CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Energy Efficiency Enhancement of Residential Buildings in Pakistan by using Phase Change Materials in Building Envelope

by

Madeeha Khan

A thesis submitted in partial fulfillment for the degree of Master of Science

in the

Faculty of Engineering
Department of Mechanical Engineering

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Dedication:

To my parents

Raja Khizar Rehman (Late)

Mrs. Zahida Perveen

And

"It is with my deepest gratitude and warmest affection that I dedicate this thesis to my Supervisor "Dr. M. Mahabat Khan" who have been constant source of knowledge and inspiration for me in this whole period."

CERTIFICATE OF APPROVAL

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Abstract

Due to population rise and industrial development, an unprecedented increase has been observed in energy demand at global as well as at the national level. Energy consumption in residential building is highest among all, as per an estimation, the residential sector is responsible for 22% of overall energy consumption in the world. However, the residential sector of Pakistan consumes 45% of total energy. Keeping in view the high energy demand of residential sector, the study aims to improve the thermal energy performance of residential buildings using Phase Change Materials (PCM). For this purpose, an advanced building simulation software *EnergyPlus* is used to evaluate the energy consumption for a typical residential building under different scenarios. The effects of PCM in the reduction of heating and the cooling energy consumption are investigated in five different cities of Pakistan, i.e. Islamabad, Karachi, Lahore, Quetta and Peshawar.First of all, for the selection of appropriate PCM, 15 different PCMs are integrated into a single room house to assess the best performing PCM for all selected cities. The results show that CrodaTherm24 having a melting temperature of 24 °C is an optimal PCM that can be used in given 5 cities for saving heating and cooling energy consumption. A maximum saving of 14% using a 10 mm layer of optimal PCM for the base case house is achieved in Islamabad and Quetta city. A parametric study is also conducted to examine the outcomes of PCM thickness variation, location of its placement in walls and roof. It is concluded that building energy consumption can be reduced if 40 mm thick PCM is placed on inner sides of walls and roof of building envelops in Pakistan. These selected parameters for optimal PCM are used to model a multizone single and two storey residential house with PCM. The monthly and annual energy consumption in these multizone houses are analyzed with and without PCM installation in five selected cities. The energy saving of 45% have been achieved in Islamabad in single storey traditional residential house, 35% in Karachi, 33% in Lahore, 35% in Peshawar and 50% in Quetta whereas in two storey house energy saving of 12%, 14%, 13%, 13% and 14% have been achieved in Islambad, Karachi, Lahore, Peshawar and Quetta respectively with the use of PCM.

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Abbreviations

ACH	Air Change Rate
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BCP	Building Code of Pakistan
CondFD	Conduction Finite Difference
CTF	Conduction Transfer Function
CV	Control Volume
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
IWEC	International Weather for Energy Calculations
MTOE	Million Tons of Oil Equivalent
PCM	Phase Change Material
RCC	Reinforced Cement Concrete
TARP	Thermal Analysis Research Program
TMY	Typical meteorological year
U.S	United States
3D	3 dimensional

Chapter 1

Introduction

Global energy demand is increasing due to population rise and industrial developments which raised serious concerns over energy supply difficulties. It is estimated by United Nations that world population will reach up to 9.7 billion by the end of 2050 if the growth rate will remain same at 1.07% as reported in 2020 with a population of 7.8 billion [1]. Likewise, world-wide energy demand is projected to rise by 19% by the end of 2040 [2]. With the rapid increase in global population, the change in lifestyle of people, increase in the use of devices and appliances by individuals for transportation and comfort level, increase in global warming are also contributing factors in the global rise of energy demand [2]. The need for energy in the building sector is also rising due to urbanization, change of climatic conditions by global warming and use of new building standards.

The International Energy Agency (IEA) stated that the building sector consumed 35% of global energy in 2020 as shown in Figure 1.1 [3]. The share of the residential building is highest i.e. 22% of global energy is consumed by residential buildings. The demand for energy in the buildings sector is also predicted to increase by 24% globally in 2050 [4]. Most of the energy consumed in buildings is for air conditioning and space heating [4]. Pakistan is the fifth largest populated country of the world consist of approximately 220 million people with an annual growth rate of 2% [1]. In 2018, the total energy consumed by Pakistan was 73 MTOE (Million Tons of Oil Equivalent) and projected to reach 147 MTOE in 2030 [5].

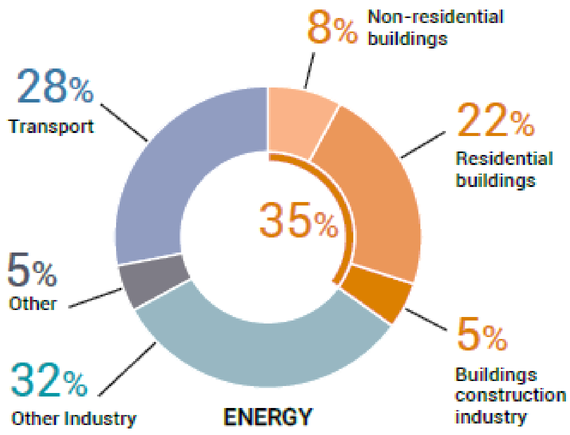


FIGURE 1.1: Global share of buildings and construction final energy [3]

Following the global trend, the residential sector of Pakistan also has the highest percentage share in electricity consumption according to Pakistan Economic Survey 2019-20 as shown in Figure 1.2 [6]. The residential buildings had staggering 45% of the share of overall energy consumption in year 2020. This translates to approximately 33 MTOE which means mere a 3% reduction energy consumption in residential building would result in 1 MTOE worth savings. Residential houses in Pakistan are generally made of reinforced concrete and bricks without considering any socio-cultural factors and local climates causing higher energy consumption. Moreover, personalized active systems for heating and air conditioning such radiant gas heaters and split air conditioners are used which are increasing the energy usage as well as the cost.

The thermal performance of building envelope plays a vital role in achieving building energy efficiency. Building codes have been made by many developed countries for energy conservation in buildings. Pakistan also defined building code in 2013 [7] but the implementation of these codes is not seen in typical residential houses which are still using old construction materials. There are different methods to design energy efficient buildings to conform to these codes such as low-carbon buildings, net-zero energy building and passive buildings. All these methods require the use of thermal insulation in building envelopes.The traditional thermal insulation material used by many countries have some constraints.

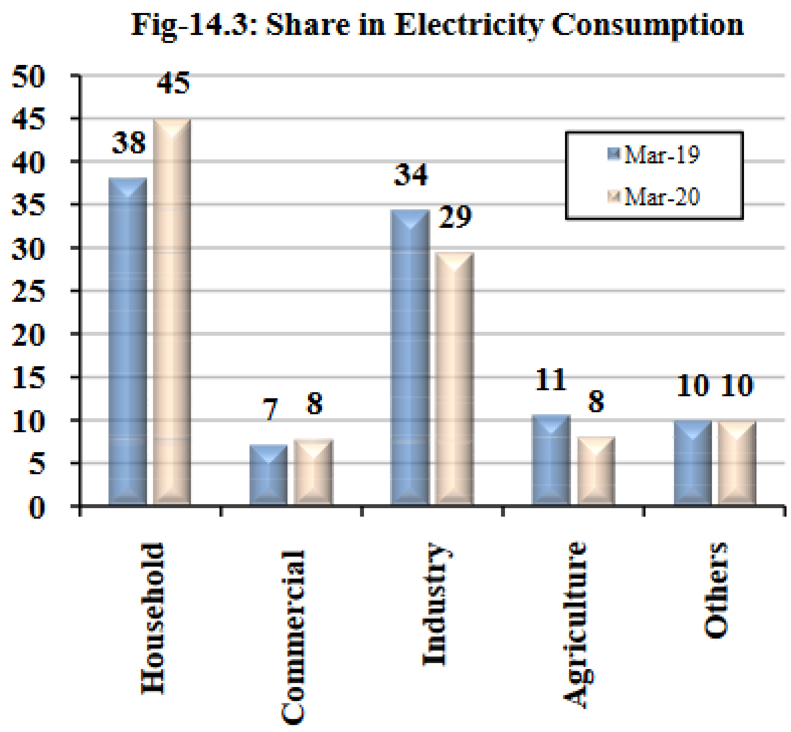


FIGURE 1.2: The percentage share of different sectors in Electricity Consumption of Pakistan [6]

