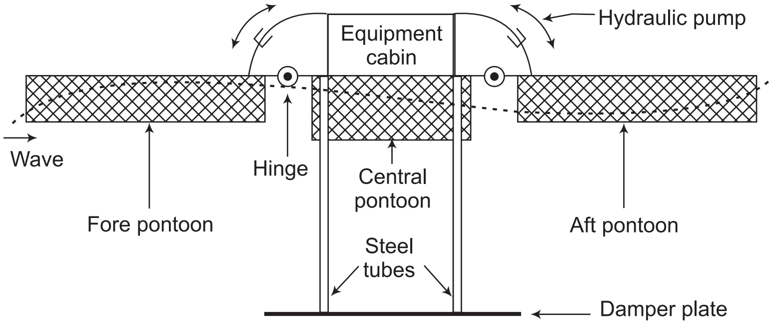
Figure 10.12 Pitching type devices

3. Heaving and Pitching Float Type

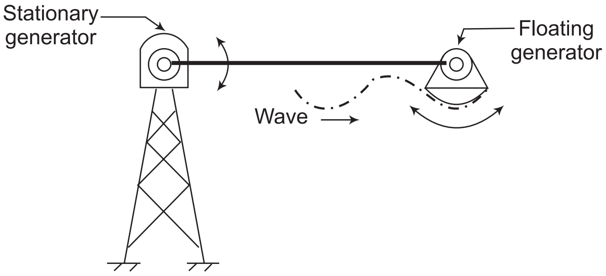
Pitching and heaving motion of a float can also be used to extract wave energy. Several designs have been tried. A system consisting of three pontoons, which move relative to each other in the wave, is shown in Fig. 10.13 (a). A damper plate is attached to central pontoon, which ensures that it stays still as the fore and aft pontoon move relative to central pontoon by pitching about the hinges. Energy is extracted by hydraulic pumps attached to hinges. Electricity can be generated via a hydraulic turbine and generator.

The idea of three pontoons system is further modified to form "Pelamis Wave Energy Converter". In this design a number of semi-submerged cylindrical sections (known as "Pelamis") are joined with flexible linkages to follow surface wave profile. The sections articulate with the movement of the waves, each resisting motion between it and the next section, creating pressurized oil to drive a hydraulic ram which drives a hydraulic motor. The machine is long and narrow (snake-like) and points into the waves; it attenuates the waves, gathering more energy than its narrow profile suggests. Its articulating sections drive internal hydraulic generators (through the use of pumps and accumulators).

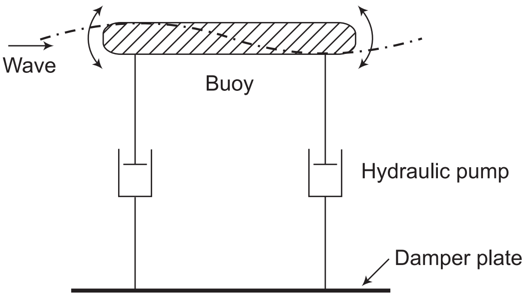
A specially shaped float known as Dolphin rides the wave and rolls as well as heaves as the wave passes. The two motions are converted to unidirectional motion by ratchets wheel arrangement and used to operate floating and stationary generators respectively. In another very simple design a large float is used to produce differential motion between two extreme sides of the float. The motion can be used to operate hydraulic pump. These concepts are shown in Fig. 10.13.



(a) Three pontoon with hydraulic pump



(b) Buoy dolphin



(c) Large buoy to cause differential motion

Figure 10.13 Heaving and pitching float type devices

4. Oscillating Water Column Type

This device comprise a partly submerged concrete or steel structure, which has an opening to the sea below the water line, thereby enclosing a column of air above a column of water. The wave impinging on the device causes the water column to rise and fall, which alternately compresses or depressurizes the air column. The air is allowed to flow through a turbine, which drives the generator. The specially developed axial flow Well's turbine, which operates with either directions of airflow, is used to extract energy as shown in Fig. 10.14. Conventional (unidirectional) air turbine with rectifying valves can also be used. Main advantages of oscillating water column device are: (i) the air velocity can be increased by reducing the cross section area of the air channel. Thus the slow wave motion can be coupled to high-speed turbine motion. (ii) generating equipment are kept away from immediate saline water environment.

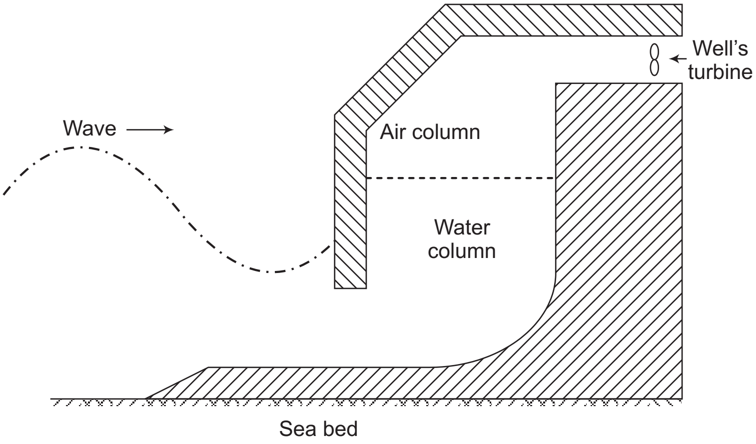


Figure 10.14 Oscillating water column device

5. Surge Devices

When a moving wave is constricted a surge is produced raising its amplitude. Such a device is known as tapered channel device (TAPCHAN) and shown in Fig. 10.15. The TAPCHAN comprises a gradually narrowing channel with wall heights typically 3 to 5 m above sea level. The waves enter from the wide end of the channel, and as they propagate towards narrower region, the wave heights get amplified until the crests spills over the walls to a reservoir, which provides a stable water supply to a low head turbine. The arrangement can be implemented successfully at low tide sites only.

An offshore, floating wave power vessel having TAPCHAN plant on a steel platform is suggested to make the system insensitive to tidal range.

10.3.3 Present Status

Seacoasts with exposure to prevailing wind and long fetches are likely to have the greatest wave energy density. The United Kingdom, the west coast of United States and the south coast of New Zealand have good wave climate. Some of the important sites of the world along with wave energy potentials are indicated in Fig. 10.16.

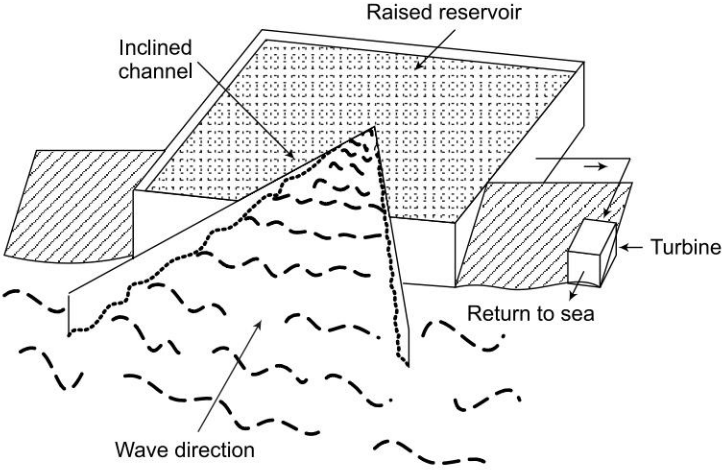


Figure 10.15 Tapered channel device

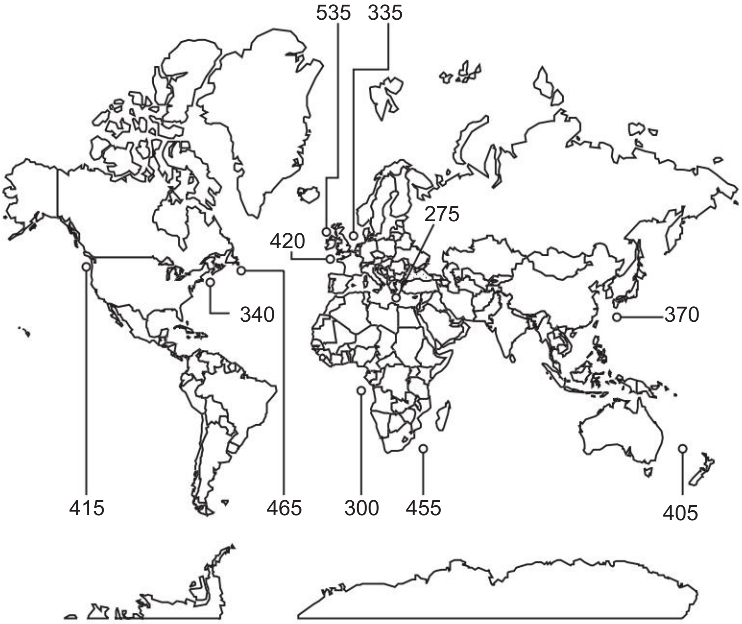


Figure 10.16 Average annual wave energy at some locations in MWh/m

Wave energy is passing through R & D phase and has not reached maturity from several points of view. Main countries involved in its development are Denmark, India, Ireland, Japan, Norway, Portugal, UK and USA. These efforts have largely been uncoordinated and so a wide variety of technologies have emerged. Some of them have been deployed in the sea as demonstration schemes.

Large-scale offshore devices are likely to remain uneconomical in near future. Development of small-scale modular shoreline devices at shore-based sites seems to become more economical and competitive. Few small-scale devices are already operating satisfactorily.

Wave power projects are planned or committed in various regions, mainly as demonstration plants. Two 1 MWe TAPCHAN plants are under installation, one in Indonesia and the other on an island off the coast of Tasmania. Also 1 MWe multi-resonant oscillating water column unit is to be installed in Tonga. Oscillating water column plants of 75 and 50 kWe have been built in UK and Japan respectively. In July 2008, the world's first commercial wave farm was commissioned in Portugal, at the Agucadora Wave Park, which consists of three 750 kilowatt Pelamis devices. The wave farm was shut down in November 2008 as a result of the financial collapse of Babcock & Brown due to the global economic crisis

Wave energy program was started in India in 1983 with preliminary studies at IIT Chennai. Initial research concluded that oscillating water column (OWC) was the most suitable for Indian conditions. A 150 kW pilot OWC plant was built onto the breakwater of the Vizhingam Fisheries Harbour, near Trivendrum (Kerala) in 1991. The scheme operated successfully, producing data that were used for the design of a superior generator and turbine. This has led to installation of improved power module in 1996. A plant of total capacity of 1.1 MWe comprised of 10 caissons is being developed at the same site.

10.3.4 Environmental Impacts

Wave power is essentially non-polluting. No appreciable environmental effects are foreseen from isolated floating wave power devices. However, onshore wave energy installations may change visual landscape and degrade scenic ocean front views. It may also cause disturbance to marine life including changes in distribution and types of life near the shore, and possible threat to navigation from collision due to low profile floating wave devices. It would usually be both possible and necessary to avoid hazards to or from marine traffic by judicious sitting and by provision of navigation aids.

10.4 OCEAN THERMAL ENERGY

Ocean thermal energy exists in the form of temperature difference between the warm surface water and the colder deep water. A heat engine generates power utilizing well-established thermodynamic principle, where heat flows from high temperature source to low temperature sink through engine, converting a part of the heat into work. In the present case the surface water works as heat source and deep water as heat sink to convert part of the heat to mechanical energy and hence into electrical energy. The facility proposed to achieve this conversion is known as OTEC (ocean thermal energy conversion). A minimum temperature difference of 20 °C is required for practical energy conversion. The resource potential is expected to be many terawatts. Main advantages of OTEC are: (i) the resource supplies steady power without fluctuations and independent of vagaries of weather, (ii) the availability hardly vary from season to season, (iii) at a suitable site the resource is essentially limited only by the size of the system, (iv) the required machinery requires only marginal improvements in well-tried engineering devices, e.g. heat exchanger, turbine, etc. No dramatically new or physically impossible devices are required and (v) it also has the ability to create some useful by products such as desalinated water and nutrients for mariculture. Major disadvantages are: (i) low efficiency and (ii) high installation cost.

The possibility of using ocean water temperature difference to produce power was first conceived by a French physicist d'Arsonval in 1881 and verified by one of his student Claude on a test plant in Cuba in 1929. Subsequently French scientist constructed two more OTEC plants, one on a ship stationed near Brazil and the other stationary plant off the West African coast. The process did not attract further attention until 1970s, when the rising oil prices and perception of resource scarcity triggered serious development efforts. Since that time, some progress has been made in OTEC technology. Active developments are underway in France, USA and Japan.

10.4.1 Origin and Characteristics of Resource

The origin of OTEC may be traced to solar radiation on ocean surface. In fact the ocean is the world's largest solar collector. Therefore, the resource is virtually inexhaustible source of energy. Absorption of solar energy in water takes place according to Lambert's law of absorption. This law states that each layer of equal thickness absorbs the same fraction of light that passes through it. Expressing mathematically:

$$-\frac{d\,I(x)}{dx} = k\,I\,(x)$$

or

$$I\,(x) = I_0\,e^{-k\,x} \tag{10.11}$$

where I_0 and $I(x)$ are intensities of radiation at the surface (i.e. $x = 0$) and at depth x from the surface. The factor k is known as extinction coefficient or absorption coefficient. The value of k for very salty seawater is 0.5 m^{-1} (for clear fresh water $k = 0.05\ \text{m}^{-1}$). At this rate, more than 95 per cent absorption occurs within a depth of 6 m. Thus almost all the absorption occurs very close to the surface raising its temperature while deep water at about 1000 m or so remains cool and unaffected by the solar radiation. There will be no thermal convection currents between the warmer, lighter water at the surface and cooler, heavier deep water. Also heat transfer through thermal conduction across the large depth is too low. Thus mixing is retarded and so warmer water stays at the top providing a huge heat source while cold water stays at depth providing a huge heat sink. Both reservoirs are maintained annually by solar radiation.

In most tropical and some subtropical areas the surface temperature may reach 27 °C while at 1-km depth water stays at about 4 °C, providing a potential energy generation opportunity. Unlike tidal and wave energy, OTEC is a source of firm power. Such plants can operate indefinitely and are well suited to base load generation. The best sites are in the tropical belt between about 20° N and 20° S latitude. There are, however, several locations outside this area that might be suitable for OTEC plants. Some of these are in the Gulf Steam off the Florida coast, in the Gulf of Mexico and near the Hawaiian Islands.

Let us establish simplified mathematical expression for an ideal system to get an idea of the effect of temperature difference, flow rate etc. on the output. The working fluid undergoes a temperature difference of ΔT, between source temperature T_h and sink temperature T_s. Thus $\Delta T = Th - T_s$. The heat flow rate can be given as:

$$P_i = \rho Q s \Delta T$$

where ρ is density of seawater, s is specific heat of water and Q is working fluid flow rate. The mechanical power available from the heat engine,

$$P_o = \eta_{\text{carnot}} P_i$$

The efficiency of an ideal Carnot engine is given by $\eta_{\text{carnot}} = \Delta T / T_h$

Thus mechanical output power of an ideal Carnot engine is:

$$P_o = \frac{\rho s Q}{T_h} (\Delta T)^2 \tag{10.12}$$

The output available from practical real heat engine will be substantially less than this as it cannot follow ideal Carnot cycle and the temperature range of working fluid will be less than ΔT due to non-idealness of heat exchanger (evaporator, condenser, etc.).

As per Eq. (10.11), the output is proportional to the square of temperature difference and directly to the flow rate of working fluid. Let us calculate the required flow rate for a 10 MW OTEC plant for T_h = 24 °C, T_s = 4 °C, from Eq. (10.11),

$$Q = \frac{(10 \times 10^6) \times (24 + 273)}{1025 \times (4.2 \times 10^3) \times 20^2} = 1.7 \text{ m}^3/\text{s} = 6209 \text{ tons/h}$$

Thus for a 10 MW plant the required flow rate will be 6209 tons/h. This would require pumping of large quantities of water. Also very large size heat exchanger, evaporator, condenser and turbine are required to handle bulk amount of fluid. Note that 10 MW is only about one hundredth of the size of modern coal fired or nuclear power plant. Also the theoretical maximum efficiency for T_h = 24 °C and ΔT = 20 °C is 6.7 per cent. Attained efficiency after providing auxiliary loads (pumping, etc.) is about 2.5 per cent.

10.4.2 Ocean Thermal Energy Conversion Technology

OTEC plants can operate on open and closed cycles. In open cycle (also known as Claude cycle) plant, warm water from the ocean surface is flash evaporated under partial vacuum. Low-pressure steam obtained is separated and passed through turbine to extract energy. The exhaust of turbine is condensed in direct contact condenser. Cold water drawn from a depth of about 1000 m is used as cooling water in direct contact condenser. The resulting mixture of used cooling water and condensate is disposed in the sea. If surface contact condenser is employed, the condensate could be used as desalinated water. Thus an open loop OTEC plant can provide a substantial quantity of desalinated water. The scheme is shown in Fig. 10.17.

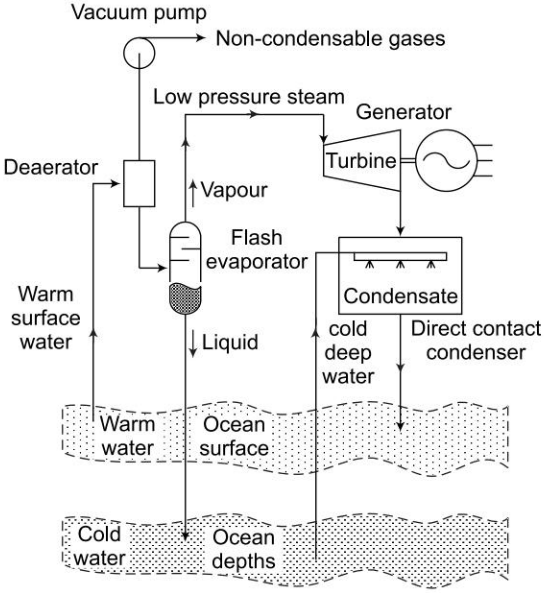


Figure 10.17 Open cycle OTEC plant

In closed cycle (also known as Anderson cycle) plant, warm surface water is used to evaporate a low boiling point working fluid such as ammonia, freon or propane. The vapor flows through the turbine and is then cooled and condensed by cold water pumped from the ocean depths. Because of low quality heat a large surface areas of heat exchangers (evaporator and condenser) are required to transfer significant amount of heat and large amount of water need to be circulated. The schematic diagram of closed loop OTEC plant is shown in Fig. 10.18. The operating pressures of the working fluid at the boiler/evaporator and condenser are much higher and its specific volume is much lower as compared to water in open cycle system. Such pressures and specific volumes result in turbine that is much smaller in size and hence less costly as compared to that in open cycle system. Although both systems are being explored, the closed cycle system appears to be more promising in near future.

Both open and closed cycle plants can be mounted on a ship or built on shore. The ship option requires submarine power cable for power transport. However, if the plant is located far (more than about 50 km) from shore the transmission cost becomes prohibitive. Alternatively for a plant, which is hundreds of kilometers from shore, it has been suggested to use electricity on board to produce chemical storage of energy (e.g. H_2). The hydrogen could be liquefied and transported by tanker to point of use. The shore option is feasible only at certain favorable locations, where the sea bottom slopes sharply downwards. Their main advantage is lower cost of installation, operation and maintenance.

In both open and closed cycle, cooling water taken from the sea depth is nutrient-rich and can be diverted to lagoon to develop mariculture after utilizing its cooling effect.

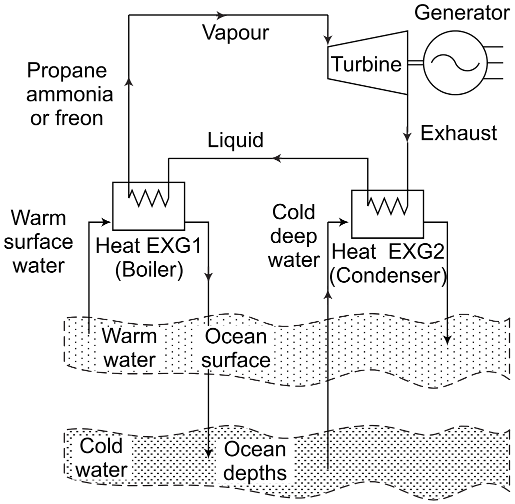


Figure 10.18 Closed cycle OTEC plant

10.4.3 Present Status

A 50 kWe floating closed cycle test plant was installed off Hawaii in 1979. The Tokyo Electric Power Co. built and operated a 100-kWe shore based closed cycle plant in the Republic of Nauru. Encouraged by the performance of this plant the company is now planning a 20 MWe on the same island of Nauru. The Japanese Government is designing a 10 MWe floating plant and also considering a land-based plant. Several other countries are designing/proposing pilot OTEC plants. Commercialization of OTEC will require demonstration of technical performance, reliability and cost effectiveness. Currently the only continuously operating OTEC system is located in Okinawa Prefecture, Japan.

In India, conceptual studies on OTEC plant for Kavaratti (Lakhshadweep island), Andaman Nicobar Islands and at Kulasekharapatnam (Tamil Nadu) were initiated in 1980. A preliminary design for 1 MWe (gross) closed Rankine cycle floating plant was prepared by IIT Chennai in 1984. In 1997, National Institute of Ocean Technology (NIOT) signed a memorandum of understanding with Saga University, Japan for joint development of 1 MW plant of earlier studies near the port of Tuticorin (Tamil Nadu). The objective is to demonstrate the OTEC plant for one year, after which it could be moved to the Andaman Nicobar Islands for power generation. NIOT plans to build 10–25 MW shore based plants in due course by scaling up the 1 MW test plant and possibly a 100 MW range of commercial plant thereafter. In 2002, India tested a 1 MW floating OTEC pilot plant near Tamil Nadu. The plant was ultimately unsuccessful due to a failure of the deep-sea cold water pipe.

10.4.4 Environmental Impacts

A number of potential environmental impacts due to use of OTEC have been identified as follows:

(i) It is feared that biota including eggs, larvae and fish could be entrained and destroyed due to intake and expulsion of large volumes of water. Appropriate siting of intake may reduce the problem.

(ii) Changes in local temperature and salinity might also effects the local ecosystem, impact coral and influence ocean currents and climate.

(iii) In open cycle OTEC system, CO_2 dissolved in warm water is released to atmosphere. However, the quantity of CO_2 released is very small and under worst conditions would be only 1/15 that of oil or 1/25 that of coal based generation of same power. It could be reinjected into warm water discharge.

(iv) Release of large quantities of cold water into warmer surface environment will also have biological effects, which are yet to be known. Actual environmental impacts will have to be estimated from small-scale trials.

The deposition and growth of microorganisms inside the pipes of evaporator and condenser heat exchanger is known as *biofouling*. Biofouling reduces the heat transfer efficiency and thereby lowers the performance. Such biofouling is one of the major problems in OTEC design, since increasing the surface area available for heat transfer also increases the opportunity for microorganisms to attach themselves. Among the methods being tried to keep the fouling under control are mechanical cleaning by continuous circulation of close fitting balls and the chemical cleaning (chlorination) by additives to the water. Use of biocides to prevent fouling is cited as a source of pollution, but the release of chlorine can be held to about 1/10 the limit allowed by environmental protection agency.

REVIEW QUESTIONS

1. What is the source of tidal energy? What is the minimum tidal range required for a practical tidal plant? How much is the potential in tides?
2. What are the main hurdles in the development of tidal energy?
3. Comment on the variation of tides with location.
4. What do you understand by spring and neap tides? How are they caused?
5. What is the effect of pumping on the output of the tidal plant?
6. Where is the largest tidal plant located? Give its details?
7. What are the potential sites for tidal energy in India?
8. What is the present status of tidal current energy development?
9. What are the main advantages and disadvantages of ocean wave energy?
10. What types of sites are considered suitable for wave power development?
11. Explain the operation of oscillating water type of wave device.
12. What are the main advantages and disadvantages of OTEC system?
13. Explain the technologies available for OTEC.
14. What are relative advantages and limitations of floating and shore based OTEC plants?
15. What are the environmental impacts of OTEC?
16. What do you understand by biofouling? How is the problem handled?

17. Draw a schematic layout of linked basin tidal plant and explain its operation.

18. Derive an expression for average annual wave energy at a particular site.

19. Explain the present status of development of ocean energy resources.

PROBLEMS

1. A single basin type tidal power plant has a basin area of 3 km^2. The tide has an average range of 10 m. Power is generated during flood cycle only. The turbine stops operating when the head on it falls below 3 m. Calculate the average power generated by the plant in single filling process of the basin if the turbine generator efficiency is 0.65. Estimate the average annual energy generation of the plant

(*Ans.* 39.93 MW, 1.75×10^8 kWh)

2. Water is pumped rapidly from the ocean into the basin at high tide to give an increased water level of 1 m in a tide power basin. If tidal range is 5 m and the efficiency of pump/generator system is only 60%, find the energy gain due to use of pumping.

(*Ans.* 164%)

3. A deep ocean wave of 2.5 m peak to peak appears at a period of 10 s. Find the wavelength, phase velocity and power associated with the wave. At this power rate, what is the average annual wave energy in MWh/m?

(*Ans.* 156.14 m, 15.61 m, 61.3256 kW/m, 537.2 MWh/m)

OBJECTIVE TYPE QUESTIONS

1. The tidal range:
(a) remains constant throughout the lunar month
(b) is maximum in the middle of the lunar month and minimum by the end (also start) of the month
(c) is minimum in the middle of the lunar month and maximum by the end (also start) of the month
(d) is maximum in the middle and end (also start) of the lunar month and minimum in the first and third quarter of the lunar month

2. The turbine used in a tidal range plant is:
(a) Pelton turbine
(b) Kaplan turbine with variable pitch blades
(c) Kaplan turbine with fixed pitch blades
(d) Francis turbine

3. Pumping of water from ocean to basin during high tide:
(a) increases the net energy generation
(b) decreases the net energy generation
(c) helps in uniform power generation
(d) deceases the net tidal range

4. Minimum tidal range required for power generation is about:
(a) 1 m
(b) 5 m
(c) 10 m
(d) 20 m

5. Two basin tidal schemes:
   (a) are more economical than single basin schemes
   (b) operate on ebb cycles in both basins
   (c) produce less uniform power
   (d) produce more uniform power

6. Power in waves is:
   (a) directly proportional to the square of its amplitude and to the period of motion
   (b) inversely proportional to the square of its amplitude and to the period of motion
   (c) directly proportional to the square of its amplitude and inversely proportional to the period of motion
   (d) inversely proportional to the square of its amplitude and directly proportional to the period of motion

7. The energy flux in waves is:
   (a) less than that in wind energy
   (b) more than that in wind energy
   (c) comparable to that in wind energy
   (d) more than that in wind energy but less than solar energy

8. Deep-water surface waves are those where:
   (a) water depth is more than 1000 m
   (b) water depth is more than 100 m
   (c) water depth is more than the wavelength
   (d) water depth is more than about half the wavelength

9. Wave energy is basically harnessed in the form of:
   (a) thermal energy (b) chemical
   (c) mechanical energy (d) electrical energy

10. In pitching type wave energy conversion machines:
   (a) the wave strikes horizontally
   (b) the wave strikes vertically
   (c) the wave moves the float up and down
   (d) None of the above

11. The minimum temperature difference between source and sink required by a practical heat engine is:
   (a) 540 °C (b) 120 °C
   (c) 10 °C (d) 20 °C

12. OTEC is characterized as having:
   (a) high efficiency and low installation cost.
   (b) low efficiency and high installation cost.
   (c) low efficiency and low installation cost.
   (d) high efficiency and high installation cost.

13. In tropical regions the ocean surface temperature may go as high as:
   (a) 80 °C (b) 40 °C
   (c) 17 °C (d) 27 °C

14. Compared to open cycle system a closed cycle OTEC system:
   (a) has higher working pressure in boiler/turbine and lower specific volume of working fluid
   (b) has lower working pressure in boiler/turbine and higher specific volume of working fluid
   (c) has higher working pressure in boiler/turbine and higher specific volume of working fluid

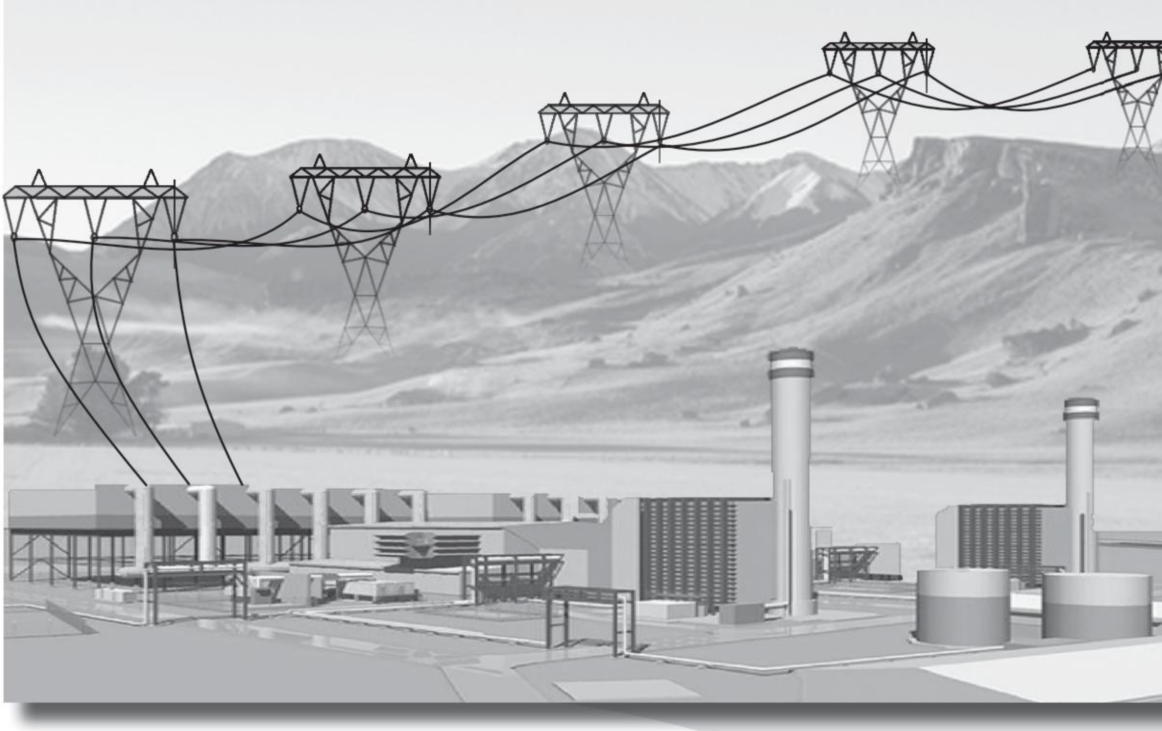
(d) has lower working pressure in boiler/turbine and lower specific volume of working fluid

15. Ocean thermal energy conversion system to generate power is most suitable in:
(a) sub-tropical region (b) tropical region
(c) cold region (d) moderate climate region

16. Ocean waves are indirectly caused by:
(a) gravitational force of moon (b) gravitational force of sun
(c) solar energy (d) geothermal energy

17. The total energy of a sea wave is the sum of its:
(a) potential energy and hydro energy
(b) potential energy and kinetic energy
(c) mechanical energy and thermal energy
(d) kinetic energy and thermal energy

18. Tidal waves are caused by the periodic rising and falling of oceans associated with the:
(a) position of moon (b) position of earth
(c) position of mountains (d) position of the sea



CHAPTER 11

Small Hydro Resources

Learning Objectives

In this chapter you will be able to:

- Recognize the nature and characteristics of small hydro resources
- Analyse the technologies of harnessing the small hydro resources
- Appraise the present status and future prospects of these technologies

11.1 INTRODUCTION

The force of falling water has been mankind's important source of power and energy through the ages. Hydropower has been harnessed to do useful work – to grind grain, saw lumber and provide power to do other tasks. The Greeks used vertical axis water wheels as early as 85 BC and horizontal axis wheels from about 15 BC. The origins of water wheels can also be traced back to ancient Egypt, Persia and China where these were used for irrigation as well as grinding grain or flour. Hydropower was the only source of mechanical energy (other than wind) until the development of the steam engine in the nineteenth century. The early hydraulic units were relatively small and their outputs rarely exceeded few hundred kilowatts.

Hydropower is the most established renewable resource for electricity generation. Large-scale hydropower is a well-established, mature and proven technology. However the concept of small hydro resources is recent and is expanding very fast.

In large-scale surveys and studies the potential for small-scale generation from rivers has been greatly neglected due to techno-economic reasons. Recently, due to advancements in the design of low head turbines, improvements in construction technology and availability of better control techniques, small hydro resources have also become viable. Environmental factors are also important and cannot be judged by global surveys but only by evaluating local conditions. About 18 per cent of potential large-scale hydropower sites have already been developed and there is strong opposition from environmentalists for the development of remaining sites. Small hydro resources are largely free from such environmental effects and, therefore, their potential is increasingly being utilized.

Small hydro plants (SHPs) projects include those installations that have low head (generally under 40 m) and small capacity. There is no international consensus on the definition of small hydropower. Different countries are following different norms keeping the upper limit ranging from 5 to 50 MWe. In India, hydropower projects of ratings less than about 25 MWe are regarded as SHPs. They are considered as non-conventional as they have been conceived and built after oil crisis of 1973. Major differences between a small and large hydro plants are that the former can be designed and built by local staff and smaller organizations using 'off-the-shelf' components or locally made machinery. It has standard designs for plant components, and often not connected to grid and usually meant for local use. The later on the other hand is grid connected and requires a tailor made design for each particular scheme, often have very expensive equipment and staff cost to maintain the grid.

Depending on the capacities these plants are classified as, micro (less than 100 kWe), mini (100 kWe-1 MWe) and small (1 MWe-25 MWe). These boundaries however, are not very rigid. At the low end of the range, simplicity of design and control is usually essential for economic viability, even at the expense of efficiency of operation. However, at the high end of the range, the magnitude of the investment is likely to warrant fairly sophisticated protection and control devices. Micro, hydro schemes are used in remote areas where the grid does not exist. Typically it provides power to just one rural industry or one rural community with power as small as 200 W. Mini and small schemes sometimes make small contribution to national grid supplies.

The small/mini/micro schemes are further classified as: (i) storage and (ii) run-of-the-river schemes. A storage scheme makes use of a dam to stop river flow, building up a reservoir of water behind the dam. The water is then released through turbines when power is needed. The advantage of this approach is that rainfall can accumulate during the wet season of the year and then release power during some or all of the drier periods of the year. A run-of-the-river scheme does not stop the river flow, but instead diverts a part of the flow into a channel and pipe and then through a turbine.

Micro-hydro schemes are almost always run-of-the-river type. The disadvantage of this approach is that water is not carried over from rainy to dry seasons of the year and generation depends on availability of flow. The advantages are: (i) the scheme can be built locally at low cost, and its simplicity gives rise to better long-term reliability, (ii) the environmental damage is negligible, as river flow pattern downstream of the plant is not affected, (iii) also there is no flooding upstream of the plant, (iv) the scheme does not displace large number of people as large projects with big dams sometimes do.

11.2 ADVANTAGES AND DISADVANTAGES OF SMALL HYDRO SCHEMES

Advantages

(i) Hydroelectric energy is a continuously renewable energy source.

(ii) It is a much more concentrated energy resource than either wind or solar power.

(iii) Hydroelectric energy is non-polluting—no heat or noxious gases are released.

(iv) Hydroelectric energy has low operating and maintenance costs, it is essentially inflation proof.

(v) Hydroelectric energy technology is a proven technology that offers reliable and flexible operation.

(vi) Small hydro plants can be tailored to the needs of the end use market within the limits of water resources available.

(vii) It serves to enhance economic development and living standards, especially in remote areas with limited or no electricity at all.

(viii) For small hydro plants the civil work does not need elaborate construction work. Also, no expensive powerhouse or highly optimized electromechanical equipment are required.

(ix) It has short gestation period.

(x) A small hydro plant requires few operating personnel, some of them being operated entirely by remote control.

(xi) There is no need of long transmission lines because the output is consumed near the source.

(xii) High performing electrical equipment (alternator, control circuit, battery storage, regulator, etc.) can be easily found in the market.

(xiii) The possibility of retrofits and additional turbines and generators makes the upgrading of existing installations attractive.

Disadvantages

(i) Hydro systems, unlike solar components for example do require some maintenance.

(ii) The quality of small power station is not as good as that of bigger one as these power plants are generally designed on the basis of short term raw data. Thus the ground conditions of operation are much different from those considered for the design.

(iii) Majority of SHPs are located in remote places and not connected with the grid. Therefore, transmission of surplus power to other places is not possible. Therefore, during low demand period, they continue to operate at low load factor that leads to loss of power generation which in turn results in poor revenue collection.

(iv) In the absence of adequate hydrological and geological data there are always uncertainties about its potential as a resource. Also, once commissioned there is no surety of a buyer at a rate that is comparable to the outcome of the investment. Due to these reasons private developers avoid to have a stake in small hydro.

(v) The rotation of turbines can kill fishes, especially young fishes swimming downstream.

(vi) Spilling of water over spillways can result in super saturation of water with gases from the air. The gas bubbles, absorbed into fish tissue, may cause damage and ultimately kill the fish.

(vii) Most hydroelectric facilities require construction of dam. Dams present a migratory barrier that can affect the free movement of fish species and their reproduction cycle. However, the effects upon stream ecology are minor compared to those caused by large hydroelectric facilities.

(viii) The existence of a reservoir can make the water becoming stratified, with warmer water collecting at the surface and cooler water lying at the bottom. In this way, the cold water is isolated from aeration and it loses its oxygen. Many species of fish cannot live in such environment due to low oxygen content and temperature.

11.3 LAYOUT OF A MICRO-HYDROSCHEME

The layout of a typical micro-hydro scheme is shown in Fig. 11.1. Main components of the scheme are: (i) diversion weir, (ii) water conductor system with regulating gates and spillways, (iii) desilting tank with spillway, (iv) head race channel, (v) forebay tank with desilting basin and spillway, (vi) penstock, (vii) power house and (viii) tail race channel.

11.3.1 Diversion Weir and Channel

Diversion weir is designed to divert and maintain constant flow in the channel for variable flow in the river through the year. If the channel overfills, damage will result. Special attention is required to save channel during seasonal flooding. The intake structure regulates the flow. Further control or regulation is provided by spillways.

Water conductor system is a channel between weir and desilting tank and between desilting tank and forebay. It should be designed to ensure least loss of head due to seepage and flow velocity should be adequate to prevent settling of silt. The most commonly used channel section is trapezoidal. The channel follows the contour of the hillside so as to preserve the elevation of the diverted water.

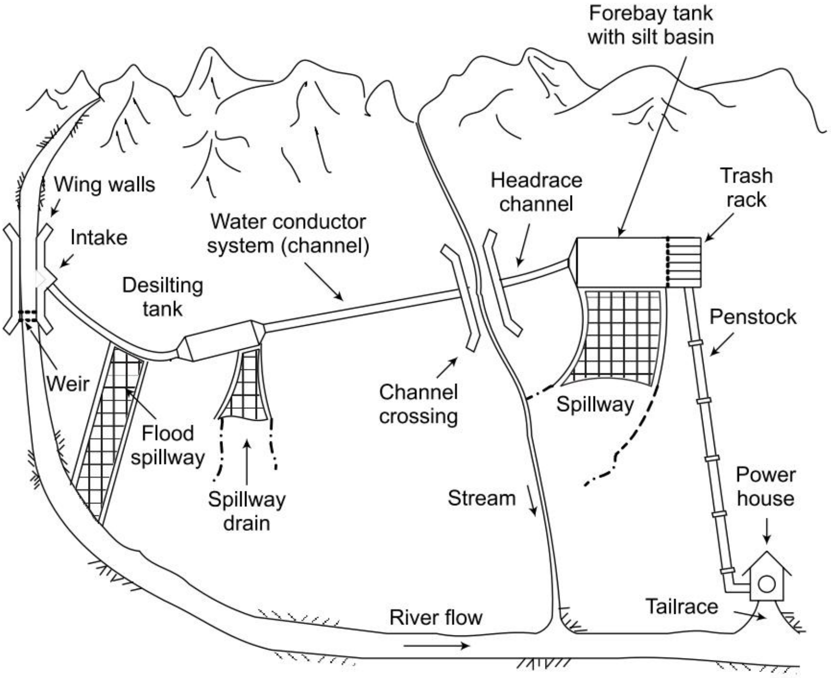


Figure 11.1 Typical layout of a microhydro power station

11.3.2 Desilting Tank

Desilting tank is usually provided in the initial reaches of water to trap the suspended silt load and pebbles, etc., so as to minimize erosion damages to the turbine runner. Abrasive effects become more pronounced with increasing head. The size of the silt particles to be trapped for medium head turbines is 0.2 to 0.5 mm and that for high head is 0.1 to 0.2 mm. The depth of silt tank may be 1.5 to 4 m and horizontal flow velocity should not exceed 0.4 to 0.6 m/s. The deposits of silt tank are periodically flushed out to make room for further deposition.

11.3.3 Forebay, Penstock and Tailrace

Forebay is a temporary storage of water (pondage), to be finally utilized for energy generation. Storage size ranges from 2 minute to 6 hours depending on the economic justifiability. Trash racks are also provided to prevent entry of trash, debris and ice, etc. Flow velocity through trash rack is kept at 0.6 to 0.9 m/s, so that there is no significant head loss. Penstock is a water conduit joining forebay and turbine. It should be sized such that frictional losses do not reduce the head unduly. A bell mouth entry is provided to reduce the head loss and to ensure smooth entry of water. Tailrace is a simple water channel to transport discharge from turbine back to the river with maximum flow of 1 m/s.