Firstly, it is recommended to increase the thickness of thermal insulation for better results which are not feasible in some scenarios such as space constraints in lightweight buildings [8]. Therefore, it becomes difficult to maintain space heating and cooling demands and indoor thermal comfort in lightweight buildings. Secondly, toxic fumes are generated from organic thermal insulation materials which are easy to burn and inorganic thermal insulation material have high cost and density making them not suitable for building energy conservation applications [9].

The phase change material (PCM) are latent energy storage materials and can be used in building envelopes to improve the energy performance of buildings. These materials have different melting temperature ranges with different thermal properties and have the capability to store and release a large amount of energy per unit mass at nearly constant temperature during their phase change [10]. When PCM is in the solid phase, it can absorb latent heat from a system and change its phase to liquid state without effecting inside temperature whereas it releases heat when outside temperature drops and changes back to solid state. If PCM is installed in building envelope, it can absorb most of building internal and external heat load during the day time when its melts from the solid phase and store latent heat energy and release it later at night when it changes to solid-phase again and vice versa [11]. PCMs must be selected according to room temperature requirements for its better utilization. In this way, PCM can maintain the indoor room temperature and can reduce the energy consumption of buildings. In the summer season, PCM will keep the walls and room at lower temperature during phase change and the additional heat released by PCM can be dissipated using fans and natural ventilation of the building, while in winter, the released heat will reduce the heating load requirements.

Many experimental and numerical studies have been conducted on the use of PCM in building applications for different countries. The results of these studies show that energy consumption are reduced and indoor thermal comfort is improved when PCM is installed effectively inside the building [12]. There are many other parameters which are important to consider for the effective utilization of PCM in buildings include; type of PCM, surrounding climate, weight and location of installation of PCM. PCMs can be installed in different active and passive ways of building energy applications. There are limited number of studies found regarding use of PCMs in building envelopes of Pakistan. Therefore, more detailed studies should be conducted by considering different design parameters and varying weather conditions in different cities of Pakistan.

1.1 Scope of Research Study

The purpose of this research study is to reduce the energy consumption of residential buildings built in Pakistan using phase change material. PCM can be installed in different active and passive ways but this study focus on passive ways only such as use of PCM in building envelope such as wall and roof. A computational method such as numerical modeling will be used to evaluate the effect of phase change materials on residential buildings of Pakistan and different parameters affecting the performance of phase change materials will be studied. Advanced building simulation software EnergyPlus will be used for simulation purpose.

1.2 Research Objective

The objectives of this research study are the following:

1. Investigate the potential of PCMs in the reduction of heating/cooling energy consumption of residential buildings of Pakistan.
2. Identify the optimal PCM that can be used in building envelope of different cities of Pakistan.
3. Evaluate the effect of different parameters of PCM such as thickness, installation position on building energy saving.

1.3 Thesis Overview

The thesis is structured as follow. Chapter 2 covers the extensive literature review regarding different types of PCMs and their utilization in buildings for energy consumption reduction and enhance energy savings. Chapter 3 is about problem formulation in which a base case model whose energy requirement will be calculated is considered. The details of a building envelope, surrounding climate, internal and external heat additions in the building are explained. The numerical methodology and solution algorithms of EnergyPlus are also elaborated in this chapter. Chapter 4 explains the results of simulations which are run without and with PCM. It also explains the effect of different varying parameters of PCM on building energy consumption. Finally, the research work is concluded in Chapter 5.

Chapter 2

Literature Review

2.1 Phase Change Materials

Phase Change Material (PCM) can absorb or release the latent energy when the material's temperature overpasses or undergoes phase change [13]. A typical cycle of phase change of PCM is presented in Figure 2.1. PCMs usually have high latent energy with nearly constant melting temperature. Therefore, these materials can store large amount of energy while maintaining the temperature and they can shift peak loads in buildings [14].

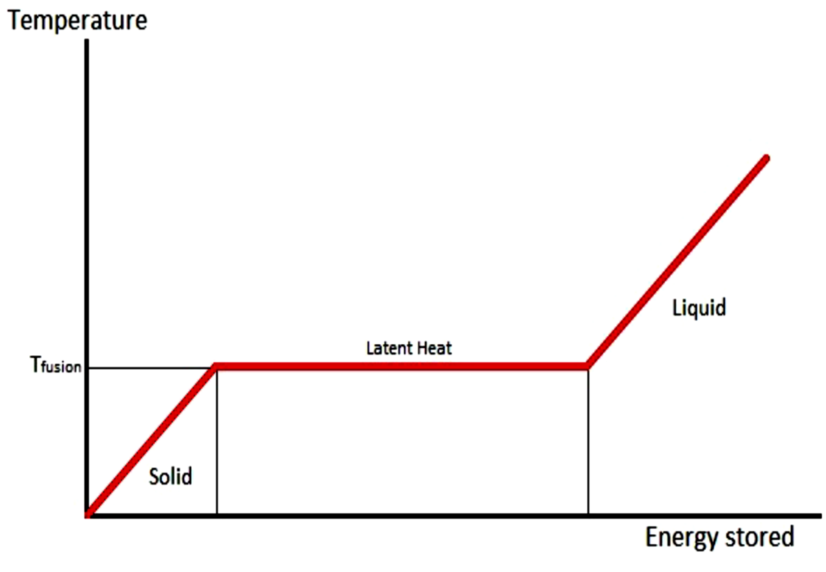


FIGURE 2.1: Solid-Liquid Phase Change Diagram [13]

Moreover, thermal conductivity of PCMs in generally very low with high heat capacities which play important role in building envelopes [14]. Phase change materials can be used for finishing materials, roofs, floors, inside walls, and for thermal insulation as well. These properties of PCMs make them ideal candidates for improving thermal efficiency of buildings [15]. The commercially available phase change materials for buildings have different melting temperature ranges and are generally non-toxic and non-corrosive [16].

2.2 Types of Phase Change Materials

Chemically, available PCMs comprise of unique ranges of melting temperatures and are classified as organic compounds, inorganic compounds, and eutectic mixtures as shown in Figure 2.2 [10].