11.3.4 Power House

1. Speed Governor

The frequency and voltage of the generator output depends on shaft speed. Voltage variations up to 7 per cent are tolerable and may not adversely affect most of the loads. Frequency variations up to 5 per cent above rated value (but none below it) are considered as safe. In a small system, voltage and frequency may exceed these limits during switching operations for a short duration. To control the speed, governors are used. Traditional governors give high performance, but are too expensive to be justified in a micro-hydro plant (especially below 10 kW rating). Non-conventional approaches are usually used to reduce the cost. The quality of control is poor but it can still be adequate to satisfy most common end users. In one such approach the flow through the turbine is set at a constant value to keep the input power as constant. Therefore, mechanical input to the generator remains constant. The load imposed on the generator is also kept fairly constant. This requires a ballast (stabilizing) load across the generator, to be increased or decreased accordingly as the user load varies. The generated energy that is not used productively is wasted in ballast load (also known as dump load). An electronic load controller (ELC) is employed to perform this function. Thus electronic load controller ensures that the generator always supplies a constant electrical load. In this way both the mechanical input and electrical output remain constant and therefore, the speed remains constant. In this approach, the part of generated energy that is consumed in ballast load is wasted. For run-of -the-river schemes, this is irrelevant as there is no provision for storage of unused water for later productive use.

2. Turbine

A suitable turbine is used to get mechanical power at the shaft from flowing stream of water. Various types of turbines and their characteristics are discussed in Sections 11.4 and 11.5.

3. Generator

A generator coupled with turbines gives electrical output from mechanical input. The details of various types of generators used in SHPs are given in Section 11.6.

11.4 WATER TURBINES

Turbines convert available energy in the form of falling water into rotating shaft power. They operate on the principle of either ‘impulse’ (equal pressure on each side of the runner) or ‘reaction’ (pressure drops across the runner). A brief description of most common types of turbine is given here.

11.4.1 Impulse Turbines

In impulse turbines pressure energy is converted first in a nozzle into the kinetic energy of a high-speed jet of water, which is then converted to rotation in contact with the runner blades by deflection of water and change of momentum. The runner can operate in air and the water remains at atmospheric pressure before and after making contact with runner blades. It needs casing only to control splashing and to protect against accidents. The three impulse turbines considered here are the (i) Pelton, (ii) Turgo and (ii) cross flow (also known as Banki, Mitchell or Ossberger turbine).

1. Pelton Turbine

The Pelton Turbine consists of a wheel with a series of split buckets set around its rim as shown in Fig. 11.2. A high velocity jet of water is directed tangentially at the wheel. The jet hits each bucket and is split in half, so that each half is turned and deflected back almost through 180°. Nearly all the energy of the water goes into propelling the bucket and the deflected water falls into a discharge channel below. Care must be taken to allow plenty of space on either side of a Pelton runner to allow deflected water to exit without splash interference. For optimum efficiency the jet velocity needs to be about twice the speed of the bucket. The runner of such a turbine is large for the power produced. The use of two or more jets placed symmetrically around the rim will allow a smaller runner for a given flow of water and hence an increased rotational speed. The required power can still be attained.

Following options are available for control:

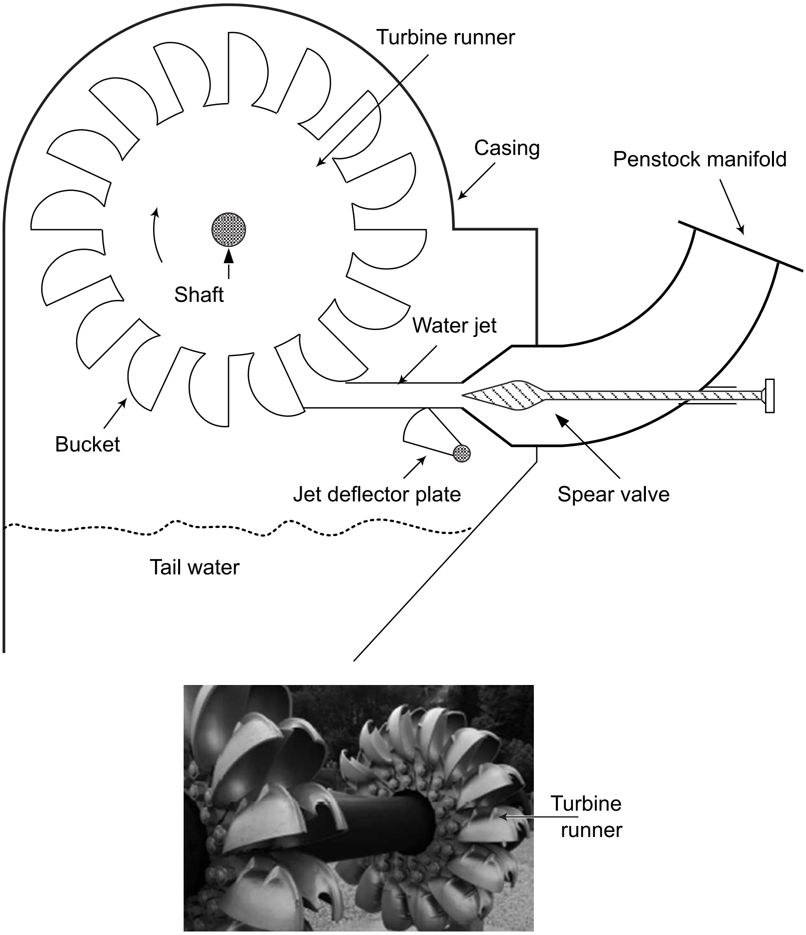
(a) *Replacement of nozzles*: It is possible to divide the yearly flow variation in two, three or more parts and make a nozzle for each flow. The turbine operator can then remove one nozzle and replace it with the desired nozzle. This is very low cost method of controlling the flow.

(b) *Spear valves*: A needle valve or spear valve (as shown in Fig. 11.2), which is so called because streamlined spearhead, is arranged to move within the nozzle, allowing variation in effective orifice cross section area without introducing energy loss.

(c) *Varying the number of jets*: If multi-jet turbine has shut off valves fitted on each of its jets, it can be run at different flow rates by simply altering the number of jets playing on the runner

(d) *Deflector plate*: The water jet can be deflected away from the buckets of the runner if a jet deflector plate (show in Fig. 11.2) is rotated into its path. This is very quick and does not require the shutdown of the flow in the penstock, with consequent pressure surge danger.

(e) *Shut-off valves*: It is usual to place a valve, either a gate valve or a butterfly valve, in the turbine manifold. However, certain precautions are to be observed on its use. Pelton wheels are often driven by long penstocks in which surge pressure effects, due to valve closure, can be very dangerous and lead to damage caused by bursting of the penstock. The valve must always be closed slowly, particularly during the last phase just before shut-off. Gate valves are sometimes used mistakenly to regulate flow, by partially closing them. This causes damage on the valve plate due to cavitation effects (explained in Section 11.5).



Courtesy: www.leonardo-energy.org [46]

Figure 11.2 Pelton turbine

2. Turgo Turbine

The Turgo turbine, shown in Fig. 11.3 is similar to the Pelton but the jet is designed to strike the plane of the runner at an angle (typically 20°) so that the water enters the runner on one side and exits on the other. Therefore, the flow rate is not limited by the spent fluid interfering with the incoming jet (as is the case with Pelton turbines). As a consequence, a Turgo turbine can have a smaller diameter runner than a Pelton for an equivalent power. It, therefore, runs at a higher speed. It shares the general characteristics of impulse turbines listed for Pelton.

Turgo does have certain disadvantages also. Firstly it is more difficult to fabricate it as compared to a Pelton wheel, since the buckets (or vanes) are complex in shape, overlapping and more fragile than Pelton buckets. Secondly, the Turgo experiences a substantial axial load on its runner which must be met by providing a suitable bearing on the end of the shaft.

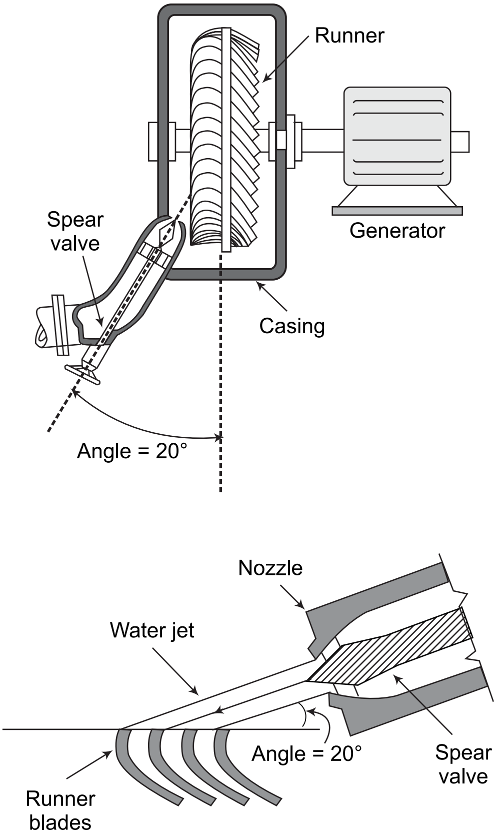


Figure 11.3 Turgo turbine

3. Crossflow Turbine

Crossflow turbines are also called Banki, Mitchell or Ossberger turbines. A Crossflow turbine, shown in Fig. 11.4, has a drum-shaped runner consisting of two parallel discs connected together near their rims by a series of curved blades. The shaft of the runner is always kept horizontal in all cases (unlike Pelton and Turgo turbines which can have horizontal as well as vertical orientations). In operation a rectangular nozzle directs the jet to the full length of the runner. The water enters the top of the runner through the curved blades imparting most of its kinetic energy. It then passes through the runner and strikes the blades again on exit, imparting a smaller amount of energy before falling away with little residual energy.

The effective head driving the cross flow runner can be increased by inducement of a partial vacuum inside the casing. This is done by fitting a draught tube below the runner which remains full of tail water at all times. Careful design of valve and casing is necessary to avoid conditions where water might back up and submerge the runner.

Because of symmetry of a crossflow turbine the runner length can theoretically be increased to any value without changing the hydraulic characteristics of the turbine. Hence, doubling runner length merely doubles the power output at the same speed.

The lower the head, the longer the runner becomes, and conversely on high heads the crossflow runner tends to be compact. There are, however, practical limits to length in both cases. If the blades are too long they will flex, leading quickly to fatigue failure at the junction of blade and disc. In case of short runner operating on high head, efficiency losses at the edges become considerable.

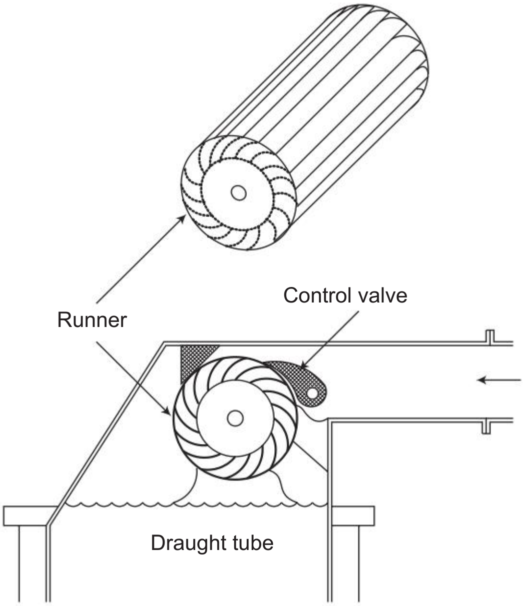


Figure 11.4 Crossflow turbine

Two major attractions in the crossflow have led to a considerable interest in this turbine. Firstly, it is a design suitable for a wide range of heads and power ratings. Secondly, it lends itself easily to simple fabrication techniques, a feature which is of interest in developing countries. The runner blades, for instance, can be fabricated by cutting a pipe lengthwise in strips.

11.4.2 Reaction Turbines

Reaction turbines exploit the oncoming flow of water to generate hydrodynamic lift forces to propel the runner blades. They are distinguished from the impulse type by having a runner that always functions within a completely water-filled casing. All reaction turbines have a diffuser known as a 'draft tube' below the runner through which the water discharges. The draft tube slows the discharged water and reduces the static pressure below the runner and thereby increases the effective head. The two main types of reaction turbine are: (a) Francis turbine and (b) the propeller turbine (with Kaplan variant).

In general, reaction turbines will rotate faster than impulse types given the same head and flow conditions. The propeller type will rotate even faster than Francis. These high speeds have the very important implication that the reaction turbines can often be directly couple to a generator without any speed-increasing drive system.

Significant cost savings are made in eliminating the drive and the maintenance of the hydro unit becomes very much simpler.

On the whole, reaction turbines need more sophisticated fabrication than impulse types, because they involve the use of large, more intricately profiled blades. The extra expense involved is offset by high efficiencies and the advantage of high running speeds at low heads from relatively compact machines. However, for use in micro-hydro in developing countries, these turbines are less attractive due to fabrication constraints.

All reaction turbines are subject to the danger of cavitation (explained in Section 11.5), and tend to have poor part flow efficiency characteristics.

1. Francis Turbine

Figure 11.5 illustrates the construction of Francis turbine. The inlet has a spiral shape. Casing is scrolled to distribute water around the entire perimeter of the runner. The guide vanes, direct the water tangentially to the runner. The runner blades are profiled in a complex manner. In operation, water enters around the periphery of the runner through guide vanes, passes through the runner blades before exiting axially from the center of the runner. This radial flow acts on the runner vanes (blades), causing the runner to spin. The guide vanes (or wicket gate) may be adjustable to allow efficient turbine operation for a range of water flow conditions.

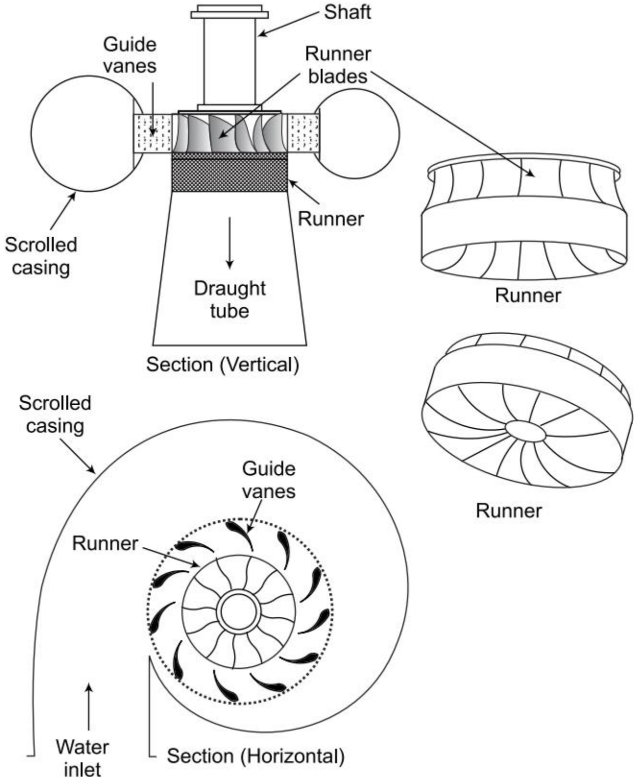


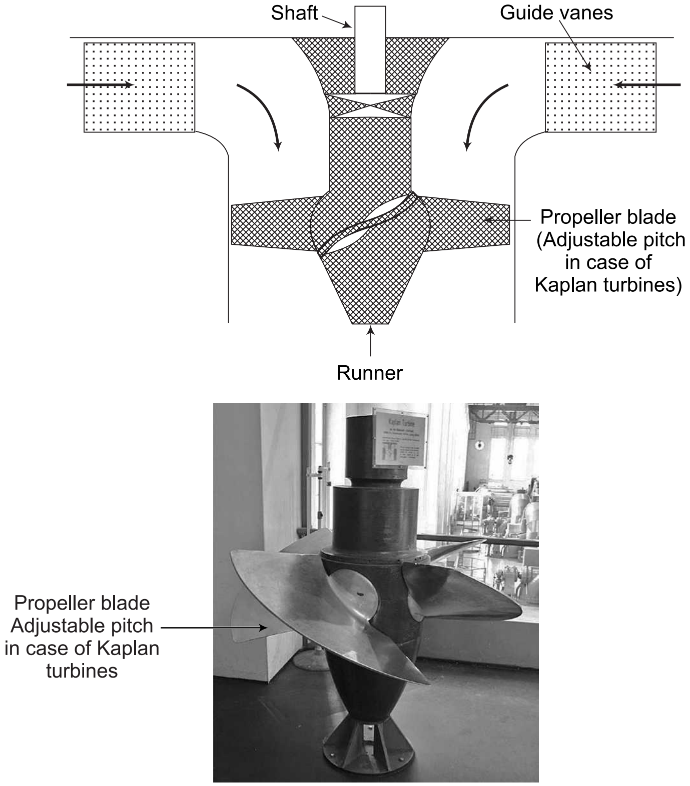
Figure 11.5 Francis turbine

As the water moves through the runner its spinning radius decreases, further acting on the runner. The water imparts most of its 'pressure' energy to the runner and leaves the turbine via a draught tube.

The guide vanes regulate the water flow as it enters the runner, and usually are linked to a governor system which matches the flow to turbine loading.

2. The Propeller Turbine and Kaplan

Propeller type turbines are similar in principle to the propeller of a ship, but operating in reversed mode. Typical construction is shown Fig. 11.6. It is often fitted inside a continuation of the penstock tube. Water flow is regulated by use of swiveling gates (wicket gates) just upstream of the runner (propeller). The part flow efficiency characteristic tends to be poor. This kind of propeller turbine is known as a 'fixed-blade axial-flow' turbine, since the geometry of the turbine does not change. Although traditionally the propeller is profiled to optimize the effect of pressure lift force acting on it, designs have been produced with flat section blades which offer less efficiency but are more easily fabricated. This kind of design can be considered seriously for micro hydro applications where low cost and ease of fabrication are priorities. It is also possible to consider casting the propeller casing in concrete.

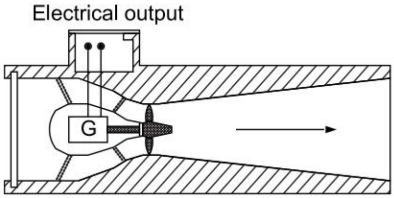


Courtesy: www.leonardo-energy.org [46]

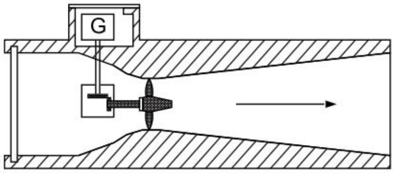
Figure 11.6 Propeller turbine

Large-scale hydro sites make use of more sophisticated versions of propeller turbine. Varying the pitch of propeller blades simultaneously with wicket gates adjustment has the effect of maintaining high efficiency under part flow conditions. Such turbines are known as 'variable pitch' propeller types or **Kaplan** turbines. Wicket gates are carefully profiled to induce tangential velocity or 'whirl' in the water. Water enters radially or axially through these guide vanes. Variable pitch designs involve complex linkages and are usually not cost effective in any except the largest of micro hydro applications.

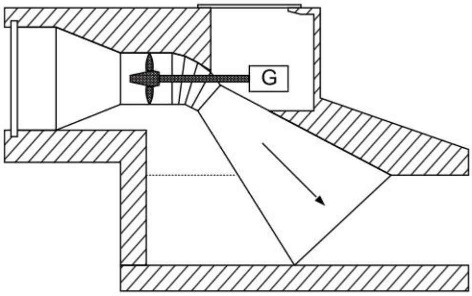
Propeller (Kaplan) turbine can be installed in vertical, horizontal or inclined positions. A number of installation designs and arrangement of drives are possible. Figure 11.7 shows three typical designs for horizontal and inclined installation of the turbine. In 'bulb type' design the generator (and gear box if any) is contained in a waterproof bulb, submerged in the flow. Only electric cable duly protected leaves the bulb. The 'cross' design requires a complex right angle drive to transmit power to the generator, which is placed in a separate chamber. 'S' design requires the bend in the water passage to link the turbine with the generator. A typical design for vertical installation of the turbine is shown in Fig. 11.8.



(a) 'Bulb' design



(b) 'Cross' design



(c) 'S' design

Figure 11.7 Horizontal and inclined installations of a propeller turbine

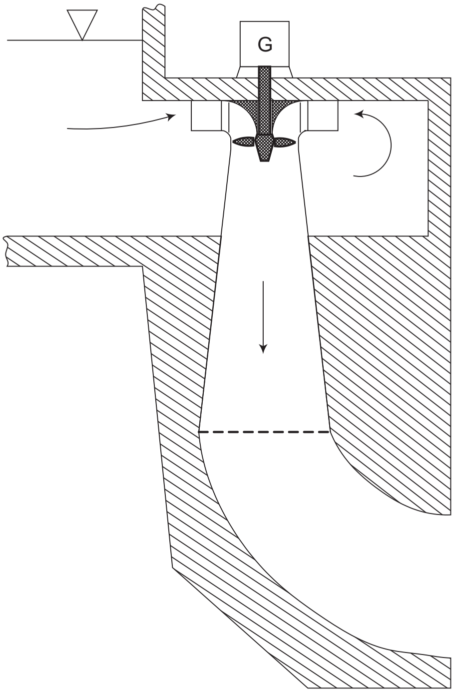


Figure 11.8 Vertical installation of propeller turbine

3. Reverse Pumps or Pumps-as-Turbines (PATs)

Centrifugal pumps can also be used as turbines. Potential advantages are: low cost owing to mass production, availability of spare parts and wider dealer/support networks. Because of high speed they can be directly coupled to generator without requiring coupling drive. A PAT closely coupled to an induction motor sometimes referred to as 'monobloc' pump, is commercially available. The motor runs as an induction generator.

The disadvantages of PATs are: as yet poorly understood characteristics, no direct correlation between pump characteristics and turbine characteristics, lower typical efficiencies, unknown wear characteristics and poor part flow efficiency. In general, PATs are most appropriate for medium head sites.

In many countries pumps are manufactured in large quantities for water supply and irrigation purposes, whereas there may be no local manufacturer for water turbines. In these countries PATs may be economical for a wide range of heads and flows.

11.5 TURBINE CLASSIFICATION, CHARACTERISTICS AND SELECTION

Turbines can be crudely classified as high-head, medium-head, and low-head machines, as shown in Table 11.1. But this is relative to the size of machine: what is low head for a large turbine can be high head for a small turbine; for example a Pelton

Turbine might be used at 50 m head with a 10 kW system but would need a minimum head of 150 m to be considered for a 1 MW system.

Table 11.1 Turbine classification

Turbine runner	Head classification		
	High (>50 m)	**Medium (10–50 m)**	**Low (< 10 m)**
Impulse	Pelton	Crossflow (Mitchel/Banki)	Crossflow (Mitchel/Banki)
	Turgo	Turgo	
	Multi-jet Pelton	Multi-jet Pelton	
Reaction		Francis	Propeller (axial flow)
		Pump-as-turbine (PAT)	Kaplan (modified propeller)

Small turbines designed for micro hydro applications often will have no method of altering the flow rate of water. On larger machines, some method of altering the flow is normal. If flow control devices are fitted to the turbine, then the same head of water can be maintained above the turbine while flow reduces. Different turbine types respond differently to changed flow at constant head. Therefore an important aspect of their characteristics is their performance at part flow conditions. Typical efficiency characteristics are given in Fig. 11.9.

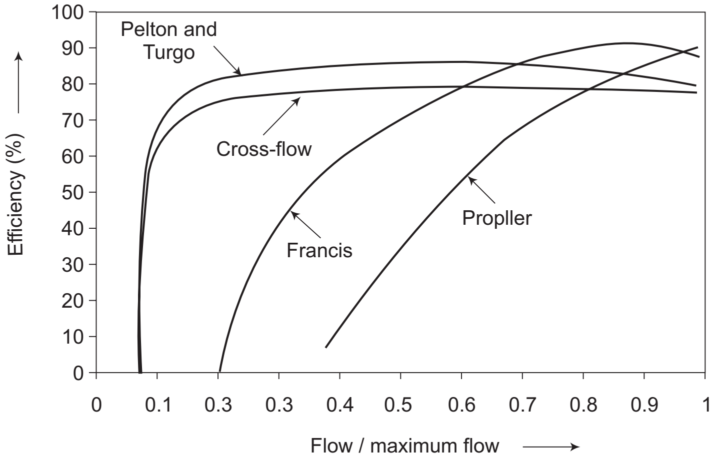


Figure 11.9 Part flow efficiencies of various turbines

An important point to notice is that the Pelton and cross flow turbines retain high efficiency when running below designed flow. In contrast the Francis drops in efficiency, producing very poor power output if run at below half the normal flow. Fixed pitch propeller turbines perform very poorly except at 80 to 100 per cent of full flow.

Francis is one of the few turbines which turns at a reasonable speed at certain power and head combination. An impulse turbine operated under these conditions of head and flow would be much larger, expensive, cumbersomely slow turning and would need a greater speed increasing transmission.

In addition to giving high speed at low head-to-power ratios, reaction turbines are particularly suited to low head applications for a second reason. Since power conversion is caused partly by pressure difference across the blades, the drop in head below the blades (known as 'suction head') is as effective in producing power as the head above the turbine. It is generally difficult or expensive to place micro hydro turbine lower than about 2 meters above the surface level of water down steam of the turbine. On a low head site of, say, 10 meters the suction head then represent 20 per cent of the power available at the site. This is likely to be very significant in terms of the overall economy of the scheme.

In contrast, impulse turbines do not usually make use of any suction head as their casing runs at atmospheric pressure. However, sophisticated cross flows on low heads often use suction heads.

Having noted the advantage of using a suction head, it should also be observed that the magnitude of the usable suction is limited. This is because very low water pressures are induced on the blades of a reaction turbine running under high suction. These can be low enough to vaporize the water in pockets (or 'cavities') of vapor attached to the internal surfaces of the turbine. The cavities form and collapse at a very high rate which after a period of time can cause serious pitting and cracking of the blades. The phenomenon is known as '**cavitation**'. In practical terms great care must be taken to situate the runner at a position which prevents the possibility of damage to cavitation.

Appropriate turbine is selected based on the guidelines depending mainly on the available head (H), discharge (Q) and power required (P). For a particular head they will tend to run most efficiently at a particular speed, and require a particular flow rate. The required speed at the generator shaft is achieved using speed-increasing gear or pulley and belt drive.

The approximate ranges of head, flow and power applicable to the different turbine types are summarized in the chart of Fig. 11.10 (up to 500 kW power). These are approximate and dependent on the precise design of each manufacturer.

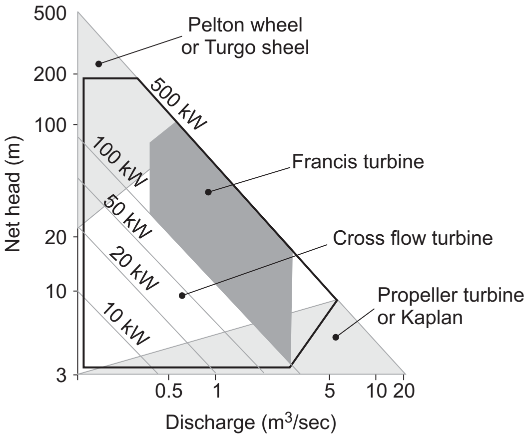


Figure 11.10 Head-flow ranges of small hydro turbines [47]

11.6 GENERATORS

Generation of electrical power is possible both by dc as well as ac generators. DC generators, above 2 kW, are expensive and brush gear requires appreciable maintenance. When the distribution network is small (less than 1000 m), voltage transformation may not be necessary, dc generation may be considered favorably. Under this condition dc generation has certain advantages: (i) The exact shaft speed is irrelevant so long as its automatic voltage regulator (AVR) maintains constant voltage. As a result no governor or load controller is required and there can be considerable saving in cost. (ii) Storage batteries may be charged during excess generation to provide for peak loads. Also during shut down of generator for maintenance, batteries may provide standby supply.

In addition, low power (12V, 24 V at up to 2 kW) dc generators and associated low voltage loads such as lights, radios, televisions, motors, fans, batteries etc. are standard accessories for automobiles and are readily available in bulk at cheap rates. It is therefore, sensible to consider the use of a low voltage dc generation system for small schemes (less than 2 kW) and where all the loads are very close to the generator.

AC system in general has many advantages and is an obvious choice except in small and very specialized cases. An ac supply system can be either single-phase or three-phase. Three-phase system is used universally in all conventional power systems. However, at low ratings, single-phase system becomes more convenient as the complexity of three-phase is not justified at this level. As an approximate rule, therefore, systems up to 10 kW may be single-phase, while those above 5 kW may be three-phase.

Both synchronous and induction types of ac generators are suitable for micro-hydro power generation. Induction generators are less common but are increasingly being used in small schemes. Main advantages of induction generators are that they are easily and cheaply available (as motors), are rugged, reliable, require little maintenance and can withstand 100 per cent over speed. Below 25 kW rating induction machines are less costly than synchronous machines.

The voltage of a simple synchronous generator falls very rapidly with load. An AVR must therefore be provided to control the dc field current to stabilize the voltage. The frequency of a synchronous generator is directly related to shaft speed. A good governor is required for speed control in order to limit the frequency variations within acceptable limits. In a simple non-conventional approach as explained above, the flow at the turbine input is set to a constant value. An ELC senses the frequency variations and switches appropriate ballast load to keep these variations within limits. Thus an ELC ensures constant speed and thus frequency by maintaining a constant total (resistive) load at the generator. It would appear that voltage will also remain constant and AVR may be avoided. However, if the power factor of the load changes, output voltage would also change requiring change of excitation to maintain the voltage.

Induction motors are simple, rugged, reliable, and plentiful. These are the most common type of electrical machines. Manufacturers generally do not make induction machines specified as generators. Therefore, an induction motor is used as induction generator. Up to 25 kW rating an induction motor tends to cost less than a synchronous generator. Larger size induction generator costs more than a synchronous generator of same rating, but may still be selected in preference to later because of other advantages of induction machine. When an induction motor is used as generator, the losses in the generator mode will be supplied from the mechanical input power, the rated electrical power of the machine as generator will be significantly less than its rating as motor. A de-rating factor of 0.8 is normally used to accommodate this feature. Also when an induction machine is driven as generator it will produce a terminal voltage approximately 10 per cent lower than the supply voltage for which it is designed as motor.

Induction generators can be easily used when connected to existing grid. However, when used in stand-alone applications, such as micro-hydro scheme, capacitors can be used across its terminals for excitation. Various configurations of capacitor connections are shown in Fig. 11.11. Such self-excited induction generators are now increasingly being used in schemes of less than 50 kW size. The most important drawback of an induction generator is its poor voltage regulation. Even when driven at constant speed, its output voltage drops rapidly with load. On the other hand, even at constant load, its voltage changes rapidly with speed. A recently developed IGC (induction generator controller) combines the functions of both a load controller and an automatic voltage regulator. A scheme with IGC is shown in Fig. 11.12. Essentially, the IGC senses the generator output voltage, which it then controls

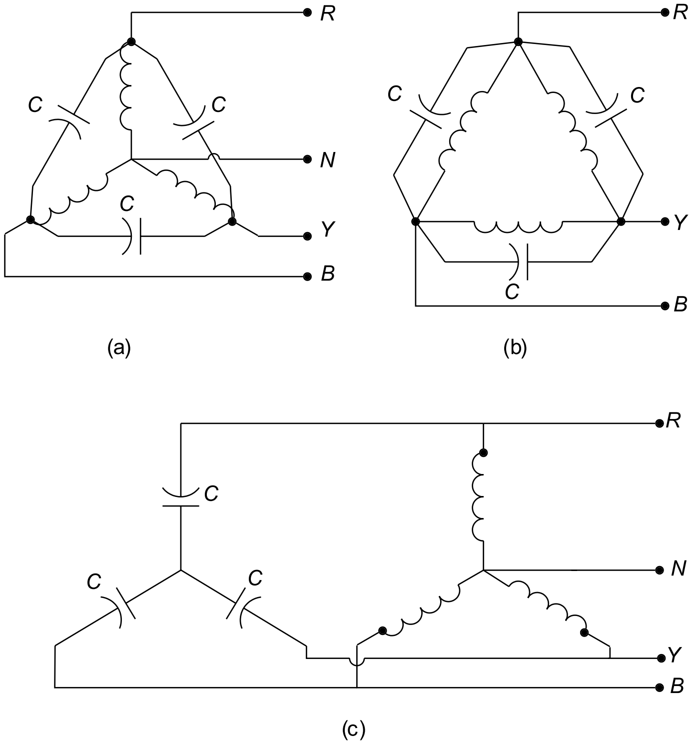


Figure 11.11 Exciter capacitor connections for 3-phase self excited ind Gen

by diverting required amount of power to a ballast load. This will also correct the frequency variation if the load is purely resistive. When the load is reactive, provided load power factor is not less than 0.8, limited frequency rise (10 per cent maximum) is allowed and thus effectively increasing leading VAR available from generator excitation capacitors. The increased leading VAR then supplies the lagging power requirement of the load. When such a load is connected to the generator, the voltage drops more than that would be the case for a purely resistive load of same power. The IGC then responds by reducing the ballast load until the voltage returns to normal value. As the voltage change is more than what would be the case for the true (active) power change, the reduction in ballast load is more than the true power change. As a result, turbine speed and thus generator frequency increases. The load power factor is thus corrected as explained above. The operation of an IGC may appear to be similar to that of an ELC (electronic load controller), but voltage rather than frequency is sensed and thus the need for an AVR is avoided.

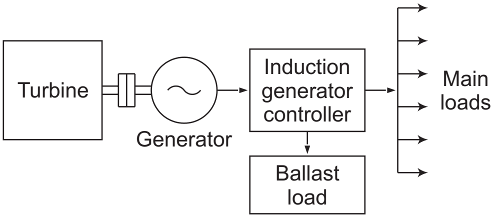


Figure 11.12 Induction generator controller scheme

Very small micro-hydro schemes, up to 10 kW are likely to be best served by single-phase supply, requiring a single-phase induction generator. A capacitor-run induction generator or a single winding induction generator with excitation capacitor connected across its terminals can be used. However, single-phase induction machines are not normally manufactured above 2 kW. For larger ratings, a 3-phase machine can be used as a single-phase generator with C-2C arrangement of excitation capacitors, as shown in Fig. 11.13. The generator may be used satisfactorily to supply single-phase power up to 80 per cent of the machine's rating.

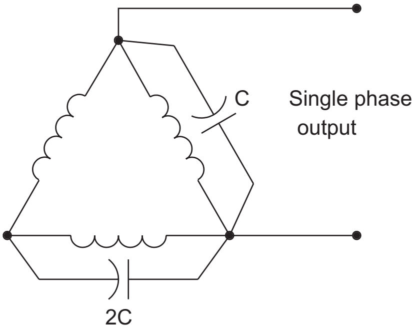


Figure 11.13 Single phase supply from 3 phase Ind Gen

Example 11.1

Estimate the power available from a proposed micro hydro scheme at a site having a small stream with 100 litres per second flow at a head of 30 m. Assume density of fresh water as 996 kg/m^3 and overall efficiency of the whole system as 55%.

Solution

Given:
density of fresh water, $\rho = 996$ kg/m^3
overall efficiency of the system $\eta_o = 0.55$
water discharge rate, $Q = 100$ litres per second $= 0.1$ m^3/s
gross head, $h = 30$ m
The available gross power may be estimated as:

$$P_{\text{net}} = \eta_o mgh \quad \text{Watts}$$

where m is flow rate of water in kg/s
m may be written as: ρQ
Therefore, the available gross power may be estimated as

$$\begin{aligned} P_{net} &= \eta_o \rho Qgh \quad \text{Watts} \\ &= 0.55 \times 996 \times 0.1 \times 9.81 \times 30 \text{ Watts} \\ &= 16.121 \text{ kW} \end{aligned}$$

Example 11.2

A micro hydro system is to be designed to supply a 1 phase, 220 V, 50 Hz electrical distribution system having a predicted demand of 3 kW at 0.8 p.f. lagging. ELC governor and AVR are used to regulate the output. Calculate the required VA rating of the generator. A water-cooled ballast comprising ordinary kettle elements each rated at 230 V, 500 W is to be used. How many kettle elements are required in the ballast load? The temperatures of water entering and leaving the ballast tank are 20 °C and 45 °C respectively. Calculate the required flow of water in the ballast tank. Assume specific heat of water as 4200 J/kg-K.

Solution

Maximum expected load demand = 3 kW at 0.8 p.f.
Therefore VA demand = 3 / 0.8 = 3.75 kVA
Add 60% extra to the kVA capacity to ensure generator and AVR reliability and to compensate for VAR drawn by the ELC.
Therefore, net required VAR rating of the generator = 3.75 × 1.6 = 6 kVA

Resistance of one kettle element = $\dfrac{V^2}{P} = \dfrac{230^2}{500} = 105.8 \quad \Omega$

At 220 V the power dissipation in one element will be $\dfrac{V^2}{R} = \dfrac{220^2}{105.8} = 457.47\ W$

Seven such elements may be connected in parallel to dissipate 3431.1 W (= 7 × 457.47).

Over ballasting provided by seven elements = $\frac{3431.1 - 3000}{3000} \times 100 = 14.4\%$.

In practice, about 10% over ballasting is generally used and, therefore, this design is acceptable. (Use of six elements does not provide over ballasting at all)

With the generator output of 3 kW, the rate of maximum heat dissipation in the ballast is 3 kW or 3000 J/s.

Temperature difference of cooling water at entry and exit of ballast tank = 25 °C

The flow rate in kg/s may be calculated as: $\frac{3000}{4200 \times 25} = 0.02857$ kg/s

Or the required flow rate of water in litre/s = 0.02857 litre/s

Example 11.3

The effective head of water in a Pelton wheel is 40 m from forebay to the turbine runner. Calculate the velocity of water in the jet.

Solution:

Potential energy of water at height h between intake level and turbine runner = mgh
This energy is converted to kinetic energy on the buckets = ½ (mv^2)
where v is velocity of water jet

Thus: $mgh = \frac{1}{2}(mv^2)$

$$v = \sqrt{2gh} = \sqrt{2 \times 9.81 \times 40} = 28 \text{ m/s}$$

Example 11.4

A Pelton wheel consists of two jets each of 5 cm diameter. Estimate the power developed for the jet velocity of 10 m/s.

Solution

Volume of water flowing through each jet per second = $\pi \times \left(\frac{0.1}{2}\right)^2 \times 10 = 0.07854 \text{ m}^3/\text{s}$

Mass of water flowing through each jet per second = 0.07854 × 1000 = 78.54 kg/s (assuming density of water as 1000 kg/m^3)
The associated energy per second = ½ (78.54×10^2) = ½ × 7854 W
Therefore, power in two jets = 7.854 kW

Example 11.5

A micro-hydro power station for 60 kW has a head of 20 m. At an efficiency of 85% for turbine-generator unit, calculate the required flow of water, assuming a load factor of 100%.

Solution

Given
The load is continuous at 60 kW.
Head, h = 50 m
Efficiency, η = 0.85

The efficiency of water ρ may be assumed as 1000 kg/m^3
The generated power from a flow of Q m^3/s is given by:

$$P_o = \eta \times Q \times \rho \times g \times h$$
$$60\times10^3 = 0.85 \times Q \times 10^3 \times 9.81 \times 20$$
$$Q = 60/(0.85 \times 9.81 \times 20)$$
$$= 0.3598 \text{ m}^3/\text{s}$$

11.7 PRESENT STATUS

The present global installed capacity of hydropower plants is about 6,27,000 MW, which accounts for about 23 per cent of the world's total installed electric power generation capacity and about 5 per cent of the world's primary energy supply. A number of large and medium sized hydro schemes have been developed. Large hydro schemes are commonly associated with large reservoirs, which give rise to much environmental concern.

Small hydro plants generally do not displace large number of people as large projects sometimes do or cause other environment problems. There is a growing trend of development towards small hydro plants with only a small upstream pondage. River courses suitable for accommodating hydro plants of up to 10 MW capacities are more common than larger ones, but the exploitable potential is limited for technical and economic reasons. The potential of small hydropower across the globe has been estimated as 1, 73, 000 MW while the global total installed capacity was found to be 75,000 MW (2013). Over 50 per cent of the world's potential of small hydropower was found to be in Asia. [59]

Starting in 1958 China has continued a focused policy on small-scale hydropower development at the local level in parallel with the large-scale development planned and executed by the central government. By the end of 2013 China achieved a total installed capacity of over 65,680 MW accounting for 51 per cent of the total exploitable potential of 1,28,000 MW. These installations produce annually a total of 2,17,300 GWh electricity, and the above numbers are growing fast each year. This is by far the largest capacity installed in any country.

In India, Ministry of New and Renewable Energy has been vested with the responsibility of developing Small Hydro Power (SHP) projects up to 25 MW station capacities. The estimated **potential** for power generation in the country from such plants is about 20,000 MW. The Ministry has created a database of potential sites of small hydropower. A total of 6,474 potential sites with an aggregate capacity of 19,749.44 MW for projects up to 25 MW capacity have been identified. Most of this potential lies in Himalayan States as river-based projects and in other States on irrigation canals. The SHP program is now essentially private investment driven. Projects are normally economically viable and private sector is showing lot of interest in investing in SHP projects. The viability of these projects improve with increase in the project capacity. Total installed small hydropower capacity at the end of year 2013 was 3496 MW. [59]

REVIEW QUESTIONS

1. What are the major advantages of mini / micro hydro resources?
2. With the help of neat diagram explain the layout of a typical micro hydro plant.
3. Explain various types of generating systems and generators considered for use in micro hydro resources.
4. Discuss various types of speed governors used in SHPs. Which type is justified in a micro hydro scheme?
5. Explain various types of turbines considered for use in micro hydro resources.
6. Explain various types of controls available in Pelton turbine.
7. Compare the relative advantages and disadvantages of Pelton and Turgo turbines.
8. Compare the part flow characteristics of various types of turbines.
9. What do you understand by "cavitation"?
10. What are the present trends in micro hydropower development?

PROBLEMS

1. Estimate the net power available from a proposed micro hydro scheme at a site having a small stream with a flow rate of 200 litres per second at a head of 35 m. Assume density of fresh water as 996 kg/m^3 and overall efficiency of the whole system as 50%.

   (*Ans.* 34.1976 kW)

2. A micro hydro system is to be designed to supply a 1 phase, 220 V, 50 Hz electrical distribution system having a predicted demand of 5.2 kW at 0.8 p.f. lagging. ELC governor and AVR are used to regulate the output. Calculate the required VA rating of the generator. A water-cooled ballast comprising ordinary kettle elements, each rated at 230 V, 1200 W, is to be used. Calculate the number of kettle elements required in the ballast load and the available over ballasting? The temperatures of water entering and leaving the ballast tank are 15 °C and 45 °C respectively. Calculate the required flow of water in the ballast tank. Assume specific heat of water as 4200 J/kg K.

   (*Ans.* 10.4 kVA, 5, 5.58%, 0.04127 litre/s)

OBJECTIVE TYPE QUESTIONS

1. Which one of the following factor is not responsible for recent development of SHP?
   (a) Advancements in the design of low head turbines.
   (b) Improvements in construction technology.
   (c) Availability of better control techniques.
   (d) Availability of small streams .

2. Small hydro plants (SHPs) have:
- (a) high head and small capacity
- (b) low head and small capacity
- (c) low head and large capacity
- (d) large head and large capacity

3. Which one of the following statement is not true for a micro hydro scheme?
- (a) It has a capacity less than 100 kW.
- (b) It is used where a grid does not exist.
- (c) Power is generated for local use only.
- (d) Complicated and sophisticated control scheme is used.

4. In micro hydro projects the allowable voltage and frequency variations are?
- (a) ± 7% and ± 5% respectively
- (b) +7% and +5% respectively
- (c) ±7% and +5% respectively
- (d) ±7% and –5% respectively

5. Electronic load controller:
- (a) saves energy and stores it for later use
- (b) dissipates surplus energy in ballast load
- (c) controls the flow of water into the turbine
- (d) controls the power generated by the generator

6. In impulse turbines:
- (a) water remains at atmospheric pressure before and after making contact with runner blades
- (b) water remains at atmospheric pressure before entering the runner blades but the pressure reduces thereafter
- (c) water enters at low pressure, which increases after making contact with runner blades
- (d) water pressure remains below atmospheric before and after making contact with runner blades

7. A Turgo runner moves faster than Pelton wheel because:
- (a) the jet cross section is large
- (b) the jet speed is faster
- (c) the spent fluid interferes with the incoming jet
- (d) the spent fluid does not interfere with the incoming jet

8. In a reaction turbine the length of draught tube is limited by the:
- (a) strength of material
- (b) speed of flowing water
- (c) possibility of cavitation
- (d) the amount of available discharge

9. Main advantages in using a Pumps-as-Turbine (PAT) are:
- (a) low cost and possibility of direct coupling to generator
- (b) high cost and possibility of direct coupling to generator
- (c) low cost and low speed
- (d) low cost and high efficiency

10. Compare the part flow efficiencies of Pelton and Propeller turbines:
- (a) Pelton and Propeller both operate at constant efficiencies irrespective of flow
- (b) Pelton and Propeller both operate at higher than full flow efficiency
- (c) the efficiency of Pelton is lower than that of Propeller at part flow
- (d) the efficiency of Pelton is higher than that of Propeller at part flow

11. Use of Pelton wheel is desirable for the conditions of:
(a) low head and high discharge (b) high head and low discharge
(c) high head and high discharge (d) low head and low discharge

12. Use of Propeller turbine is desirable for the conditions of:
(a) low head and high discharge (b) high head and low discharge
(c) high head and high discharge (d) low head and low discharge

13. For small schemes (less than 2 kW), use of 12–24 V, dc generation is desirable where:
(a) only dynamic loads are used
(b) only lamp loads are used
(c) all loads are far away from the generator
(d) all loads are close to the generator

14. An induction generator controller (IGC), controls:
(a) only the voltage and not the frequency
(b) only the frequency and not the voltage
(c) both the voltage as well as the frequency
(d) the power input to the generator

15. The function of weir in a small hydro power project:
(a) to regulate the flow of water
(b) to maintain a permanent water level above the intake mouth during both high and low flow season
(c) to check the quality of water
(d) to assist desilting of water

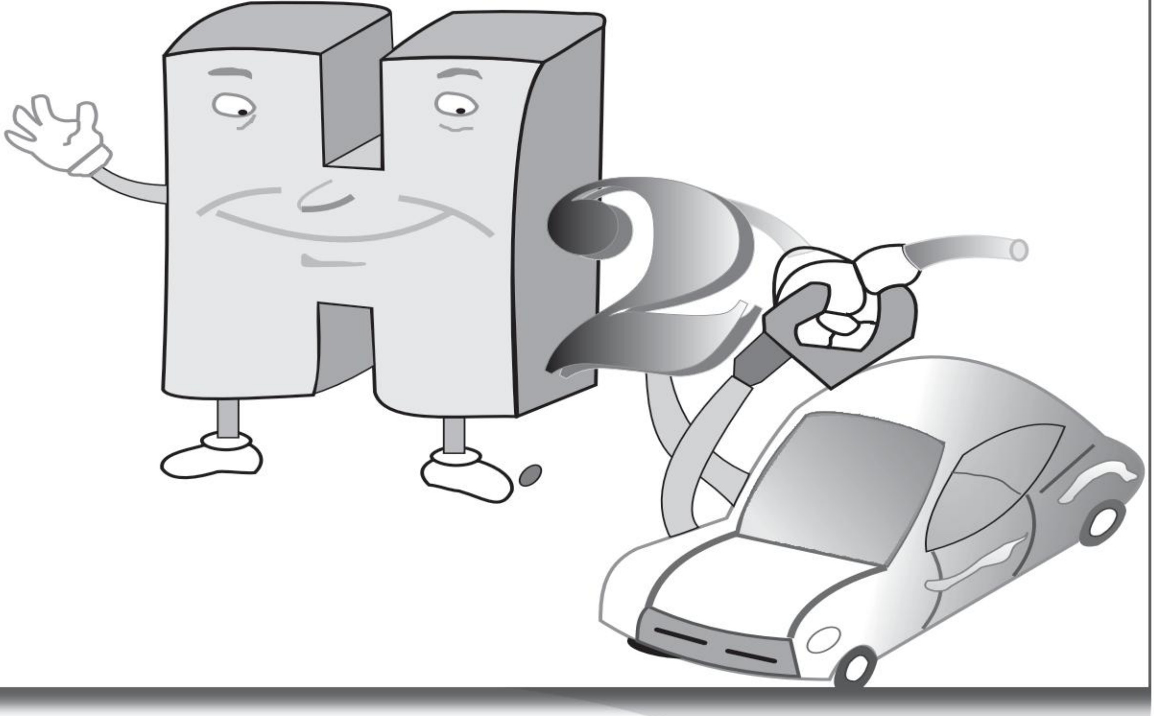
16. When available water head is 'zero', the small hydropower project can be set up:
(a) depending on quality of water
(b) depending on density of water
(c) depending on the speed of water and the area of the runner
(d) depending on the depth of water

17. Which country has the maximum operational small hydropower plants in the world?
(a) India (b) China
(c) USA (d) Brazil

18. Small hydropower projects utilizing the flow of water within the natural river, requiring little or no impoundment are known as:
(a) storage hydropower projects (b) diversion projects
(c) run-of-river projects (d) pumped projects

19. Kaplan turbine is a type of:
(a) impulse turbine with adjustable flow
(b) impulse turbine without adjustment of flow
(c) reaction turbine with non-adjustable blades
(d) reaction turbine with adjustable blades

20. The downstream channel of outflowing water from a small hydropower plant is termed as:
(a) tailrace (b) headrace
(c) open channel (d) penstock



CHAPTER 12

Emerging Technologies

Learning Objectives

In this chapter you will be able to:

- Discuss various types of fuel cell technologies
- Predict future prospects of fuel cell as energy conversion device and hydrogen as universal energy carrier
- Analyse various aspects of use of hydrogen as energy carrier

12.1 INTRODUCTION

In this chapter some newly emerging technologies are covered. Fuel cell and hydrogen fuel technologies are relatively new and in the initial stages of development. The principle of the fuel cell was discovered way back in 1838 by German scientist Christian Friedrich Schönbein, and published in one of the scientific magazines of the time. Based on this work, the first fuel cell was demonstrated by Welsh scientist Sir William Robert Grove in the February 1839. However, turning this idea into a practical means of energy conversion has proved to be elusive. Its wide spread use is hindered mainly due to its high cost as compared to other available technologies. Many companies are working on techniques to reduce the cost in a variety of ways including reducing the amount of platinum needed in each individual cell. United Technologies Corporation's UTC Power subsidiary was the first company to manufacture and commercialize a large, stationary fuel cell system for use as a co-generation power plant in hospitals, universities and large office buildings. UTC Power continues to market this fuel cell as the PureCell 200, a 200 kW system.

Hydrogen is an energy carrier, and not an energy source, because it is usually produced from other energy sources via petroleum combustion, wind power, or solar photovoltaic cells. Electrochemical extraction of energy from hydrogen via fuel cells is an especially clean method of meeting power requirements, but not an efficient one, due to the necessity of adding large amounts of energy to either water or hydrocarbon fuels in order to produce the hydrogen. A number of issues like production, delivery, storage, conversion and end use applications are involved in order to realize hydrogen economy.

12.2 FUEL CELL

A fuel cell is an electrochemical energy conversion device that continuously converts chemical energy of a fuel directly into electrical energy. Continuous operation requires supply of fuel and oxidant and removal of water vapour, spent fuel, spent oxidant, inert residue and heat, etc. It is known as a cell because of some similarities with a primary cell. Like a conventional primary cell it also has two electrodes and an electrolyte between them and produces dc power. It is also a static power conversion device. However, active materials are generally supplied from outside unlike conventional cell where it is contained inside the cell. Fuel is supplied at the negative electrode, also known as fuel electrode or *anode* and oxidant is supplied at positive electrode, also known as oxidant electrode or *cathode*.

The only exhaust of a fuel cell, if pure hydrogen is used as fuel (and pure oxygen as oxidant), is water vapor, which is not a pollutant. In case of hydrocarbon fuel, carbon dioxide is also produced. If air is used as oxidant, nitrogen (spent air) is also produced in the exhaust. No other pollutant such as particulate matter, NO_x and SO_x are produced. Some amount of heat is also produced, which can be easily dissipated to atmosphere or used locally for heating purpose. No cooling water is required unlike conventional thermal power conversion devices where substantial quantity of cooling water is required. As conversion of chemical energy of fuel to electrical energy occurs directly without intermediate thermal stage, the efficiency of conversion is better and not limited by Carnot efficiency of thermal stage. The efficiency of a practical fuel cell may be around 50 per cent. The average cell voltage is typically about 0.7 V (on rated load) and several cells may be connected in series to increase the voltage. The current depends on the electrode area and can be increased by connecting several cells in parallel. Thus modules of different sizes can be constructed by series-parallel connection of required number of cells. There general large-scale use will require the development of low cost fuel cell with reasonably long life.

Main advantages of fuel cell are: (i) it is quiet in operation as it is a static device, (ii) it is less pollutant, (iii) its conversion efficiency is more due to direct single stage energy conversion, (iv) fuel cell plant can be installed near point of use, thus transmission and distribution losses are avoided, (v) no cooling water is needed as required in condenser of a conventional steam plant. The heat generated can be easily removed and discharged to atmosphere or used locally, (vi) because of modular nature, any voltage/current level can be realized and the capacity can be added later on as the demand grows, (vii) fuel cell plants are compact and require less space, (viii) availability of choice from large number of possible fuels, (ix) can be used efficiently at part load from 50 per cent to 100 per cent and (x) no charging is required.

12.2.1 Potential Applications

Once fuel cells of reasonably low cost and long life become available, they will be preferred in large number of applications. Some of their potential applications are listed below:

1. Fuel cells can be effectively used for *load leveling*. When the generation exceeds the demand, excess generated energy can be converted and stored as hydrogen by electrolysis of water. During peak load time, when the demand exceeds the generation, the stored hydrogen would be used in fuel cells to meet additional demand.
2. A central station power plant using fuel cell is also possible using gasified coal as fuel. The efficiency of such a plant would be higher due to direct energy conversion as compared to conventional thermal plants. Thus coal will be used more efficiently with reduced emissions.
3. Fuel cells are also suited for dispersed generation. By locating the fuel cells near load center, transmission and distribution cost would be avoided/reduced, although there would be some cost for transporting the hydrogen.
4. To meet the demand of isolated sites such as construction sites, military camps and small village community or hamlet, fuel cells are more suited than diesel generator set.
5. For remote and inaccessible locations fuel cell can be used unattended for a long period.
6. Emergency/auxiliary supply to critical loads such as hospitals, etc., can be better met using fuel cells as compared to diesel generator set.
7. Fuel cells can also be used as a mobile power source in vehicles, submarines, spacecrafts, etc. Hydrogen–Oxygen, alkali fuel cell has been used successfully to provide electric power in Apollo and shuttle spacecrafts in USA.

8. Fuel cells are also proposed as a power source for propulsion of electric vehicles.
9. Fuel cells can be used to power portable electronic devices (e.g. mobile phones and other low power appliances, especially those used in military) as substitute for primary or re-chargeable batteries. Instead of waiting for several hours for recharging, small cartridge of methanol can be replaced in the same way as an ink cartridge in a computer printer.

12.2.2 Classification of Fuel Cells

Fuel cells can be classified in several ways.

1. Based on the Type of Electrolyte

(a) Phosphoric Acid Fuel Cell (PAFC)
(b) Alkaline Fuel Cell (AFC)
(c) Polymer Electrolytic Membrane Fuel Cell (PEMFC)
or Solid Polymer Fuel Cell (SPFC)
or Proton Exchange Membrane Fuel Cell (PEMFC)
(d) Molten Carbonate Fuel Cell (MCFC)
(e) Solid Oxide Fuel Cell (SOFC)

2. Based on the Types of the Fuel and Oxidant

(a) Hydrogen (pure) – Oxygen (pure) fuel cell
(b) Hydrogen rich gas – air fuel cell
(c) Hydrazine – Oxygen/hydrogen peroxide fuel cell
(d) Ammonia – air fuel cell
(e) Synthesis gas – air fuel cell
(f) Hydrocarbon (gas) – air fuel cell
(g) Hydrocarbon (liquid) – air fuel cell

3. Based on Operating Temperature

(a) Low temperature fuel cell (below 150 °C)
(b) Medium temperature fuel cell (150 °C–250 °C)
(c) High temperature fuel cell (250 °C–800 °C)
(d) Very high temperature fuel cell (800 °C–1100 °C)

4. Based on Application

(a) Fuel cell for space applications
(b) Fuel cell for vehicle propulsion
(c) Fuel cell for submarines
(d) Fuel cell for defense applications
(e) Fuel cell for commercial applications

5. Based on the Chemical Nature of Electrolyte

(a) Acidic electrolyte type
(b) Alkaline electrolyte type
(c) Neutral electrolyte type

12.2.3 Phosphoric Acid Fuel Cell (PAFC)

PAFC was developed in 1980s. The basic phosphoric acid fuel cell is shown in Fig. 12.1. It consists of two electrodes of porous conducting material (commonly nickel) to collect charge, with concentrated phosphoric acid filled between them, to work as electrolyte. Pure hydrogen or a hydrogen rich gas is supplied at negative electrode and oxygen or air is supplied at positive electrode. The pores provide an opportunity to gas, electrolyte and electrode to come into contact for electrochemical reaction. The reaction is normally very slow and a catalyst is required in the electrode to accelerate the reaction.

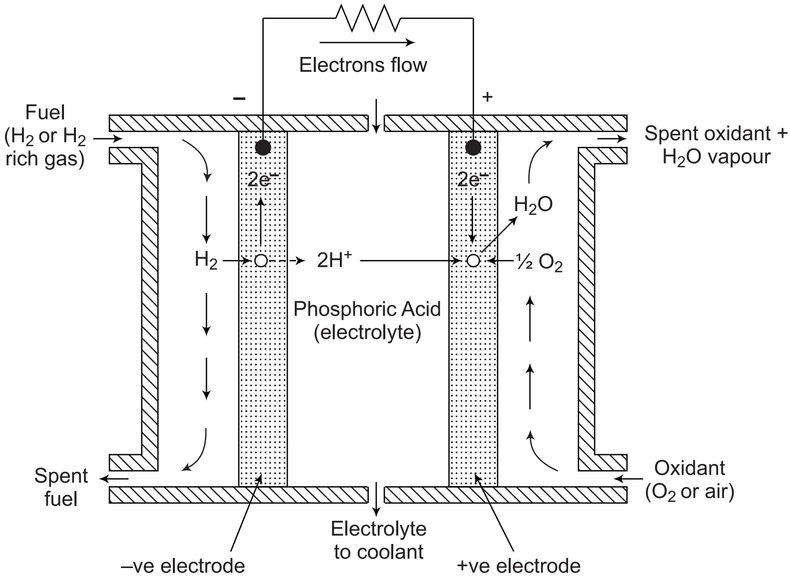


Figure 12.1 Phosphoric Acid Fuel Cell

Platinum serves as best catalyst for both electrodes and used for premium fuel cells. In general, a less expensive material such as nickel (for negative electrode) and silver (for positive electrode) is used wherever possible. Thus finely divided platinum or nickel/silver deposited on the outer surface of electrodes are used as catalyst. During the usage of the cell, the catalyst gradually loses its activity. This loss of activity is often attributed to "poisoning" (inactivation) of catalyst by the impurities (mostly sulphur compounds) in the fuel.

At the negative electrode, hydrogen gas is converted to hydrogen ions (H^+) and an equal number of electrons (e^-). Thus:

$$H_2 \rightarrow 2H^+ + 2e^-$$

The electrons originating at negative electrode flow through the external load to positive electrode. Also the H^+ ions migrate from negative electrode towards positive electrode through the electrolyte. On reaching the positive electrode they interact with O_2 to produce water. Thus:

$$½\ O_2 + 2\ H^+ + 2\ e^- \rightarrow H_2O$$

Combining the above equations indicates that a fuel cell combines H_2 and O_2 to produce water (plus electrical energy). The overall reaction is therefore,

$$H_2 + ½\ O_2 \rightarrow H_2O$$

The above reaction is true for any type of hydrogen-oxygen cell. The operating temperature of PAFC is 150 °C–200 °C. At atmospheric pressure it produces an ideal emf of 1.23 V at 25 °C, which reduces to 1.15 V at 200 °C. The actual value is always less than this and decreases with current. Normally at rated values of current the voltage lies between 0.7 V and 0.8 V.

12.2.4 Alkaline Fuel Cell (AFC)

Alkaline fuel cell, the oldest of all fuel cells uses 40 per cent aqueous KOH as electrolyte. The operating temperature is about 90 °C. The electrodes and other details are same as explained for PAFC. Like PAFC it also works with H_2 and O_2 active materials and same level of emf is produced. The operation and movements of charge carriers is shown in Fig. 12.2. At positive electrode oxygen, water (from electrolyte) and returning electrons from the external load combine to produce OH^- ions:

$$½\ O_2 + H_2O + 2\ e^- \rightarrow 2\ OH^-$$

These OH^- ions migrate from positive to negative electrode through electrolyte. On reaching positive electrode these OH^- ions combine with H_2 to produce water. An equivalent number of electrons are liberated that flow through external load towards positive electrode. Thus:

$$H_2 + 2\ OH^- \rightarrow 2\ H_2O + 2\ e^-$$

The overall reaction is same as that with PAFC. That is:

$$H_2 + ½\ O_2 \rightarrow H_2O$$

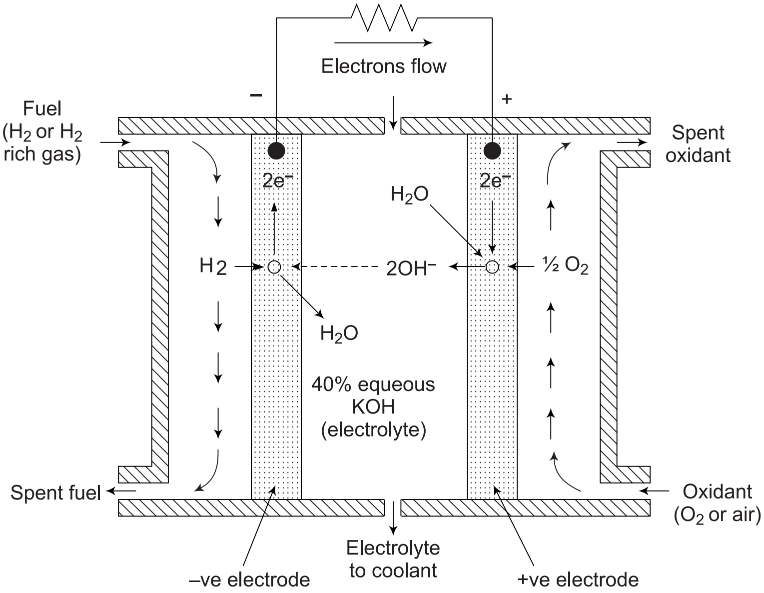


Figure 12.2 Alkaline Fuel Cell

The fuel used in AFC must be free from CO_2, because this gas can combine with potassium hydroxide electrolyte to form potassium carbonate. This increases the electrical resistance of the cell, which in turn decreases the available output voltage of the cell. Similarly, if air is used instead of pure oxygen the CO_2 must first be removed from the air by scrubbing with lime.

12.2.5 Polymer Electrolyte Membrane Fuel Cell (PEMFC) or Solid Polymer Fuel Cell (SPFC) or Proton-Exchange Membrane Fuel Cells (PEMFC)

A solid membrane of organic material (such as polystyrene sulphonic acid) that allows H^+ ions to pass through it is used as an electrolyte. The desired properties of the membrane are: (i) high ionic conductivity, (ii) non permeable (ideally) to reactant gases, i.e. hydrogen and oxygen, (iii) low degree of electro-osmosis (motion of liquid induced by applied potential across membrane), (iv) high resistance to dehydration, (v) high resistance to its oxidation or hydrolysis, and (vi) high mechanical stability.

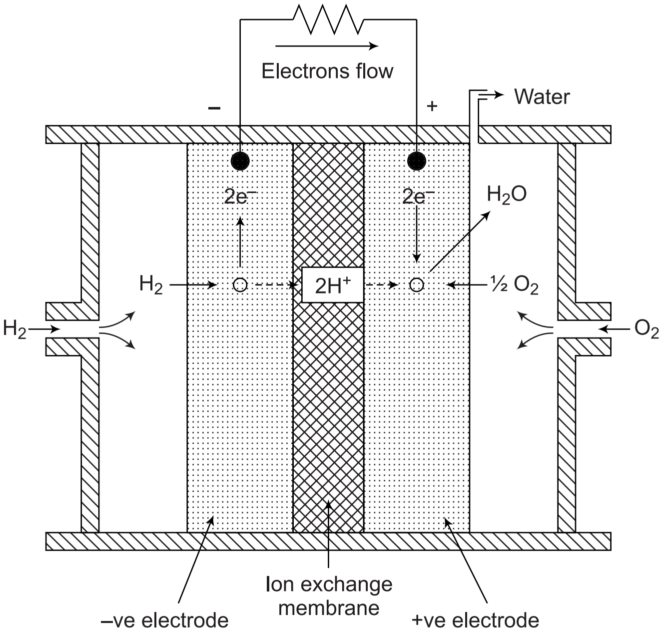


Figure 12.3 Polymer Electrolyte Membrane Fuel Cell

The basic components of cell are shown in Fig. 12.3. A thin layer (about 0.076 cm thickness) of the membrane is used to keep the internal resistance of the cell as low as possible. Finely divided platinum deposited on each surface of the membrane serves as electrochemical catalyst and current collector. Hydrogen enters a closed compartment, interacts with negative electrode and converted into H^+ ions and equal number of electrons (e^-):

$$H_2 \rightarrow 2H^+ + 2e^-$$

The H^+ ions are transported to positive electrode through the membrane and electrons return to positive electrode through external resistance. At positive electrode, the ions, electrons and oxygen (O_2) interact to produce water.

$$\tfrac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

Thus the overall reaction is:

$$H_2 + \tfrac{1}{2} O_2 \rightarrow H_2O$$

On positive electrode the coolant tubes run through the ribs of current collectors. The current collectors also hold wicks, which absorb water, produced in electrochemical reaction and carry it over by capillary action. Water leaves the oxygen compartment through an exit. The advantageous feature of this membrane is that it retains only limited quantity of water and rejects excess water produced in the cell. The cell operates at 40–60 °C. The ideal emf produced is 1.23 V at 25 °C.

Direct Methanol Fuel Cell (DMFC)

In a modified version of this fuel cell, methanol is used directly without reforming instead of pure hydrogen. This is known as **Direct Methanol Fuel Cell (DMFC)**. The complicated catalytic reforming process is not required. Storage of methanol is much easier than that of hydrogen because it does not need to be done at high pressures or low temperatures.

The liquid methanol (CH_3OH) is oxidized in the presence of water at the anode, generating CO_2, hydrogen ions and the electrons. The hydrogen ions travel through the electrolyte and react with oxygen from the air and the electrons from the external circuit to form water at the anode completing the circuit. The excess water and CO_2 are discharged as exhaust.

Anode Reaction:	$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$
Cathode Reaction:	$3/2\ O_2 + 6\ H^+ + 6e^- \rightarrow 3\ H_2O$
Overall Cell Reaction:	$CH_3OH + 3/2\ O_2 \rightarrow CO_2 + 2\ H_2O$

Initially developed in the early 1990s, DMFCs were not embraced because of their low efficiency and power density, as well as other problems. Improvements in catalysts and other recent developments have increased power density 20-fold and the efficiency may eventually reach 40 per cent.

These cells have been tested in a temperature range from about 50–120°C. They can produce small amount of power over a long period of time. This low operating temperature, long life and no requirement for a fuel reformer make the DMFC an excellent candidate for very small to mid-sized applications, such as cellular phones, digital cameras, laptop computers and other consumer products. These micro fuel cells offer longer life compared to lithium-ion batteries and may be instantly recharged by replacing the disposable fuel cartridge.

One of the drawbacks of the DMFC is that the low-temperature oxidation of methanol to hydrogen ions and carbon dioxide requires a more active catalyst, which typically means a larger quantity of expensive platinum catalyst is required than in conventional PEMFCs. This increased cost is, however, expected to be more than outweighed by the convenience of using a liquid fuel and the ability to function without a reforming unit.

One other concern driving the development of alcohol (ethanol) based fuel cell is the fact that methanol is toxic and flammable. Therefore, some companies have embarked on developing a Direct Ethanol Fuel Cell (DEFC). The performance of the DEFC is currently about half that of the DMFC, but this gap is expected to narrow with further development.

The technology behind Direct Methanol Fuel Cells (DMFC) is still in the early stages of development, but it has been successfully demonstrated powering mobile phones and laptop computers—potential target end uses in future years.

12.2.6 Molten Carbonate Fuel Cell (MCFC)

In MCFC, carbonate of alkali metals (Na, K or Li) in molten (liquid) phase is used as electrolyte. This requires the cell operation at a temperature above melting points (i.e. about 600–700 °C) of the respective carbonates. Because of high temperature operation catalyst is not necessary. Porous nickel is used for electrodes and electrolyte is held in sponge like ceramic matrix.

A special feature of these cells is that during operation they oxidize hydrogen to water and carbon monoxide (present in fuel) to carbon dioxide. Hence gaseous mixtures of hydrogen and carbon monoxide (synthesis gas), which are relatively inexpensive to manufacture can also be used. This feature offers the prospects for use of a variety of fossil fuels including coal (gasified). These fuels are first converted (reformed) to get a mixture of H_2 and CO and desulphurized to prevent poisoning of electrodes. The theoretical value of emf at no load is approximately 1 V at 700 °C. However, actual voltage at load is somewhat lower (about 0.8 V).

The discharges, mainly consisting of steam, carbon dioxide and nitrogen from spent oxidant (air), are at a temperature exceeding 540 °C. These hot gases could be used to provide industrial process heat or to generate additional power employing waste heat boiler (heat exchanger) and steam turbine. The overall efficiency of fuel would thus be increased substantially.

The operation of MCFC is explained with the help of diagram shown in Fig. 12.4. At the fuel electrode H_2 and CO react with CO_3^{--} ions present in the electrolyte and release two electrons each to the electrode as given below:

$$H_2 + CO_3^{--} \rightarrow H_2O + CO_2 + 2e^-$$

$$CO + CO_3^{--} \rightarrow 2\,CO_2 + 2e^-$$

These electrons circulate through external resistance, forming load current, and reach the oxidant electrode. The CO_2 produced at fuel electrode is circulated through an external path to oxidant electrode, where it combines with O_2 and returning electron through external path to produce CO_3^{--}:

$$O_2 + 2\,CO_2 + 4\,e^- \rightarrow 2\,CO_3^{--}$$

The CO_3^{--} ions thus produced are responsible for transportation of charge from positive to negative electrode within electrolyte. The overall reaction may be written as:

$$H_2 + CO + O_2 \rightarrow H_2O + CO_2$$

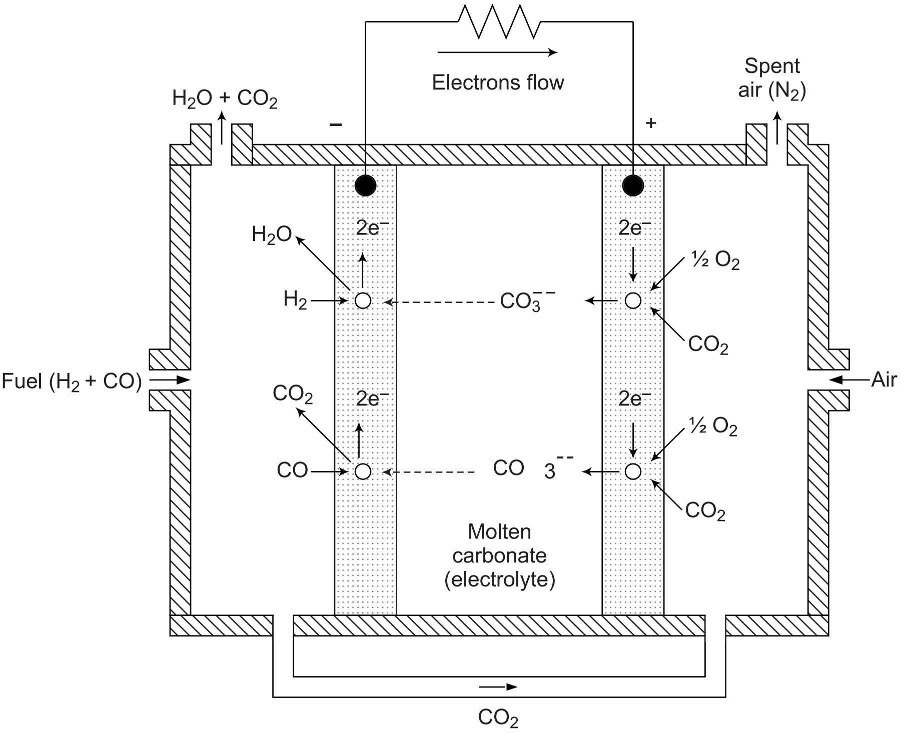


Figure 12.4 Molten Oxide Acid Fuel Cell

12.2.7 Solid Oxide Fuel Cell (SOFC)

Certain solid oxides (ceramics) at high temperature can be used as electrolyte. For example, zirconium oxide containing a small amount of other oxide to stabilize the crystal structure has been used as an electrolyte. The material is able to conduct O^{--} ions at high temperature. The negative electrode is made of porous nickel and positive electrode employs metal oxide, e.g. indium oxide. The operating temperature is in the range of 600 °C - 1000 °C. Due to high temperature operation, catalyst is not required. These cells could utilize same fuels as used in MCFC. At the fuel electrode H_2 and CO react with O^{--} ions present in the electrolyte to produce H_2O and CO_2. The two electrons released (per ion) flow through external path to constitute load current. Like MCFC, the heat of discharge can be utilized as process heat or for additional power generation using steam plant. The output voltage at full load is about 0.63 V. A tubular construction of SOFC is shown in Fig. 12.5. The reactions at the electrodes are:

At positive electrode: $H_2 + O^{--} \rightarrow H_2O + 2\,e^-$

And $CO + O^{--} \rightarrow CO_2 + 2\,e^-$

At negative electrode: $O_2 + 4\,e^- \rightarrow 2\,O^{--}$

The overall reaction is: $H_2 + CO + O_2 \rightarrow H_2O + CO_2$

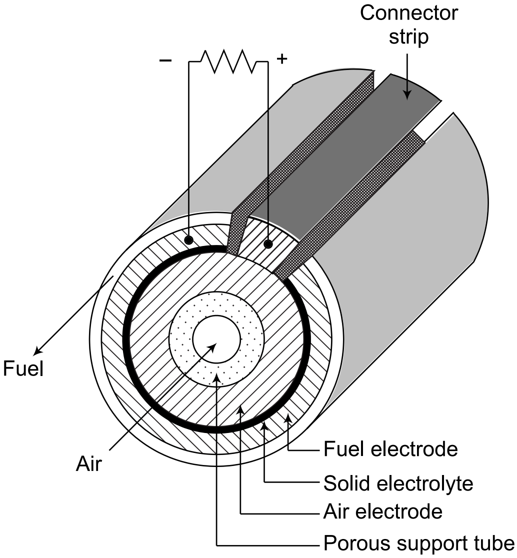


Figure 12.5 Solid Oxide Fuel Cell

12.2.8 Development Stages and Relative Performances of Various Fuel Cells

Various characteristics of fuel cells are summarized in Table 12.1. PAFC has reached commercial or pre-commercial stage. It can tolerate the presence of CO_2 in the fuel or oxidant, however, presence of sulphur compounds have to be avoided as they lead to poisoning of catalysts and cause corrosion of internal parts (coolant circuit). At low temperature, phosphoric acid has low conductivity. High temperature operation is limited by the stability problem of electrode material. Thus a moderate operating temperature of 150–200 °C is maintained. Efforts are on to increase the life of cell to at least 5 years. PAFC is suitable for stationary applications. PEMFC is also being developed as portable power source for mobile electronic devices, transportation and domestic applications. The catalyst in the cell is intolerant to presence of CO or SO_2 in the fuel. AFC is already in the market. Requirement of pure H_2 and O_2 has restricted its use to space and military applications only. MCFC and SOFC are in the early stages of development. Like PAFCs these are also being developed for stationary applications. These are more efficient than PAFC. With cogeneration the efficiency of these fuel cells may reach close to 90 per cent. However, they suffer from short life, high temperature stresses and high cost. They can run on a large variety of fuels such as natural gas, landfill gas, biogas, etc. Main problem in MCFC is that the electrolyte is very corrosive and current density is low. Very high operating temperature is the main concern in SOFC.

Table 12.1 Characteristics of various fuel cells

S.N.	Fuel cell	Op. Temp.	Fuel	Efficiency
1.	PEMFC	40–60 °C	H_2	48–58 %
2.	AFC	90 °C	H_2	64%
3.	PAFC	150–200 °C	H_2	42%
4.	MCFC	600–700 °C	H_2 and CO	50%
5.	SOFC	600–1000 °C	H_2 and CO	60–65%

12.2.9 Fuels for Fuel Cells

Hydrogen is primary fuel and main source of energy for all fuel cells. Thus pure hydrogen or hydrogen rich gases are generally used in fuel cells. Some fuel cells like (MCFC & SOFC can also utilize CO along with H_2). All type of fuels can be classified into two categories: (i) direct type and (ii) indirect type.

1. *Direct type fuels* are directly introduced in the cell as such, without any transformation or reforming, to serve as active material. Examples are pure hydrogen, mixture of hydrogen with other gases, hydrazine (N_2H_4) and methanol.
2. *Indirect type fuels* are hydrogen rich fuels, which are first converted (reformed) to mixture of H_2 and some other products, e.g. CO, CO_2 and N_2, etc. Hydrocarbon fuels are decomposed by reaction with steam at high temperature in presence of a catalyst. The process is known as *steam reforming* of fuels. The products containing mainly H_2, CO and CO_2 are then supplied to the fuel cell.

Common fuels used in fuel cells are listed below:

1. Hydrogen Pure hydrogen gas is a premium fuel for all fuel cells. Pure hydrogen with pure oxygen is used in space and military applications. However, production and storage of pure hydrogen is expensive. Hydrogen rich gases obtained from reforming of other fuels is more economical alternative.

2. Hydrazine (N_2H_4) Hydrazine, a liquid fuel, has high energy density and convenient to store. However, it is toxic, costly and highly reactive. It is introduced directly to cell without any transformation.

A compact AFC (Alkaline fuel cell) with hydrazine fuel and hydrogen peroxide/oxygen as oxidant is proposed for vehicle propulsion. Oxygen is obtained either by catalytic decomposition of hydrogen peroxide or from ambient air. Electrodes are made of Ni screen with Ni (at negative electrode) and silver (at positive electrode) as catalysts. The reaction at the negative electrode is:

$$N_2H_4 + 4\,OH^- \rightarrow N_2 + 4\,H_2O + 4\,e^-$$

and at positive electrode:

$$O_2 + 2\,H_2O + 4\,e^- \rightarrow 4\,OH^-$$

The overall reaction is:

$$N_2H_4 + O_2 \rightarrow N_2 + 2\,H_2O$$

Thus hydrazine is oxidized to produce water and nitrogen, which are discharged to atmosphere.

3. Ammonia (NH_3) Ammonia is an indirect type fuel. It can be stored in liquid form and can be easily decomposed catalytically at high temperature. Part of hydrogen produced is burnt in air to provide the required heat for decomposition. The product, i.e. mixture of H_2 and N_2 is introduced into a fuel cell (e.g. AFC). Nitrogen present in the mixture is discharged with exhaust.

4. Hydrocarbons (Gases) Hydrocarbons such as methane, propane etc. are first converted to mixture of H_2 and CO by steam reforming.

$$\text{Hydrocarbons } (CH_4, C_3H_8, \text{etc.}) \xrightarrow{\text{steam reforming at 900 °C, Ni catalyst}} H_2 + CO$$

The mixture is then used as such or after removal of CO by water gas shift reaction, as required. Commercial fuels such as natural gas, LPG, biogas, coal gas, landfill gas and gasified coal can be used in this way for large-scale generation of power.

5. Hydrocarbons (Liquid) Light hydrocarbons (naphtha) are first steam reformed to get H_2 and CO. The product gas mixture is then used as fuel as explained above.

6. Synthesis Gas Mixture of H_2 and CO in various proportions, along with other impurities (known as synthesis gas) can be produced economically from conventional or non-conventional sources. The (H_2 + CO) mixture can be used as fuel in MCFC and SOFC. For use in hydrogen fuel cells, CO is to be removed and hydrogen content is increased by a process known as water gas shift reaction, as given below:

$$CO + H_2O \text{ (steam)} \xrightarrow{\text{400 °C, 27 atm, cobalt molybdate catalyst}} CO_2 + H_2 + 1440 \text{ kJ/kg}$$

CO_2 present in the products is also removed if the mixture is to be used in AFC.

7. Methanol Methanol is used both as direct as well as indirect type fuel. It can be catalytically reformed with steam at about 200 °C to yield mixture of H_2 and CO. The mixture is then used as discussed above.

Methanol can also be used directly without reforming in direct methanol fuel cell, a modified version of proton membrane exchange fuel cell.

12.2.10 Efficiency of a Fuel Cell

In a fuel cell, electrochemical reactions take place whereby reactants are converted to products in a steady flow process. If the temperature and pressure of the flow stream from entrance to exit (during reaction) remain unchanged, from first law of thermodynamics:

$$\Delta Q - \Delta W = \Delta H + \Delta\,(\text{KE}) + \Delta(\text{PE}) \qquad (12.1)$$

where ΔQ = heat transferred to the steady flow stream from the surrounding
ΔW = net work done by the flow stream on the surrounding
ΔH = change in enthalpy of the flow stream from entrance to exit (of the cell)

The change in KE and PE of the stream are usually negligible. Thus:

$$\Delta W = \Delta Q - \Delta H \qquad (12.2)$$

For ΔW to be the maximum, the process must be reversible.

Entropy is an indicator of heat per kelvin temperature (T). For a reversible process, from second law of thermodynamics, we have,

$$\Delta Q = \int T dS$$

But the surrounding temperature is constant. Thus, reversible heat transfer takes place at temperature T, which is the prevailing temperature at inlet and exit. Thus,

$$\Delta Q_{rev} = T \, \Delta S \tag{12.3}$$

where T is the temperature of the process and it remains constant, ΔS is change in entropy

Thus from Eq. (12.2):

$$\Delta W_{max} = -(\Delta H - T \, \Delta S) \tag{12.4}$$

The energy available to perform useful work is called 'Gibbs Free Energy' G. It is given by:

$$G = H - TS$$

or $$\Delta G = \Delta H - (T \, \Delta S - S \, \Delta T)$$

As there is no change in temperature, $\Delta T = 0$, and thus:

$$\Delta G = \Delta H - T \, \Delta S \tag{12.5}$$

Therefore, from Eq. (12.4): $\Delta W_{max} = -\Delta G$ (12.6)

Combining Eq. (12.3) and Eq. (12.5) we can write:

$$\Delta G = \Delta H - \Delta Q$$

Or $$\Delta Q = \Delta H - \Delta G \tag{12.7}$$

The efficiency of energy conversion of a fuel cell: $\eta = \dfrac{\Delta W}{-\Delta H}$

Maximum efficiency $\quad \eta_{max} = \dfrac{\Delta W_{max}}{-\Delta H} = \dfrac{\Delta G}{\Delta H}$

For H_2–O_2 cell at 25 °C, $\Delta G = -237191$ kJ/kg mole, $\Delta H = -285838$ kJ/kg mole and therefore:

$$\eta_{max} = 0.83$$

Thus, even in ideal cell 17 per cent of the enthalpy would be liberated as heat. Actual cell will produce even more heat. In order to avoid excessive temperature rise, heat is to be removed from the cell during the operation. This can be done by passing excess air at positive electrode or by circulating the electrolyte through an external cooler.