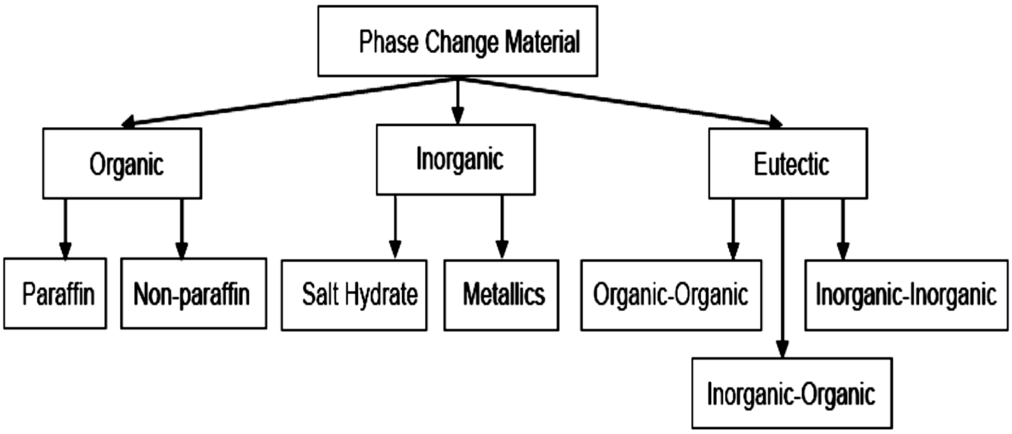


FIGURE 2.2: Classification of Phase Change Material [10]

Organic PCM includes paraffin, non-paraffin, glycols, alcohols, fatty acids etc. Majority of the organic phase change materials are non-toxicant, non-reactive, and resist corrosion. These PCMs have relatively low operating temperature ranges. On the other hand, inorganic phase change materials are metals and hydrates [17] and can store large amount of energy as compared to organic phase change materials [18]. Inorganic PCMs are comparatively cheaper than organic PCMs but they are prone to corrosion and chemical reactions. The mixture of phase change materials are called eutectics, they are made for achieving desired higher melting and latent heat points. Eutectics combinations are organic-organic, inorganic-inorganic, and organic-inorganic [19].

2.3 Phase Change Materials in Building Applications

The utilization of PCMs in building applications can increase thermal resistance and lead to energy conservation. Organic PCMs are mostly used in buildings due to their low operating temperatures, chemical stability and non-toxicity which make them ideal candidate for the utilization in the buildings. Whereas, the high operating temperatures and the tendency to corrosiveness and chemical reactivity make inorganic PCMs unsuitable for the use in buildings. The outdoor and indoor climate is separated by a building envelope which protects the building from cold, heat, rain, wind, fire, noise, glare, and visibility. Therefore, the building envelope decides the quality of performance of HVAC systems as HVAC loading tends to decrease in the presence of a well-insulated and air-tight building envelopes [20]. There are various methods for attaining thermal protection and comfort from the building envelope. Many guidelines and standards are developed for envelope design. A research conducted by Dimoudi et al. showed that up to 34.1% to 36.8% cooling loads reduction can be achieved by modifying building envelope with the use of insulation, light paint on walls and roof or shading [21]. Arif et al. also conducted research that manifested 29% cooling loads reduction by optimizing building envelope orientation [22].

PCMs used for the building envelopes are generally passively operated by encapsulation techniques [12]. There are two ways through which PCM encapsulation can be achieved. The first method is the micro-encapsulation which uses small rod or spherical-shaped particles that are encapsulated in a thin, polymeric film of great molecular weight. Macro-encapsulation is the second way, consisting of PCM inclusion in some kind of packages like tubes, panels, spheres, pouches, or different receptacles [23]. PCMs are incorporated in building applications with both of these encapsulation methods. The incorporation of PCM can be done in concretes, roof, insulation, gypsum, underfloor, plaster, and wallboards of buildings [17]. It is also possible to utilize PCM in boards of gypsum plaster, concrete made from micro-encapsulated paraffin or plaster. The European and American studies show that when PCM-intensified cellulose and foam insulation are applied in walls with wood frames, it decreased the cooling loads of peak-hour up to 30% - 40% and also reduced heating loads up to 16% in the winter season [24],[25].

Furthermore, Tardieu et al. [26] conducted a study in New Zealand where he experimentally analyzed the application of PCM-augmented gypsum boards structures with wooden frames. On the other hand, Cabeza et al. [27] investigated the PCM-intensified concretes in the fields in Lleida, Spain. It was reported by both of the researchers that PCM-enhanced materials resulted in daily temperature fluctuations decrease by up to 4 °C in the indoor space. Different wood-framed floors, attic systems, and walls consisting of a PCM bio-based package assembled in plastic foil bottles under the Arizonian field conditions were tested by Muruganantham et al. [28]. It was reported that upto 12% to 30% savings in cooling energy and upto 9% - 29% savings in heating energy could be achieved [28]. Hawes et al. reported a 30% rise in thermal energy storage where PCM incorporated concrete walls were built. Approximately 12% energy savings was achieved by incorporating 5% PCM into compressing concrete mix using micro-encapsulation was also reported by Hunger et al. [29].

Athientis et al. [30] revealed that that when 25% butyl stearate PCM containing gypsum board was used in Montreal, the room temperature faced a 4 °C decrease. Similarly a 10 °C decrease in peak temperature of Dayton days was observed by Kissock et al. [31] where 30% paraffinic PCM K18 was imbibed in the wallboards. In northeast China, the room temperature was 1.02 °C decreased as reported by Shilei et al. [32] by integrating a combination of lauric and capric acid in the wallboards. It was shown by Chen et al. [33] that it is possible to increase the energy savings by 17% if enthalpy and temperature of phase transition are maintained at 60 kJ/kg and 23 °C respectively during colder months in northern

China. Several authors also observed how PCM walls perform in test rooms when they are exposed to outdoor weather conditions. In France, 20 °C reduction in a test cell's indoor temperature was observed by Ahmad et al. [34], when PCM and a vacuum insulation sheet was installed in compound wallboard. Neeper [35] conducted a theoretical investigation and reported the maximum storage of diurnal energy is possible when the PCM melting temperature reach near the average comfortable room temperature.

Li et al. [36] conducted an experimental study in which he analyzed the incorporation of PCM into the glazed roof of the building envelope. It was found that around 47.5% saving is possible and the period of payback can be limited up to 3.3 years with appropriate selection of the PCM's melting temperature.The researchers also observed reductions in fluctuations in the room temperature when PCMs are installed as Tardieu et al. [26] suggested that in Auckland, it is possible to decrease the daily fluctuation of indoor temperature by 4 °C on hot summer days through PCM wallboards. The study of Figueiredo et al. [37] manifested that when PCM is integrated into a room's walls, it can decrease overheating up to 7.23%. Subsequently, it was maintained that this overheating reduction could be increased further to approximately 34% by implementing the optimization process in PCM utilization. Stritch et al. [38] conducted a study through which it was maintained that PCM can prove to be a valuable passive technique for achieving the goal of such buildings that comprise net-zero energy. This is done by decreasing building energy usage on a day-to-day basis. PCM is also capable of absorbing additional heat throughout the day and then discharge the stockpiled heat at night.

To expand experimental conclusions beyond an experiments limitation (e.g. unrealistic design, specific location, and small scale), numerical simulation softwares are used. Only few modelling tools are capable of simulating hysteresis effects of PCMs in building envelopes. All of the inorganic PCMs and the majority of the non-paraffin organic PCMs show considerable hysteresis effect, along with supercooling. If these factors are neglected, then accuracy issues can arise when materials with hysteresis are modelled [39], [40]. According to some studies, hysteresis constitutes to be vital energy performance aspect for such building envelopes that have PCM incorporation in them. Kuznik and Virgone [41] established that separate curves of enthalpy for PCM freezing and melting should be incorporated into numerical simulations for improving their accuracy. It was demonstrated by Goia et al. [42] that when PCM simulation is done through simplified methods without taking hysteresis into account, it can lead to considerable under- or over prediction of temperatures, leading to under-or over prediction regarding energy consumption. Furthermore, Baghban et al. [43] discovered that separate freezing and melting properties should be used for achieving a good arrangement between simulations and experimental results.