12.2.11 VI Characteristics of Fuel Cell

The theoretical emf of a fuel cell can be calculated from the change in Gibbs free energy, ΔG during the reaction:

$$E = \frac{-\Delta G}{nF} \tag{12.8}$$

where n = number of electrons transferred per molecule of the reactant

F = Faraday's constant (96500 coulombs per gram mole)

For H_2–O_2 cell, $n = 2$. Also at 25 °C, and at atmospheric pressure, $\Delta G = -237191$ kJ/kg mole and $\Delta H = -285838$ kJ/kg mole. Therefore, cell emf:

$$E = \frac{-237191}{2 \times (96500)} = 1.23 \text{ V}$$

The value of E at 200 °C is 1.15 V. The actual value of cell output voltage, V attained on load is less than E. The difference between actual and theoretical voltage is known as *polarization*, V_P. The effect of polarization is to reduce the voltage and thereby efficiency of the cell from its maximum value. All the losses in the fuel cell may be included under voltage efficiency η_v, which may be expressed as:

$$\eta_v = \frac{\text{on load voltage}}{\text{theoretical open circuit volteg (emf)}} = \frac{V}{E}$$

The VI characteristic of a fuel cell is shown in Fig. 12.6. Voltage regulation is poor for small and large values of output current. Therefore, in practice the operating point is fixed in range BC of the characteristics where voltage regulation is best and the output voltage is roughly around 0.6–0.8 V.

At no load, the terminal voltage is equal to the theoretical open circuit voltage. As the cell is loaded (current is supplied to load), voltage and hence efficiency drops significantly. The departure of output voltage from ideal emf is mainly due to following reasons.

1. Activation Polarization (Chemical Polarization) This is related to activation energy barrier for the electron transfer process at the electrode. Certain minimum activation energy is required to be supplied so that sufficient number of electrons is emitted. At low current densities significant numbers of electrons are not emitted. This energy is supplied by the output of the cell, resulting in potential loss. It can be reduced by an effective electrochemical catalyst and also by increasing the operating temperature.

2. Resistance Polarization At larger current there is additional contribution from internal electrical resistance of the cell. The internal resistance is composed mainly of resistance of bulk electrolyte and interface contact resistance between electrode and electrolyte. The resistance polarization can be reduced by: (a) using more concentrated (i.e. high conductivity) electrolyte, (b) increasing the operating temperature, and (c) using proper shape and spacing of electrolyte to reduce the contact resistance.

3. Concentration Polarization This type of polarization tends to limit the current drawn from the cell. This is related to mass transport within the cell and may further be subdivided into two parts.

(a) Electrolyte polarization: It is due to slow diffusion in the electrolyte causing change in concentration at the electrode. This effect can be reduced by increasing the electrolyte concentration or by stirring/circulating the electrolyte.

(b) Gas side polarization: It is caused due to slow diffusion of reactants through porous electrode to the site of reaction or slow diffusion of product away from the reaction site. Increasing the operating temperature also reduces this effect.

As observed in the above discussion, all the losses in the fuel cell are reduced as operating temperature is increased. Therefore, in practice, a fuel cell is usually operated at higher end of its operating temperature range.

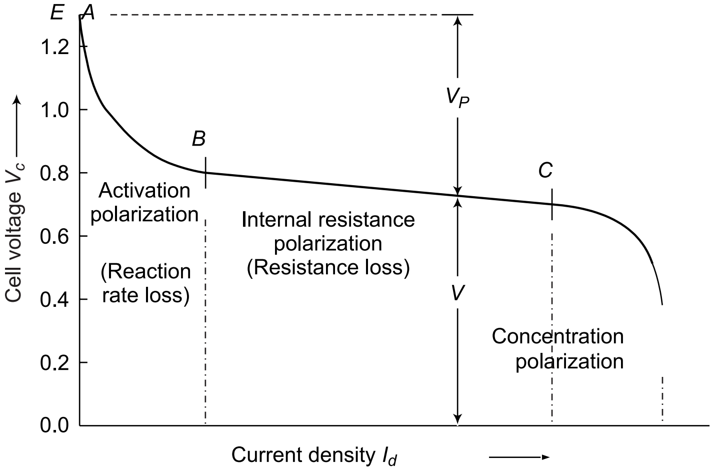


Figure 12.6 VI characteristic of fuel cell

Example 12.1

Find the ideal fuel cell voltage at no load and maximum efficiency for the direct methanol fuel cell having following reactions:

Anode Reaction: $CH_3OH + H_2O\ (l) \rightarrow CO_2 + 6H^+ + 6e^-$

Cathode Reaction: $3/2\ O_2 + 6\ H^+ + 6e^- \rightarrow 3\ H_2O\ (l)$

Overall Cell Reaction: $CH_3OH + 3/2\ O_2 \rightarrow CO_2 + 2\ H_2O\ (l)$

What flow rate in kg/h of methanol and oxygen would be required to produce an electrical power output of 100 kW? At what rate heat is to be removed from the cell? Given for standard conditions, the change in Gibb's free energy, $\Delta G° = -56.8$ kCal/mol, and the change in enthalpy, $\Delta H° = -39.59$ kCal/mol.

Solution

Given,

$$\Delta G° = -\ 39.59 \text{ KCal/mol, which is equivalent to } \Delta G° = -166.3 \text{ kJ/mol}$$

$$\Delta H° = -56.83 \text{ kCal/mol, which is equivalent to } \Delta H° = -238.7 \text{ kJ/mol}$$

From Eq. (12.6), the electrical work output per mole of fuel (methanol) consumed:

$$\Delta W_{\max} = -\Delta G = 166.3 \text{ kJ}$$

That means, 166.3 kJ electrical work is produced from 1 mole (i.e. 32 g) of methanol and $\frac{3}{2}$ mole (i.e. 1.5 × 32 g) of oxygen

In other words, 166.3 kW electrical power is produced from flow rate of 32 g/s of methanol and 48 g/s of oxygen

Required flow rate of methanol for electrical output of 100 kW $= \dfrac{32\times100}{166.3}$

$= 19.24$ g/s

$= 23.09$ kg/h

Required flow rate of oxygen for electrical output of 100 kW $= \dfrac{48\times100}{166.3}$

$= 28.86$ g/s

$= 34.63$ kg/h

The heat transferred is given by Eq. (12.3): $\Delta Q = T\,\Delta S$

which may be rewritten (from Eq. (12.7)), as:

$$\begin{aligned}\Delta Q &= \Delta H^\circ - \Delta G^\circ\\ &= -56.83 + 39.59\\ &= -17.24 \text{ kCal/mol}\end{aligned}$$

Negative sign indicates that heat is removed from the cell and transferred to the surroundings.

Thus 1 mole (i.e. 32 g) of methanol produces 17.24 Cal of heat.

As calculated above, the fuel consumption rate for 100 kW electrical power generation is 19.24 g/s

Consumption of fuel at the rate 19.24 g/s produces heat at the rate of $\dfrac{17.24\times19.24}{32}$ = 10.366 kCal/s

Thus, the required heat removal rate from the cell at electrical output of 100 kW is 10.366 kCal/s

12.2.12 Fuel Cell Power Plant

The block diagram showing main components of a fuel cell power plant is given in Fig. 12.7. Electrical energy is generated from primary fossil fuels through fuel cell. Fuel is managed and supplied by fuel processing unit. In this unit, fuel is received, stored, reformed, purified and supplied to fuel cell modules. Fuel cell modules convert fuel energy electrochemically into dc power using ambient air as oxidant. Basic configurations of cell, module and plant are shown in Fig. 12.8. A number of cells are stacked to form a module. Several modules are interconnected to form a power-generating unit. Fuel gas and air are supplied to modules from common supply pipes. The exhaust is collected in a common pipe and discharged to atmosphere either directly or after recovery of heat in a cogeneration unit. Power generating unit generates electrical power as dc. Industrial/commercial loads are normally rated for standard ac supply such as 3 ph., 400 V, 50/60 Hz or 1 ph., 230/110 V, 50/60 Hz. The electrical power-conditioning unit, converts dc output of fuel cell to ac using inverter and also controls and regulates it.

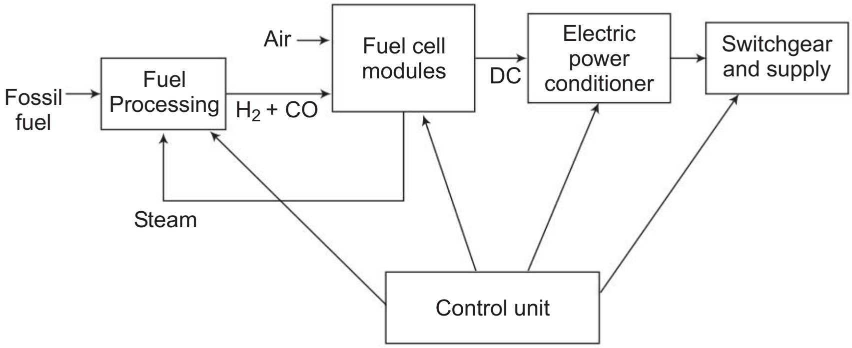
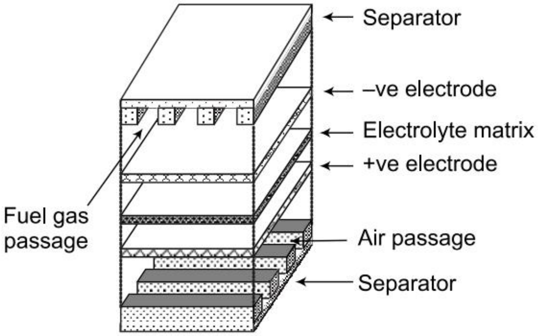


Figure 12.7 Fuel cell based electrical power generation scheme



Single cell

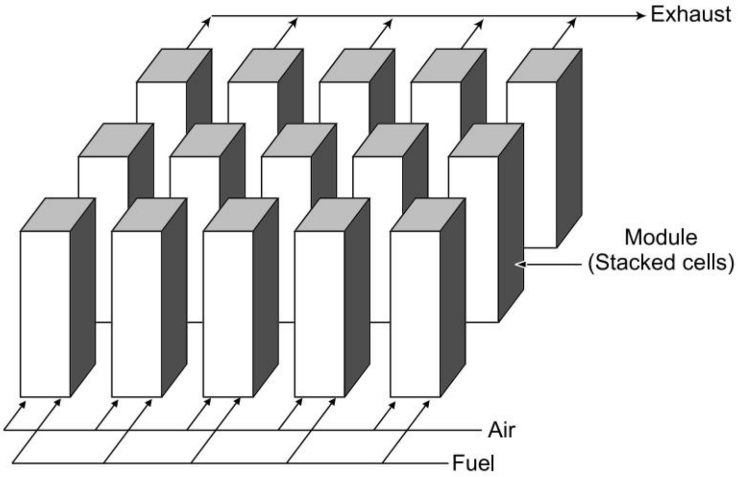


Figure 12.8 Power generation unit

12.2.13 Present Status

Fuel cell technology and its applications in various fields are at development stage. Stackable modules of size 200–250 kW are available. Demonstration projects are being installed at different places.

A number of companies are engaged in manufacturing fuel cells. For example, 'UTC Fuel Cells' has delivered more than 250 fuel cell power plants around the world that can run on waste methane such as landfill gas. 'Fuel Cell Energy' offers 1.5 MW and 3 MW sized plants for stationary applications utilizing natural gas or waste methane gas as fuel.

Fuel cell units for homes and small commercial applications are in initial stages of commercialization. 'Avista Labs' is marketing fuel cell with capacities 100–5000 W to USA and European Union.

All major automakers are working on fuel cell and/or hydrogen vehicle program. A number of demonstration vehicles are being tested including cars, buses, trucks and locomotives, etc., in USA, Canada, Europe, Japan, China and Australia. Fuel cells are also powering boom lifts, forklifts, golf carts and utility vehicles in USA and other developed countries. In USA, 1 MW fuel cell plant is being developed to replace diesel locomotive engine.

US army is very much interested in portable fuel cells to replace batteries for powering field equipment. Sony, Motorola, Panasonic, Casio and NEC, etc., are developing fuel cells for devices including cellular telephones and hand held computers etc. Main hurdles in the popularity of fuel cells are lack of hydrogen infrastructure and limited life span of fuel cell. However, these issues are making progress.

Fuel cells continue to face major technological hurdles that may require many years of research and development before they can be overcome. In addition, fuel cells are not likely to be implemented in isolation. They must be part of a larger shift in fuel infrastructure and efficiency standards, which will require sustained political and economic pressure and time. Finally, like any technology, economy of scale will require a natural maturation process over many years or decades.

Taken together, these hurdles suggest that the widespread adoption of fuel cell technology is not likely in the short term. Successful advancement of fuel cell technology will require a sustained, long-term commitment to fundamental research, commercial development, and incremental market entry.

12.2.14 Environmental Effects

With hydrogen as fuel, the exhaust of a fuel cell contains only water vapor, which is not a pollutant apart from some amount of heat. If air is used as oxidant, spent air, which is mostly nitrogen, is also present in the exhaust. This is again not a pollutant. No cooling water is required as the generated heat can be easily utilized in cogeneration unit or discharged easily to atmosphere. The heat can also be utilized for fuel reforming process. In case of hydrocarbon fuels, CO_2 is also produced. However, as the fuel is used more efficiently, the amount of CO_2 emission is less, compared to that when same fuel is used in conventional thermal plants with same output. Other pollutants are negligible compared to conventional thermal plants, as shown in Table 12.2.

Table 12.2 Emissions from various plants in kg/GJ of output

S.N.	Pollutant	Quantity in various type of plants			
		Fuel Cell Plant	Coal Fired Plant	Oil Fired Plant	Natural Gas Fired Plant (comb. cycle)
1.	NO_X	0.0000429–0.001718	0.2607	0.15337	0.18044
2.	Particulate	0.0–0.000733	0.0644	0.02362	0.00128
3.	SO_X	0.0	0.7733	0.23199	0.0
4.	*VOCs	0.0–0.00386	–	–	–
5.	CO_2	47.258	89.79	72.6	47.258

*VOC = volatile organic compounds

12.3 HYDROGEN AS ENERGY CARRIER

Hydrogen is the simplest element. An atom of hydrogen consists of only one proton and one electron. It is also the most plentiful element in the universe. Despite its simplicity and abundance, hydrogen doesn't occur naturally as a gas on the Earth – it is always combined with other elements. Water, for example, is a combination of hydrogen and oxygen (H_2O).

Hydrogen holds the potential to provide clean, reliable and affordable energy supply that can enhance economy, environment and security. It is flexible and can be used by all sectors of economy. It is non-toxic and recyclable. Due to these qualities it is considered to be an ideal energy carrier in the foreseeable future. An energy carrier moves and delivers energy in a usable form to consumers.

Hydrogen can be produced by using a variety of energy sources, such as solar, nuclear and fossil fuels and can be converted to useful energy forms efficiently and without detrimental environmental effects. When burned as fuel or converted to electricity it joins with oxygen to produce energy with water as the only emission. When air is used for combustion instead of oxygen, some NO_x is also produced, which can be reduced by lowering the combustion temperature.

Despite all these benefits, realization of hydrogen economy faces multiple challenges. Unlike gasoline and natural gas, hydrogen has no existing, large scale supporting infrastructure. Building of such an infrastructure will require major investment. Although hydrogen production, storage and delivery techniques are currently in commercial use by the chemical and refining industries, existing hydrogen storage and conversion technologies are too costly for widespread use in energy applications.

The individual segments of hydrogen energy system; production, delivery, storage conversion and end use applications are closely interrelated and interdependent as shown in Fig. 12.9. Design and application of a hydrogen economy must carefully consider each of these segments as well as the whole system.

Hydrogen can be produced in centralized facilities and distributed to an energy conversion site via pipeline or stored and shipped via rail or road. It can also be produced at decentralized locations onsite where it will be stored and/or fed directly into conversion device for stationary, mobile or portable applications.

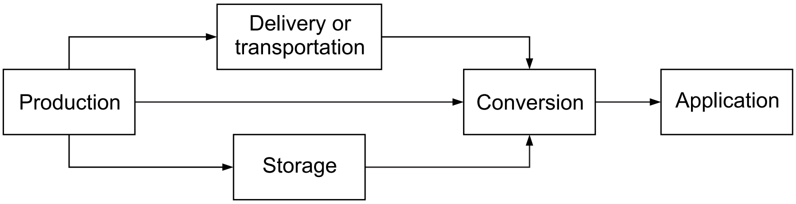


Figure 12.9 Hydrogen energy system

12.3.1 Properties of Hydrogen

Hydrogen is an odorless and colorless gas. It has the simplest and lightest atom with one proton and one electron and molecular weight of 2.016. Important properties are listed and compared with natural gas and gasoline in Table 12.3.

Table 12.3 Comparison of various properties of hydrogen with other fuels

S.N.	Properties	Gasoline	Natural gas	Hydrogen
1.	Density (kg/m^3)	730	0.78	0.0837
2.	Boiling point, (°C)	38 to 204	–156	–253 (20.3 K)
3.	Lower heating value, (MJ/kg) (MJ/m^3)	44.5 32	48 37.3	125 10.4 (gas), 8520 (liquid)
4.	Higher heating value, (MJ/kg) (MJ/m^3)	50.8 36.6	55 42.6	141.90 11.89 (gas), 10046 (liquid)
5.	Flammable limit, % in air	1.4–7.6	5–16	4–75
6.	Flame speed, (m/s)	0.4	0.41	3.45
7.	Flame temperature, (°C)	2197	1875	2045
8.	Flame luminosity	High	Medium	Low

12.3.2 Production

Although hydrogen is the third most abundant element on the earth, it does not exist in free state, except for small quantities in the upper atmosphere. It is, therefore, not a primary energy source. However, large amounts of combined hydrogen are present in compounds such as water, fossil fuels and biomass. It can therefore, be produced through two routes:

(a) Fossil fuels, such as natural gas, coal, methanol, gasoline etc., and biomass are decomposed by thermo-chemical (steam reforming or partial oxidation) methods to obtain hydrogen. The CO produced in the process is eliminated by water gas shift reaction. This route of hydrogen production causes CO_2 emission. The *energy* content of the produced *hydrogen* is less than the *energy* content of the original fuel, some of it being lost as excessive heat during production.

(b) Hydrogen can also be produced by splitting water into hydrogen and oxygen by using energy from nuclear or renewable sources such as solar, wind, geothermal, etc., through electrical or thermal means (i.e. electrolysis and thermolysis respectively). Water splitting is also possible through bio-photolysis process using solar radiation.

Splitting of water is thus possible at the expense of renewable energy to produce secondary fuel H_2. On use, H_2 and O_2 recombine to produce water again and energy is released. This route is therefore a clean and sustainable route of energy supply.

1. Thermo-chemical Methods

Steam reforming of methane is the most energy efficient, commercialized technology currently available and most cost effective when applied to large, constant loads. The method accounts for 95 per cent of the hydrogen production in USA. The steam reforming method has been described in the previous section on fuel cell. Partial oxidation (thermal gasification) method of biomass has been described in Chapter 8 on biomass.

2. Electrolysis of Water

Electrolysis is the simplest method of hydrogen production. Currently, this method is not as efficient or cost effective as thermo-chemical method using fossil fuels or biomass. But it would allow for more distributed hydrogen generation and open the possibilities for use of electricity generated from renewable and nuclear resources for hydrogen production.

An electrolysis cell essentially consists of two electrodes, commonly flat metal or carbon plates, immersed in an aqueous conducting solution called electrolyte, as shown in Fig. 12.10. A direct current decomposes water into H_2 and $O_{2,}$ which are released at cathode (–ve electrode) and anode (+ve electrode) respectively. As water itself is poor conductor of electricity, an electrolyte, commonly aqueous KOH is used.

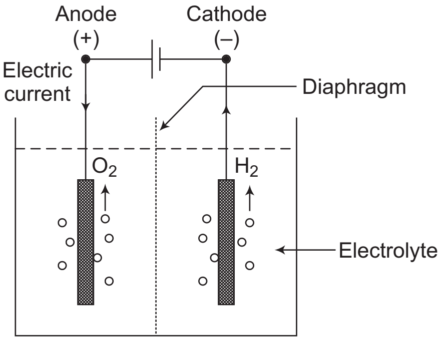


Figure 12.10 Electrolytic cell

Ideally, a decomposition voltage of 1.23 V per cell should be sufficient at normal temperature and pressure; however, due to various reasons a voltage of about 2 V per cell is applied in practice. The energy required is 3.9–4.6 kWh per m^3 of hydrogen produced. About 60–70 per cent of this energy is actually utilized in electrolysis. Therefore, the efficiency of electrolysis process is about 60–70 per cent, which can be improved up to 80 per cent by using catalyst such as porous platinum or nickel. A diaphragm (usually woven asbestos) prevents electronic contact between the electrodes and passage of gas or gas bubbles. Electrolysis method is most suitable when primary energy is available as electrical energy, e.g. solar photovoltaic energy. It is also suitable where cheap electricity is available from other sources such as wind, geothermal, etc.

3. Thermolysis of Water

When primary energy is available in the form of heat (e.g. solar thermal), it is more logical to produce hydrogen by splitting water directly from heat energy using thermolysis. This would be more efficient than conversion of heat, first to electricity (using heat engine – generator) and then producing hydrogen through electrolysis. The efficiency of thermal plant is usually in range 32–38 per cent and that of electrolysis is 80 per cent. The overall efficiency through thermal-electrical-hydrogen route would thus be only 25–30 per cent.

Direct thermal decomposition of water is possible but it requires a temperature of at least 2500 °C; because of temperature limitations of conversion process equipment, direct single-step water decomposition cannot be achieved. However, sequential chemical reactions at substantially lower temperature can be devised to split water into H_2 and O_2. In the reaction series, water is taken up at one stage and H_2 and O_2 are produced in different stages. The energy is supplied as heat at one or more stages and partly released at some stage in the cycle. Apart from decomposition of water, all other materials are recovered when the cycle is completed. Therefore, the method is known as *thermo-chemical cycle*. The efficiency of conversion from heat energy to hydrogen is better than its conversion through electrolysis route only when the upper temperature of thermo-chemical cycle is above 700 °C. For the upper temperature of 950 °C the efficiency of conversion is about 50 per cent. This is a marked improvement over what is possible through electrolysis route. Several thermo-chemical cycles have been proposed and are under investigation. One such cycle is given below:

$$2\,CrCl_2 + 2\,HCl \xrightarrow{325\,°C} 2\,CrCl_3 + H_2$$

$$2\,CrCl_3 \xrightarrow{875\,°C} 2\,CrCl_2 + Cl_2$$

$$H_2O + Cl_2 \xrightarrow{850\,°C} 2\,HCl + \tfrac{1}{2}\,O_2$$

At present, no commercial process for thermal splitting of water using thermo-chemical cycle is in operation.

4. Biophotolysis

In this method the ability of the plants (especially algae) to split water during photosynthesis process is utilized. An artificial system is devised, which could produce hydrogen and oxygen from water in sunlight using isolated photosynthetic membrane and other catalysts. Since this process is essentially a decomposition of water using photons in the presence of biological catalysts, the reaction is called photolysis of water.

There are three distinct functional components coupled together in the system as shown in Fig. 12.11: (i) photosynthetic membrane, which absorbs light, split water to generate oxygen, electrons and protons, (ii) an electron mediator, which is reducible by photo-synthetically generated electrons and (iii) a proton activator that will accept electrons from the reduced mediator and catalyze the reaction: $2\,H^+ + 2\,e^- \rightarrow H_2$.

A system with chloroplast (small bodies containing the chlorophyll in green plants) as a photosynthetic membrane to split hydrogen and oxygen, ferredoxin as e^- mediator and hydrogenase (an enzyme) or finely dispersed platinum as proton activator, has been successfully tested. The method is being extensively studied further.

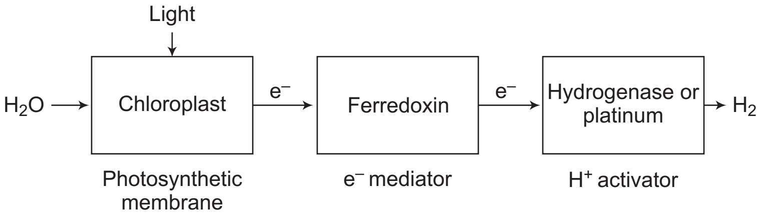


Figure 12.11 Functional components of biophotolysis

12.3.3 Storage

Hydrogen can be stored as a discrete gas or liquid or in a chemical compound. For a given amount of energy, hydrogen weighs about one third of the fossil fuels, but it is bulkier. In gaseous form it occupies 3.6 times the volume occupied by natural gas and in liquid form it occupies 3.8 times the volume occupied by gasoline. However, in practice the volume penalty is 20 to 50 per cent less, since hydrogen can be converted to other forms of energy at the user end more efficiently then fossil fuels.

Large amounts of hydrogen for subsequent distribution would probably be stored in the underground facilities similar to those used for natural gas, e.g. depleted oil and gas reserves and aquifers. On low or moderate scale, hydrogen is frequently stored in strong steel tank or cylinder. The storage of compressed hydrogen gas in tanks is the most mature technology though the very density of hydrogen translates to inefficient use of space. The inefficiency can be mitigated with high compression such as 350–700 atm. However, further improvement in cost, weight and volume efficient storage is required in order to make it more acceptable by the end user.

Hydrogen can also be stored as compact storage in liquid form at low temperature. It takes up low storage volume but requires cryogenic containers, as boiling point of hydrogen is 20 K. Furthermore, the liquefaction of hydrogen is energy intensive process and results in large evaporative losses. About one third of the energy content of hydrogen is lost in the process.

Hydrogen can be stored at high densities in reversible metal hydrides. When required, it can be released by heating the hydride and original metal (or alloy) is recovered for further recycling. The chemical equations are:

Charging H_2 + Metal → hydride + heat (hydrogen is stored and heat is released)

Discharging hydride + heat → H_2 + Metal (heat is stored and hydrogen is released)

The pressure of gas released by heating depends mainly on temperature. At fixed temperature, the pressure remains essentially constant until the hydrogen content is almost exhausted. Metal hydrides offer the advantage of lower pressure storage, comfortable shape and reasonable volumetric store efficiency but have weight penalties and thermal management issues. It is also very safe. In case of accidental breakdown of storage, the gas remains in hydride and does not escape. To be suitable as a storage medium, metal hydride should have following desirable properties:

(i) The metal (or alloy) should be inexpensive.
(ii) The hydride should contain a large amount of hydrogen per unit volume and per unit mass.
(iii) Formation of hydride from metal by reaction with hydrogen should be easy and the hydride should be stable at room temperature.
(iv) The gas should be released from hydride at significant pressure and moderately high temperature (preferably below 100 °C)

The reactions with three more promising hydrides of alloys are given below:

(i) Lanthanum-Nickel: $\text{La Ni}_5 + 3\,\text{H}_2 \underset{\text{Dischareg}}{\overset{\text{Charge}}{\rightleftarrows}} (\text{La Ni}_5)\,\text{H}_6 + \text{heat}$

(ii) Iron-Titanium: $\text{Fe Ti} + \text{H}_2 \underset{\text{Dischareg}}{\overset{\text{Charge}}{\rightleftarrows}} (\text{Fe Ti})\,\text{H}_2 + \text{heat}$

(iii) Magnesium-Nickel: $\text{Mg}_2\,\text{Ni} + 2\,\text{H}_2 \underset{\text{Dischareg}}{\overset{\text{Charge}}{\rightleftarrows}} (\text{Mg}_2\,\text{Ni})\,\text{H}_4 + \text{heat}$

These hydrides contain somewhat more hydrogen then an equal volume. In theory $(\text{La Ni}_5)\,\text{H}_6$ contains 1.35 per cent of hydrogen by weight, $(\text{Fe Ti})\,\text{H}_2$ contains 1.9 per cent and $(\text{Mg}_2\,\text{Ni})\,\text{H}_4$ contains 3.6 per cent. Due to heavy weight, hydride storage is not suitable for mobile storage such as vehicles. Some complex-based reversible hydrides such as aluminates have recently demonstrated improved weight performances over metal hydrides along with modest temperatures for hydrogen recovery.

Chemical hydrides are emerging as another alternative to direct hydrogen storage. The chemicals considered for store applications are class of compounds that can be stored in solution as an alkaline liquid. Since the hydrogen is chemically bound in compound and released by catalytic process, chemical hydrides present an inherent safer option than direct storage of volatile and flammable fuel. It is also volumetric efficient, however, cost and recycling issues are to be addressed.

Hydrogen can, in principle, be reversibly adsorbed on carbon structures (e.g. carbon nanotubes). However, the design of practical system requires a better understanding of the fundamental adsorption/desorption process and development of high volume manufacturing process for the material.

12.3.4 Delivery

A key element in the overall hydrogen energy infrastructure is the delivery system that moves hydrogen from its point of production to an end use device. Delivery system requirements vary with production method and end use application. Hydrogen is very efficient energy carrier. For distances greater than 300 km, it is cheaper to transmit energy as hydrogen than electricity via overhead transmission lines. The transport of energy through a gas network is done with much less loss (<0.1 per cent) than in a power network (8 per cent). Infrastructure includes the pipelines, trucks, storage facilities, compressors, and dispensers involved in the process of delivering hydrogen.

Hydrogen produced in centralized locations can be delivered: (i) via pipe line or (ii) stored in tanks, cylinders, tubes, etc., that are loaded onto truck and rail cars and transported to consumers. For high demand areas pipeline is cheapest. For low demand areas it is transported via road/rail. In the range of about 300 km hydrogen is being transported via high-pressure cylinders. For very long distances in range 1500 km, hydrogen is usually transported as liquid in super insulated, cryogenic tanker on road or rail.

Hydrogen is relatively difficult to store and transport in comparison with petroleum fuels. Gaseous hydrogen has two principle drawbacks. Firstly, the unusually low volumetric energy density of gaseous hydrogen means that the gas must be compressed to extremely high pressure to be used as a transport fuel. Secondly, the tiny molecules have a higher propensity to leak than other gases and require particularly complex storage materials. One method of avoiding these two difficulties is to compress the hydrogen into a liquid, but this is energetically expensive and difficult to handle because liquid hydrogen boils at around –253 °C.

At present, the hydrogen delivery technologies cost more than the conventional fuel delivery. Improvements are needed in areas such as: fueling components (like compressors, seals, valves, hosepipes and hydrogen detectors), material selection for pipelines and transportation containers for hydrogen. Key challenges to hydrogen delivery include reducing delivery cost, increasing energy efficiency, maintaining hydrogen purity, and minimizing hydrogen leakage.

The existing high-pressure natural gas pipelines are not suitable for hydrogen transport. At ambient temperature and pressures below 100 bar, the principal concern for high-strength steel is hydrogen embrittlement and corrosion. Hydrogen has an active electron, and therefore behaves somewhat like a halogen. For this reason, hydrogen pipes have to resist corrosion. The problem is compounded because hydrogen can easily migrate into the crystal structure of most metals. Hydrogen will diffuse into any surface flaws that occur due to material defects, construction defects or corrosion, resulting in a loss of ductility, increased crack growth or initiation of new cracks. These will ultimately lead to material failure. Higher pressures are thought to increase the likelihood of material failure although no threshold value has been defined independently of other factors. Hydrogen can be transported at high pressures using pipes constructed of softer steels that reduce the rate of embrittlement, and there is much industrial experience in this area spanning many decades. For metal piping at pressures up to 480 bar, high-purity stainless steel piping with a maximum hardness of 80 HRB is preferred

12.3.5 Conversion

Hydrogen can be converted into useful forms of energy in several ways. Some of the hydrogen conversion technologies are unique to hydrogen, but all of them are efficient and less polluting than conventional fuels.

Once produced and delivered to consumer center, hydrogen is used: (i) to fuel internal combustion engines in the same manner as gasoline or natural gas to produce mechanical and electrical energy, (ii) for electrochemical conversion in fuel cells that generate electrical and thermal energy, (iii) for hydrogen/oxygen combustion for steam generation, (iv) for catalytic combustion and (v) in metal hydride technologies.

Hydrogen and electricity are often considered as complementary energy carriers for the future. Hydrogen has some unique properties, which in conjunction with electricity makes it an ideal energy carrier for future.

The specially designed/modified IC engine with hydrogen as fuel operates at high efficiency and produces no pollutants (except NO_x, which is typically one order of magnitude smaller than emission from a comparable gasoline engine). Small amounts of unburned hydrocarbons, CO and CO_2 have also been detected in hydrogen engines due to lubricating oil. A hydrogen engine is able to run even on lean mixtures of fuel, though with lower output. Due to lower energy content in a stoichiometric mixture in the engine's cylinder, the use of hydrogen in IC engines leads to some loss of power. Same engine running on hydrogen will have about 15 per cent less power output as compared to its operation with gasoline.

In turbines and jet engines hydrogen can be used similar to conventional jet fuels. Use of hydrogen avoids the problem of sediments and corrosion of turbine blades. This prolongs the life and reduces maintenance. The inlet gas temperature can be increased beyond normal gas turbine temperature of 800 °C, thus overall efficiency can be increased. However, the exhaust contains NO_x, which is a pollutant.

Hydrogen has traditionally been used in space program as fuel for rocket engines. The space programs are currently the biggest consumer of liquid hydrogen. In fact, tremendous experience in hydrogen technology, including production, handling, liquefaction, storage, transportation, operational use and safety procedures has been gained as a result of space program. This experience may serve as basis for further development and diversification of hydrogen energy technologies.

Combustion of hydrogen in oxygen results in pure steam with flame zone temperature above 3000 °C. Additional water has to be added to adjust the steam temperature to desired level. Such a steam generator is close to 100 per cent efficient, since there are no emissions and little or no losses. The hydrogen steam generator can be used to generate steam for spinning reserve in power plants, for peak load power generation, for industrial use and as a micro-steam generator in medical and biotechnology.

It is also possible to burn hydrogen in oxygen in presence of a suitable catalyst at temperatures significantly lower than flame combustion (i.e. from ambient to 500 °C). This principle can be used to design catalytic burner and heaters. These burners can be used in house hold applications such as cooking ranges and space heaters.

Direct generation of electricity from hydrogen is possible through fuel cell. Fuel cell technologies have already been covered in detail in previous section. These are more efficient than conversion through thermal link.

The property of hydrogen to form reversible metal hydrides may be used not only for its storage but also for various thermal energy conversion processes. Heat is generated while charging, i.e. chemical combination of hydrogen with metal (and alloy). Conversely, heat is absorbed while discharging, release of hydrogen from metal hydride.

Charging $M + xH_2 \rightarrow MH_{2x} + \text{heat}$

Discharging $MH_{2x} + \text{heat} \rightarrow M + xH_2$

Using this principle, any heat, such as waste heat, solar heat, geothermal heat, etc., can be stored, which can be released later for use. By increasing the pressure of hydrogen supplied, the temperature of heat released can be increased. Thus by regulating the pressure at the time of release of heat, the temperature can be increased or decreased.

The above-mentioned principle of controlling the temperature by regulating the pressure can be used for space heating/cooling/refrigeration, operated by a heat energy source such as solar thermal energy.

In many applications, such as hydrogenation of vegetable oils, high purity hydrogen is needed. Hydriding substance absorbs only hydrogen and no other elements, which may be present as impurities. Using this property of hydrides it is possible to purify hydrogen, in an inexpensive way.

The hydrogen purification technique may also be applied for separation of deuterium. Using titanium-nickel alloy as the hydriding substance, it is possible to obtain 85 per cent pure deuterium after only two steps. With three or four steps, it is possible to obtain 99.9 per cent and 99.999 per cent pure deuterium respectively.

12.3.6 Applications

Hydrogen can be used in combustion based power generation, such as gas turbine using hydrogen alone or mixed with natural gas. Such applications are proposed for stationary power generation including backup power units, stand-alone power plants, distributed generation for buildings and cogeneration. Alternatively, hydrogen may be obtained from steam reforming of natural gas and then used in fuel cell to generate electricity.

Portable applications for fuel cell based generation include consumer electronics, business machinery and recreational devices. These portable power applications range from 25 W for portable electronics to 10 kW system for critical commercial and medical functions and on site power generation for individual homes and office buildings.

Hydrogen is also being proposed for commercial vehicles (bus, trucks, cars, trains, etc.). Technologies are being developed to use hydrogen in both fuel cells and IC engines including methanol system.

12.3.7 Safety Issues

Like any other fuel or energy carrier, hydrogen poses risk if not properly handled or controlled. Some properties of hydrogen make it potentially less hazardous while other characteristics could make it more dangerous in certain situations.

Since hydrogen has the smallest molecule it has a greater tendency to escape through small openings than other liquid or gaseous fuels. As natural gas has over three times the energy density per unit volume, the natural gas leak would result in more energy release than hydrogen leak.

In case of leak, hydrogen will disperse much faster than any other fuel, thus reducing the hazard level. The key parameter that determines if a leak would ignite is the lower flammability limit and hydrogen's lower flammability limit (which is 4 per cent by volume) is four times higher than that of gasoline and slightly lower than that of natural gas.

Hydrogen has very low ignition energy (0.02 mJ) about one order of magnitude lower than other fuels. Consequently, a very weak spark can ignite it.

Because of its low density, hydrogen disperses more readily in an open (or ventilated) space, and it would therefore take much longer for the flammability limit to be reached.

Hydrogen flame is nearly invisible, which may be dangerous, because people in the vicinity of the flame may not even know there is fire. This may be remedied by adding some chemicals that will provide the necessary luminosity.

The emissions from hydrogen flame make it less likely to ignite or hurt nearby people or material by radiant heat transfer.

Liquid hydrogen presents another set of safety issues, such as risk of cold burns and the increased duration of leaked cryogenic fuel. The low temperature of the liquid may cause air to liquefy around control valves, pipes etc. if they are not properly insulated. Since oxygen is more readily liquefied than air, oxygen rich liquid may form around these points. This would greatly increase the flammability danger.

Liquid oxygen could also be formed from the air present in an empty tank or pipe when it is being filled with liquid hydrogen. The air must therefore be removed by purging with helium before filling with hydrogen.

Hydrogen onboard vehicle may pose a safety hazard. The hazards should be considered in different stages, i.e. when: (i) vehicle is inoperative, (ii) vehicle is in normal operation and (iii) in collision. The source of fire or explosion may arise from the fuel storage, from fuel supply line or from fuel cell. Largest amount of hydrogen at given time is present in the tank. Several tank failure modes may be considered in both normal operation and collision. Most of the failure modes may be either avoided or the occurrences and the consequences minimized by: (i) leak prevention through proper system design and installing protection equipment, (ii) leak detection by adding an odorant to the hydrogen fuel, and (iii) ignition prevention by automatically disconnecting battery, thus eliminating the electrical spark, which are the cause of 85 per cent fire after collision, in gasoline powered vehicles.

12.3.8 Present Status

The United States currently produces about nine million tons of hydrogen per year. This hydrogen is used primarily in industrial processes including petroleum refining, petrochemical manufacturing, glass purification, and in fertilizers. It is also used in the semiconductor industry and for the hydrogenation of unsaturated fats in vegetable oil.

Only a small fraction of the hydrogen produced in the United States is used as an energy carrier, most notably by the National Aeronautics and Space Administration (NASA). Hydrogen is the optimum choice for fuel cells, which are extremely efficient energy conversion devices that can be used for transportation and electricity generation.

Expanding the use of hydrogen as an energy carrier requires a fundamental change in the way we produce, deliver, store, and use energy. Putting it all together is the ultimate challenge. To achieve the goal of commercially viable hydrogen and fuel cell systems, research and development efforts are focused on the most promising technologies, and demonstrations are validating fully integrated systems operating in real world conditions. While there are barriers to overcome, the benefits outweigh the costs.

In 2003 President George Bush proposed what is called the Hydrogen Fuel Initiative (HFI), which was later implemented by legislation through the 2005 Energy Policy Act and the 2006 Advanced Energy Initiative. These aim at further developing hydrogen fuel cells and its infrastructure technologies with the ultimate goal to produce fuel cell vehicles that are both practical and cost-effective by 2020. Thus far the United States has contributed 1 billion dollars to this project.

REVIEW QUESTIONS

1. What is a fuel cell and what are its main advantages?
2. What are potential applications of fuel cell?
3. What are the main obstacles in the way of widespread use of fuel cells?
4. Describe the classification of the fuel cells.
5. Comment on relative performances of various types of fuel cells.
6. Explain the principle of operation of alkaline fuel cell.
7. Describe various fuels used in fuel cells along with chemical reaction involved.
8. Discuss VI characteristics of a fuel cell and define various types of polarizations.
9. Draw a conceptual block diagram of a fuel cell power plant and explain the details of each block.
10. What is the present state of development in fuel cell technology?
11. Comment on environmental effect of fuel cell.
12. Comment on the possibilities of hydrogen as potential energy carrier in future.
13. Explain various methods of production of hydrogen for use as energy carrier.
14. Describe various methods of storage of hydrogen.
15. Discuss various conversion technologies of hydrogen to useful applications.
16. Comment on the safety issues related to use of hydrogen.

PROBLEMS

1. Find the emf generated at standard conditions, in a fuel cell supplied with methane as fuel. The overall cell reaction (including reformation) is as follows:

$$CH_4 + 2H_2O = CO_2 + 8H^+ + 8e^-$$

The change in Gibb's free energy, at standard conditions $\Delta G° = -817.97$ kJ/mol.