However, the effect of phase change was analyzed numerically through heat capacity and enthalpy techniques using different softwares. TRNSYS, software for building simulation was used by Kuznik et al. [44] for simulating PCM walls where the process of phase change was conducted through the effective method of heat capacity. The experiment data were in general agreement with the calculated surface temperature of the internal wall [44]. The PCM behavior was modelled by Heim et al. [45] in a building of three-zone utilizing ESP-r (building simulation software). While using heat capacity method, the phase transition effect was included in the equation of energy. EnergyPlus, another building simulation software, was used by Pederson et al. [46] for simulating Minneapolis buildings with the PCM walls. In EnergyPlus, the PCM effect was modelled via the enthalpy method. It was demonstrated that PCM's incorporation decreases the greatest cooling load up to 1000W at a specific simulation environment. Taberes-Valesco et al. [47], concluded that a buildings thermal performance with PCM can be accurately predicted by EnergyPlus as hysteresis of PCM can be encountered in EnergyPlus.

Different numerical studies are conducted by many researchers to evaluate the effect of PCMs on building energy using EnergyPlus. A numerical analysis was conducted by Ji et al. [9] to evaluate the energy saving by PCM when incorporated in ideal room in Guangzhou city of China. PCM incorporation reduce building energy consumption by 20.9%. Sovetova et al. [48] also performed EnergyPlus based simulation to investigate the effect of PCMs on residential building energy consumption located in eight different cities. Thirteen different PCMs are selected in this study whereas optimal PCM show a reduction of 17% to 34% in building energy consumption. Alam et al. [15] used 5 different PCMs in residential buildings of 6 different cities of Australia to investigate the effect of PCM on heating and cooling consumption reduction. It was found that 17% to 23% annual energy saving can be achieved in five selected cities with the implementation of PCM. A multi-function optimization method is also used by Markarian and Fazelpour for finding the optimal PCM's melting temperatures that can reduce cooling and heating loads of 5 Iranian cities i.e. Tehran, Bandar Abas, Yazd, Shiraz, and Tabriz. Results showed that a PCM having 25 °C melting temperature can outperform regarding the cooling load and PCM with 21 °C melting temperature is favorable for heating performance [49].

Researchers have also discovered that PCMs efficiency relies on PCM types, PCM amount, local climate, and the location in buildings. A study conducted by Wang et al. [39] discover the ideal melting temperatures of PCM using EnergyPlus-based simulation which was carried out in Shanghai. The simulations result showed that the ideal melting temperature was different for different rooms. However, a range of ideal melting temperature can be considered 20-26 °C as it happens to be a comfortable range of temperature for human bodies. Moreover, the PCM's ideal melting temperature is seasonal. The incorporation of such PCM wallboards that have seasonal optimal melting temperatures can save energy in the summer season and may comprise a higher saving rate of energy during winters [43]. Ahangari et al. [50], after conducting his study, declared that the ideal PCM melting temperature as an interior building constituent is near the average set-point of room temperature. It was also observed that PCM embedding in a buildings walls reduces the demand for cooling energy up to 12.3% in winters and decreases the demand for heating energy up to 17.5% in dry weather.

Kendrick et al. [8] investigate the effect of use of PCM wallboard in light weight buildings located in Shangai city using EnergyPlus. Different room in building are analyzed separately having different indoor conditions. It was found that PCM wallboard will improve indoor thermal comfort by reducing temperature fluctuations. The performance of PCM was found improved in winter season and optimal melting range of PCM for different room was observed as 22 °C to 26 °C similar to human comfort temperatures. The ideal PCM layer's location in a building wall near Nanjing was also investigated by Jin et al. [51]. It is discovered that the ideal location was found to be near the exterior surface of wall.

It is concluded from above literature review that phase change materials can save energy when when used in residential buildings. The PCMs can be incorporated into the building envelope, involving walls, floor, and roof . The interior thermal comfort can be fundamentally improved and cooling and heating loads can be reduced. The PCM effect over energy saving can be influenced by many factors and few studies have been done regarding the PCM parameters influence and their mechanism of energy saving.The optimum PCM parameters in a particular climate must be determined to achieve maximum energy savings. The building energy simulation software EnergyPlus can be used in numerical modelling of residential buildings.

Chapter 3

Problem Formulation

A numerical study is conducted to investigate the effect of the use of phase change material in a building envelope. The charging and discharging process of PCM is a dynamic process therefore dynamic energy models are used to assess the behavior of PCM in the building during different scenarios. A single room made of typical construction materials is considered as a base case house. The energy consumption requirements of this single room which is considered as thermal zone are calculated using the heat balance method. It involves conductive heat transfer through walls, windows and door, convective and radiation heat transfer through windows and infiltration. Similarly, heat is added to this zone through internal heat sources such as occupants, lights and equipment through convection and radiation as shown in Figure 3.1. An ideal HVAC system is used to maintain indoor temperatures by using thermostats. Later, PCM is added in the building envelope to evaluate their effect on building energy consumption of this zone.

Sketchup software combined with the Openstudio is used for 3D modelling and building energy simulation software EnergyPlus version 9.0 is used for dynamic energy modelling and heat transfer calculations. EnergyPlus is a validated simulation engine and well recognized to simulate the overall energy of a designed building.It is developed by the U.S. Department of energy for whole building simulation. This software models heating, cooling, ventilation and lighting processes of a building. It also can simulate multiple zone airflow, natural ventilation and modular systems using time steps of less than one hour. Moreover, internal loads such as occupants, equipment and lighting can be incorporated in building to find electricity and energy consumption. The models can be made more realistic by adding scheduling profiles for occupants, lighting, HVAC and other electrical equipment used in different zones. These scheduling profiles made building models more realistic and reduced overall energy consumption.

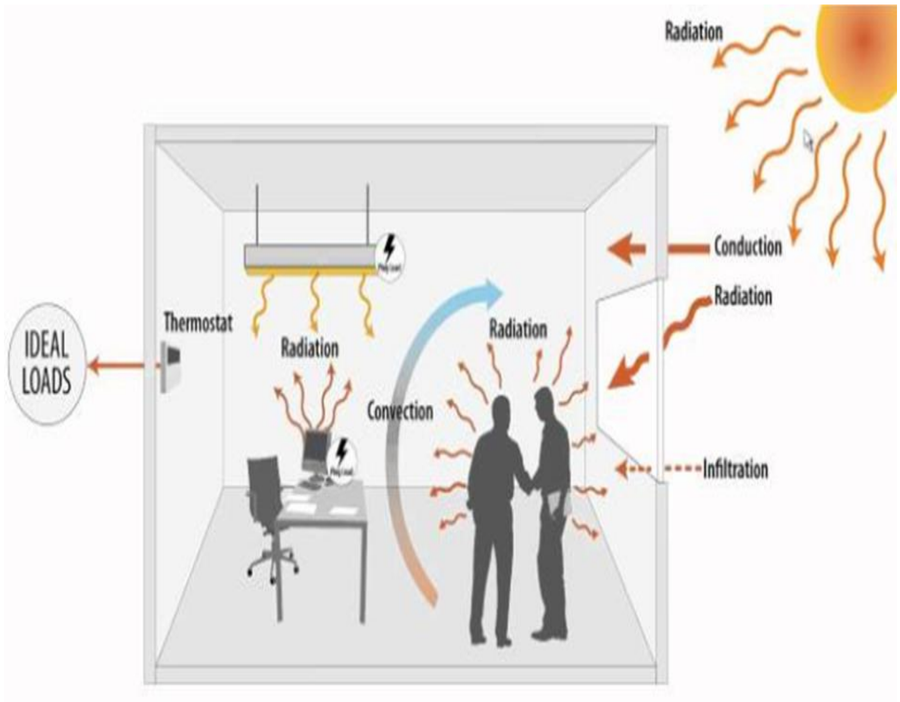


FIGURE 3.1: Thermal Zone [52]