(*Ans.* 1.0595 V)

OBJECTIVE TYPE QUESTIONS

1. A fuel cell is basically:
   (a) an electro-mechanical energy conversion device
   (b) an electro-static energy conversion device
   (c) an electro-chemical energy conversion device
   (d) a thermo-electric energy conversion device

2. Wide-spread use of fuel cell is hindered mainly due to:
   (a) its high cost
   (b) its high weight and size
   (c) its high efficiency
   (d) non-availability of hydrogen

3. Which fuel cell has the lowest operating temperature?
   (a) PAFC
   (b) PEMFC
   (c) SOFC
   (d) MCFC

4. Which fuel cell has the highest operating temperature?
   (a) PAFC
   (b) PEMFC
   (c) SOFC
   (d) MCFC

5. Direct methanol fuel cell is a modified version of:
   (a) PAFC
   (b) PEMFC
   (c) SOFC
   (d) MCFC

6. As a load is applied on an open circuited fuel cell and it is gradually increased:
   (a) its efficiency increases
   (b) its output voltage increases
   (c) its output voltage remains unchanged
   (d) its output voltage decreases

7. For proper operation of a fuel cell, in which region of the VI characteristics, the operating point is set:
   (a) in the low load region
   (b) in the middle, near flat region
   (c) in the high load region
   (d) in any region irrespective of load

8. With pure hydrogen and pure oxygen as input the exhaust from fuel cell contains:
   (a) water vapor CO, NO_2 and CO_2
   (b) water vapor CO and CO_2
   (c) water vapor and CO_2
   (d) water vapor only

9. Hydrogen can be used:
   (a) as primary energy source only
   (b) as energy carrier only
   (c) both as primary energy source as well as energy carrier
   (d) neither as primary energy source nor as energy carrier

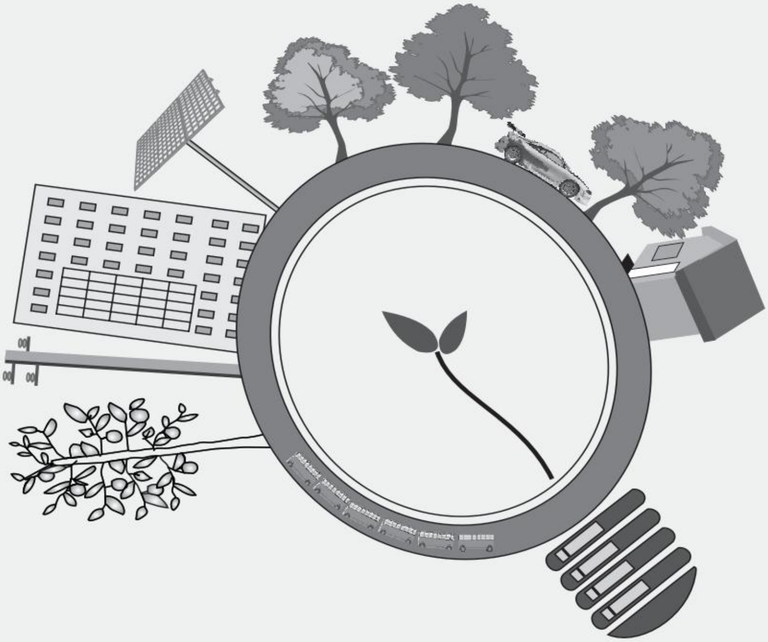
10. 95% of hydrogen production in the U.S.A. is met:
   (a) through electrolysis of water
   (b) through thermolysis of water
   (c) through steam reforming of methane
   (d) through biophotosynthesis

11. The simplest method of hydrogen production is:
   (a) electrolysis of water
   (b) thermolysis of water
   (c) steam reforming of methane
   (d) biophotosynthesis

12. Most mature technology available for hydrogen storage is:
(a) liquid hydrogen storage at low temperature
(b) metal hydride
(c) carbon nanotubes
(d) compressed hydrogen gas in steel tank or cylinder

13. Metal hydride is used for the storage of:
(a) hydrogen energy
(b) wind energy
(c) biomass energy
(d) solar energy

14. Which fuel is used in fuel cells?
(a) Oxygen
(b) Sulfur
(c) Carbon
(d) Hydrogen



CHAPTER 13

Miscellaneous Non-Conventional Energy Technologies

Learning Objectives

In this chapter you will be able to:

- Recognize basic principles and features of Magneto hydrodynamic (MHD) power conversion, Thermoelectric and Thermionic energy conversion
- Describe the Technologies of MHD, thermoelectric and thermionic power conversions
- Appraise specific applications of these technologies

13.1 INTRODUCTION

In this chapter some technologies that convert thermal energy directly into electrical energy (without a mechanical link) are covered. The technologies considered are: (i) MHD, (ii) thermoelectric, and (iii) thermionic power converters. These technologies are based on new concepts and at present in initial stages of exploration. A feature common to all of them is that there are no moving parts. This feature is particularly of special interest to overcome motion related limitations / problems of conventional power conversion systems. While MHD is intended for large-scale central station power generation, the latter two are being developed for low power special purpose applications.

13.2 MAGNETO HYDRODYNAMIC POWER CONVERSION

A magneto hydrodynamic (MHD) power generator is a device, which converts the kinetic energy of the conducting (electrically) material, flowing in presence of magnetic field directly into electrical energy. In practical MHD generator, the energy of motion of the conducting fluid is derived from heat obtained by burning of fossil fuel. Thus, heat is converted directly into electrical energy.

Faraday demonstrated the principle of MHD generation in 1836 by conducting an experiment on Thames River. Because water of Thames River is salty, it has certain conductivity. The conducting fluid interacted with earth's magnetic field to produce a small current through electrodes connected across the banks. Conventional electromagnetic power converters use the same principle. However, instead of using solid metal, a conducting fluid is utilized in MHD generation.

MHD generators have not been employed for large-scale mass energy conversion because other techniques with comparable efficiencies have a lower lifecycle investment cost. Advances in natural gas turbines achieved similar thermal efficiencies at lower costs, by having the gas turbine's exhaust drive a Rankine cycle steam plant. To get more electricity from coal, it is cheaper to simply add more low-temperature steam-generating capacity.

There are two basic designs of MHD generator, based on basic principle of operation: (i) Faraday generator and (ii) Hall generator

13.2.1 Faraday Generator: Basic Principle

Let a conducting gas, having conductivity, σ mho/m, moves at a speed, u across magnetic field, B. The speed, u and magnetic field, B are held mutually perpendicular along x-axis and y-axis respectively. Two electrodes, each having area A, are held at a distance, d along z-axis, thus perpendicular to both u and B, as shown in Fig. 13.1. Magnitude of force acting on a charged particle having charge q is given by: $q\,u\,B$. This force, as per right hand rule, will be acting in upward direction (on positively charged particle). The positively charged particles will be collected by the upper electrode and negatively charged particles by lower electrode, causing a potential difference V across them. The resulting electric filed between the plates is given by:

$$E = -\frac{V}{d}$$

Due to this field, another force (qE) will be acting on the charged particle in the downward direction. Net force acting on the charged particle:

$$F_{net} = qE + quB$$

or

$$F_{net} = -q\frac{V}{d} + quB$$

If no load is connected across the electrodes (i.e. open circuit condition), no current will flow, and there will be no net movement of carriers between electrodes. Therefore, no net force will be acting on the charged particles. A voltage, V_o(open circuit voltage) appears across the electrodes (also the same across the generator terminals). Thus:

$$F_{net} = -q\frac{V_o}{d} + quB = 0$$

$$V_o = B\,u\,d \tag{13.1}$$

Voltage V_o is the internally generated voltage of MHD generator. When a load R_L is connected across the terminals of the generator, a lesser voltage V appears across the terminals because of internal voltage drop IR_g due to internal resistance R_g.

The ratio $\dfrac{V}{V_o} = \dfrac{R_L}{R_L + R_g} = K$ is known as 'loading factor' or 'performance coefficient'.

We can write,

Terminal voltage, $V = KV_o = KBud$ (13.2)

Load resistance, $R = \dfrac{1}{1-K} \times R_g$

If σ is the conductivity of the gas between the electrodes, the internal resistance R_g is given by:

$$R_g = \frac{1}{\sigma}\frac{d}{A} \tag{13.3}$$

where A is the area of each electrode and d is the separation between them.

Current supplied by the generator,

$$I = \frac{V}{R_L} = KV_o\frac{1-K}{R_g} = V_oK(1-K)\frac{1}{R_g}$$

$$= Bud\;K(1-K)\frac{\sigma A}{d}$$

$$= \sigma BuK(1-K)A$$

Current density in the generator,

$$J = \frac{I}{A} = \sigma Bu\;K(1-K) \tag{13.4}$$

From Eq. (13.3), $R_L = \dfrac{1}{1-K} \times \dfrac{d}{\sigma A}$ (13.5)

The output power, or power delivered to load R_L,

$$P = VI = (IR_L)I = I^2R_L = \left(\frac{V_o}{R_L + R_g}\right)^2 R_L$$

$$= \frac{V_o^2}{R_g}\frac{R_L}{R_L + R_g}\frac{R_g}{R_L + R_g} = \frac{V_o^2}{R_g}K(1-K) = (Bud)^2\frac{\sigma A}{d}K(1-K)$$

$$P = \sigma B^2u^2K(1-K)dA \tag{13.6}$$

Power density (power per unit volume) delivered,

$$\frac{P}{dA} = \sigma B^2 u^2 K(1-K) \tag{13.7}$$

From Eq. (13.6) it is evident that power delivered by the generator to the load depends on loading factor K. Maximum power is delivered at $K = 0.5$. Thus from Eq. (13.6), the expression for maximum power may be written as:

$$P_{\max} = \frac{1}{4} \times \sigma B^2u^2\, dA \tag{13.8}$$

Please note that at $K = 0.5$, the internal resistance, R_g equals the load resistance R_L, and the network satisfies the maximum power transfer theorem.

Maximum power density (power per unit volume) delivered,

$$\frac{P_{\max}}{dA} = \frac{1}{4} \times \sigma B^2u^2 \tag{13.9}$$

Combining Eq. (13.6) and Eq. (13.8), the output power,

$$P = 4\,P_{\max}\,K(1-K)\,dA \tag{13.10}$$

The output power density (power per unit volume),

$$\frac{P}{dA} = 4P_{\max}\,K(1-K) \tag{13.11}$$

Power developed by the generator,

$$P_{\text{developed}} = V_oI = V_o\frac{V_o}{R_g + R_L} = V_O^2\frac{K}{R_L} = V_O^2K\left(\frac{1-K}{KR_g}\right) = (Bud)^2(1-K)\frac{\sigma A}{d}$$

$$P_{\text{developed}} = \sigma B^2u^2(1-K)\,dA \tag{13.12}$$

Power density (power per unit volume) developed by the generator,

$$P_{\text{developed}/dA} - \sigma B^2u^2(1-K) \tag{13.13}$$

If the terminals of the generator are short circuited (i.e. $R_L = 0$), the resulting short circuit current is given by,

$$I_{SC} = \frac{V_o}{R_g} = Bud \times \frac{\sigma A}{d} = \sigma BuA \tag{13.14}$$

The short circuit current density,

$$J_{SC} = \frac{I_{SC}}{A} = \sigma Bu \tag{13.15}$$

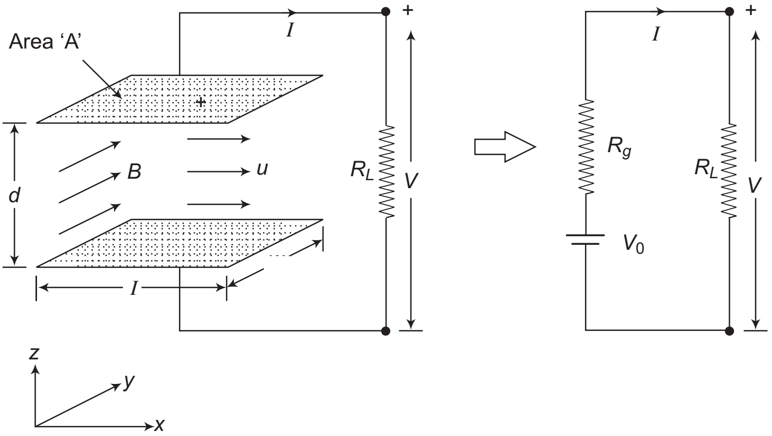


Fig. 13.1 Basic principle of MHD generation and equivalent circuit

13.2.2 Hall Generator: Basic Principle

In a Faraday generator, the current flows in the z-direction from lower electrode to upper electrode. The magnetic field '*B*' acts on this Faraday-generated current and produces a voltage in the flow direction of the working fluid (i.e. *x*-direction), due to Hall Effect. This differential voltage in the flow direction short through the electrode leads to power loss due to Hall Effect current. There are two possible solutions: use segmented electrodes (instead of single piece), and connect each electrode pair across separate load, as shown in Fig. 13.2. Another possibility is to utilize Hall current only; each electrode pair is short circuited outside the generator and the load is connected between the two ends of MHD generator, as shown in Fig. 13.3.

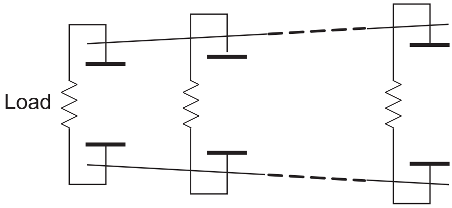


Fig. 13.2 MHD electrode connections to minimize the HALL current

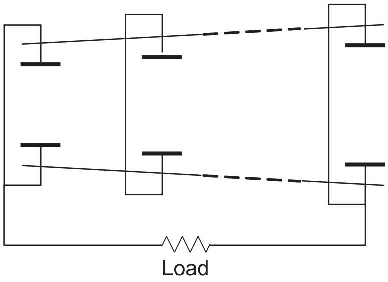


Fig. 13.3 MHD electrode connections to maximize the HALL current (HALL Generator)

13.2.3 General Principle of MHD Generator

Let us assume that a charged particle having a charge 'q' is moving across a magnetic field density $\vec{B}$ with speed $\vec{v}'$. The force $\vec{F}$ acting on the charged particle:

$$\vec{F} = q(\vec{v}' \times \vec{B}) \tag{13.16}$$

If an electric field $\vec{E}$ is also operating in the same region, the net force acting on the particle,

$$\vec{F} = q\vec{E} + q(\vec{v} \times \vec{B}) \tag{13.17}$$

The particle velocity $\vec{v}'$ is the vector sum of gas velocity $\vec{u}$ and particle drift velocity, $\vec{v}$ (due to Faraday current), $\vec{v}' = \vec{u} + \vec{v}$, therefore,

$$\vec{F} = \left[q\vec{E} + q(\vec{u} \times \vec{B})\right] + q(\vec{v} \times \vec{B}) \tag{13.18}$$

where $\vec{E}' = \vec{E} + (\vec{u} \times \vec{B})$, is the effective electric field seen by the moving particle

The force acting on the particle is also related to drift velocity, by the expression,

$$\vec{F} = \frac{q\vec{v}}{\mu} \tag{13.19}$$

Substituting for $\vec{F}$ from Eq. (13.19) into Eq. (13.18), we get,

$$\vec{v} = \mu\left[\vec{E} + (\vec{u} \times \vec{B})\right] + \mu(\vec{v} \times \vec{B}) \tag{13.20}$$

Now, let us apply this general equation for the specific case of Fig. 13.1, where the components of $\vec{u}$ and $\vec{B}$ along x, y and z axes are as follows:

$\vec{u}$ = (u, 0, 0) as the gas flows only along x-axis

$\vec{B}$ = (0, B, 0) as the magnetic field is applied along y-axis

From Eq. (13.20), the individual components of drift velocity, (and substituting $\mu B = \beta$), are:

The component along x-axis, $v_x = \mu E_x - \beta v_2$ (13.21)

The component along z-axis, $v_z = \mu E_z + \beta u + \beta v_x$ (13.22)

There will be no component along y-axis (in this particular case of Fig. 13.1).

Rearranging the terms in Eqs (13.21) and (13.22), we get,

$$v_x = \frac{\mu(E_x - \beta E_z) - \beta^2 u}{1 + \beta^2} \tag{13.23}$$

$$v_z = \frac{\mu(E_z + \beta E_x) + \beta u}{1 + \beta^2} \tag{13.24}$$

The current density J, is related to particle drift velocity v as,

$$J = \frac{\sigma v}{\mu} \tag{13.25}$$

where σ is the conductivity of the medium between the electrodes.

Using Eqs (13.23–13.25), the expressions for current densities along z-axis and x-axis respectively may be written as:

$$J_x = \frac{\sigma(E_x - \beta E_z) - \sigma \beta B u}{1+\beta^2} \tag{13.26}$$

$$J_z = \frac{\sigma(E_z + \beta E_x) + \sigma B u}{1+\beta^2} \tag{13.27}$$

These are the basic equations for current densities in x and z directions. Either of these currents may be collected by electrodes and passed through the external load. MHD generator based on the former approach is known as Hall Generator, while the one based on the later approach is known as Faraday generator.

13.2.4 MHD Generator

MHD generator is a divergent channel or duct made of a heat resistant alloy (e.g. Inconel) as shown in Fig. 13.4. Magnetic field is applied at right angles to the channel length and electrodes are provided at right angles to both magnetic field and flow of gas. A conducting fluid (ionized gas) is forced into the MHD channel at high speed and high temperature through a nozzle. It expands as it moves forward and leaves the duct at lower temperature and pressure. In this respect an MHD converter system is a heat engine, which receives heat at high temperature, converts a part of it into useful work (electricity in this case) and rejects the remaining heat at lower temperature. The efficiency of MHD converter alone is about 20–25 per cent. In practice, however, MHD converter is never made to operate alone. The exhaust of MHD system is used to raise steam for conventional steam plant. Thus by using MHD as topping cycle for the conventional steam system, an overall efficiency of 50–60 per cent should be possible.

MHD generation looks more promising for direct thermal to electrical power conversion in large-scale central power stations. Several economical and physical factors have led to design outputs of the order of 1000 MW or so.

As seen in Eq. (13.4), the output power per unit volume of the duct is proportional to the conductivity of the working fluid. Practical MHD generator requires minimum conductivity of 10 mho/m. The working fluid, a gas, itself is a nonconductor at ordinary temperature. It is rendered conducting in two ways:

(i) *By inducing ionization in the working fluid* Ionization by thermal means alone would require a temperature of several tens of thousands of degrees Celsius. More practical way is to inject a solid seed material up to about 1 per cent of the total flow rate. The seed material contains an element commonly potassium or cesium, which ionizes relatively easily when heated.

(ii) *By incorporating a liquid metal into flowing carrier gas*

The power output of MHD generator is also proportional to squares of magnetic flux density and gas speed. Due to limitations of enhancing conductivity beyond certain limit, a strong magnetic field and high gas velocities are required for large outputs. Conventional electromagnets are not practical in the range of required flux density of above 2 tesla. Consequently, superconducting magnets are being proposed for such applications. The required gas velocities for large outputs are in the range around 1000 m/s.

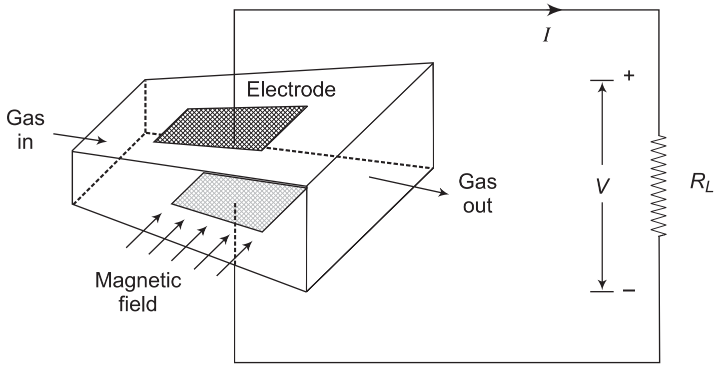


Fig. 13.4 MHD generation or channel or duct

Advantages

Main advantages are:

(i) Conversion efficiency of MHD – Steam hybrid plant may be as high as around 50–60 per cent. The fuel is better utilized.
(ii) MHD generation uses no moving parts and therefore, all problems/limitations associated with it are also absent.
(iii) MHD unit is capable of rapid starting (reaching full power level soon after starting) and taking up peak loads in an interconnected system.
(iv) Lower emission of pollutants due to better pollution control.
(v) MHD plant is compact and requires comparatively less space.

Disadvantages/Limitations

MHD generation also has some serious limitations. Most important among them are:

(i) Very high operating temperature restricts the choice of material for various equipment.
(ii) Life of equipment is short due to high temperature stresses.
(iii) The output power is available as dc. Inversion is required for integrating it into a grid.
(iv) There are technical limitations on enhancing the fluid conductivity and the strength of magnetic field.

13.2.5 MHD Systems

There are two types of MHD generating systems: (i) open cycle and (ii) closed cycle. In open cycle system the working fluid is used on once through basis whereas in closed cycle system, working fluid is continuously recirculated.

1. Open Cycle System

Main features of an open cycle system are shown in Fig. 13.5. Hot flue gases at about 2300–2700 °C, obtained from burning of coal (or other fuel) in combustor are used as working fluid, after mixing with seed material. Aqueous potassium carbonate is generally sprayed for the purpose of seeding. To attain such a high temperature, compressed air is preheated at least up to 1100 °C before supplying to combustor. The working fluid enters the MHD channel through a nozzle and produces dc output. Inverter is used to obtain 50 Hz ac output for supply to consumers. The exhaust of MHD channel is first used to preheat the air intake for combustor and then to raise the steam in waste heat steam generator. The steam so produced is used to generate additional power through conventional turbine – generator system. The flue gases are released to atmosphere through chimney after seed recovery and removal of pollutants. The recovered seed material is recycled after mixing additional quantity to make up for the loss of seed. Seed recovery is important for prevention of atmospheric pollution and for economic reasons.

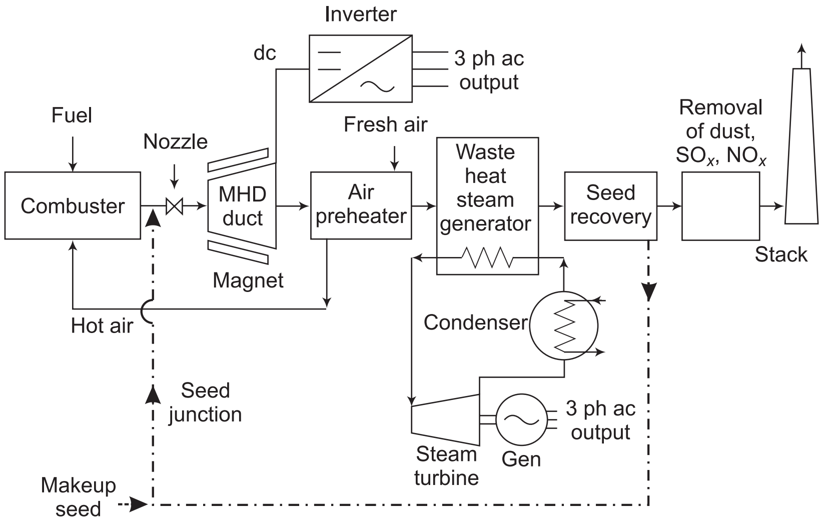


Fig. 13.5 Open cycle MHD generating system

2. Closed Cycle System

The closed cycle works on Brayton cycle with inert carrier gas (Argon or Helium). Two general types of closed loop systems are discussed here.

(a) Seeded Inert Gas Carrier System Complete system has three loops: (i) combustion loop (open), (ii) argon loop (closed) and (iii) steam loop (closed), as shown in Fig. 13.6. In the first loop, coal is gasified and burnt in combustor. The flue gases are passed through primary heat exchanger (HX1), air preheater and air purifier (if required) and then discharge to atmosphere.

In argon loop or MHD loop, a seeded inert gas (argon or helium) is compressed and then heated in primary heat exchanger. Small quantity of seed material is then added to make up for the loss of seed through leakage, etc. The seed, Cesium metal is more expensive than potassium but attains adequate conductivity at relatively lower temperature of 1900 °C. As little makeup seed is required due to closed loop operation, an expensive but better seed material may be advisable. The lower temperature operation also permits wider choice of material for various equipment. However, operation at lower temperature also reduces the thermal efficiency of the cycle. The dc output available from MHD generator is inverted to obtain grid quality ac.

The residual heat of used argon is utilized to generate additional power through waste heat boiler (secondary heat exchanger, HX2), turbine and generator. A part of the steam produced is also used to power argon cycle compressor through a steam turbine.

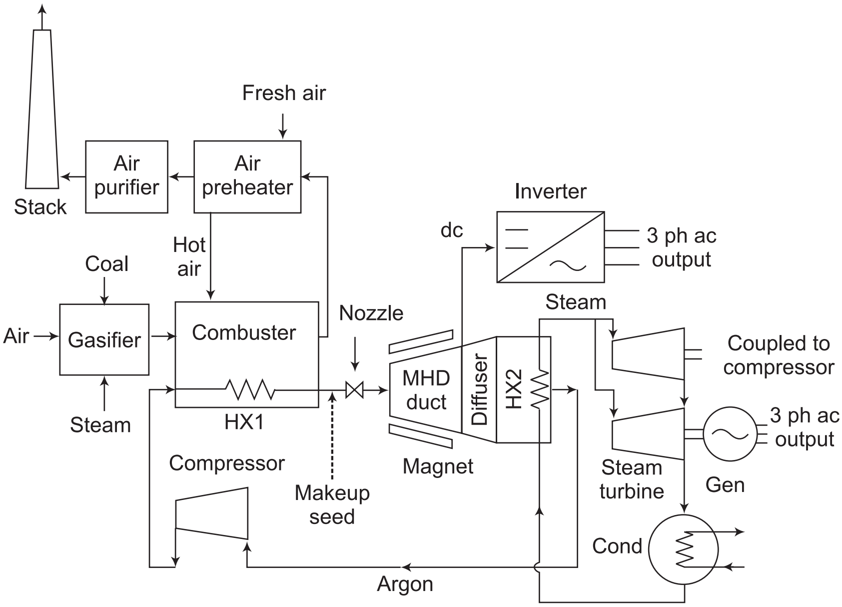


Fig. 13.6 Seeded inert gas carrier, dosed cycle MHD generating system

(b) Liquid Metal-Inert Gas Carrier System In this system, instead of seeding, a liquid metal (such as Na, K or Li) is incorporated in the inert carrier gas for conductivity requirement. These metals are excellent electrical conductor in liquid state but their vapors are poor conductor. Therefore, these are used in the working fluid in liquid state only.

Liquid sodium based closed loop MHD generating system with coal as input energy, is shown in Fig. 13.7. The carrier gas is pressurized and heated by passage through primary heat exchanger within the combustor. The hot gas is then incorporated into liquid metal (usually sodium) to form working fluid. The working fluid thus consists of gas bubbles uniformly dispersed in an approximately equal volume of liquid sodium metal. After passing through the MHD duct, the liquid metal is separated from carrier gas. The residual heat in the gas is utilized in the same way as explained above for the case of seeded inert gas carrier system.

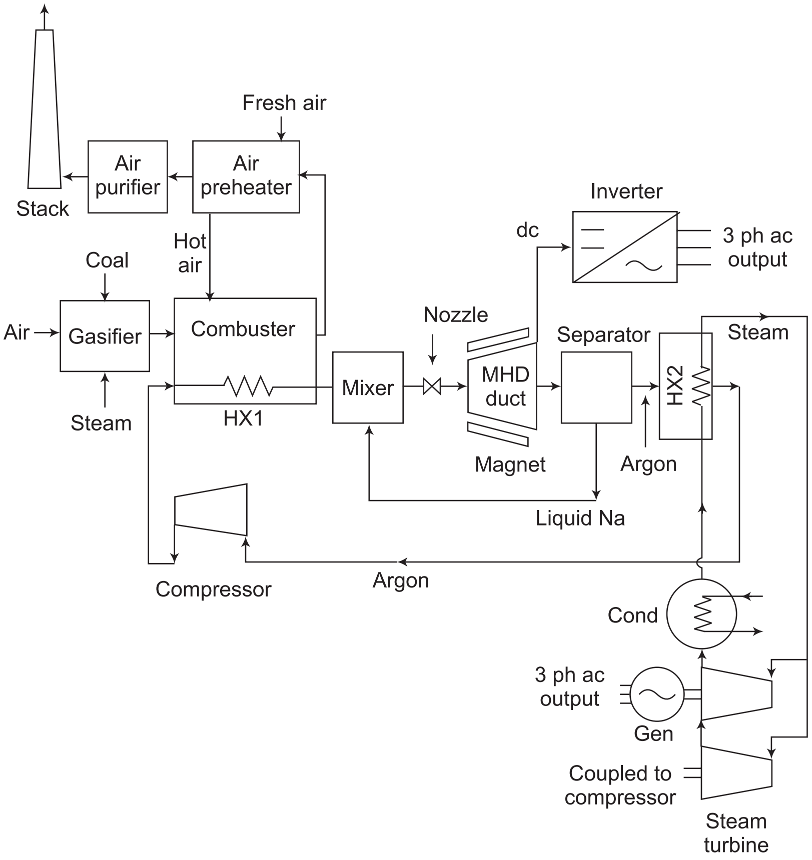


Fig. 13.7 Liquid metal-inert gas carrier, closed cycle MHD generating system

The boiling point of sodium is below 882.9 °C and therefore working fluid temperature is usually kept around 815 °C. Lower operating temperature offers the benefit of wider material choice but at the same time lowers the thermal efficiency. The operating temperature and hence the efficiency can be increased by replacing sodium by lithium that has a boiling point of 1300 °C. However, lithium is much more expensive than sodium.

MHD system can also be coupled to a fast breeder reactor. Liquid metals have both excellent electrical and thermal conduction properties. Therefore, a liquid metal is used as coolant in the reactor as well as working fluid in MHD duct. A layout diagram of liquid potassium fast breeder reactor fueled MHD system is shown in Fig. 13.8. After receiving heat from the reactor, the liquid potassium is passed through a nozzle to get high speed. The vapours formed due to nozzle action are separated, condensed and returned to the reactor. The residual heat of working fluid is utilized to generate additional power in steam plant in the same way as discussed earlier.

MHD plant may also be operated by the heat obtained from burning of hydrogen in pure oxygen. On combustion in pure oxygen, hydrogen produces water (steam) at flame temperature above 3000 °C. The steam thus produced may be used as working fluid in MHD duct after seeding and subsequently in steam turbine for conventional power generation. In this way the need for waste heat steam generator is avoided.

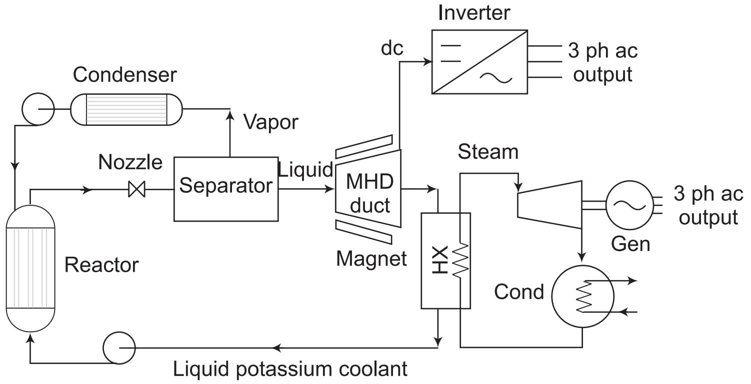


Fig. 13.8 FBR coupled, closed cycle MHD generating system

Example 13.1

Calculate the open circuit voltage and maximum power output for a MHD generator having following data:

Plate area = 0.25 m^2
Distance between the electrodes = 0.50 m
Flux density = 1.8 Wb / m^2
Average gas velocity = 1200 m / s
Gaseous conductivity = 10 mho / m

Solution

Given,

$A = 0.25\ \text{m}^2$, $d = 0.5$ m, $B = 1.8\ \text{Wb/m}^2$, $u = 1200$ m/s, $\sigma = 10$ mho/m

From Eq. (13.1), the open circuit voltage of the generator:

$$\begin{aligned} V_o &= B\,u\,d \\ &= 1.8 \times 1200 \times 0.5 = 1080\ \text{V} \end{aligned}$$

Maximum power output of the generator is given by Eq. (13.9):

$$\begin{aligned} P_{\max}/Ad &= \frac{1}{4}\sigma u^2 B^2 \\ P_{\max} &= \frac{1}{4}\sigma u^2 B^2 Ad \\ &= \frac{1}{4}\times 10 \times 1200^2 \times 1.8^2 \times 0.25 \times 0.5 \\ &= 1.458\ \text{MW} \end{aligned}$$

Example 13.2

An MHD duct has the dimensions; length $l = 2$ m, average vertical height, $d = 0.35$ m, average width, $w = 0.5$ m. The magnetic flux density, $B = 4.2$ T along w, and the gas velocity, $u = 600$ m/s along l. At a performance coefficient of $K = 0.65$, calculate:

(a) generated voltage and its gradient

(b) load voltage

Solution

(a) From Eq.(3.1), Generated voltage,

$$\begin{aligned} V_o &= B\,u\,d \\ &= 4.2 \times 600 \times 0.35 \\ &= 882 \text{ V} \end{aligned}$$

Generated voltage gradient,

$$E = \frac{V_o}{d} = \frac{882}{0.35} = 2{,}520 \text{ V/m}$$

(b) Load voltage,

$$V = KV_o = 0.65 \times 882 = 573.3 \text{ V}$$

Example 13.3

The ionized gas in example 13.2 has a conductivity of 60 mho/m. Calculate:

(a) current density and current in the system

(b) short circuit current density and short circuit current

(c) power output

(d) power density generated in the duct

(e) total power generated

(f) heating losses in the duct

(g) maximum possible power delivered to load

Solution

Given: $\sigma = 60$ mho/m

(a) From Eq. (13.4), the current density,

$$J = \frac{I}{A} = \sigma\,Bu\,K(1-K) = 60 \times 4.2 \times 600 \times 0.65 \times (1-0.65)$$

$$= 34{,}398 \text{ A/m}^2$$

Current in the system,

$$I = 34{,}398 \times 0.5 \times 2 = 34.398 \text{ A}$$

(b) From Eq.(3.15), short circuit current density,

$$J_{SC} = \frac{I_{SC}}{A} = \sigma Bu = 60 \times 4.2 \times 600 = 1{,}51{,}200 \text{ A/m}^2$$

Short circuit current $= I_{SC} = A \times I_{SC} = w \times l \times I_{SC} = 0.5 \times 2 \times 1{,}51{,}200$
$= 151.2$ kA

(c) From Eq. (13.6), power output

$$P = \sigma B^2 u^2 K(1-K)dA = 60\times 4.2^2 \times 600^2 \times 0.65\times 0.35\times 0.35\times (0.5\times 2)$$

$$= 30.339036 \text{ MW}$$

(d) From Eq. (13.13) power density generated in the duct,

$$P_{\text{developed}/dA} = \sigma B^2 u^2 (1-K) = 60\times 4.2^2 \times 600^2 \times 0.35$$

$$= 133.358 \text{ MW/m}^3$$

(e) Total power generated in the duct,

$$P_{\text{developed}} = 133.358\times dA = 133.358\times 0.35\times 0.5\times 2$$

$$= 46.675 \text{ MW}$$

(f) Heating losses in the duct = power developed – power output

$$= P_{\text{developed}} - P$$

$$= 46.675 - 30.339$$

$$= 16.336 \text{ MW}$$

(g) From Eq. (13.8), maximum possible power delivered to the load

$$P_{\max} = \frac{1}{4}\times \sigma B^2 u^2 dA = \frac{1}{4}\times 60\times 4.2^2 \times 600^2 \times 0.35\times (0.5\times 2)$$

$$= 33.339 \text{ MW}$$

13.3 THERMOELECTRIC POWER CONVERSION

A thermoelectric power converter converts heat directly to electricity through thermoelectric effect. Its salient features compared to other methods are: compactness, lightweight, noiseless operation, no moving parts and highly reliable. It has the lowest maintenance of any commercial power source and can also be operated by low-grade waste heat (< 200 °C). It is ideally suited for remote and harsh environments. It is being intended for high tech applications associated with aerospace, military, telecommunications and control of unmanned vehicle monitored from remote location. It is designed for 20 years' service life.

Seebeck Effect

Basic principle behind thermoelectric power generator is **Seebeck effect**, which was discovered in 1821 and is stated as: "whenever there is a temperature difference between the two junctions in a loop, made up of two dissimilar conductors, thermal electromotive force is produced in the loop". Such a loop is known as a thermocouple and shown in Fig. 13.9. The effect is more pronounced in thermocouples formed with *P* type and *N* type semiconductor materials. In *N* type material, current flows in the direction of heat flow. The emf produced is proportional to the temperature gradient between the two junctions. The power produced, *P* is:

$$P = Q_h - Q_c = I^2 R_L \tag{13.28}$$

where Q_h = heat flow rate into hot junction

Q_c = dissipated heat flow rate from cold junction

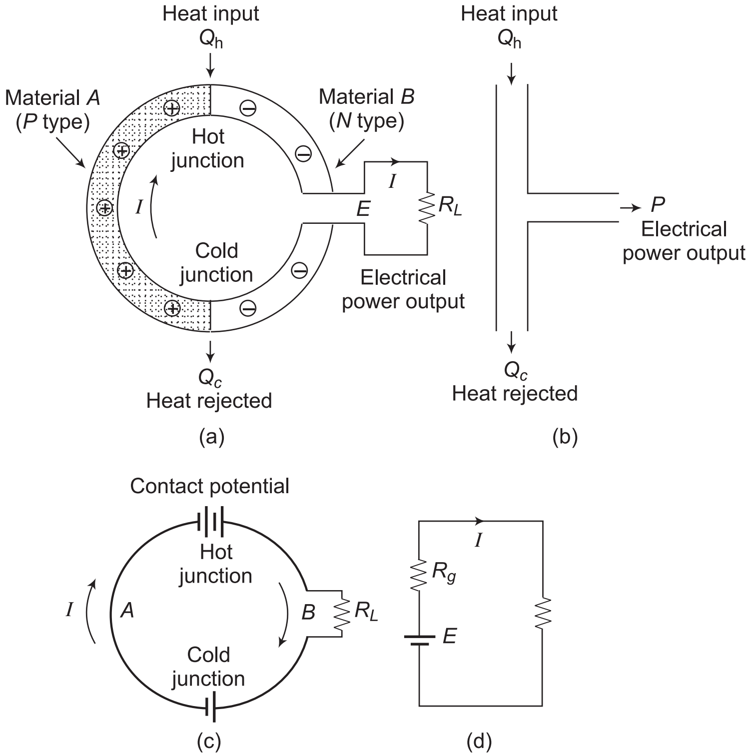


Fig. 13.9 Elementary thermocouple

Material *A* and *B* have different carrier concentration. When a junction is formed, a contact potential is produced due to transfer of carriers across the junction from high concentration to low concentration side. When both junctions are held at same temperature, contact potentials are same and net voltage in the loop is zero. In case of differential temperature, more carriers at high temperature junction will cross to other side of the junction as they acquire higher energy, thus increasing the contact potential at this junction. A net emf is thus produced in the loop.

The open circuit emf of the thermocouple is given by:

$$E = \alpha_{AB}\,\Delta T \tag{13.29}$$

where, $\Delta T = T_h - T_c$

$\alpha_{AB} = |\alpha_A - \alpha_B|$; Seebeck coefficient for junction of material *A* and *B*

α_A = Absolute Seebeck coefficient for material *A*, V/K

α_B = Absolute Seebeck coefficient for material *B*, V/K

From Fig. 13.9, the power output to load R_L can be written as:

$$P = I\,E - I^2 R_g = I^2 R_L \tag{13.31}$$

where R_g is the total resistance of the two materials in series.

$$R_g = R_A + R_B = \rho_A \frac{L_A}{A_A} + \rho_B \frac{L_B}{A_B} \tag{13.32}$$

where ρ_A and ρ_B are resistivities of material *A* and *B* respectively

L_A A_A and L_B, A_B are lengths and cross section areas of blocks of material A and B respectively.

The expression for current, I can be written as:

$$I = \frac{E}{R_g + R_L} = \frac{\alpha_{AB}\ \Delta T}{R_g + R_L}$$

Therefore, from Eq. (13.31) the power output,

$$P = I^2 R_L = \left(\frac{\alpha_{AB}\,\Delta T}{R_g + R_L}\right)^2 R_L \tag{13.33}$$

Or $$P = I\,\alpha_{AB}\Delta T - I^2 R_g = \left(\frac{\alpha_{AB}\ \Delta T}{R_g + R_L}\right)\alpha_{AB}\Delta T - \left(\frac{\alpha_{AB}\ \Delta T}{R_g + R_L}\right)^2 R_g \tag{13.34}$$

According to maximum power transfer theorem, maximum output power is delivered when, $R_L = R_g$, thus,

$$P_{\max} = \frac{\alpha_{AB}^2\ \Delta T^{\ 2}}{4R_g} \tag{13.35}$$

The current at maximum power,

$$I_{\text{max-power}} = \frac{\alpha_{AB}\ \Delta T}{2R_g} \tag{13.36}$$

Peltier Effect

An effect complementary to Seebeck effect, discovered in 1830, is known as **Peltier effect**. According to this, "heat is absorbed or generated whenever a current passes through a junction between different materials, depending on the direction of current". Peltier effect is a reversible effect. Thus, if a current is forced through a thermocouple by connecting an electrical source, one junction will become cold and will thus absorb energy from ambient and the other junction will become hot and dissipate heat to surroundings. This principle can be used for evacuation of heat (i.e. cooling/refrigeration) from one area and releasing it to another area (heating) through electrical means.

The heat rate absorbed (or evolved) can be given as,

$$Q_p = \pi_{AB} \,.\, I \tag{13.37}$$

where $\pi_{AB} = \pi_A - \pi_B$, known as Peltier coefficient and

I = current through the junction

The relationship between Seebeck coefficient and Peltier coefficient as derived by Kelvin is given as:

$$\pi_{AB} = \alpha_{AB} \,.\, T \tag{13.38}$$

where T is temperature of the junction in Kelvin

Thus, $$Q_p = \alpha_{AB} \,.\, T \,.\, I \tag{13.39}$$

Thomson Effect

When an electric current flows through a material having temperature gradient there is an evolution (or absorption) of heat. This phenomenon is called Thompson effect. The Thomson effect is reversible, as reversing the direction of current flow reverses the direction of heat transfer without change in magnitude.

The heat rate removed from the system:

$$Q_{th} = -I.\tau.\Delta T \tag{13.40}$$

where, τ is Thomson coefficient.

Kelvin also found the relationship between Seebeck coefficient and Thomson coefficient as:

$$\tau_{AB} = \tau_A - \tau_B = -T\frac{d\alpha_{AB}}{dT} \tag{13.41}$$

13.3.1 Thermoelectric Power Generator

An elementary thermoelectric generator consisting of one pair of thermocouple is shown in Fig. 13.10. The voltage and power output of one pair is very small. Several such units may be connected in series to get a workable voltage.

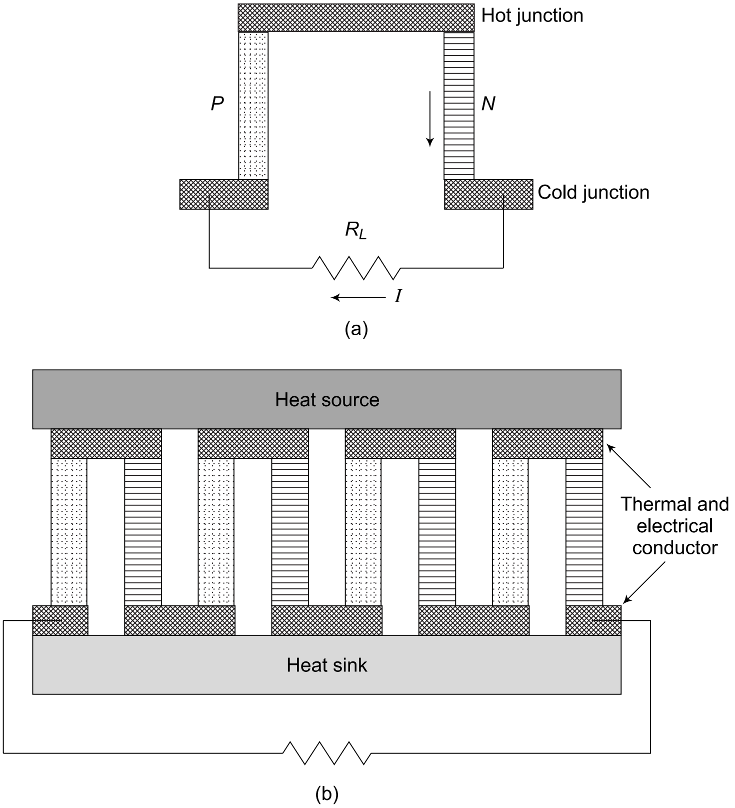


Fig. 13.10 (a) Elementary thermoelectric generator
(b) A single thermoelectric converter

Metallic thermocouple elements are used where mechanical considerations such as ductility are more important. The Seebeck effect of metallic thermoelectric elements is however, low. The Seebeck coefficient and the figure of merit ZT for some materials are given in Table 13.1. Semiconductor materials have much higher thermoelectric coefficients.

Table 13.1 Seebeck coefficient and figure of merit for some metals

S.N.	Metal	μV / K	ZT (approx.)
1.	Bismuth	– 75	0.208
2.	Nickel	–18	0.112×10^{-1}
3.	Copper	+ 2.5	0.231×10^{-3}

Extrinsic semiconductor materials (binary compounds) made from bismuth (Bi), antimony (Sb), tellurium (Te), and selenium (Se) have large figure of merit and are used either in refrigeration or in cold parts of thermoelectric legs. Lead telluride (Pb Te) is most commonly used material at temperatures below 600 °C. In this range of temperature the figure of merit, ZT for lead telluride is in range of 0.2 to 0.8. This is an intermetallic compound containing around 61.9 per cent Pb and 38.1 per cent Te in its pure form. Both lead and tellurium are soluble to a very small extent in PbTe. An excess of Te leads to a p-type semiconductor, while an excess of Pb leads to an n-type material. Silicon germanium (Si-Ge) alloys are the best materials in high temperature range (above 600 °C). They also have good mechanical properties: high mechanical strength, low coefficient of expansion and lightweight.

A highly efficient single pair of the thermoelectric element produces a net voltage of about 300–500 μV per Kelvin. A module (thermopile) is formed by series connection of large number of such elements. In a typical commercial module an electrical output of 10 W at 6 V and with 100 °C at hot junction is obtained. The thermal efficiency of thermoelectric generator is generally very low (typically around 8 per cent). Higher efficiencies of the order of 14 per cent are being attempted to make it compete with solar PV system.

The heat required at the hot junction may be supplied by: (i) burning fossil fuel, (ii) solar thermal energy, (iii) decay of radioisotope or (iv) nuclear fuel.

Thermal Efficiency

The thermal efficiency of thermoelectric converter (shown in Fig. 13.10(a)) is defined as the ratio of power P delivered to load resistance R_L to heat energy rate Q_h supplied to hot junction from the source. Thus:

$$\eta = \frac{P}{Q_h} \tag{13.42}$$

where, $P = I\,\alpha_{AB}\,(T_h - T_c) - I^2 R_g$

Now, let us consider energy balance at hot plate.

1. heat energy Q_h is supplied to the hot plate from the heat source
2. as the current flows through the junction an amount of heat Q_p (Peltier effect) is absorbed at the junction

3. an amount of heat Q_c is conducted away from the plate through two blocks
4. an amount of joule heat Q_j is generated uniformly in two blocks due to flow of current through resistance R_g. Half of this heat, $Q_j/2$ moves towards hot junction and remaining half moves towards cold junction. Thus,

$$Q_h + \tfrac{1}{2} Q_j = Q_p + Q_c \tag{13.43}$$

$$\begin{aligned} Q_h &= Q_p + Q_c - \tfrac{1}{2} Q_j \\ &= \pi_{AB} . I + K (T_h - T_c) - 0.5 I^2 R_g \\ &= \alpha_{AB} .T_h . I + K (T_h - T_c) - 0.5 I^2 R_g \end{aligned}$$

where K is total thermal conductivity of the two legs in parallel.

Therefore, the thermal efficiency is given as:

$$\eta_{th} = \frac{I\alpha_{AB}(T_h - T_c) - I^2 R_g}{\alpha_{AB} T_h I + K(T_h - T_c) - 0.5 I^2 R_g}$$

$$= \frac{T_h - T_c}{T_h} \frac{I - \left(\frac{R_g}{\alpha_{AB}}\right) I^2 \frac{1}{(T_h - T_c)}}{I - 0.5\left(\frac{R_g}{\alpha_{AB}}\right) I^2 \frac{1}{T_h} + \left(\frac{K}{\alpha_{AB}}\right)\frac{T_h - T_c}{T_h}} \tag{13.44}$$

Please note that $\frac{T_h - T_c}{T_h}$ is the Carnot efficiency

Total thermal conductivity is:

$$K = k_A \frac{A_A}{L_A} + k_B \frac{A_B}{L_B} \text{ W/K} \tag{13.45}$$

and total resistance of two blocks is given by:

$$R_g = L_A/(A_A\, \sigma_A) + L_B/(A_B\, \sigma_B) \tag{13.46}$$

where k_A, k_B are thermal conductivities of material A and B respectively in W/m-K

σ_A, σ_B are electrical conductivities of material A and B respectively in mho/m

L_A, L_B are length of two legs in m

A figure of merit Z for thermoelectric converters is defined as:

$$Z = \frac{\alpha_{AB}^2}{KR_g} \tag{13.47}$$

From Eq. (13.43), it is clear that the efficiency varies with current I. To find out the current at maximum efficiency, η_{th} can be differentiated and equated to zero.

i.e. $\frac{d\eta_{th}}{dI} = 0$, gives:

$$I_{\text{max-eff}} = \frac{(\alpha_{AB}/R_g)(T_h - T_c)\left[\sqrt{1 + Z(T_h + T_c)/2} - 1\right]}{Z(T_h + T_c)/2} \tag{13.48}$$

$$= (T_h - T_c)\, M \tag{13.49}$$

where M is called the 'coefficient of merit'.

$$M = \frac{(\alpha_{AB}/R_g)\left[\sqrt{1+Z(T_h+T_c)/2}-1\right]}{Z(T_h+T_c)/2} \tag{13.50}$$

The maximum thermal efficiency will then be:

$$\eta_{\max} = \frac{T_h - T_c}{T_h} \frac{M - M^2\left(\dfrac{R_g}{\alpha_{AB}}\right)}{M - M^2\left(\dfrac{R_g}{2\alpha_{AB}}\right)\left(\dfrac{T_h - T_c}{T_h}\right) + \left(\dfrac{K}{\alpha_{AB} T_h}\right)} \tag{13.51}$$

The coefficient of merit M depends on $[Z(T_h + T_c)/2]$, that is, the figure of merit Z and the average temperature between hot and cold junctions.

The power output at maximum thermal efficiency may be given as:

$$P_{\text{max-eff}} = I_{\text{max-eff}}\, \alpha_{AB}\,(T_h - T_c) - (I_{\text{max-eff}})^2 R_g \tag{13.52}$$

From Eq. (13.44), we can find the efficiency at maximum power output by substituting for I from Eq. (13.36)

$$I = I_{\text{max-power}} = \frac{\alpha_{AB}\,\Delta T}{2R_g}$$

Thus:

$$\eta_{th-\max-\text{power}} = \frac{T_h - T_c}{T_h} \frac{I_{\max-\text{power}} - \left(\dfrac{R_g}{\alpha_{AB}}\right) I^2_{\max-\text{power}} \dfrac{1}{(T_h - T_c)}}{I_{\max-\text{power}} - 0.5\left(\dfrac{R_g}{\alpha_{AB}}\right) I^2_{\max-\text{power}} \dfrac{1}{T_h} + \left(\dfrac{K}{\alpha_{AB}}\right)\dfrac{T_h - T_c}{T_h}} \tag{13.53}$$

Example 13.4

Following data are given for a thermoelectric generator:

Length of thermoelectric material blocks; $L_A = L_B = 6$ cm

Areas of thermodynamic blocks, $A_A = 1.6\ \text{cm}^2$, $A_B = 1\ \text{cm}^2$

Hot and cold junction temperatures; $T_h = 600$ °C, $T_c = 35$ °C

Seebeck coefficients; $\alpha_A = 200\ \mu\text{V/°C}$, $\alpha_B = -300\ \mu\text{V/°C}$

Specific resistance; $\rho_A = 10^{-3}$ ohm-cm, $\rho_B = 8 \times 10^{-4}$ ohm-cm

Calculate the following:

(a) Seebeck open-circuit voltage of thermoelectric generator
(b) Resistance of the two materials
(c) Maximum power output
(d) Current at maximum power output

Solution

(a) Seebeck coefficient of material pair *AB*,

$$\alpha_{AB} = \alpha_A - \alpha_A = 200 - (-300) = 500\ \mu\text{V/K}$$

$$T_h = 600 + 273 = 873\ \text{K}$$

$$T_c = 35 + 273 = 308\ \text{K}$$

$$\Delta T = T_h - T_c = 873 - 308 = 565\ \text{K}$$

From Eq. (13.29), open circuit voltage of thermoelectric generator:

$$E = \alpha_{AB}\,\Delta T = 500 \times 565 = 282.5\ \text{mV}$$

(b) Given:

$$\rho_A = 10^{-3}\ \text{ohm-cm} = 10^{-5}\ \text{ohm-m},\ \rho_B$$

$$= 8 \times 10^{-4}\ \text{ohm-cm} = 8 \times 10^{-6}\ \text{ohm-m}$$

$$L_A = L_B = 6\ \text{cm} = 0.06\ \text{m}$$

$$A_A = 1.6\ \text{cm}^2 = 1.6\times10^{-4}\ \text{m}^2,\ A_B = 1\ \text{cm}^2 = 1\times10^{-4}\ \text{m}^2$$

From Eq. (13.32):

$$R_g = R_A + R_B = \rho_A \frac{L_A}{A_A} + \rho_B \frac{L_B}{A_B} = 10^{-5} \times \frac{0.06}{1.6\times10^{-4}} + 8\times10^{-6} \times \frac{0.06}{1\times10^{-4}}$$

$$R_g = 3.75\times10^{-3} + 4.8\times10^{-3} = 8.55\times10^{-3}\ \text{ohm}$$

(c) As calculated above

$$\Delta T = 565\ \text{K},\ \alpha AB = 500\ \mu\text{V/K} = 500 \times 10^{-6}\ \text{V/K}$$

From Eq. (13.35), maximum power output;

$$P_{\max} = \frac{\alpha_{AB}^2\,\Delta T^2}{4R_g} = \frac{500\times10^{-6}\times500\times10^{-6}\times565^2}{4\times8.55\times10^{-3}} = 2.33\ \text{W}$$

(d) From Eq. (13.36), current at maximum thermal efficiency,

$$I_{\text{max-power}} = \frac{\alpha_{AB}\,\Delta T}{2R_g} = \frac{500\times10^{-6}\times565}{2\times8.55\times10^{-3}} = 16.5\ \text{A}$$

Example 13.5

For the data given in previous example, assume thermal conductivities as $k_A = k_B = 25$ mW/cm-°C. Calculate the following:

(a) Total thermal conductivity *K* of the two materials in parallel
(b) The value of the figure of merit, *Z*
(c) The coefficient of merit, *M* at maximum thermal efficiency
(d) The current at maximum thermal efficiency, $I_{\text{max-eff}}$. Compare with current at maximum power, $I_{\text{max-power}}$

(e) Power output at maximum efficiency. Compare with maximum power output.

(f) The maximum thermal efficiency

Compare with Carnot efficiency of the system, and the efficiency at maximum power output

Solution

(a) Given: $k_A = 25$ mW / cm-°C = 2.5 W / m-K = k_B

From Eq. (13.45), total thermal conductivity K of the two materials in parallel,

$$K = k_A \frac{A_A}{L_A} + k_B \frac{A_B}{L_B} = 2.5 \times \frac{1.6 \times 10^{-4}}{6 \times 10^{-2}} + 2.5 \times \frac{1.0 \times 10^{-4}}{6 \times 10^{-2}}$$

$$= 10.833 \times 10^{-3}\,\text{W/K}$$

(b) From Eq. (13.47), the figure of merit, Z is given by:

$$Z = \frac{\alpha_{AB}^2}{KR_g} = \frac{(500 \times 10^{-6})}{(10.833 \times 8.55 \times 10^{-3})} = 2.699 \times 10^{-3} \text{ per Kelvin}$$

(c) The coefficient of merit, M at maximum thermal efficiency, from Eq. (13.50),

$$M = \frac{(\alpha_{AB}/R_g)\left[\sqrt{1 + Z(T_h + T_c)/2} - 1\right]}{Z(T_h + T_c)/2}\, A/K$$

$$= \frac{(500 \times 10^{-6} / 8.55 \times 10^{-3})\left[\sqrt{1 + 2.699 \times 10^{-3} \times (873 + 308)/2} - 1\right]}{2.669 \times 10^{-3} \times (873 + 308)/2}$$

$= 0.0224495$ A/K

(d) From Eq. (13.49), the current at maximum thermal efficiency, I_{max}.

$$I_{\text{max-eff}} = (T_h - T_c)M = (873 - 308) \times 0.0224495$$

$$= 12.68396 \text{ A}$$

From Eq. (13.36) current at maximum power output,

$$I_{\text{max-power}} = \frac{\alpha_{AB}\,\Delta T}{2R_g} = \frac{500 \times 10^{-6} \times 565}{2 \times 8.55 \times 10^{-3}} = 16.520 \text{ A}$$

(e) From Eq. (13.52), power output at maximum efficiency,

$$P_{\text{max-eff}} = I_{\text{max-eff}}\ \alpha_{AB}\,(T_h - T_c) - (I_{\text{max-eff}})^2 R_g$$

$$= 12.68396 \times 500 \times 10^{-6} \times 565 - 12.68396^2 \times 8.55 \times 10^{-3}$$

$$= 2.20767 \text{ W}$$

(f) From Eq. (13.51), Maximum thermal efficiency,

$$\eta_{\max} = \frac{T_h - T_c}{T_h} \frac{M - M^2\left(\dfrac{R_g}{\alpha_{AB}}\right)}{M - M^2\left(\dfrac{R_g}{2\alpha_{AB}}\right)\left(\dfrac{T_h - T_c}{T_h}\right) + \left(\dfrac{K}{\alpha_{AB} T_h}\right)}$$

$$= \frac{873 - 308}{873} \frac{0.0224495 - 0.0224495^2 \times \left(\dfrac{8.55 \times 10^{-3}}{500 \times 10^{-6}}\right)}{0.0224495 - 0.0224495^2 \times \left(\dfrac{8.55 \times 10^{-3}}{2 \times 500 \times 10^{-6}}\right) \times \left(\dfrac{565}{873}\right) + \left(\dfrac{10.833 \times 10^{-3}}{500 \times 10^{-6} \times 873}\right)}$$

$$= 0.647 \times \frac{0.0224495 - 0.008618}{0.0224495 - 0.008616 \times 0.647 + 0.0248178} = 0.647 \times 0.33178$$

$$= 0.21466$$

Or $\eta_{\max} = 21.466\%$

Carnot efficiency, $\eta_{\text{Carnot}} = \dfrac{T_h - T_c}{T_h} = \dfrac{873 - 308}{873} = 0.647$

Or $\eta_{\text{Carnot}} = 64.7\%$

From Eq. (13.53) the efficiency at maximum power output is given by,

$$\eta_{th-\max-\text{power}} = \frac{T_h - T_c}{T_h} \frac{I_{\max-\text{power}} - \left(\dfrac{R_g}{\alpha_{AB}}\right) I^2_{\max-\text{power}} \dfrac{1}{(T_h - T_c)}}{I_{\max-\text{power}} - 0.5\left(\dfrac{R_g}{\alpha_{AB}}\right) I^2_{\max-\text{power}} \dfrac{1}{T_h} + \left(\dfrac{K}{\alpha_{AB}}\right) \dfrac{T_h - T_c}{T_h}}$$

$$= 0.647 \times \frac{16.52 - \left(\dfrac{8.55 \times 10^{-3}}{500 \times 10^{-6}}\right) \times 16.52^2 \times \dfrac{1}{565}}{16.52 - 0.5 \times \left(\dfrac{8.55 \times 10^{-3}}{500 \times 10^{-6}}\right) \times 16.52^2 \times \dfrac{1}{873} + \left(\dfrac{10.833 \times 10^{-3}}{500 \times 10^{-6}}\right) \times 0.647}$$

$$= 0.647 \times \frac{8.26023}{27.865}$$

$$= 0.19179$$

Or $h_{\text{th - max -power}} = 19.179\%$

13.3.2 Peltier Cooling

The principle of Peltier effect can be used for cooling or heat pumping. Major attraction of Peltier cooling is that the complete system is static and compact which leads to silent, least maintenance operation, small size, weight and high reliability. When a current I is forced through a thermocouple, heat is absorbed from ambient at cold junction at temperature T_c and rejected to ambient at higher temperature T_h. A schematic diagram of Peltier cooling is shown in Fig. 13.11.

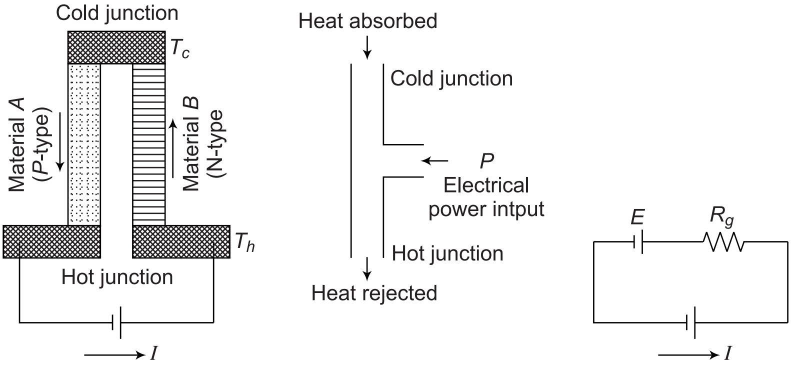


Fig. 13.11 Peltier cooler

Now, as discussed in Section 13.3.1, let us consider energy balance at cold junction.

1. Heat energy rate Q is supplied by the ambient at cold junction
2. as the current flows through the junction an amount of heat Q_p (Peltier effect) is absorbed at the junction
3. An amount of heat Q_c is conducted to cold junction from hot junction through two blocks
4. An amount of joule heat Q_j is generated uniformly in two blocks due to flow of current through resistance R_g. Half of this heat, $Q_j/2$ moves towards hot junction and remaining half moves towards cold junction. Thus,

Thus, $Q = Q_p - Q_c - ½\, Q_j$

where, $Q_p = \alpha_{AB} . T_c . I$ (refer Eq. (13.39))

$Q_c = K\,(T_h - T_c)$

and $Q_j = I^2 R_g$

Therefore,

$$Q = \alpha_{AB} . T_c . I - K(T_h - T_c) - 0.5\, I^2 R_g \tag{13.54}$$

where, K = total thermal conductivity of the two blocks in parallel.

$\alpha_{AB} \left|\alpha_A - \alpha_B\right|$; Seebeck coefficient for junction of material A and B

The electrical power required to pump heat from cold to hot junction (from Fig. (13.11)) is given by:

$$P = I . E + I^2 R_g$$

But from Eq. (13.29):

$$E = \alpha_{AB}\, \Delta T = \alpha_{AB}\, (T_h - T_c)$$

Therefore,

$$P = I \,.\, \alpha_{AB}\,(T_h - T_c) + I^2 R_g \tag{13.55}$$

The coefficient of performance, COP is given as:

$$\text{COP} = \frac{\text{Amount of cooling produced, } Q}{\text{Electrical input, } P}$$

$$= \frac{\alpha_{AB} T_c I - K(T_h - T_c) - 0.5 I^2 R_g}{I \alpha_{AB} (T_h - T_c) + I^2 R_g} \tag{13.56}$$

The current for maximum cooling can be obtained by differentiating Eq. (13.54) and equating to zero:

Thus: $$\frac{dQ}{dI} = 0 = \alpha_{AB} . T_C - I R_g$$

Or the current for maximum cooling is therefore:

$$I_{\max} = \frac{\alpha_{AB} T_c}{R_g} \tag{13.57}$$

Under this condition the maximum cooling rate is as follows:

$$Q_m = \alpha_{AB} T_c I_{\max} - K(T_h - T_c) - 0.5 I_{\max}^2 R_g \tag{13.58}$$

Example 13.6

Following data are given for a Peltier cooling system:

Seebeck coefficients, $\alpha_A = 200$ μV/°C, and $\alpha_B = -300$ μV/ °C

Electrical resistivity, $\rho_A = \rho_B = 1.5 \times 10^{-3}$ ohm-cm

Thermal conductivities, $k_A = k_B = 20 \times 10^{-3}$ W/cm^{-}°C

Temperatures, $T_h = 27$ °C and $T_c = -7$ °C

Dimensions of thermocouple, $A_A = A_B = 1.5$ cm^2 and $L_A + L_B = 1.2$ cm

At maximum cooling state, calculate:

(a) the required current, (b) the input electrical power required, (c) the amount of heat removed (or cooling) and (d) coefficient of performance (COP)

Solution

Given:

$\alpha_{AB} = 200 - (-300) = 500$ μV/ °C $= 0.5 \times 10^{-3}$ V/K

$k_A = k_B = 20 \times 10^{-3}$ W/ cm– °C = 2 W/m–K

$T_h = 300$ K and $T_c = 260$ K

$A_A = A_B = 1.5 \times 10^{-4}$ m^2 and $L_A = L_B = 1.2 \times 10^{-2}$ m

$\rho_A = \rho_B = 1.5 \times 10^{-5}$ ohm-m

(a) From Eq. (13.32):

$$R_g = R_A + R_B = \rho_A \frac{L_A}{A_A} + \rho_B \frac{L_B}{A_B}$$

$$= 1.5 \times 10^{-5} \times \frac{0.012}{1.5 \times 10^{-4}} + 1.5 \times 10^{-5} \times \frac{0.012}{1.5 \times 10^{-4}}$$

$= 0.0024$ ohms

From Eq. (13.57), the current for maximum cooling:

$$I_{\max} = \frac{\alpha_{AB} T_c}{R_g}$$

$$= \frac{0.5 \times 10^{-3} \times 260}{0.0024}$$

$$= 54.166 \text{ A}$$

(b) From Eq. (13.55), the input electrical power required:

$$P = I_{\max} \alpha_{AB} (T_h - T_c) + I_{\max}^2 R_g$$

$$= 54.166 \times 0.5 \times 10^{-3} \times (300 - 260) + 54.166^2 \times 0.0024$$

$$= 8.1248 \text{ W}$$

(c) From Eq. (13.45), total thermal conductivity K of the two materials in parallel,

$$K = k_A \frac{A_A}{L_A} + k_B \frac{A_B}{L_B} = 2 \times \frac{1.5 \times 10^{-4}}{1.2 \times 10^{-2}} + 2 \times \frac{1.5 \times 10^{-4}}{1.2 \times 10^{-2}} = 0.05 \text{ W/K}$$

From Eq. (13.58), the amount of cooling (or heat removal):

$$Q_m = \alpha_{AB} T_c I_{\max} - K(T_h - T_c) - 0.5 I_{\max}^2 R_g$$

$$= 0.0005 \times 260 \times 54.166 - 0.05 \times (300 - 260) - 0.5 \times 54.166^2 \times 0.0024$$

$$= 1.521 \text{ W}$$

(d) From Eq. (13.56), coefficient of performance, at maximum cooling

$$COP = \frac{\alpha_{AB} T_c I_{\max} - K(T_h - T_c) - 0.5 I_{\max}^2 R_g}{I_{\max} \alpha_{AB} (T_h - T_c) + I_{\max}^2 R_g}$$

$$= \frac{1.521}{8.1248} = 0.18718$$

Or COP = 18.718%

13.3.3 Applications

Because of high cost of thermoelectric material, these generators are not yet widely used in commercial applications. In low power range (1 W to 1000 W) fossil fuel based thermoelectric generators using gas, as fuel may be more economical than IC engine driven generators. It provides handy reliable and simple source of auxiliary standby power source especially for remote areas. Due to reliability and robustness, these are used in military applications. Kerosene fueled thermoelectric generators, are being used by peasants in remote places of Siberia. Radioisotope (polonium) fueled and nuclear-fueled thermoelectric generators have been used in space applications such as, moon probes, satellites and weather stations. High cost and low efficiency are the main disadvantages of thermoelectric generators.

The “Cordless-Electric Company” has developed a model “TEG 5000” of thermoelectric generator. Like the transistor or microchip, this electric generator is solid-state, makes no noise, and has no moving parts. This generator burns natural gas or propane. The efficiency is claimed to be 12 per cent. This generator has the output of 5 kW, 115 V, 60 Hz, enough to power the average U.S. home. Weighing just 27 pounds, the generator can be carried like a briefcase. With the push of a button, it delivers full electrical power in just 20 seconds.

Peltier effect can be used to pump heat from cold junction to hot junction through thermos-electric means. This principle is being used to maintain cold and hot chambers in service cart of airhostess during air journey.

13.4 THERMIONIC POWER CONVERSION

A thermionic generator converts heat directly to electricity by using the effect of thermionic emission. It has several advantages such as: (i) no moving parts, (ii) quiet operation, (iii) reliable, (iv) long life, as there is no wear, (iv) high power density, (v) uses temperature differentials up to 550 °C, (vi) scalable from milliwatts to megawatts, (vii) withstands harsh environments, (viii) projected low manufacturing cost and (ix) reasonable efficiency. Compared to thermoelectric converter, the thermionic converter is more suitable for use at high temperature generated by combustion. It exhibits a better figure of merit with increase of temperature, while for thermoelectric converter the figure of merit deteriorates with rise of temperature.

In principle, a thermionic converter consists of two metals (electrodes) with different work functions sealed into an evacuated vessel. The electrode with larger work function is maintained at higher temperature than one with smaller work function. The hot electrode (emitter) emits electrons and acquires positive charge whereas colder electrode (collector) collects electrons and becomes negatively charged. A voltage is thus developed between the electrodes and a direct current will flow in an external circuit connecting them as shown in Fig. 13.12. The voltage, which may be around 1 V (or so), is determined primarily by calculating the difference in work functions of the electrode materials. Current densities of few tens to few hundreds of amperes per square cm of emitter area are achieved above 1000 °C emitter temperature.

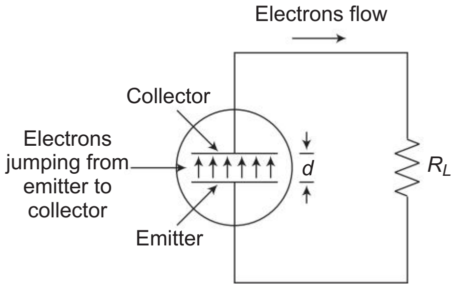


Fig. 13.12 Elementary thermionic converter

The output voltage is the Fermi potential difference between the emitter and the collector (assuming thermoelectric effect in the converter to be negligible). The output power depends on emitter temperature and work function magnitude difference between emitter and collector. Thermal efficiencies in range 5–25 per cent have been achieved.

The emission of electrons from emitter is inhibited by space charge (electron cloud) resulting from accumulation of electrons in its vicinity. The electron cloud deters additional electrons from crossing the gap. This space charge can be greatly reduced: (i) by decreasing the gap between the electrodes and (ii) by introducing small quantity of cesium to neutralize the space charge. Cesium has low ionization potential and thus can be ionized relatively easily through thermal means. At high temperature (above about 1000 °C), cesium ionizes to produce +ve ions. By combining with electrons in the vicinity of the emitter, the +ve ions help to decrease the space charge.

In the ideal case, the space charge barrier and back emission current from collector to emitter are neglected. The ideal current density, J_o would then be given by:

$$J_o = \begin{cases} A_E\, T_E^{\,2}\ \exp\left(-\dfrac{\varphi_E}{k\ T_E}\right), & V_o \le V_c \\ A_E\, T_E^{\,2}\ \exp\left(-\dfrac{\varphi_C}{k\ T_E}\right).\exp\left(-\dfrac{eV_o}{k\ T_E}\right), & V_o > V_c \end{cases} \tag{13.59}$$

where V_o = output voltage, V

φ_E, φ_C = work functions of emitter and collector respectively, eV

$V_C = (\varphi_E - \varphi_C)/e$ = contact potential between emitter and collector, V

A_E = Richardson constant of emitter (ideal value = 120 A/(cm^2 K^2))

T_E = Temperature of emitter

From Eq. (13.59) it is clear that emitter work function and temperature are two critical parameters for large thermionic current. Low emitter work function is needed for high emission at low temperature. For significant emission an emitter temperature of at least 1000 °C is generally needed and still higher temperatures are better. Also large work function difference between emitter and collector is desirable for large output voltage. Although temperature has little effect on the generated voltage, the current (per unit emitter area) increases with temperature, resulting in the increase in the power output.

A common thermionic combination is a tungsten emitter and a cesium coated copper, nickel or silver collector. Cesium is coated on collector in such a way that final work function potential of the collector becomes that of cesium. Cesium has one of the lowest work function of about 1.75 eV. The magnitudes of work functions for some materials are given in Table 13.2.

Table 13.2 The magnitude of work functions for some materials

S. N.	Material	Work function (eV)
1.	Pt (Platinum)	6.15
2.	Ni (Nickel)	5.0
3.	Ag (Silver)	4.65
4.	W (Tungston)	4.5
5.	Cu (Copper)	4.3
6.	Mo (Molybdenum)	4.25
7.	Li (Lithium)	2.21

8.	Na (Sodium)	2.0
9.	K (Potassium)	1.9
10.	Cs (Cesium)	1.75

The biggest problem with thermos-electrics is that while heat pushes electrons in one direction, the material itself redistributes most of that heat through simple conduction. This means that most of the heat is not usefully harnessed, and instead flows through the system in all directions, drastically reducing the efficiency. In addition, fabrication and operation of TEC's has been difficult and expensive.

Thermionic converters are special because the electrons move across a gap - and that gap, since it is not a solid, is an excellent insulator. The heat is trapped on one side, leaving the other side ready to accept a steady flow of excited electrons. This means the heat is utilized more efficiently.

Themionic emission can be further enhanced by lowering the work function of the cathode by optimizing the "Avto effect". The method involves precise texturing of cathode surface at the nanoscale level. This causes a marked reduction in the material's work function, allowing electrons to flow more freely into the vacuum. "Power Chips plc (US OTC: PWCHF)" is working on developing "Power Chips™" which are projected to be the most effective heat-energy converters. Power Chips will operate up to 70–80 per cent of the maximum (Carnot) theoretical efficiency. This may be one of the first industrial applications of nanotechnology. "Power Chips plc" also proposes to use this device in a hybrid electric car to harness additional power from the waste heat of the exhaust.

In the past, application of thermionic converters has been limited to space power systems, because of their high operating temperature and relatively low efficiency. Several recent advances in thermionic energy conversion technology have greatly improved the efficiency of these devices.

Potential areas of applications identified for thermionic converter are: (i) centralized and distributed power generation, (ii) residential and commercial site applications, (iii) land, sea and air vehicles, (iv) aerospace and military systems and (v) electronics and data communications.

Applications can be divided into two categories according to their heat source: (a) primary heat, the system is called topping cycle or (b) waste heat, the system is called bottoming cycle. Bottoming cycle consumes no fuel hence they are some of the most cost-effective applications.

Concentrating solar power collectors currently harvesting thermal energy in residential and commercial venues could be retrofitted with a topping cycle based thermionic converter. Compared to photovoltaic system, which produces only high cost electricity, thermionic-based system could convert one fifth of the captured energy into electricity and rest into thermal energy for water and/or space heating. Heating system fired by gas, oil or other fuel could also be used to provide electrical supply through thermionic converter during power grid outage periods.

High power-to-weight ratio, low noise and broad scalability, offers great potential in aerospace and military systems. Applications range from portable power generators for tactical systems, solar energy arrays to waste heat recovery from exhaust of a variety of land, sea and air propulsion systems.

In fossil fuel based conventional plants, part of waste heat may be recovered as useful electricity using thermionic converter in bottoming cycle. It increases over all generating efficiency, by reducing fuel consumption. Also it releases no additional chemical emissions into atmosphere or water supplies.

REVIEW QUESTIONS

1. Describe the basic principle of operation of an MHD generator. Derive expressions for maximum power generation per unit volume of generator.
2. What are the major advantages and limitations of MHD generating system?
3. With the help of schematic diagram explain the operation of closed cycle MHD generating system.
4. Explain the heating and cooling applications of thermoelectric system. Comment on the type of materials used for low and high temperature applications.
5. Mention the merits of thermionic converter. On what parameters the output voltage and current depend?
6. Comment on the type of materials required in a thermionic converter.
7. What are the potential applications of thermionic converters?

PROBLEMS

1. Calculate the open circuit voltage and maximum power output for a MHD generator having following data:

   Plate area = 0.25 m^2

   Distance between the electrodes = 0.50 m

   Flux density = 2 Wb/m^2

   Average gas velocity = 1000 m/s

   Gaseous conductivity = 10 mho/m

   (*Ans.* 1000 V, 1.25 MW)

2. An MHD duct has the dimensions; length $l = 1.5$ m, average vertical height, $d = 0.4$ m, average width, $w = 0.5$ m. The magnetic flux density, $B = 4$ T along w, and the gas velocity, $u = 800$ m/s along l. At a performance coefficient of $K = 0.7$, calculate:
   (a) generated voltage and its gradient
   (b) load voltage

   (*Ans.* 3,200 V/m, 896 V)

3. The ionized gas in example 13.2 has a conductivity of 65 mho/m. Calculate:
   (a) current density and current in the system
   (b) short circuit current density and short circuit current
   (c) power output
   (d) power density generated in the duct
   (e) total power generated
   (f) heating losses in the duct
   (g) maximum possible power delivered to load

(*Ans.* 43,689 A/m^2, 32.76 kA, 2,08,00 A/m^2, 156 kA, 41.932 MW, 199.68 MW/m^3, 59.904 MW, 17.972 MW, 49.92 MW)

4. Following data are given for a thermoelectric generator:

Length of thermoelectric material blocks; $L_A = L_B = 5$ cm
Areas of thermodynamic blocks, $A_A = 1.5$ cm^2, $A_B = 1$ cm^2
Hot and cold junction temperatures; $T_h = 527$ °C, $T_c = 27$ °C
Seebeck coefficients; $\alpha_A = 250$ µV/°C, $\alpha_B = -250$ µV/°C
Specific resistance; $\rho_A = 10^{-3}$ ohm-cm, $\rho_B = 9 \times 10^{-4}$ ohm-cm

Calculate the following:

(a) Seebeck open circuit voltage of thermoelectric generator
(b) Resistance of the two materials
(c) Maximum power output
(d) Current at maximum power output

(*Ans.* 250 mV, 7.83 × 10^{-3} Ohms, 1.995 W, 15.964 A)

5. For the data given in previous example, assume thermal conductivities as $k_A = k_B =$ 25 mW/cm-°C. Calculate the following:

(a) Total thermal conductivity K of the two materials in parallel
(b) The value of the figure of merit, Z
(c) The coefficient of merit, M at maximum thermal efficiency
(d) The current at maximum thermal efficiency, $I_{\text{max-eff}}$. Compare with current at maximum power, $I_{\text{max-power}}$
(e) Power output at maximum efficiency. Compare with maximum power output.
(f) The maximum thermal efficiency. Compare with Carnot efficiency of the system, and the efficiency at maximum power output

(*Ans.* 12.5×10^{-3} W / K, 2.554278×10^{-3} per Kelvin, 0.02503 A / K, 12.5172 A, 15.9642 A, 1.90249 W, 18.24%, 62.5%, 17.147%)

6. Following data are given for a Peltier cooling system:

Seebeck coefficients, $\alpha_A = 250$ µV/°C, and $\alpha_B = -250$ µV/ °C
Electrical resistivity, $\rho_A = \rho_B = 1.2 \times 10^{-3}$ ohm-cm
Thermal conductivities, $k_A = k_B = 20 \times 10^{-3}$ W/ cm- °C
Temperatures, $T_h = 27$ °C and $T_c = -3$ °C
Dimensions of thermocouple, $A_A = A_B = 1.5$ cm^2 and $L_A + L_B = 1$ cm

At maximum cooling state, calculate:

(a) the required current, (b) the input electrical power required, (c) the amount of heat removed (or cooling) and (d) coefficient of performance (COP)

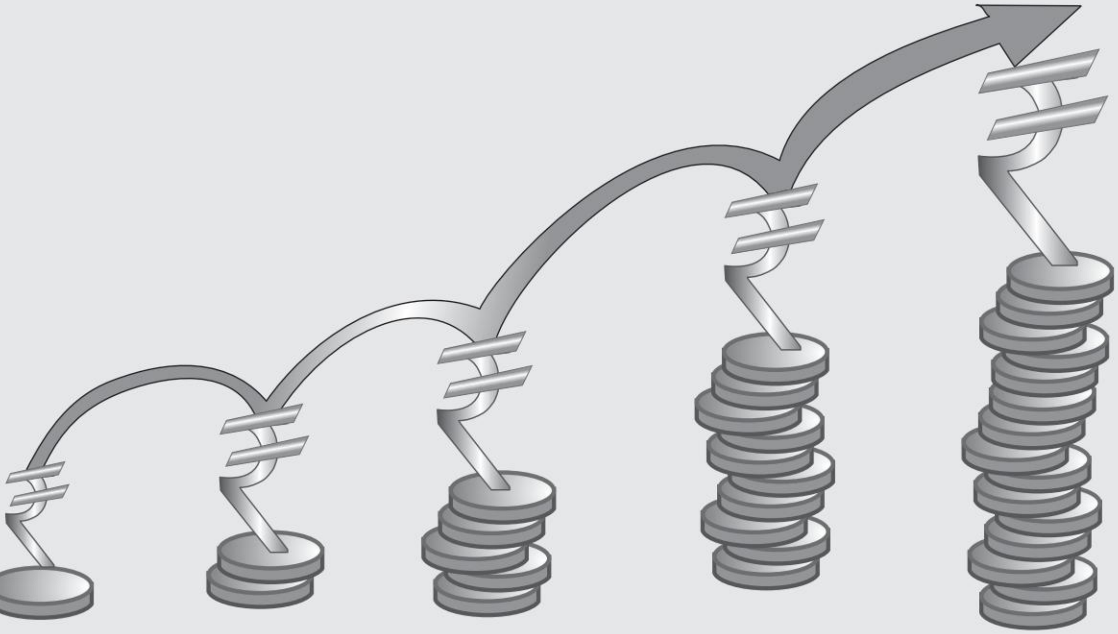
(*Ans.* 84.375 A, 12.656 W, 3.895 W, 30.776%)

OBJECTIVE TYPE QUESTIONS

1. In a practical MHD system, the exhaust of MHD generator:

(a) is used as hot air for combustion in a furnace.
(b) is used as input to gas turbine to generate additional power.
(c) is used as input to a boiler to raise steam for steam turbine to generate additional power.
(d) is let off to atmosphere.