Furthermore, EnergyPlus can measure the impact of phase change materials on the energy use of buildings. PCM follows different melting and freezing curves during its charging and discharging process, therefore PCM hysteresis must be considered to understand the behaviour of PCM precisely. This software provides this added benefit as the specification and properties of PCM material can be defined using Phase Change Hystersis object given in version 9 of EnergyPlus.
After defining PCM properties, it will be used in different parts of the building envelope such as walls, floor and roof with other constructions to perform building energy simulations repeatedly. Different phase change materials are installed in building to evaluate their impact on building energy consumption and to select

optimum PCM. The detailed methodology followed in this section is given in Figure 3.2.

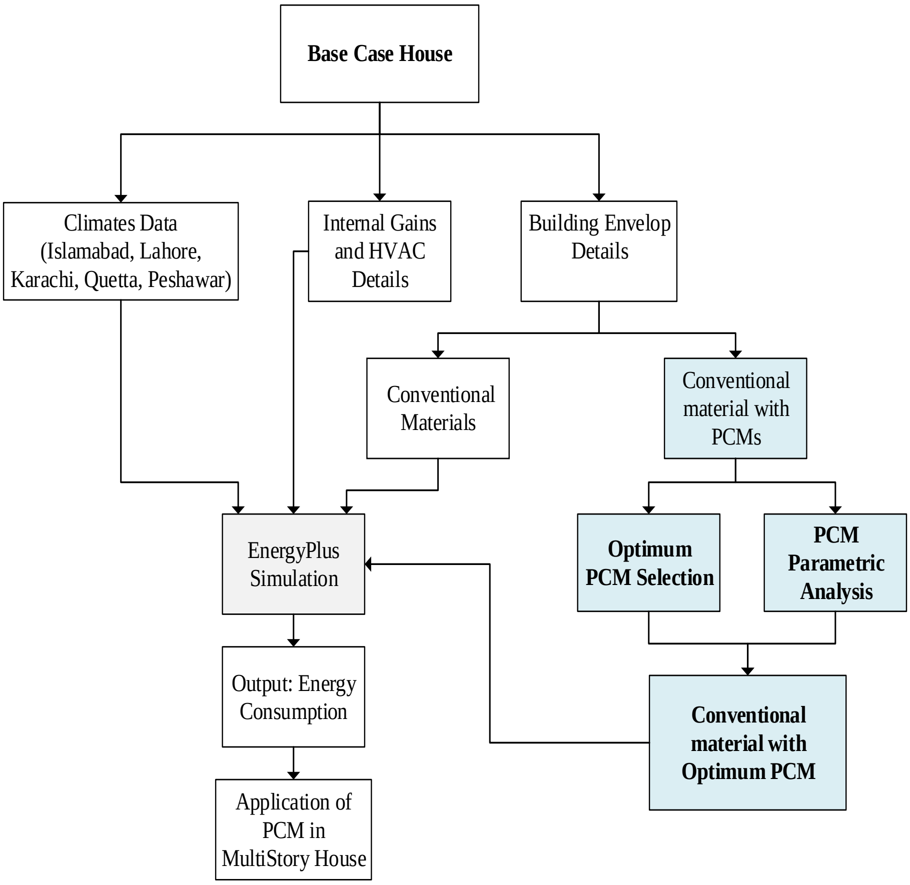


FIGURE 3.2: Methodology

3.1 Three-Dimensional Model of a Single-Room Base Case

A Google SketchUp software integrated with Openstudio is used for 3D modelling of the buildings used in this study. The integration of Sketchip with Openstudio is required to export the 3D model files into EnergyPlus Building Energy Simulation software. A single room house is modelled with dimensions $4m \times 4m \times 3m$ as shown in Figure 3.3. The door is on the south wall and two windows are made on the north and west wall. The floor area is $16m^2$. The size of both windows is

$2.5m \times 1m$, and a distance of 1m from floor whereas the dimensions of door used are $0.8m \times 2m$. All external walls and roof are exposed to the outdoor environment whereas the floor is in contact with the ground and not exposed to the outdoor environment. This single room modeled in Sketchup is considered as a base case house and imported into the EnergyPlus simulation engine.

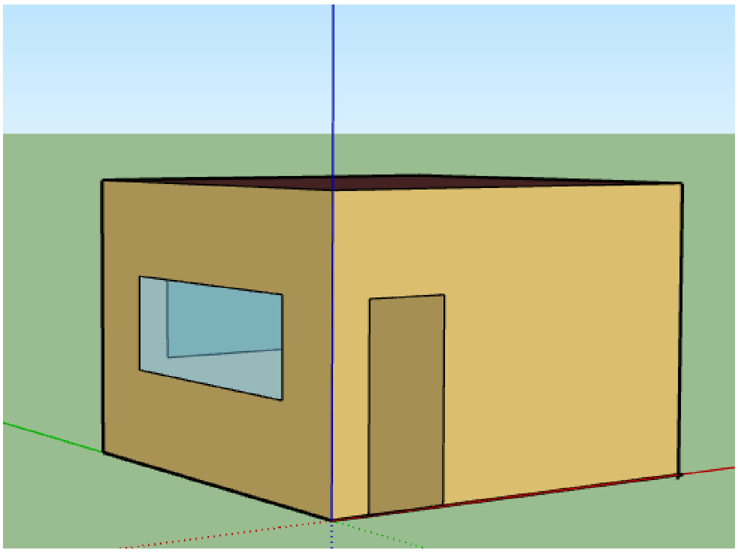


FIGURE 3.3: Base Case House

3.2 Building Envelope Details

Building envelopes details of this house are added in EnergyPlus under material and constriction objects. The general constructions used in typical residential houses of Pakistan are used for walls, roof and floor as given in Table 3.1. The thermophysical properties of all materials used are shown in Table 3.2. According to building code of Pakistan (BCP-2011) [7] overall thermal resistance U-value for wall and roof should be 0.57 and 0.44 W/(m^2.K). The U-values for used typical constructions are higher than standard U-values of wall and roof as no thermal insulation is used in typical construction materials of Pakistan. Firstly, these constructions are used for base case house energy consumption calculation, then PCM will be added which are serving the purpose of thermal insulation as well. Building thermal insulation used nowadays in modern houses of Pakistan are also considered for comparison purpose.

Table 3.1: Construction Details [53]

Name	**Constructions (Outside to Inside)**	**U-Value [W/m^2-K]**
Walls	Plaster, Brick, Plaster	2.74
Roof	Plaster, Bitumen, RCC Slab, Plaster	4.9
Floor	Cement Mortar, Concrete, Aggregate, Sand, Earth/Soil	2.2
Windows	Single Glazed	5.8
Door	Plywood	2.56

Table 3.2: Thermal Properties of Materials [53]

Material	**Thickness (m)**	**Conductivity (W/m-K)**	**Density (kg/m^3)**	**Specific Heat (J/kg-K)**
Plaster (Walls)	0.0095	0.431	1250	1088
Brick	0.2286	0.711	2000	836
Plaster (Roof)	0.0095	0.38	1150	840
Bitumen	0.0095	0.5	1700	1000
RCC Slab	0.1016	0.735	2300	665
Cement Mortar	0.0095	0.72	1650	920
Concrete	0.0508	0.753	2000	656
Aggregate	0.0762	1.8	2240	840
Earth/Soil	0.2286	0.837	1300	1046
Single Glazed Glass	0.0063	1.046		
Plywood	0.0508	0.13	410	840

3.2.1 Phase Change Material

Different phase change materials are considered in this study to find the optimal PCM under Pakistan climatic conditions. The selection of optimal PCM for building envelopes of Pakistan is done based on the percentage of energy consumption saving. A total of 15 widely used commercially available PCMs from RubiTherm SP-Line [54], PCM Products [55], RubiTherm RT-Line [56], PureTemp [57], and CrodaTherm [58] are selected having melting temperatures between 18°C to 25°C as these are normal room temperatures used in residential houses of Pakistan. These PCMs are already used in many experimental and numerical studies for building energy enhancement applications. The properties of all the selected PCMs are given in Table 3.3. The properties considered are melting and freezing temperature, latent heat of fusion and density, thermal conductivity and specific heat for solid and liquid phases. All these properties are added in EnergyPlus under Phase Change Hysteresis section.

TABLE 3.3: Properties of Phase Change Materials

PCM	Melting Temp [°C]	Freezing Temp [°C]	Latent Heat [KJ/kg]	Thermal Conductivity [W/mK]		Density [kg/m^3]		Specific Heat [KJ/kg .°C]	
				Liquid	Solid	Liquid	Solid	Liquid	Solid
SP21EK	22	21	170	0.5	0.5	1400	1500	2.00	2.00
SP24E	24	23	180	0.5	0.5	1400	1500	2.00	2.00
SP25E2	25	24	180	0.5	0.5	1400	1500	2.00	2.00
A22H	22	22	216	0.18	0.18	820	820	2.85	2.85
A25H	25	25	226	0.18	0.18	810	810	2.15	2.15
RT21HC	21	20	190	0.2	0.2	770	880	2.00	2.00
RT22HC	22	21	190	0.2	0.2	700	760	2.00	2.00
RT25HC	25	23	230	0.2	0.2	770	880	2.00	2.00
PureTemp18	18	18	192	0.15	0.25	860	950	1.74	1.47
PureTemp20	20	20	171	0.14	0.23	860	950	2.15	2.07
PureTemp23	23	23	201	0.15	0.25	830	910	1.99	1.84
CrodaTherm 19	19	18	175	0.16	0.23	850	911	1.80	2.50
CrodaTherm 21	21	20	190	0.15	0.18	850	891	1.90	2.30
CrodaTherm 24W	23	23	184	0.16	0.22	843	906	2.20	3.70
CrodaTherm 24	24	21	183	0.16	0.29	842	949	1.70	2.40

Each PCM is added separately in building envelope to investigate their effect on annual energy consumption of a building and to find optimal PCM among 15 different PCM. Firstly, a layer of 10 mm of each PCM is placed as inner most layer of external walls and roof of base case house as shown in Figure 3.4a Figure 3.5a. The best PCM for building envelope of Pakistan is selected based on maximum energy saving. Then the effect of the different parameter of PCM is also considered for optimizing PCM utilization in building envelope and saving maximum heating and cooling energy consumption.

Then PCM is placed at four different positions in a wall as shown in Figure 3.4 to select best position for PCM in terms of annual energy saving. Similarly, four different configurations of PCM placement are considered for roof as shown in Figure 3.5 to find the best position of PCM in roof. After selecting the best placement position of PCM in walls and roof, effect of PCM thickness on annual energy saving is also analyzed by varying the thickness of PCM in walls and roof from 10 mm to 100 mm with an increment of 10 mm. The optimal thickness of PCM will be found.

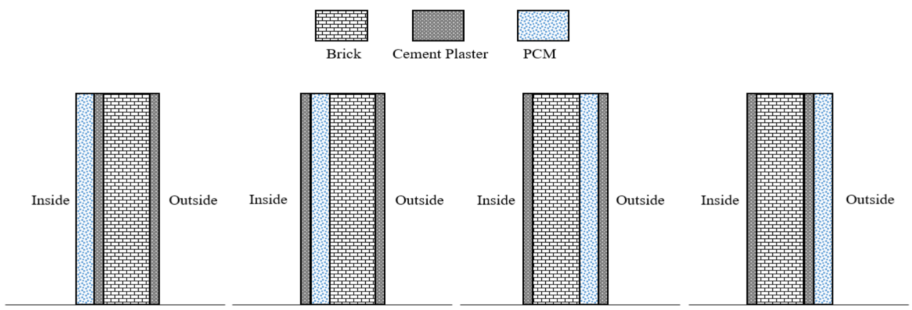


Figure 3.4: PCM Placement in Walls a) Wall A b) Wall B c) Wall C d) Wall D

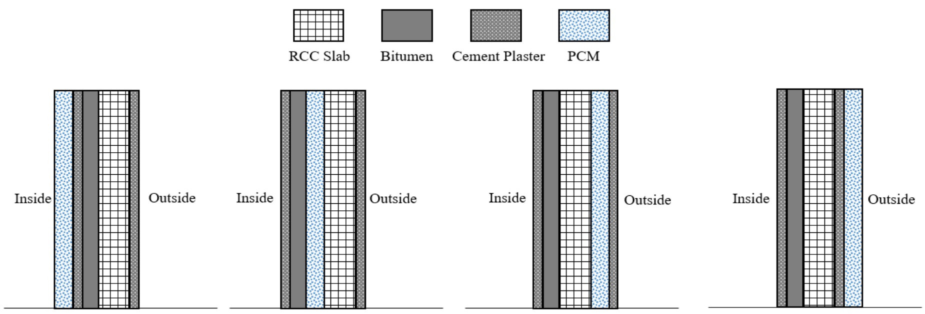


Figure 3.5: PCM Placement in Roof a) Roof A b) Roof B c) Roof C d) Roof D

3.3 Internal Heat Gains

The internal heat gain sources in buildings are occupants, lighting and equipment. The internal loads of a building are calculated using these heat gain sources. The base case single-room house is assumed as a living room. The heat gain parameters for this room are given in Table 3.4 which are used in EnergyPlus for energy consumption calculations. Moreover, the metabolic heat generation rates used for occupants are taken from chapter 9 of ASHRAE handbook [59]. There are different metabolic heat generation rates in this book for different activities like sleeping, seating and writing etc. The general schedules of a living room are also considered.

TABLE 3.4: Internal Heat Gain Parameters [15]

Parameters	**Value**	**Schedules**
People (W/m^2)	0.0625	
Metabolic rate (W/person)		
Writing, seating, standing	108	7 am-6 pm
Cooking, cleaning	171	6 pm-8 pm
Reading, relaxing	108	8 pm-10 pm
Lighting (W/m^2)	2.5	6 pm-10 pm
Electric equipment (W/m^2)	1.875	7 am-10 pm

3.4 HVAC

As the aim of this study is to calculate energy requirements of a building under different operating conditions, ideal HVAC system present in EnergyPlus software is used to calculate heating and cooling consumption of base case house instead of using any particular HVAC system. The ZoneHVAC: Ideal Loads AirSystem present in EnergyPlus [60] is a Variable Air Volume (VAV) system with variable humidity and supply temperature. This system automatically adjusts supply airflow rates to maintain indoor temperature and balance heating and cooling loads inside the thermal zone. The indoor comfort temperatures are maintained by using heating and cooling set point and setback for winter season and summer season given in Table 3.5. This ideal HVAC system will operate from 7 am to 10 pm everyday. The zone temperatures are controlled by zone control type schedule in which heating in on in winter season and cooling is on in summer season whereas both will operate in remaining seasons.