2. Techno-economic factors make MHD generator feasible:
   - (a) only for large scale central power station
   - (b) only for small scale distributed power generation
   - (c) at any situation irrespective of size.
   - (d) only to meet peak power demand.
3. The working fluid used in an MHD system coupled to a fast breeder reactor is a:
   - (a) hot flue gas
   - (b) seeded inert gas
   - (c) liquid metal– inert gas mixture
   - (d) liquid metal only
4. MHD generators have not become popular because:
   - (a) of difficulties in material selection
   - (b) of difficulties to obtain strong magnetic field
   - (c) other systems, such as natural gas turbines achieved similar thermal efficiencies at lower costs
   - (d) of the need to operate at high temperature
5. The biggest advantages of thermoelectric power generator are:
   - (a) it is cheap and compact
   - (b) it is cheap and bulky
   - (c) it has lowest maintenance and has ability to use high grade heat
   - (d) it has lowest maintenance and has ability to use low grade heat
6. The biggest disadvantages of thermoelectric power generator are:
   - (a) it is cheap and compact
   - (b) it has low cost and low efficiency
   - (c) its high cost and low efficiency
   - (d) its high reliability and low cost
7. The principle used to maintain cold and hot chambers in service cart of airhostess is:
   - (a) Seebeck effect
   - (b) Peltier effect
   - (c) Avto effect
   - (d) Tunneling effect
8. In a thermionic generator, the space charge around the emitter can be greatly reduced by:
   - (a) by decreasing the gap between the electrodes
   - (b) by increasing the gap between the electrodes
   - (c) by decreasing the temperature
   - (d) by increasing the temperature
9. In applications requiring high temperature, generated by combustion:
   - (a) both thermoelectric and thermionic generators are equally suitable
   - (b) thermoelectric generators are more suitable than thermionic generator
   - (c) thermionic generators are more suitable than thermoelectric generator
   - (d) none of the two are suitable at high temperature
10. Avto effect causes enhanced thermionic emission:
    - (a) by increasing the gap between the electrodes
    - (b) by increasing the voltage between the electrodes
    - (c) by choosing appropriate material of cathode
    - (d) by precise texturing of cathode surface at the nanoscale level



CHAPTER 14

Financial and Economic Evaluation

Learning Objectives

In this chapter you will be able to:

- ➤ Know about the analytical methods of conducting financial evaluation
- ➤ Discuss economic feasibility of various renewable energy technologies for better management and sound decision-making
- ➤ Illustrate economic concepts with the help of a large number of numerical problems
- ➤ Conduct comparative economic evaluation of alternatives

14.1 INTRODUCTION

For all projects aiming at the production/consumption of energy it is necessary to choose the most economic energy supply route for a given requirement. Large numbers of energy systems with their unique peculiar features are available. The energy supply through solar energy system for example, is diurnal and generally requires storage for its use, whereas wind energy is fluctuating and intermittent and generally requires a grid connection to maintain steady supply. To get a meaningful insight of these complex alternatives a systematic evaluation of their financial and economic aspects is essential. Such studies also help to optimize the allocation of funds by concentrating on those applications which are financially/economically more rewarding besides being socially acceptable and environmentally sustainable. Many failures can be avoided by proper understanding of the financial and economic strengths/weaknesses of various available options.

This chapter introduces the students, how to conduct economic feasibility studies to help management make sound investment decisions for capital projects in the private and public sectors with particular reference to renewable energy systems. The engineering economics seeks to provide the analytical framework for decision making from an economic point of view, and to advance the engineer's role in the decision process. The economic concepts and analytical methods required for the preparation of economic feasibility studies are briefly discussed in this chapter.

14.2 BASIC TERMS AND DEFINITIONS

1. Cash Flow Diagram

Any organization usually has frequent receipts and disbursements taking place over a particular interval of time. These transactions can be shown on a cash flow diagram. A cash flow diagram is simply a graphical representation of cash flows drawn on time scale, as shown in Fig. 14.1. The horizontal line represents the progression of time from left to right. The time scale is divided into equal intervals, known as interest periods. The numbers 1, 2, 3, · · ·, *n*, on time scale represent the end of corresponding periods. Time "0" represent the starting date or present time. A vertical arrow pointing upwards indicates positive cash flow (cash receipt, income) and the arrow pointing

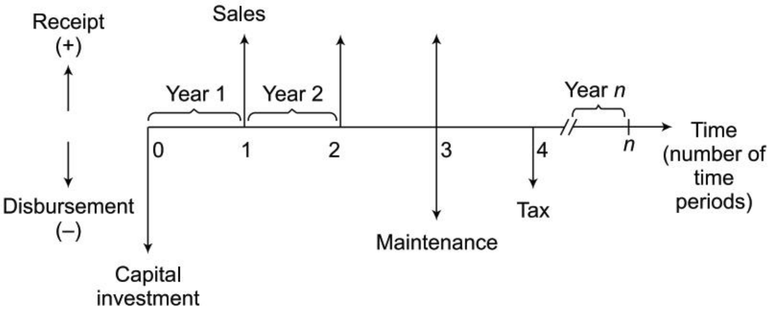


Figure 14.1 Cash flow diagram

downwards indicate negative cash flow (disbursement, cost). At any point in time the net cash flow would be represented as:

Net cash flow = receipts – disbursements

Within one interest period cash flows may take place at any time, however, a simplifying assumption is made in that all cash flows occur at the end of interest period. This practice in engineering economics is known as **end of period convention**. Thus for all receipts and disbursements occurring within a given interest period, the net cash flow is assumed to occur at the end of interest period.

2. Principal Amount, P

This is the amount of money that is being considered initially. It might be an amount to be invested or loaned or it may refer to initial value or cost of a plant or machinery.

3. Interest, I

Interest is the payment (other than the sum borrowed) made for the money borrowed from the bank or financer. In other words, interest is the consideration which the money lender receives for the use of money lent. Alternatively, interest may be regarded as the return obtained by the productive investment of capital.

4. Interest Rate

Interest rate is essentially a measure of productivity of money as a resource. Alternatively, interest rate is a measure of investor's preference for the time value of money. Thus an interest rate of 10 per cent would mean that the investor regards a sum of money worth 10 per cent less next year than it is worth this year. Interest rates are also quoted for a period other than one year. However, unless otherwise stated, it is customarily understood to be specified on annual (per annum) basis.

5. Cost of Capital

It is usually defined as the minimum rate of return that an investor (or company) expects to earn on its investment.

6. Number of Time Periods, n

The number of time intervals over which the amount of money is being invested or borrowed. Although "*n*" is usually the number of years, it may represent other time periods such as number of quarters or months.

14.2.1 Kinds of Interest

1. Simple Interest

Simple interest is directly proportional to the capital involved, the number of interest periods and the interest rate. The total interest, I on principal, P for n number of interest periods at interest rate, i (expressed as fraction) is given by:

$$I = P\,n\,i$$

In general, simple interest is applied only for the short term periods, like duration of less than one year.

2. Compound Interest

When the simple interest is added to the principal amount so that the amount becomes the principal amount for the next term (period), the interest so obtained is called compound interest. These days compound interest approach is used more frequently than that of simple interest.

An amount, P invested at an annual interest rate of i compounded annually, after n years becomes:

$$F = P(1 + i)^n \tag{14.1}$$

In the above equation:

P is known as present value of the investment
i is the annual interest rate
n is number of interest periods, and
F is the future value of the investment

When the period of interest is less than one year, compound interest rates may be quoted in two ways:

(a) Nominal Interest Rate Nominal interest rate is the annual interest rate obtained simply by converting the interest rate specified for one period (where the period is less than one year) to a year disregarding the effect of compounding after each period. For example, an interest rate of 2% compounded each month for a year is typically quoted as 24% (2 × 12) nominal interest rate or annual interest rate.

(b) Effective Interest Rate It represents the actual or exact rate of interest upon the principal during a specified period. The effective interest rate based on a year is referred to as the effective annual interest rate.

If i represents the nominal interest rate per year, and m the number of interest (compounding) periods per year, the effective annual interest rate i_e may be expressed as:

$$i_e = \left(1 + \frac{i}{m}\right)^m - 1 \tag{14.2}$$

Now for 24% nominal interest rate, the effective interest rates:

- *For quarterly compounding (m = 4)*

$$i_e = \left(1 + \frac{0.24}{4}\right)^4 - 1 = 0.262 \text{ or } 26.2\% \text{ per annum}$$

- *For monthly compounding (m = 12)*

$$i_e = \left(1 + \frac{0.24}{12}\right)^{12} - 1 = 0.268 \text{ or } 26.8\% \text{ per annum}$$

- *For daily compounding (m = 365)*

$$i_e = \left(1 + \frac{0.24}{365}\right)^{365} - 1 = 0.27115 \text{ or } 27.115\% \text{ per annum}$$

- *For continuous compounding ($m = \infty$)*
  When the interest is compounded continuously, i.e., an infinite number of times per year, the annual effective rate of interest will be given by:

  $$i_e = e^i - 1 \tag{14.3}$$

  $$i_e = e^{0.24} - 1$$

  $$= 0.27125 \text{ or } 27.125\% \text{ per annum}$$

  Continuous compounding is very seldom used in engineering economic studies.

14.3 CALCULATIONS FOR THE CASE OF SINGLE PAYMENT (OR RECEIPT)

14.3.1 Single Payment Compound Amount Factor or Future Value Factor

When an amount *P* is invested for *n* equal interest periods with *i* as interest rate, the future value of investment obtained according to Eq. (14.1) is:

$$F = P\,(1 + \mathrm{i})^n$$

As shown in cash flow diagram, (Fig. 14.2) the present value *P* is an outlay and it is represented by a downward arrow at time zero "0", while its future value *F* is an inflow represented by an upward arrow.

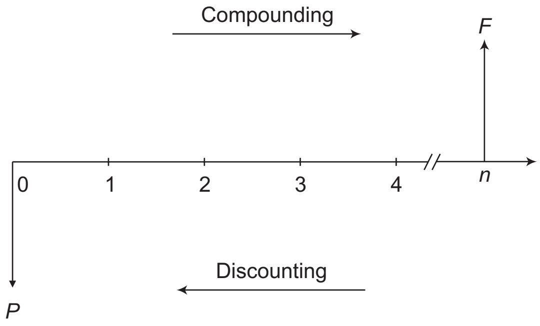


Figure 14.2 Single payment and future value

The factor $(1 + i)^n$, which is used to multiply *P* in order to derive *F* is called "single payment compound amount factor". It is usually designated as: *(F/P, i, n)*. Therefore, the above relationship can be written as:

$$F = P\,(F/P, i, n) \tag{14.4}$$

Example 14.1

What will be the amount of ₹ 2000 invested at 12% interest compounded annually at the end of 6 years?

Solution

Given,

$$P = 2000$$
$$i = 0.12$$
$$n = 6$$

From Eq. (14.1),

$$F = 2000\,(1 + 0.12)^6$$
$$\approx ₹\,3948$$

Example 14.2

Find the number of years in which an investment of ₹ 10 lakh will double in value, if the interest rate is 12.25%

Solution

Given,

$$P = 10 \text{ lakh}$$
$$F = 20 \text{ lakh}$$
$$i = 0.1225$$

From Eq. (14.1),

$$20 = 10(1 + 0.1225)^n$$
$$2 = (1 + 0.1225)^n$$
$$\log 2 = n \log (1.1225)$$
$$n = \log 2/\log (1.1225)$$
$$n = 6$$

14.3.2 Single Payment Present Worth Factor

If the future value of an investment (or payment) is known, we can derive its present value, given an interest rate and the number of compounding periods for P in Eq.(14.1), giving;

$$P = F\left[\frac{1}{(1+i)^n}\right] \tag{14.5}$$

The expression in brackets, which is used to multiply F to obtain P, is called "**single payment present worth factor**", and is designated as: (P/F, i, n). Therefore, Eq. (14.5) can be written as:

$$P = F\,(P/F, i, n) \tag{14.6}$$

The process used in converting the future value to its present value is called "**discounting**" and has wide application in engineering economy. In the above expression the present value is calculated by discounting the future value of a given amount. The term "i" is known as discount rate.

Example 14.3

What is the present value of future payment of ₹ 100,000 due 10 years from now, if the nominal interest rate is 6%?

Solution

Given,

$$F = 100{,}000$$
$$i = 0.06$$
$$n = 10$$

From Eq. (14.5),

$$P = F\left[\frac{1}{(1+i)^n}\right]$$

$$= 100000\left[\frac{1}{(1+0.06)^{10}}\right] = ₹\,55{,}839$$

14.4 CALCULATIONS FOR UNIFORM SERIES OF PAYMENTS (OR RECEIPTS)

14.4.1 Uniform Series Compound Amount Factor

Business firms and individual investors, in order to meet their future capital investment requirements, set aside each year a certain amount of savings which over time accumulate to an amount that, hopefully will meet their expected needs. In this case the investment process involves investing an amount A each year. At the end of n^{th} year the principals plus the interest earned compounded annually becomes F, the future value of the investment as shown in Fig. 14.3.

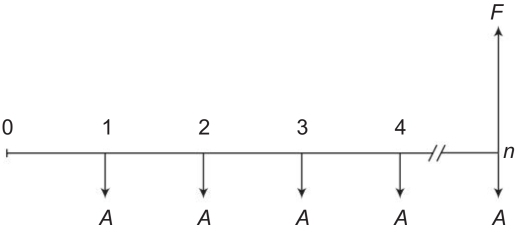


Figure 14.3 Uniform series of future value

The accumulated future amount F after n years may be calculated as:

$$F = A\left[\frac{(1+i)^n - 1}{i}\right] \tag{14.7}$$

where A is the annual amount invested each year and compounded annually to accumulate F. The expression in the bracket is known as "**uniform series compound amount factor**" and is designated as: (F/A, i, n).

Therefore, Eq. (14.7) can be written as:

$$F = A\,(F/A, i, n) \tag{14.8}$$

Example 14.4

What will be the future amount of a uniform payment of ₹ 500 deposited at the end of each year with an interest rate of 9 per cent per annum, at the end of 6 years?

Solution

Given,

$$A = 500$$
$$i = 0.09$$
$$n = 6$$

From Eq. (14.7),

$$F = 500\left[\frac{(1+0.09)^6 - 1}{0.09}\right] = ₹\,3{,}762$$

14.4.2 Uniform Series Sinking Fund Factor

When the future capital expenditure for a certain activity or project is known, the required amount A to be invested annually at a given interest rate can be determined from Eq. (14.7) as:

$$A = F\left[\frac{i}{(1+i)^n - 1}\right] \tag{14.9}$$

The expression in the bracket is known as "**uniform series sinking fund factor**" and is designated as: $(A/F, i, n)$. Therefore, Eq. (14.9) can be written as:

$$A = F(A/F, i, n) \tag{14.10}$$

Example 14.5

The replacement of the tubular battery of a solar PV system at the end of four years is likely to cost ₹ 12,000. What amount should a user deposit every year to accumulate the desired amount if he earns 9 percent interest on his deposit?

Solution

Given,

$$F = 12{,}000$$
$$i = 0.09$$
$$n = 4$$

From Eq. (14.9),

$$A = 12000\left[\frac{0.09}{(1+0.09)^4 - 1}\right]$$

$$= ₹\,2{,}624$$

14.4.3 Uniform Series Present Worth Factor

It is often required to know the present value P of a series of equal payments A (or receipts) over a number of years n at a given rate of interest i. Such a series is shown in Fig. 14.4.

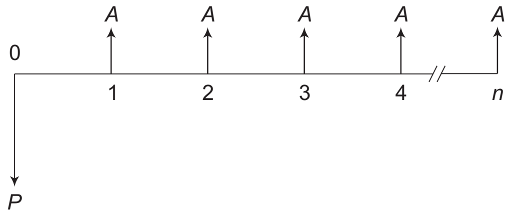


Figure 14.4 Uniform series of present value

The present worth P of a uniform series of cash flow can be determined using following equation:

$$P = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \tag{14.11}$$

The expression in the bracket is known as "**uniform series present worth factor**" and is designated as: (P/A, i, n). Therefore, Eq. (14.11) can be written as:

$$P = A\ (P/A,\ i,\ n) \tag{14.12}$$

Example 14.6

In a major maintenance drive, replacing old machinery in a plant by more efficient one can reduce energy consumption leading to saving of ₹ 30,000 at the end of each year for the next 8 years. Keeping the overall economy in mind, how much expenditure in the maintenance may be allowed if the interest rate is 10%.

Solution

Given,

$$A = 30{,}000$$
$$n = 8$$
$$i = 0.1$$

Present worth of overall savings due to enhanced efficiency after maintenance from Eq. (14.11),

$$P = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right]$$

$$= 30{,}000\left[\frac{(1+0.1)^8 - 1}{0.1(1+0.1)^8}\right]$$

$$= ₹\ 1,60{,}047$$

Therefore, at the most the above amount may be spent on the replacement at present.

Example 14.7

A 100 liter per day domestic solar water heater saves consumption of electricity in an electric geyser on 100 days of the year by heating 100 liters of water from 15 °C to 60 °C. The useful life of the solar heater is estimated as 10 years. Determine the present worth of saving through the use of solar water heater, if the efficiency of electric geyser is 90% and the cost of electricity is ₹ 4 per kWh. Assume interest rate as 12%.

Solution

Given,

$$n = 10$$

$$i = 0.12$$

Electricity saved by the solar water heater in one day:

$$= \left(\frac{1}{0.9}\right) \times 100\, kg \times 4.2 \text{ kJ/kg °C} \times (60-15)°\, C \times \left(\frac{1 \text{ kWh}}{3{,}600 \text{ kJ}}\right)$$

$$= 5.83 \text{ kWh/day}$$

Monitory worth of electricity saved by solar water heater during one year:

$$= (5.83 \text{ kWh/day}) \times (100 \text{ days/year}) \times (₹\,4\text{/kWh})$$

$$= ₹\,2{,}332$$

Therefore, annual saving, A = 2,332

Present worth of overall savings during its lifetime of 10 years may be calculated from Eq. (14.11) as;

$$P = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right]$$

$$= 2332 \times \left[\frac{(1+0.12)^{10} - 1}{0.12(1+0.12)^{10}}\right]$$

$$= ₹\,13{,}176$$

14.4.4 Uniform Series Capital Recovery Factor

In engineering economy studies, the present value of an investment is frequently known, and what is to be found is the annual receipt (**annuity**) that will be generated in the future over the life of the investment at a given rate of interest. Rearranging the terms in Eq. (14.11),

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \tag{14.13}$$

The expression in the bracket is known as "**uniform series capital recovery factor**" and is designated as: (*A*/*P*, *i*, *n*). Therefore, Eq. (14.13) can be written as:

$$A = P\ (A/P, i, n) \tag{14.14}$$

Example 14.8

A 2-kWp PV roof top plant cost ₹2, 00,000 and has a useful life of 25 years. The annual average maintenance cost is 2% of the capital cost and the discount rate is 10%. Calculate the unit cost of solar PV generated electricity if it supplies a load of 25% of its power rating for 10 hours daily.

Solution

Given,

$$P = 2,00,000$$
$$n = 25$$
$$i = 0.1$$

The annualized capital cost is:

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]$$

$$= 2,00,000\left[\frac{0.1(1+0.1)^{25}}{(1+0.1)^{25} - 1}\right]$$

$$= 22,034$$

Annual maintenance cost = 0.05 × 2, 00,000 = 10,000

Thus, total annual cost of solar PV plant = 22,034 + 10,000 = 32,034

Annual electricity production = 2 × 0.25 × 10 ×365 = 1,825 kWh

Therefore, unit cost of electricity production = $\frac{32,034}{1,825}$ = ₹17.60

14.5 CALCULATIONS FOR UNIFORM GRADIENT SERIES OF PAYMENTS (OR RECEIPTS)

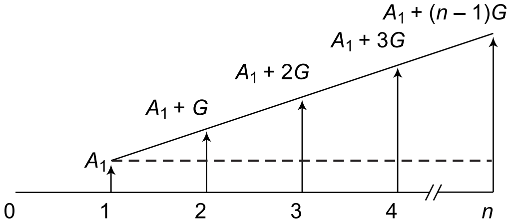
Sometimes an investment generates a uniform series of payments that either increase or decrease by a constant amount as shown in Fig. 14.5. Such a series is known as "uniform (or arithmetic) gradient series" of payments. To evaluate such a series, an equivalent "uniform series of payments" with constant cash flows A_g is found and then P_g or F_g is computed for this equivalent series using Eq. (14.7) through Eq. (14.14).

The equivalent cash flows of uniform series of payments may be obtained from:

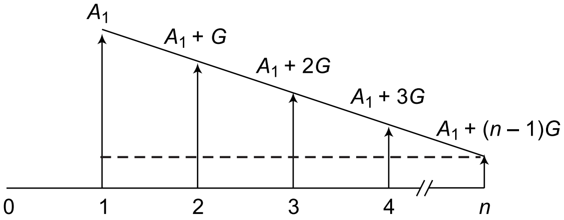
$$A_g = A_1 + G\,(A/G, i, n) \tag{14.15}$$

Where G is the constant amount of change or gradient per period (which may be positive or negative), A_1 is the payment at the end of first year and n is the number of periods. ($A/G, i, n$) is known as "uniform gradient annual series factor" or "gradient to uniform series conversion factor" and is given by:

$$(A/G, i, n) = \left[\frac{1}{i} - \frac{n}{(1+i)^n - 1}\right] \tag{14.16}$$



(a) Increasing (*G* positive)



(a) Decreasing (*G* negative)

Figure 14.5 Uniform gradient series

It may be noted that first payment starts from year 1 and continues up to year n and grading starts from year 2.

Example 14.9

A person wants to start a solar lantern manufacturing company and expects the sales revenues of ₹ 10 lakh at the end of first year. In subsequent 5 years, sales are expected to increase by ₹ 1 lakh annually. The manufacturer has applied for a loan of ₹ 40 lakh from a bank to finance the project. The bank's policy requires that the loan must not exceed 85% of the expected revenues. If the discount rate is 12%, will the manufacturer get the loan?

Solution

Given,

$$A_1 = 10 \text{ lakh}$$
$$G = 1 \text{ lakh}$$
$$i = 0.12$$
$$n = 5$$

The gradient to uniform series conversion factor from Eq. (14.16) is given by:

$$(A/G, i, n) = \left[\frac{1}{0.12} - \frac{5}{(1+0.12)^5 - 1}\right]$$

$$= 1.7745945$$

The equivalent cash flows of uniform series from Eq. (14.15):

$$A_g = 10 + 1 \times 1.7745945$$
$$= 11.7745945 \text{ lakh}$$

Present worth of the series of the cash flow may be obtained from Eq. (14.11):

$$P_g = A_g \left[\frac{(1 + i)^n - 1}{i(1 + i)^n} \right]$$

$$P_g = 11.7745945 \times \left[\frac{(1 + 0.12)^5 - 1}{0.12 \times (1 + 0.12)^5} \right]$$

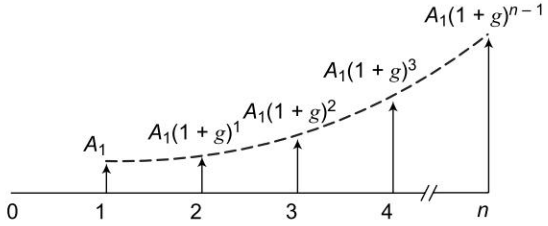
$$= 42.44 \text{ lakh}$$

85% of the expected revenues = 42.44 × 0.85 = 36.07 lakh

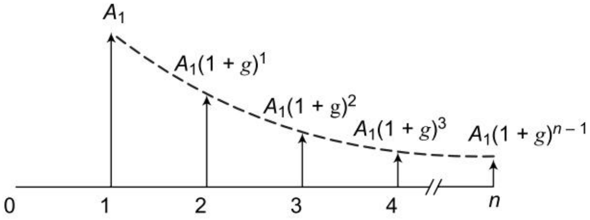
This amount is less than the amount of loan (i.e. 40 lakh); therefore, the manufacturer will not get the loan.

14.6 CALCULATIONS FOR GEOMETRIC GRADIENT SERIES OF PAYMENTS (OR RECEIPTS)

In many situations periodic cash flows are expected to increase or decrease over time, not by a constant amount (gradient) but by a constant percentage rate, i.e. a geometric growth through time as shown in Fig. 14.6. Escalation in the prices of different fuels at a constant rate each year (known as inflation) is a typical situation that can be modeled with geometric sequence of cash flow.



(a) Increasing (g positive)



(b) Decreasing (g negative)

Figure 14.6 Geometric gradient series

If g represents the change in cash flow from one period to the next (as the fraction of the cash flow of the first period), then j^{th} cash flow A_j is related to first cash flow as:

$$A_j = A_1(1+g)^{j-1} \quad \text{for } j = 1, 2 \ldots n \tag{14.17}$$

The term g can be either positive or negative depending on the increasing or decreasing cash flow series. Each term of the series may be discounted or compounded at interest rate i to obtain the value of P or F respectively. The present worth of the geometric gradient series is determined by summing all discounted terms:

$$P_{gg} = \sum_{j=1}^{n} A_1(1+g)^{j-1}\frac{1}{(1+i)^j} \tag{14.18}$$

Or

$$P_{gg} = \frac{A_1}{(1+g)}\sum_{j=1}^{n}\left(\frac{1+g}{1+i}\right)^j \tag{14.19}$$

This may be solved to give:

$$P_{gg} = \frac{A_1}{(i-g)}\left[1-\left(\frac{1+g}{1+i}\right)^n\right] \quad \text{when } i \neq g \tag{14.20}$$

and

$$P_{gg} = \frac{nA_1}{(i+i)} \quad \text{when } i = g \tag{14.21}$$

Example 14.10

The use of a small domestic biogas plant saves cooking gas equivalent to 8 LPG cylinders every year during its useful life of 15 years. If the current price of LPG cylinder is ₹ 350 and likely to increase by 20% annually, what is the present monetary worth of the life cycle fuel saving of biogas plant? Assume discount rate of 10%.

Solution

Given,

$$A_1 = 350 \times 8 = 2800$$
$$g = 0.2$$
$$i = 0.1$$
$$n = 15$$

Present worth of lifetime fuel saving from Eq. (15.20):

$$P_{gg} = \frac{2800}{(0.1-0.2)}\left[1-\left(\frac{1+0.2}{1+0.1}\right)^{15}\right] = ₹\,75{,}273$$

14.7 EFFECT OF INFLATION ON CASH FLOWS

In general, there is inflationary trend in the cost of goods and services. At times, reverse trend is also noticed. Monitory inflation occurs when the purchasing power of a currency (say rupee) declines or, in other words, there is general increase in the level of prices in an economy. On the contrary, deflation reflects an upward change in the purchase power of the currency.

Inflation may cause the borrowing cost to rise because the lender would demand a higher rate of interest to counter the effect of inflation. Therefore, it is important to take anticipated inflation into account when estimating the expected cash flows of an investment.

The average rate of inflation is usually expressed as an annual percentage rate that represents the annual increase in the sample prices of some stipulated "market basket" of commodities (usually both goods and services) over one year period. The inflation rate has a compounding effect because its value for each year is based on the previous year's price. If C_o is the present (initial) cost of a commodity and $j_1, j_2, \ldots j_n$ is the rate of inflation in year 1, 2, ..., n, then its cost at the end of corresponding years will be:

$$C_1 = C_o (1 + j_1) \tag{14.22}$$

$$C_2 = C_o (1 + j_1)(1 + j_2)$$

$$\vdots$$

$$C_n = C_o (1 + j_1)(1 + j_2) \ldots (1 + j_n) \tag{14.23}$$

If j is the average rate of inflation during year 0 to year n, the cost C_o changes to C_n as:

$$C_n = C_o (1 + j)^n \tag{14.24}$$

Conversely, if C_n is the cost of a commodity in current currency, that has inflated by average annual rate j, to obtain its cost in currency with worth that prevailed at year 0 (real value, or constant value rupee) the current value is deflated, i.e. divided by a deflator:

$$C_o = C_n/(1 + j)^n \tag{14.25}$$

14.8 COMPARATIVE ECONOMIC EVALUATION OF ALTERNATIVES

Capital projects have differences in terms of costs, benefits, and timings, the basis of comparison must take into account these differences and the time value of money. A wide variety of appraisal criteria have been suggested. However, there is no one best appraisal method for all types of conditions. Each method has its own merits and limitations. The methods discussed here merely aid in decision-making process, which may include several non-quantitative and non-economic criteria as well.

14.8.1 Payback Period

Sometimes business firms are concerned with the number of years required to recover the initial outlay of an investment. The payback period is found in two ways: conventionally and by discounting the cash flow.

Simple (Conventional) Payback Period, n_{sp}

Simple payback period is obtained by counting the number of years it takes for cumulative cash receipts (benefits, B_n) to equal the cash expenses (costs, C_n).

$$\sum_{n=0}^{n_{sp}} (B_n - C_n) = 0 \tag{14.26}$$

Example 14.11

A proposed solar PV street light will cost ₹ 10,000 and last for 20 years. The savings of electricity bill is estimated as ₹ 900 per year. What is the simple payback period of the proposal?

Solution

Given,

Initial investment, $C_o = 10{,}000$

Net annual savings = $B = 900$ per year

Now,

Simple payback period, $n_{sp} = \dfrac{10{,}000}{900} = 11.11$ years

This period is much less than the expected useful life of the street light. Hence, the proposal may be accepted.

Example 14.12

The cash flows of three project proposals during their lifetime of 5 years are given in Table 14.1. Calculate the simple payback period for each of them.

Table 14.1 Project cash flows

	Cash Flows (₹)		
Year	**Project A**	**Project B**	**Project C**
0	–2,400	–2,400	–2,400
1	600	800	500
2	600	800	700
3	600	800	900
4	600	800	1,100
5	600	800	1,300

Solution

The cumulative cash flows for the above problem are given Table 14.2.

Table 14.2 Cumulative cash flows for project *A*, *B*, *C*

Year	Cumulative Cash Flows (₹)					
	Project A		**Project B**		**Project C**	
	Current	**Cumulative**	**Current**	**Cumulative**	**Current**	**Cumulative**
0	–2,400	–2,400	–2,400	–2,400	–2,400	–2,400
1	600	–1800	800	–1600	500	–1900
2	600	–1200	800	–800	700	–1200
3	600	–600	800	0	900	–300
4	600	0	800	800	1,100	800
5	600	600	800	1600	1,300	2100

Simple payback periods as seen from Table 14.2,

For project $A = 4$ years

For project $B = 3$ years

For project C the cumulative cash flow becomes zero somewhere during year 4. If it is assumed that the cash flow of ₹ 1100 is uniformly distributed over the 4th year, the exact value of simple payback period can be determined as:

$$\text{Simple payback period for project } C = 3 + \frac{300}{1100} \approx 3.27 \text{ years}$$

Discounted Payback Period, n_{dp}

Simple payback period fails to consider the time value of money. The discounted payback period accounts for the changing value of money over time. Therefore, the discounted payback period, n_{dp} is the smallest n that satisfies:

$$\sum_{n=0}^{n_{dp}} (B_n - C_n)\frac{1}{(1+i)^n} = 0 \tag{14.27}$$

where, i is the interest rate, or the minimum rate of return.

Example 14.13

For the cash flows of three project proposals given in Table 14.1, calculate the discounted payback period for each of them, considering the rate of interest as 12%. Comment on the results.

Solution

The discounted cash flows corresponding to discounted periods are calculated and the results are tabulated in Table 14.3.

Table 14.3 Discounted and cumulative cash flow calculations

Year	Cash Flows (₹)					
	Project A		Project B		Project C	
	Discounted	Cumulative	Discounted	Cumulative	Discounted	Cumulative
0	–2,400	–2,400	–2,400	–2,400	–2,400	–2,400
1	536	–1864	714	–1686	446	–1954
2	478	–1386	638	–1048	558	–1396
3	427	–959	569	–479	641	–755
4	381	–578	509	30	699	–56
5	340	–238	454	484	738	683

Looking at the cumulative cash flow, it can be concluded that:
For Project *A* the investment is not paid back till the useful life of the project (5 years). Therefore, this is a net loss project and should be rejected.

For Project *B*: Discounted payback period,

$$n_{dp} = 3 + \frac{479}{509} = 3.94 \text{ years}$$

For Project *C*: Discounted payback period,

$$n_{dp} = 4 + \frac{56}{739} = 4.08 \text{ years}$$

From discounted payback point of view, Project *B* is better as compared to Project *C* as the investment is paid back earlier.

14.8.2 Net Present Value, NPV

The net present value method requires that all cash flows be discounted to their present value, using the firm's required rate of return *i*. It can be expressed as:

$$NPV = \sum_{j=0}^{n} \frac{B_j - C_j}{(1+i)^j} \tag{14.28}$$

where B_j stands for benefits at the end of period *j* and C_j for cost at the end of period *j* and *n* is the useful life of the project.

In C_o is the initial capital investment in the project and *A* is the uniform annual cash flow of the project, the above relation becomes:

$$NPV = C_o - A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \tag{14.29}$$

Example 14.14

For the cash flows of three project proposals given in Table 14.1, calculate the net present worth for each of them, considering the rate of interest as 12%. Comment on the results.

Solution

The net present value of each project for the lifetime of the investment (5 years) is calculated. This is in fact the net cumulative discounted cash flows. Therefore:

NPV of project $A = -238$

NPV of project $B = 484$

NPV of project $C = 683$

Comments: A has negative NPV therefore, it should be rejected. As seen earlier, Project *B* better than Project *C* from the point of view of discounted payback period. However, net present worth of Project *C* is higher due to higher cash flows in later years.

14.8.3 Internal Rate of Return, IRR

The internal rate of return for an investment expresses the profitability of a capital investment in percentage terms, a measure that is easily understood by experts and laymen alike. It is defined as the rate of return (i.e. interest rate) that makes the NPV of an investment equal to zero. Mathematically, the IRR is the interest rate I* that satisfies the equation:

$$\text{NPV }(i^*) = \sum_{j=0}^{n} \frac{B_j - C_j}{(1+i^*)^j} = 0 \tag{14.30}$$

In other words, IRR is the interest rate i^* that causes the discounted present value of the benefits in a cash flow to be equal to the present value of the costs, i.e.

$$\sum_{j=0}^{n} \frac{B_j}{(1+i^*)^j} = \sum_{j=0}^{n} \frac{C_j}{(1+i^*)^j} \tag{14.31}$$

To find IRR (i.e. i^*), Eq. (14.30) is solved using trial and error (iterative) method. Following procedure may be followed.

1. Make an initial guess for i^*
2. Calculate the value of NPV(i^*) at this value of i^*
3. If the calculated value of NPV(i^*) is positive, it indicates that the actual value of i^* would be more than the trial value. Increment the value i^* by a small step for the next trial. If the value of NPV(i^*) is negative, it indicates that the actual value of i^* would be less than the trial rate. Decrement the value i^* by a small step for the next trial. Go to step 2 for the next trial.
4. Repeat steps 2 and 3 until a situation is reached where a value i_1 gives NPV(i_1) as positive and the next higher value i_2 gives NPV(i_2) as negative.
5. Find the value of IRR by interpolation as follows:

$$\text{IRR} = i_1 + \left(\frac{i_2 - i_1}{NPV(i_1) - NPV(i_2)}\right) NPV(i_1) \tag{14.32}$$

When the IRR of an investment is greater than the "cost of the capital" of the firm, the investment is accepted. The cost of the capital is the minimum acceptable rate of return or required rate of return of the firm as explained in Section 14.2.

Example 14.15

A small windmill for water pumping requires initial costs of ₹ 20,000. It is expected to save ₹ 3000 per year. Calculate the IRR on this investment if the life of windmill is 15 years and salvage value of the windmill after its useful life is negligible.

Solution

$$C_o = 20{,}000$$

$$\text{Annual benefit} = B = 3000$$

$$n = 15$$

$$\text{NPV}\,(i^*) = \sum_{j=0}^{n} \frac{B_j - C_j}{(1+i^*)^j} = \sum_{j=0}^{n} \frac{B_j}{(1+i^*)^j} - C_0 = 0$$

$$= 3{,}000\left[\frac{(1+i^*)^{15} - 1}{i^*\,(1+\,i^*)^{15}}\right] - 20{,}000$$

With 0.15 as the initial guess for i^* the values of NPV (i^*) is calculated and tabulated as follows:

Table 14.4 Steps of calculation

Iteration number	i^*	NPV(i^*)
1	0.15	–2457
2	0.14	–1573
3	0.13	–612
4	0.12	432

Now, from Eq. (14.28):

$$\text{IRR} = 0.12 + \left(\frac{0.13 - 0.12}{432 + 612)}\right) \times 432 = 0.12 + 0.004137$$

Or $\text{IRR} = 12.4137\%$

14.8.4 Benefit to Cost Ratio or Profitability Index

The benefit to cost ratio measures the cost efficiency of a project. Let B and C be the present values of the net cash inflows (benefits) and outflow (costs) defined as:

$$B = \sum_{j=0}^{n} \frac{B_j}{(1+i)^j} \tag{14.33}$$

$$C = \sum_{j=0}^{n} \frac{C_j}{(1+i)^j} \tag{14.34}$$

The ratio B/C is known as B–C ratio.

Example 14.16

For the cash flows of three project proposals given in Table 14.1, calculate the benefit to cost ratios for each of them, considering the rate of interest as 12%.

Solution

The discounted benefits and cost are calculated and tabulated in the following table.

Table 14.5 Discounted benefits and costs

Year	Cash Flows (₹)					
	Project A		Project B		Project C	
	Discounted Benefit	Discounted Cost	Discounted Benefit	Discounted Cost	Discounted Benefit	Discounted Cost
0	0	2,400	0	2,400	0	2,400
1	536	0	714	0	446	0
2	478	0	638	0	558	0
3	427	0	569	0	641	0
4	381	0	509	0	699	0
5	340	0	454	0	738	0
Total	2162	2400	2884	2400	3082	2400

The B-C ratio of Project $A = 2162/2400 = 0.9$

The B-C ratio of Project $B = 2884/2400 = 1.2$

The B-C ratio of Project $C = 3082/2400 = 1.28$

14.8.5 Capital Recovery Cost (or Equivalent Annual Cost)

When a capital asset such as a machine or a computer is purchased, it is expected that its use will generate enough income to recover the original cost of investment. If C_{net} is the net present cost of a machine, then the capital recovery cost may be obtained by annualizing the cost as follows:

$$\text{CR} = C_{\text{net}}\left[\frac{i(1+i)^n}{(1+i)^n-1}\right] \tag{14.35}$$

If C_o is the initial cost of a machine, C_a is annual maintenance cost and S is its salvage value after useful life of n years, then at discount rate of i, the net present cost can be obtained as:

$$C_{\text{net}} = C_o - S\left[\frac{1}{(1+i)^n}\right] + C_a\left[\frac{(1+i)^n-1}{(1+i)^n}\right] \tag{14.36}$$

The situation is illustrated in Fig. 14.7.

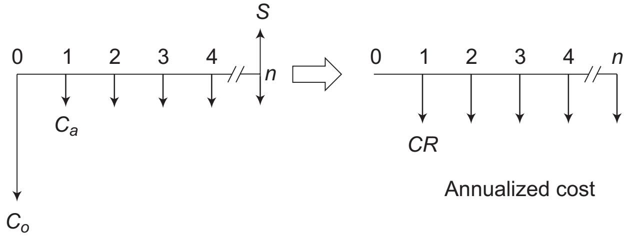


Figure 14.7 Capital recovery cost

Example 14.17

The cost of a 100-litre solar water heater is ₹ 12,000. During its useful life of 20 years its routine annual maintenance will cost ₹ 200. The replacement of insulation in 12th year will cost Rs.3000. If its salvage value is ₹ 1000, determine the capital recovery cost for an interest rate of 11%.

Solution

Given:

$$C_o = 12{,}000$$
$$C_a = 200$$
$$C_{12} = 3000$$
$$S = 1000$$
$$n = 20$$
$$i = 0.11$$

In Eq. (14.36) adding a term for discounted cost of ₹ 3000 over a period of 12 years,

$$C_{\text{net}} = 12000 - 1000 \times \left[\frac{1}{(1+0.11)^{20}}\right] + 200 \times \left[\frac{(1+0.11)^{20}-1}{0.11 \times (1+0.11)^{20}}\right] + 3000 \times \left[\frac{1}{(1+i)^{12}}\right]$$

$$= 12000 - 124 + 1593 + 858 = 14{,}327$$

Now, from Eq. (14.31), the capital recovery cost,

$$\text{CR} = 14327 \times \left[\frac{0.11 \times (1+0.11)^{20}}{(1+0.11)^{20}-1}\right] = ₹\,1{,}799$$

14.8.6 Annual Equivalent Amount (or Equivalent Uniform Annual Worth)

In this method all original cash flows are first converted to net present worth and then converted to a series of equal annual payments by multiplying this amount by capital recovery factor.

If B_j and C_j represent the benefits and costs respectively in j^{th} year, the present worth of cumulative cash flows can be determines as:

$$\sum_{j=0}^{n} \frac{(B_j - C_j)}{(1+i)^j} \tag{14.37}$$

where i represent the prevailing interest rate and n is the useful life of the investment/project. Now, the annual equivalent amount can be found as explained above:

$$\text{AE} = \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \times \sum_{j=0}^{n} \frac{(B_j - C_j)}{(1+i)^j} \tag{14.38}$$

The situation is illustrated in Fig. 14.8.

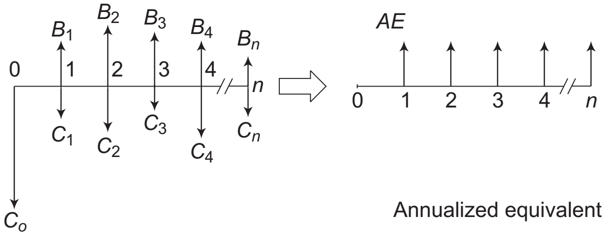


Figure 14.8 Annual equivalent amount

An important advantage of the annual equivalent amount method is in resolving the dilemma faced by a firm which must choose between two investment alternatives of different useful lives. This method does not cancel the difference in the lives of the two projects. It simply removes the difference from the analysis. Following example will elaborate this point.