TABLE 3.5: Indoor Set Air Temperatures

	Heating	**Cooling**	**Schedule**
Setpoint (°C)	18	25	7am-10 pm
Setback (°C)	12	28	10pm-7 am

3.5 Infiltration

Infiltrations due to sliding, opening and closing of windows and doors also add external heat loads to thermal zones. The heat transfer due to these infiltrationa must be considered while calculating total heating and cooling energy consumption of any conditioned thermal zone. The value of infiltration flow rate is selected from infiltration range given by Pakistan Building Code (BCP) for base case house [7] given for traditional houses of Pakistan. The infiltration flow rate is set as 0.6 ACH in EnergyPlus Software in Zone Infiltration: Design FlowRate object for energy consumption calculations.

3.6 Implementation of PCM in Multizone Residential House

Multi-zone one storey and two storey residential houses are also modelled to investigate the PCM effectiveness. The floor plan of the multi-zone houses modelled in this study are shown in Figure 3.6. All dimension shown are in meters. The floor area is 344 m^2 and floor to ceiling height for each storey is 3 m. There are 3 bedrooms in each story with an attached bathroom, one drawing room, one store-room and one kitchen. The second story has one extra common room also. This Sketchup model of both houses are shown in Figure 3.7. These houses are exposed to the outdoor environment from all sides. The same constructions details for walls, roof and floor used for base case house given in Table 3.1 are used for these houses. There are total 10 thermal zone in single storey and 21 thermal zones in two storey as all separate rooms are considered as thermal zone.

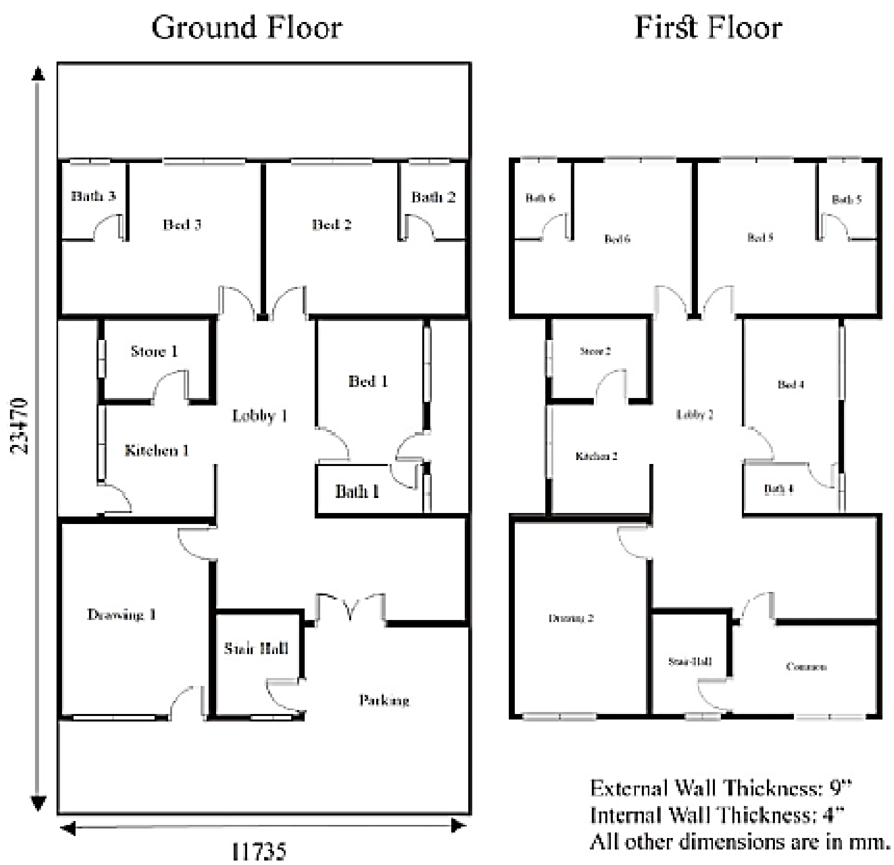
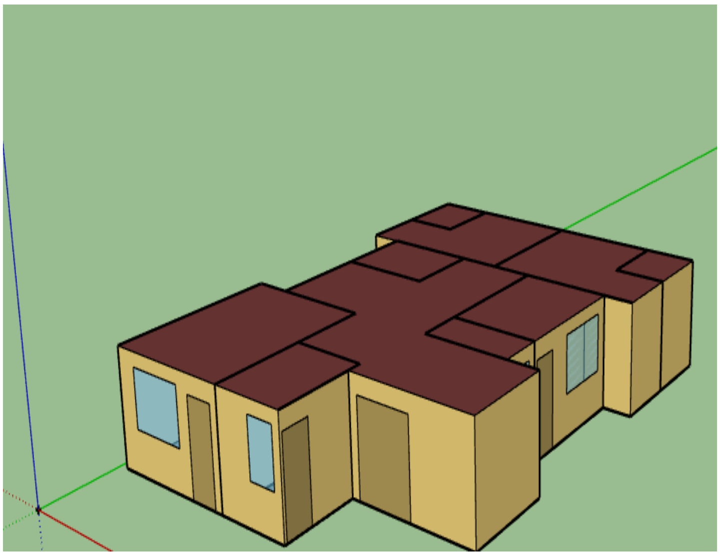
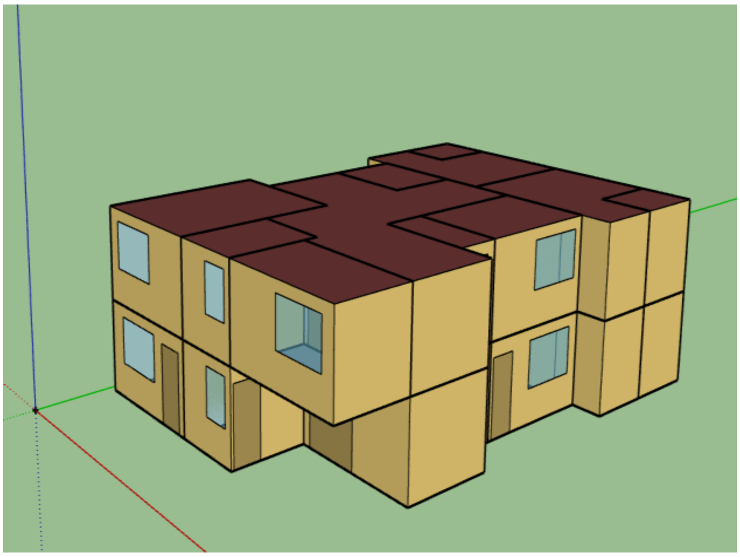


FIGURE 3.6: Floor Plan of Multizone House [61]

The bedrooms, drawing rooms and lounge are conditioned only in this study. The 3 bedrooms and 1 drawing room are conditioned ideally using zone HVAC ideal load air system in multi-zone single storey house as used in the base case house. Similarly, 9 thermal zones 3 bedrooms and 1 drawing room in each storey and 1 common room in the second storey are conditioned ideally in two-storey multi-zone house. The same indoor temperature setpoint used in the base case house are used to conditioned all thermal zones. The base case house is considered as a living room which is occupied mostly in day time and evening but bedrooms and drawing rooms are present in this house. Therefore, the different schedule profiles for occupants, lights and equipment present in bedrooms and drawing rooms used in this house are shown in Table 3.6.



a)



b)

FIGURE 3.7: 3D Model of Multizone House a) Single Storey b) Two Storey

The annual heating and cooling consumption of both houses for conditioned zones are calculated using numerical simulation in all 5 cities selected from different climates of Pakistan. Then PCM is incorporated in external walls and roof of these houses and reduction of annual energy consumption as well as heating and the cooling energy consumption is evaluated. Finally, the building energy of these house is compared with and without PCM.