Example 14.18

For a particular operation, two machines *A* and *B* having same capacity but different economic characteristics are shown in Table 14.6.

Table 14.6 Economic characteristics of two machines

Machine	Initial cost (₹)	Annual cash flow (₹)	Useful life (Years)
A	90,000	26000	5
B	75,000	26000	4

The firm's cost of capital is 10%. Evaluate the profitability of both machines by NPV method and by AE (Annual Equivalent Amount) method and comment on the results.

Solution

The NPV and AE for the two machines are computed using Eqs. (14.37) and (14.38). The results are tabulated in the Table 14.7.

Table 14.7 Computed results

Machine	Initial cost (₹)	Annual cash flow (₹)	Useful life (years)	NPV (₹)	AE (₹)
A	90,000	26000	5	8,560	2,258
B	75,000	26000	4	7,417	2,339

Looking at the table above, we see that Machine A has higher NPV than machine *B*. This higher profitability of machine *A* is obtained by a longer life of 1 year over machine *B*. However, this is misleading. *A* more accurate comparison of the two machines is obtained when annual equivalent (AE) of NPVs of both machines are computed. Looking at the AE, machine *B* is seen to have superior profitability.

14.9 EFFECT OF DEPRECIATION AND TAX ON CASH FLOW

Capital projects usually include such assets as machinery, equipment and buildings which have relatively longer life. Depreciation may be defined as the loss in the value of a physical asset with passage of time and use due to physical deterioration or technological obsolescence. With the possible exception of land, this phenomenon is a normal characteristic of all physical assets. This gradual loss of asset's value is called **depreciation**. In accounting, depreciation is treated as an annual expense, and is charge against earnings before taxes during the useful life of the asset. When an asset has been fully depreciated its initial cost is reported as having been fully recovered. However, this concept ignores the loss of value due to inflation.

Depreciation is treated as a non-cash expense and it provides a tax shield, equal to depreciation times the marginal tax rates, and thus in effect increases the cash flow of an investment.

If E is annual earning (sales-cost), T is rate of tax, D is depreciation then, for the purpose of calculation of tax, depreciation is deducted from earning. Tax is calculated on this earning, known as pretax earnings. After subtracting the tax amount the depreciation amount D is again added to find the net cash flow. Thus:

$$\begin{aligned}\text{Pretax earning} &= E - D\\ \text{Tax} &= T(E - D)\\ \text{Earning after Tax} &= (E - D) - T(E - D)\\ \text{Cash flow} &= (E - D) - T(E - D) + D\\ &= E(1 - T) + DT \qquad (14.39)\end{aligned}$$

The amount DT is known as **tax shield** which is provided in lieu of depreciation. The business firms generally prefer accelerated methods of depreciation as it increases the cash flow.

There are a number of methods for calculating the depreciation. However, the method, a business firm may use, to depreciate its capital assets depends on available options allowed under current tax laws. The simplest method is known as straight line depreciation. The annual amount of depreciation is computed by dividing the initial cost C_o of the asset by the number of years, N of its estimated life:

$$D = C_o / N \tag{14.40}$$

If a salvage value S is expected then the annual amount of depreciation is computed as follows:

$$D = (C_o - S) / N \tag{14.41}$$

The salvage value can be positive, zero or even negative. A negative salvage value is estimated if dismantling or carry away costs are anticipated.

In this method, the annual rate of depreciation remains constant. Other methods for calculating the depreciation are beyond the scope of the present book and the interested readers are advised to refer any standard book of economics for detailed treatment on this topic.

A term frequently used in the context of depreciation is **book value**. The book value of an asset is equal to the remaining investment after the total amount of depreciation has been charged to date. In other words, book value represents the current worth of an asset as shown by the book of accounts. The book value of the asset decrease every year by the amount of depreciation till it reaches the salvage value at the end of lifetime of depreciating asset.

Example 14.19

A commercial solar dryer cost a capital amount of ₹ 1,20,000 to purchase and install and has negligible salvage value after useful life of 5 years. Use straight-line depreciation and 40% tax on earnings. The discount rate is 9%. The year wise earnings are given in Table 14.8.

Table 14.8 Input data

In Rupees					
Year	**1**	**2**	**3**	**4**	**5**
Earnings, E	33,000	35,000	37,000	39,000	41,000

Calculate the net present value (NPV) of the solar dryer.

Solution

Given:

$C_o = 1,20,000$

Useful life $N = 5$

Tax rate $T = 40\%$

Discount rate $i = 0.09$

Depreciation can be calculated as $D = 1,20,000/5 = 24,000$

The steps of computation and intermediate values are tabulated in the Table 14.9.

Table 14.9 Steps of computation and intermediate values

In Rupees					
Year	**1**	**2**	**3**	**4**	**5**
Earnings, *E*	33,000	35,000	37,000	39,000	41,000
Depreciation, *D*	24,000	24,000	24,000	24,000	24,000
Pretax earnings (*E* – *D*)	9,000	11,000	13,000	15,000	17,000
Tax, D (40%)	3,600	4,400	5,200	6,000	6,800
Earnings after Tax (*E* – *D*) – *T* (*E* – *D*)	5,400	6,600	7,800	9,000	10,200
Cash Flow (Earnings after Tax + *D*)	29,400	30,600	31,800	33,000	34,200
Discounted cash flow, using Eq. (14.3)	26,927	25,755	24,555	23,378	22,228
Net discounted income	1,22,843				
Initial cost	1,20,000				
Net present value (NPV) =	2,843				

Example 14.20

A solar still costs ₹ 3, 00,000 and has expected useful life of 15 years. Its salvage value is estimated as 20,000. Compute the depreciation and year wise book value using straight-line depreciation.

Solution

Given:

$$C_o = 3,00{,}000$$
$$S = 20{,}000$$
$$N = 15$$

From Eq. (14.41),

$$D = (3,00{,}000 - 20{,}000)/15 = ₹\,18{,}667$$

In year zero, book value (BV_o) is same as C_o and then it decreases annually by an amount of D as follows:

Initial book value $BV_o = 3,00{,}000$
Book value at the end of 1^{st} year, BV_1 = ₹ 2, 81,333
Book value at the end of 2^{nd} year, BV_2 = ₹ 2, 62,666
Book value at the end of 3^{rd} year, BV_3 = ₹ 2, 44,000
.
.
.
Book value at the end of N^{th} year, BV_N = ₹ 20,000

Thus at the end of depreciating lifetime of the solar still, the book value equals the salvage value.

REVIEW QUESTIONS

1. Differentiate between nominal and effective interest rates. Explain continuous compounding.
2. What do you understand by discounting? Explain with example.
3. With the help of cash flow diagram, explain the significance of annuity.
4. What is inflation? How is the effect of inflation on annual cash flows, taken care of?
5. What is depreciation? What effect does it have on cash flows?
6. What do you understand by tax shield?

PROBLEMS

1. What will be the amount of ₹ 5000 invested at 6% interest compounded annually at the end of 12 years?

   (*Ans.* ₹ 10,061)

2. How long will it take for ₹ 15,000 invested at 8% interest compounded annually to double in value?

   (*Ans.* 9 years)

3. A person inherits ₹ 50,000 and invests it in a bank account that generates to pay 9% interest (nominal) for 4 years. Calculate the future value of this investment, if interest is compounded (a) annually; (b) quarterly; (c) daily; (d) continuously.

   (*Ans.* ₹ 70,579, ₹ 71381, ₹ 71,663, ₹ 71,666)

4. What is the present value of a single payment of ₹ 20,000 due 10 years from now, if the interest rate is 10% compounded annually?

   (*Ans.* ₹ 7,711)

5. The estimated salvage value of a solar PV collector at the end of its useful life of 25 years is ₹ 80,000. Determine its present worth for a discount rate of 10%.

   (*Ans.* ₹ 7,384)

6. A person invests ₹ 2,000 a year into an "individual retirement account" for 10 years. Calculate the accumulated value of investment if the nominal interest rate is 10% compounded quarterly.

   (*Ans.* ₹ 32,463)

7. The replacement cost of the gas holder of a 2 m^3 biogas plant at the end of 6 years is likely to be ₹ 4,500. What amount should a user deposit every year to accumulate the desired amount if he earns 8 percent interest on his deposit?

   (*Ans.* ₹ 613)

8. A solar PV power based pump installed for fishing pond gives maintenance free service during its life span of 20 years and expected to save ₹ 2400 worth of fuel each year. Determine the present worth of the life cycle fuel saving assuming discount rate of 12% per year.

   (*Ans.* ₹ 17,927)

9. What will be annual equal payments of a 20 year, ₹1,00,000 house mortgage, if the interest rate is 10%.

(*Ans.* ₹11,746)

10. To establish a producer gas plant, a piece of land is made available on lease at ₹60,000 per year with an annual increase of ₹2000 for 12 years. Payments are to be made available at the end of each year. What is the present worth of the lease payment plan if prevailing interest rate is 11%?

(*Ans.* ₹4,45,219)

11. A 100 liter per day domestic solar water heater is expected to save 600 units of electricity per year of its useful life of 18 years. If the current price of electricity is ₹4 per unit and is likely to increase by 20 per cent every year, what is the present monetary worth of life cycle fuel saving of the solar water heater? Assume a discount rate of 12%.

(*Ans.* ₹73,873)

12. The cash flows (₹in lakh) of two project proposals are given in the following table. Calculate the simple payback period for each of them.

Year	Project A	Project B
0	–1,000	–1,000
1	500	100
2	400	300
3	100	400
4	50	600
5	10	800

(*Ans.* 3 years, 3.33 years)

14. For the data given in problem 12, calculate the discounted payback periods if the minimum rate of return is given as 10%. Comment on the result.

(*Ans.* For project *A* the investment is not paid back till the life of the project, it is a net loss project, reject the proposal. For project *B*, the discounted payback period is 3.97)

15. For the cash flows of the two project proposals given in problem 12, calculate the net present worth for each of them, considering the rate of interest as 10%. Comment on the results.

(*Ans.* NPV of Project A is (–₹99 lakh), which is negative,
reject it, NPV of project *B* is ₹509 lakh)

16. A producer gas plant will cost ₹40,000 to purchase and install. The expected saving is ₹15000 worth of diesel annually. Its annual maintenance cost is estimated as ₹1200. Calculate the NPV of the investment if the useful life of the producer gas plant is 15 years and the interest rate is 11%.

(*Ans.* Rs.59,234)

17. A biomass briquetting plant requires an initial investment of ₹35,00,000. The average yearly income from the plant is estimated as ₹6,00,000 during its lifetime of 10 years. Find IRR of the project. Comment on the economic feasibility of the proposal if the specified cost of capital is 12%.

(*Ans.* 11.23% which is less than the cost of capital, economically not feasible)

18. For the cash flows of two project proposals given in problem 12, calculate the benefit to cost ratios for each of them, considering the rate of interest as 12%.

(*Ans.* 0.874, 1.407)

19. A floating drum type 2 m^3 biogas plant cost ₹ 8000. During its lifetime of 12 years, it requires routine annual maintenance of ₹ 300 and replacement of gas holder after 8 years cost ₹ 2500. What is the capital recovery cost on this expenditure if the opportunity cost of capital is 15%? The plant has no salvage value.

(*Ans.* ₹ 1927)

20. A heat exchanger costs ₹ 4,00,000 to purchase and install. During its useful life of 10 years it results in fuel saving ₹ 1,20,000 per year. The life of the heat exchanger may be extended by 4 years (i.e. total life 14 years) if a major over haul is carried out at the end of 7th year at the cost of ₹ 2,00,000. Compute the AE (annual equivalent amount) for the two cases (i) the heat exchanger is used up to 10 years only, without going for overhaul and (ii) it is used for 14 years with overhaul. Give your recommendations regarding the economic feasibility of overhaul on the basis of computations. Assume 10% interest rate and zero salvage value of the heat exchanger.

(*Ans.* Use it for 10 years only without going for overhaul)

21. A solar heating system is proposed for an office to carry 60% of annual heating load by solar energy. The solar equipment is purchased for ₹ 6,00,000 with a 20% down payment and the balance borrowed on loan at 10% interest for 10 years. The discount rate is 8%. Calculate the savings accrued by the use of solar heating system for the 10 year period with the following information.

(i) A conventional non-solar heating system would have a fuel cost of ₹ 1,20,000 for the first year.
(ii) Fuel cost is expected to increase at 10% a year.
(iii) Additional maintenance, insurance, and parasitic energy cost due to installation of the solar system are estimated to be ₹ 5,000 for the first year, subject to an inflation rate of 3%.
(iv) Additional property taxes are expected to be ₹ 8,000 for the first year subject to an inflation rate of 4%.
(v) 40% of the interest on mortgage and the extra property tax are deductible from income taxes.
(vi) Taken the inflation of economy and the durability of the installation into account, it is estimated that the resale value of the solar system at the end of 10 years will be ₹ 80,000.

(*Ans.* ₹ 60,131)

22. A 2 m^3 biogas plant costs ₹ 12,000 to install and another ₹ 1000 per year (on average) to repair and maintain. It saves 300 liters of kerosene per year to owner, as the biogas substitutes kerosene presently used for domestic cooking. Calculate the benefit to cost ratio (B/C) for the investment if the salvage value at the end of 25 years of useful lifetime is negligibly small and the discount rate is 10%. The present market price of kerosene is ₹ 10 per liter subject to annual inflation of 8%.

(*Ans.* 2.62)

23. Determine the present value of net benefits of investing ₹ 2,000 on box type solar cooker if the annual repair and maintenance cost ₹ 200 and the cooker is able to cook 400 meals in a year. The cooker has no salvage value after a useful life time of 10 years. Assume that the monetary worth of fuel saved per solar cooked meal is ₹ 1.50 and that the discount rate is 10%. What if a 5% annual escalation in fuel prices is expected?

(*Ans.* ₹ 458, ₹ 1,235)

24. An investment is made in a biomass energy system by borrowing ₹ 1,70,000 at an interest rate such that the annual payments are ₹ 27,000 for 10 years (principal plus interest). The biomass energy system has a useful life of 15 years and it saves ₹ 22,000 in the first year. Find the net present value and the discounted payback period if the annual discount rate is 10% and the conventional fuel prices are escalating at 5% per annum.

(*Ans.* ₹ 51,021, 10.5037 years)

25. Two alternative investment opportunities are given below:

	Alternative A	**Alternative B**
Capital cost	₹ 1,50,000	₹ 2,25,000
Annual receipts	₹ 60,000	₹ 70,000
Annual expenses	₹ 12,000	₹ 17,000
Estimated salvage value	₹ 30,000	₹ 45,000
Useful life	8 Years	10 years
Discount rate	15%	15%

On the basis of profitability, which alternative should be preferred?

(*Ans.* Alternative A)

OBJECTIVE TYPE QUESTIONS

1. As per "end of period convention", all cash flows are assumed to occur:
(a) at the start of interest period. (b) in the middle of interest period.
(c) at the end of interest period. (d) none of the above

2. An amount grows fastest with:
(a) yearly compounding (b) monthly compounding
(c) daily compounding (d) continuous compounding

3. Converting the future value to its present value is called:
(a) compounding (b) discounting
(c) annuity (d) deflation

4. In uniform gradient series:
(a) first payment starts from year 1 and grading starts from year 2
(b) first payment starts from year 2 and grading starts from year 1
(c) first payment starts from year 0 and grading starts from year 1
(d) first payment starts from year 1 and grading starts from year 1

5. Inflation of the cost of fuel each year by a constant percentage rate can be modeled by a:
(a) uniform series (b) uniform gradient series
(c) geometric gradient series (d) single payment at the end of nth year

6. For comparing the profitability of two projects having different useful lives, best method of analysis is:
(a) Net present value (b) Internal rate of return
(c) Benefit to cost ratio (d) Annual equivalent amount

7. Out of following characteristics, which one provides the index of profitability:
(a) Net present value (b) Capital recovery amount
(c) Benefit to cost ratio (d) Annual equivalent amount

8. Out of following characteristics, which one provides the worth in absolute terms:
(a) Net present value (b) Capital recovery amount
(c) Benefit to cost ratio (d) Annual equivalent amount

9. Depreciation of an asset is the:
(a) decrease in the value due to inflation
(b) decrease in the value due to physical deterioration with time
(c) decrease in value due to less demand
(d) decreased maintenance requirement

10. Tax shield:
(a) makes the tax amount as zero
(b) makes the cash flow as zero
(c) decreases the cash flow and increase tax amount
(d) decreases the tax amount and increase cash flow

11. At the end of life time of a project:
(a) book value becomes equal to initial cost
(b) book value becomes half of initial cost
(c) book value becomes equal to salvage value
(d) book value becomes zero

APPENDIX A

Conversions

Energy Units

From	To				
	BTU	**Calorie**	**MJ**	**kWh**	**KGOE**
BTU	1	251.9958	1.055056×10^{-3}	293.071×10^{-6}	25.1996×10^{-6}
Calorie	3.9683×10^{-3}	1	4.1868×10^{-6}	1.163×10^{-6}	10^{-7}
MJ	947.817	238.846×10^{3}	1	0.2778	23.884×10^{-3}
kWh	3412.14	859.845×10^{3}	3.5997	1	85.9845×10^{-3}
KGOE	39.6831×10^{3}	10^{7}	41.869	11.63	1

1 Btu is the heat needed to raise the temperature of 1 pound of water by 1°F.

1 gallon (U.S.) = 3.785 liters

1 barrel (bbl) = 42 gallons (U.S.) = 158.98 liters

Important Physical Constants

Mechanical equivalent of heat, J = 4.184 J/calorie

Planck constant $h = 6.626076 \times 10^{-34}$ J s

Boltzmann constant $k = 1.380658 \times 10^{-23}$ J/K, (or 8.629112×10^{-5} eV/K)

Gas constant $R = 287$ J/kg K for air

Specific heats for air, $c_p = 1$ kJ/kg K, $c_v = 0.71128$ kJ/kg K

Atomic mass unit = 1.660540×10^{-27} kg

Velocity of light $c = 2.997925 \times 10^{8}$ m/s

Electron charge $e = 1.602177 \times 10^{-19}$ C

Gravitation (std.) $g = 9.80665$ m/s^2

Units of Pressure and their Inter Relations

1 Pa = 1 N/m^2

1 Bar = 10^5 Pa = 1 kg/cm^2 = 0.1 MPa = 14.50777 psi

1 atm. pressure = 760 mm of Hg = 14.7 psi = 1.01325 Bar

Number Conversions

1 Lakh = 0.1 million = 10^5

1 crore = 10 million = 10^7

1 quad = 1 quadrillion = 10^{15}

Prefixes

10^{-24}	yocto	y
10^{-21}	zepto	z
10^{-18}	attto	a
10^{-15}	femto	f
10^{-12}	pico	p
10^{-9}	nano	n
10^{-6}	micro	μ
10^{-3}	milli	m
10^{-2}	centi	c
10^{-1}	deci	d
10^{0}	none	-
10^{+1}	deka	da
10^{+2}	hecto	h
10^{+3}	kilo	k
10^{+6}	mega	M
10^{+9}	giga	G
10^{+12}	tera	T
10^{+15}	peta	P
10^{+18}	exa	E
10^{+21}	zetta	T
10^{+24}	yotta	Y

APPENDIX B

Some public/private sector undertakings/institutes for promotion of Renewable-conventional energy sources in India:

1. National Institute of Solar Energy (NISE),
   19, milestone, Industrial Area,
   Gurgaon – Faridabad Road,
   Village: Gwalpahari, Faridabad,
   (Haryana) 122 005
2. Sardar Swaran Singh National Institute of Renewable Energy (SSS-NIRE)
   Adhikui Village (12 Km from Jallandhar)
   Jallandhar-Kapurthala Road, (Punjab)
3. National Institute of Wing Energy (NIWE),
   Velachari, Tambaram Main Road, District Pallikaranai,
   Chennai-600 100, (T. N.)
4. Tata Energy Research Institute (TERI)
   Darbari Seth Block
   IHC Complex
   Lodhi Road
   New Delhi - 110 003, India
5. Combustion Gasification & Propulsion Laboratory(CGPL),
   Deptt. of Aerospace Engg, Indian Institute of Science(IISc),
   Bangalore 560 012
   (Karnataka)

APPENDIX C

Solar Radiation Data

Table C1 Monthly average, daily and hourly global radiation in kWh/m^2 and sunshine hours on horizontal surface at New Delhi (Latitude: 28^o 35′ N, Longitude: 77^o 12′E)[43].

Month	Hour														Total kWh/ m^2-day	Sun-shine hours
	6	7	8	9	10	11	12	13	14	15	16	17	18	19		
Jan	0.000	0.004	0.096	0.271	0.433	0.556	0.618	0.615	0.552	0.430	0.268	0.099	0.005	0.000	3.987	7.6
Feb	0.000	0.020	0.163	0.364	0.540	0.670	0.727	0.728	0.659	0.534	0.358	0.165	0.021	0.000	5.001	9.0
Mar	0.001	0.066	0.260	0.475	0.655	0.781	0.845	0.844	0.769	0.635	0.458	0.249	0.064	0.001	6.138	8.2
Apr	0.010	0.130	0.339	0.554	0.727	0.848	0.910	0.903	0.833	0.699	0.523	0.318	0.122	0.010	6.935	8.6
May	0.030	0.177	0.383	0.581	0.746	0.865	0.925	0.920	0.844	0.719	0.547	0.352	0.158	0.027	7.287	8.0
Jun	0.036	0.164	0.399	0.510	0.657	0.757	0.809	0.813	0.750	0.639	0.483	0.318	0.159	0.036	6.544	5.9
July	0.026	0.130	0.275	0.425	0.549	0.640	0.672	0.671	0.606	0.518	0.412	0.273	0.141	0.032	5.34	5.8
Aug	0.012	0.101	0.243	0.392	0.512	0.607	0.640	0.659	0.595	0.510	0.392	0.255	0.107	0.013	5.053	5.6
Sep	0.003	0.079	0.248	0.431	0.587	0.698	0.757	0.747	0.689	0.571	0.417	0.244	0.074	0.003	5.602	7.0
Oct	0.000	0.036	0.202	0.406	0.581	0.701	0.764	0.758	0.692	0.569	0.391	0.191	0.033	0.000	5.355	8.8
Nov	0.000	0.009	0.128	0.319	0.495	0.620	0.685	0.680	0.613	0.490	0.315	0.125	0.010	0.000	4.523	9.2
Dec	0.000	0.003	0.085	0.259	0.425	0.543	0.605	0.605	0.538	0.418	0.255	0.086	0.003	0.000	3.843	8.0

N.B. Time indicated is LAT.

Value given for a particular hour is the radiation incident during one hour preceding the time.

Multiply by 3600 to obtain an hourly value in kJ/m^2-h.

Table C2 Monthly average, daily and hourly diffuse radiation in kWh/m^2 on horizontal surface at New Delhi (Latitude: 28° 35´N, Longitude: 77° 12´E)[43]

Month	Hour														Total kWh/ m^2-day
	6	7	8	9	10	11	12	13	14	15	16	17	18	19	
Jan	0.000	0.003	0.051	0.103	0.140	0.160	0.174	0.172	0.162	0.137	0.100	0.051	0.003	0.000	1.240
Feb	0.000	0.013	0.076	0.126	0.159	0.183	0.191	0.190	0.180	0.160	0.125	0.075	0.013	0.000	1.474
Mar	0.001	0.043	0.113	0.159	0.189	0.210	0.220	0.226	0.215	0.197	0.163	0.113	0.041	0.001	1.861
Apr	0.009	0.083	0.153	0.202	0.236	0.262	0.274	0.279	0.274	0.250	0.212	0.156	0.079	0.008	2.473
May	0.027	0.114	0.190	0.244	0.279	0.303	0.315	0.318	0.308	0.286	0.247	0.189	0.107	0.022	2.922
Jun	0.033	0.124	0.215	0.286	0.342	0.382	0.399	0.399	0.377	0.340	0.279	0.203	0.114	0.028	3.540
July	0.023	0.096	0.178	0.257	0.3156	0.358	0.372	0.365	0.333	0.291	0.241	0.174	0.101	0.023	3.135
Aug	0.009	0.074	0.153	0.224	0.277	0.317	0.334	0.331	0.302	0.265	0.210	0.149	0.075	0.010	2.727
Sep	0.002	0.053	0.123	0.178	0.222	0.256	0.269	0.263	0.248	0.217	0.167	0.118	0.048	0.002	2.152
Oct	0.000	0.026	0.087	0.128	0.154	0.169	0.179	0.177	0.169	0.154	0.126	0.083	0.021	0.001	1.465
Nov	0.000	0.007	0.057	0.099	0.122	0.137	0.145	0.146	0.142	0.124	0.099	0.055	0.006	0.000	1.141
Dec	0.000	0.002	0.054	0.092	0.123	0.144	0.155	0.156	0.147	0.125	0.092	0.043	0.002	0.000	1.117

Table C3 Monthly average, daily irradiation (global) on tilted surface in kWh/m^2 at New Delhi (Latitude: 28° 35′ N, Longitude: 77° 12′ E)[18]

Month	Array tilted at (latitude – 15°)		Array tilted at latitude		Array tilted at (latitude + 15°)		2-axis tracking
	Fixed array	1-axis tracking	Fixed array	1-axis tracking	Fixed array	1-axis tracking	
Jan	5.04	6.38	5.83	7.38	6.28	7.87	7.92
Feb	6.37	8.09	7.04	8.97	7.31	9.23	9.24
Mar	7.05	8.60	7.31	9.02	7.18	8.83	9.05
Apr	7.12	9.23	6.94	9.17	6.42	8.50	9.30
May	7.38	9.83	6.87	9.36	6.08	8.25	9.86
Jun	6.76	9.15	6.19	8.53	5.38	7.32	9.23
Jul	4.50	6.31	4.20	5.94	3.75	5.17	6.34
Aug	5.53	7.44	5.30	7.27	4.83	6.60	7.46
Sep	5.66	7.23	5.70	7.44	5.46	7.13	7.45
Oct	6.09	7.34	6.57	7.99	6.69	8.09	8.13
Nov	5.62	7.49	6.43	8.56	6.88	9.05	9.08
Dec	4.87	6.06	5.73	7.11	6.26	7.68	7.77
Annual Average	6.00	7.76	6.18	8.06	6.04	7.81	8.40

APPENDIX D

Key to Objective Questions

Chapter 1

1. (c), 2. (d), 3. (a), 4. (a), 5. (d), 6. (c), 7. (b), 8. (d), 9. (c), 10. (b), 11. (c), 12. (a), 13. (d), 14. (a), 15. (c), 16. (d), 17. (b), 18. (a), 19. (a), 20. (c), 21. (a), 22. (a), 23. (d), 24. (d), 25. (b), 26. (a), 27. (b), 28. (b), 29. (d), 30. (c), 31. (a), 32. (b), 33. (d), 34. (c), 35. (b), 36. (c), 37. (a), 38. (b), 39. (c)

Chapter 2

1. (d), 2. (c), 3. (b), 4. (d), 5. (b), 6. (d), 7. (b), 8. (d), 9. (a), 10. (c), 11. (b), 12. (b)

Chapter 3

1. (b), 2. (a), 3. (c), 4. (d), 5. (a), 6. (d), 7. (b), 8. (c), 9. (c), 10. (a), 11. (a), 12. (c), 13. (c), 14. (a), 15. (d), 16. (b), 17. (d), 18. (c), 19. (a), 20. (d), 21. (c), 22. (a), 23. (a), 24. (b), 25. (b), 26. (d), 27. (a), 28. (d)

Chapter 4

1. (b), 2. (d), 3. (a), 4. (a), 5. (d), 6. (b), 7. (b), 8. (c), 9. (a), 10. (d), 11. (a), 12. (a), 13. (c), 14. (d), 15. (a), 16. (b)

Chapter 5

1. (d), 2. (b), 3. (d), 4. (a), 5. (c), 6. (b), 7. (c), 8. (a), 9. (d), 10. (b), 11. (a), 12. (c), 13. (b), 14. (d), 15. (c), 16. (d), 17. (a), 18. (c), 19. (b), 20. (a), 21. (d), 22. (c)

Chapter 6

1. (b), 2. (b), 3. (d), 4. (d), 5. (a), 6. (c), 7. (a), 8. (d), 9. (c), 10. (b), 11. (d), 12. (b), 13. (b), 14. (c), 15. (d), 16. (b), 17. (a), 18. (b), 19. (c), 20. (a), 21. (d), 22. (a), 23. (a), 24. (d), 25. (d)

Chapter 7

1. (b), 2. (b), 3. (c), 4. (a), 5. (d), 6. (a), 7. (a), 8. (d), 9. (b), 10. (d), 11. (c), 12. (b), 13. (b), 14. (a), 15. (a), 16. (a), 17. (d), 18. (c), 19. (a), 20. (a), 21. (c), 22. (b), 23. (b), 24. (b), 25. (a), 26. (c), 27. (b), 28. (d), 29. (c)

Chapter 8

1. (b), 2. (d), 3. (a), 4. (a), 5. (d), 6. (a), 7. (b), 8. (b), 9. (c), 10. (d), 11. (c), 12. (a), 13. (b), 14. (d), 15. (b)

Chapter 9

1. (c), 2. (a), 3. (b), 4. (a), 5. (d), 6. (b), 7. (d), 8. (c), 9. (a), 10. (c), 11. (d), 12. (b), 13. (d), 14. (a), 15. (d), 16. (c), 17. (a), 18. (c), 19. (b)

Chapter 10

1. (d), 2. (b), 3. (a), 4. (b), 5. (d), 6. (a), 7. (b), 8. (d), 9. (c), 10. (b), 11. (d), 12. (b), 13. (d), 14. (a), 15. (b), 16. (c), 17. (b), 18. (a)

Chapter 11

1. (d), 2. (b), 3. (d), 4. (c), 5. (b), 6. (a), 7. (d), 8. (c), 9. (a), 10. (d), 11. (b), 12. (a), 13. (d), 14. (c), 15. (b), 16. (c), 17. (b), 18. (c), 19. (d), 20. (a)

Chapter 12

1. (c), 2. (a), 3. (b) 4. (c), 5. (b), 6. (d), 7. (b), 8. (d), 9. (b), 10. (c), 11. (a), 12. (d), 13. (a), 14. (c)

Chapter 13

1. (b), 2. (a), 3. (d), 4. (c), 5. (d), 6. (c), 7. (b), 8. (a), 9. (c), 10. (d)

Chapter 14

1. (c), 2. (d), 3. (b), 4. (a), 5. (c), 6. (d), 7. (c), 8. (a), 9. (b), 10. (d), 11. (c)

APPENDIX E

References

1. http://data.worldbank.org (accessed on Aug. 29, 2015)
2. www.iea.org/, "2014 Key world energy statistics, International Energy Agency", (accessed on Sep. 2015)
3. www.mospi.gov.in, "Energy Statistics 2015": Ministry of Statistics and Programme Implementation, Government of India, (accessed on Aug. 31, 2015)
4. http://cdiac.ornl.gov/pns/current_ghg.html, (updated February 2014) "Recent Greenhouse Gas Concentrations", Carbon Dioxide Information Analysis Centre (CDIAC), Tennessee, USA (accessed on Sep. 1, 2015)
5. http://www.giss.nasa.gov/research/briefs/ma_01/ "Science Briefs, Greenhouse Gases: Refining the role of Carbon Dioxide", National Aeronautical and Space Administration, Goddard Institute of Space Studies. (accessed on Sep. 1, 2015)
6. http://www.climate.org/topics/sea-level/, Climate Institute, Washington DC. (accessed on Sep. 1, 2015)
7. http://climate.nasa.gov/evidence/, "Global Climate Change, Vital Signs of the Planet", (updated on 28 Aug 2015), (accessed on Sep. 1, 2015)
8. http://www.livescience.com/37057-global-warming-effects.html, (accessed on Sep. 1, 2015)
9. https://www.worldenergy.org, "World Energy Resources 2013 survey": World Energy Council (accessed on Aug. 29, 2015)
10. http://www.seia.org/ , "Solar Energy Industries Association", (accessed on Aug. 29, 2015)
11. http://www.iea-pvps.org/ "Statistic Reports: International Energy Agency –Solar Photovoltaic Power systems Programme", (accessed on 7 Sep. 2015)
12. http://www.ieawind.org/, "IEA Wind 2014 Annual Reports", (accessed on Sep. 7, 2015)
13. www.ceanic.in, Central Electricity Authority of India, "All India installed capacity of power stations, 2015", (accessed on Sep. 7 2015)
14. http://mnre.gov.in/ "Ministry of new and renewable energy sources, Government of India - Physical progress, as on 31-07-2015", (accessed on Sep. 9, 2015)
15. http://www.bp.com/, "BP statistical review of world energy, June 2014, 63rd Ed", (accessed on Sep. 11, 2015)
16. http://www.ibef.org/industry/power-sector, "India brand equity foundation", (accessed on Sep. 11, 2015)

17. http://beeindia.in/content.php?page=energy_managers_auditors/ema.php?id=4,Guide Books – Bureau of Energy Efficiency, (accessed in Sep. 2015)
18. www.nei.org/, "Nuclear Energy Institute",(accessed on Sep. 19, 2015)
19. Kreith, Frank. And Goswami, D. Yogi, *Handbook of Energy Efficiency and Renewable Energy*, CRC Press, 2007
20. *TERI Energy and Environment data diary & year book* (TEDDY) 2014/15
21. Planning Commission, Government of India XIIth 5 Year Plan (2012–2017), Vol. 1, 2013
22. powermwein.nic.in/energy-efficiency, Ministry of Power, Government of India, (accessed on Sep. 22, 2015)
23. Gopinath. K. K., "A general formula for computing the coefficients of the correlation connecting global solar radiation to sunshine duration" *Solar Energy*, **41**:499 (1988)
24. Gopinath, K. K. and Soler, A., "Diffuse radiation models and monthly average, daily diffuse data for wide latitude range", *Energy*, **20**:657 (1995)
25. Garg, H. P. and Garg, S. N., "Correlation of monthly average, daily global, diffuse and beam radiation with bright sunshine hours", *Energy Conversion and Management*, **25**:409 (1985)
26. Gueymard, C., "Mean daily averages of beam radiation received by tilted surfaces as affected by atmosphere", *Solar Energy*, **37**:261 (1986)
27. Satyamurty, V. V., and Lahiri, P. K., "Estimation of symmetric and asymmetric hourly global and diffuse radiation from daily values", *Solar Energy*, **48**:7 (1992)
28. Malhotra, A., Garg, H. P., and Palit, A., "Heat loss calculation of flat plate solar collectors", *Solar Energy*, **32**:141 (1981)
29. Solanki, C. S., *Solar Photovoltaics: Fundamentals, technologies and application*, 3rd edition, PHI Learning, Private limited, 2015
30. Messenger, R., Ventre Jerry, *Photovoltaic system engineering*, CRC Press, 2000
31. Bhattacharya, T., *Terrestrial solar photovoltaics*, Narosa Publishing House, 1998
32. Green, M. A., *Solar cells: operating principles, technology and system applications*, Prentice Hall Inc., Englewood Cliffs, N.J., USA, 1982
33. "Photovoltaic report" prepared by Fraunhofer Institute solar energy system, ISE, Nov. 2015
34. Yuhang Liu, Jingbo Zhao, Zhengke Li, Cheng Mu, Wei ma, Huawei Hu, Kui Jiang, Haoran Lin, Harald Ade and He Yan, "Aggregation and morphology control enables multiple case of high-efficiency polymer solar cells", *Nature communications* **5**, Article No. 5293, 26 May 2015, doi: 10.1038/ncomms6293
35. Chuang, Chia-Hao M.; Brown, Patrick R.; Bulovik, Vladimir; Bawendi, Moungi G., "Improved performance and stability in quantum dot solar cells through band alignment engineering", *Nature materials* **13**, 25 May 2014, pp. 796-801, doi: 10.1038/nmat3984
36. William Shockley and Hans J. Queisser, "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells", *Journal of Applied Physics*, **32**, March 1961, pp.510-519; doi:10.1063/1.1736034
37. *Barnham, K. W. J.; Duggan, G., "A new approach to high-efficiency multi-band-gap solar cells". Journal of Applied Physics, 1990,* **67** *(7): 3490,* Bibcode*:* 1990JAP ... 67.3490B, doi*:*10.1063/1.345339
38. Schaller, R.; Klimov, V. (2004). "High Efficiency Carrier Multiplication in PbSe Nanocrystals: Implications for Solar Energy Conversion",*Physical Review Letters* **92** (18): 186601. arXiv:cond-mat/0404368, Bibcode:2004PhRvL..92r6601S, doi: 10.1103/PhysRevLett.92.186601, PMID 15169518
39. Batteryuniversity.com/, "BU:403 Charging lead acis", last updated 23 October 2015

40. Patel, M. R. , *Wind and solar power systems: design, analysis and operation*, CRC Press, 2nd edition, 2005
41. Kishore, V. V. N., *Renewable energy engineering and technology*, TERI, The energy and resources institute, 2010
42. Rashid, M. H.', *Power electronics: circuits, devices and applications*, Pearson Learning, 3rd Ed, 2003
43. Mohan, N., Undeland, T. M. and Robbin, W. P., *Power Electronics: converters, applications and design*, Wiley, 3rd Ed., 2003
44. Freris, L. L., *Wind energy conversion systems*, Prentice Hall, 1989
45. "Global Wind report, 2014", Global wind Energy Council, available at http://www.gwec.net/ accessed on 10 December 2015.
46. Archer, C. L. and Jacobson, M. Z., "Evaluation of global wind power", *J. Geophysics Res*., **110**, 2005
47. www.greenworldinvestor.com
48. *Annual Report 2014-15*, MNRE, mnre.gon.in/
49. Twidell, John & Weir, Anthony, *Renewable energy resources*, Taylor & Francis, 2nd Ed., 2006
50. "Biodiesel – the next generation sustainable fuel", available at ww.jatrophabiodiesel.org/
51. Dasappa., S "Thermochemical conversion of biomass", *Proc. of the course on 'renewable energy sources and energy audit*', 7-11 Jan. 2002, at CEA, Power system training Institute, Bangalore
52. Bertani., Ruggero,"Geothermal Power Generation in the world 2010-2014 Updated Report", *Proceedings, World Geothermal Congress 2015, Melbourne, Australia, 19-25, April 2015*
53. Kumar A. Garg, Kriplani S., Sehrawal P., "Utilization of geothermal energy resources for power generation in India – a review", *7th International Conference & Exposition on Petroleum Geophysics, Hyderabad 2008*, P 290
54. indianpowersector.com/, "Geothermal energy"
55. tidalenergytoday.com/, "Estimate of global potential tidal resources", accessed on Jan. 16, 2016
56. Paish, Oliver., "Small Hydropower: Technology and Current Status", Renewable and sustainable energy reviews, *Science Direct*, Vol. 6, Dec. 2002, pp. 537–556
57. Wladyslaw Bobrowicz, "Small hydroelectric power", application notes, European Copper Institute, Leonardo energy, ECI publication number Cu0150, Feb 2012, Available at www.leonardo-energy.org/node/1047
58. Harvey, Adam. *Micro-hydro design manual*, Intermediate technology publications, Southampton Row, London, 1993
59. www.smallhydroworld.org, "The *World Small Hydro* Development Report 2013 (WSHPDR 2013)"
60. Richard E. Sonntag, Claus Borgnakke and Gordon J. Van Wylen, *Fundamentals of thermodynamics*, John Wiley & Sons, 6th Ed. 2004
61. R. D. Begamudre, *Energy Conversion Systems*, New Age International Publishers,Delhi, 2000
62. R. A. Hinrichs and M. Kleinbach, "Energy: its use and environment", Thomson Learning inc., 3rd Ed., 2002
63. *Proc. National Hydrogen Energy Roadmap Workshop, Washington D.C., April 2-3, 2002*.
64. G. Zorpette, "Super charged", *IEEE Spectrum,* January, 2005, pp.26 – 31.

65. *Proceedings of National Hydrogen Energy Roadmap Workshop*, Washington DC, April 2-3, 2002.
66. Chumbo Zhang, Khalil Najafi, Luis P. Bernal, Peter D. Washabaugh, "Micro combustion – thermionic power generation: feasibility, design and initial results", *Proc. The 12th International Conference on Solid State Sensors, Actuators and Micro systems", Boston, June 8-12, 2003*.
67. Charles F. Kutscher, "The status and future of geothermal electric power", American Solar Energy Society (ASES) Conference.
68. Luan Weiling and T. U. Shantung, "Recent developments of thermoelectric power generation", *Chinese Science Bulletin*, **49**, No. 12, 2004, pp.1212–1219.
69. K. Ono and R. O. Suzuki, "Thermoelectric power generation: converting low-grade heat into electricity", *Energy Resources Overview*, Dec. 1998.
70. Samuel B. Schaevitz, Aleksander J. Franz, Klavs F. Jensen and Martin A. Schmidt, "A combustion based MEMS thermoelectric power generation", *The 11th International Conference on Solid State Sensors and Actuators", Munich, Germany, June 10-14, 2001*.
71. S. P. Sukhatme, *Solar Energy* (3rd Edition) ,Tata McGraw Hill, Delhi, 2008
72. Wladyslaw Bobrowicz, "Small Hydropower – Investors Guide", European Copper Institute and Koncern Energetyczny SA, Autumn 2006, Leonardo Energy, available at www.leonardo-energy.org,
73. T.C. Kandpal and H. P. Garg, *Financial Evaluation of Renewable Energy Technologies*, Macmillan India Ltd., Delhi, 2003
74. Peter Cassmatis, *A Concise Introduction to Engineering Economics*, Unwin Hymen, Inc., 1988

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