TABLE 3.6: Schedules for MultiStorey House

Parameters	**Values**	**Schedules**
	Common Room	
Number of People	4 to 5	
Metabolic rate (W/person)		
Writing, seating, standing	108	7am-6pm
Cooking, cleaning	171	6pm-8pm
Reading, relaxing	108	8pm-10pm
Lighting (W/m^2)	2.5	6pm-10pm
Electric equipment (W/m^2)	1.875	7am-10pm
	Bed Room	
Number of People	2	
Metabolic rate (W/person)		
Sleeping	72	9pm-6am
Writing, seating, standing	108	6am-7am
Lighting (W/m^2)	2.5	9pm-11pm
		6am - 7am
Electric equipment (W/m^2)	1.875	10pm-12pm
	Drawing Rooms	
Number of People	6 to 8	
Metabolic rate (W/person)		
Writing, seating, standing	108	6pm-10pm (Weekdays)
		4pm-10pm (Weekends)
Lighting (W/m^2)	2.5	6pm-10pm (Weekdays)
		6pm - 10pm (Weekends)
Electric equipment (W/m^2)	1.875	6pm-10pm

3.7 Climate Data

According to the Koppen climate classification system, Pakistan has 12 different Koppen climate classes as shown in Figure 3.8. The five different climates considered in this study are following:

- Arid Climate of Karachi (BWhw)
- Semi-Arid Climate of Lahore (BShw)
- Humid Subtropical Climate of Islamabad (Cwb)
- Hot Semi-Arid Climate of Peshawar (BSh)
- Hot-summer Mediterranean climate of Quetta (Csa)

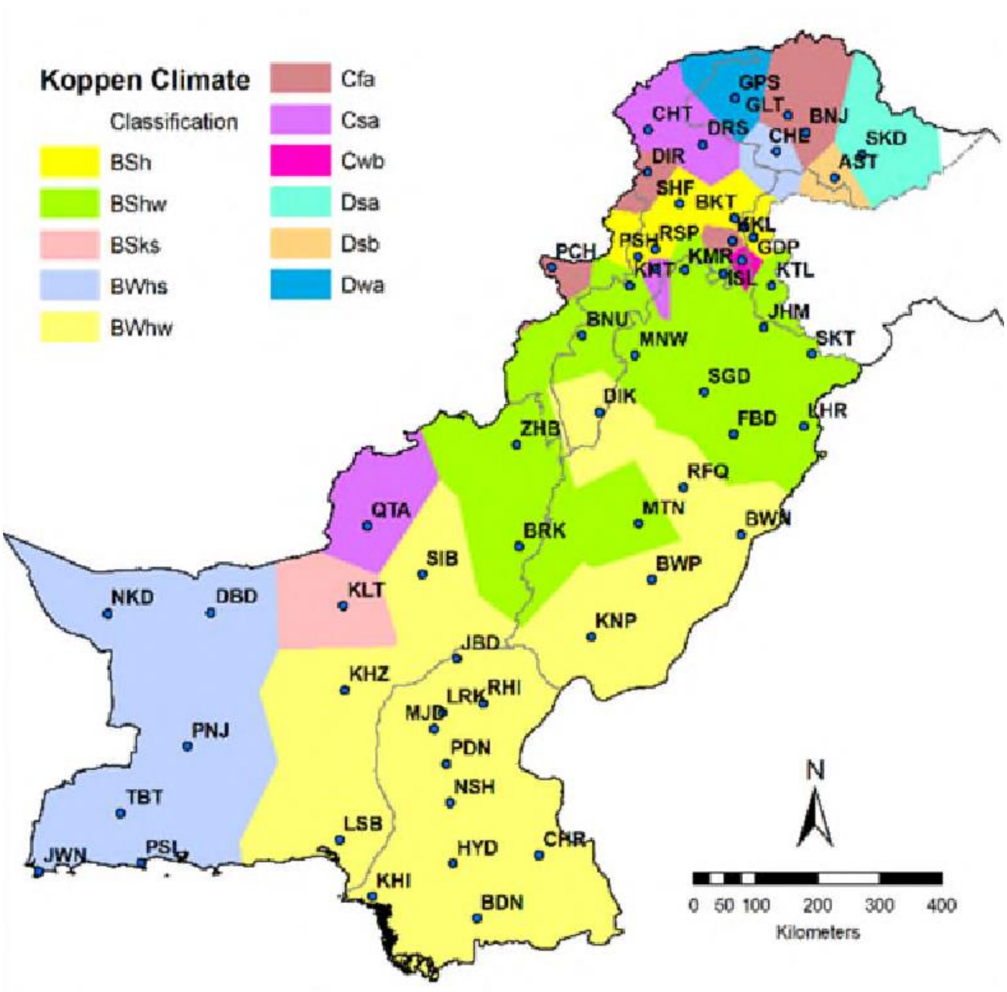


FIGURE 3.8: Koppen Climate Classification of Pakistan [62]

To run a building energy simulation for all these climates in EnergyPlus, weather files based on Typical meteorological year (TMY) are needed. These weather files contain hourly readings of outdoor temperature, wind velocity, relative humidity, solar radiation and sky conditions etc for this specific location collected over a long period. Weather data is recorded for a different number of years for these cities to generate TMY as presented in Table 3.7. EnergyPlus weather files made by Lawrie, Linda and Crawley use these TMY data is used for building energy simulations [63].

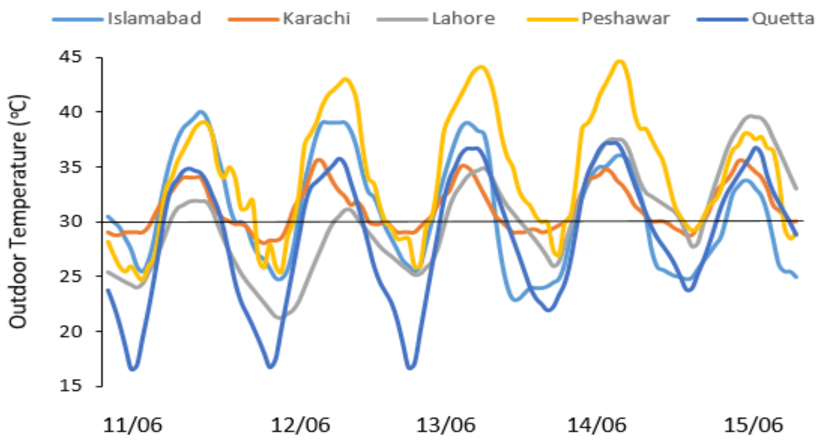


FIGURE 3.9: Outdoor Temperature Profiles for one week of Summer Season

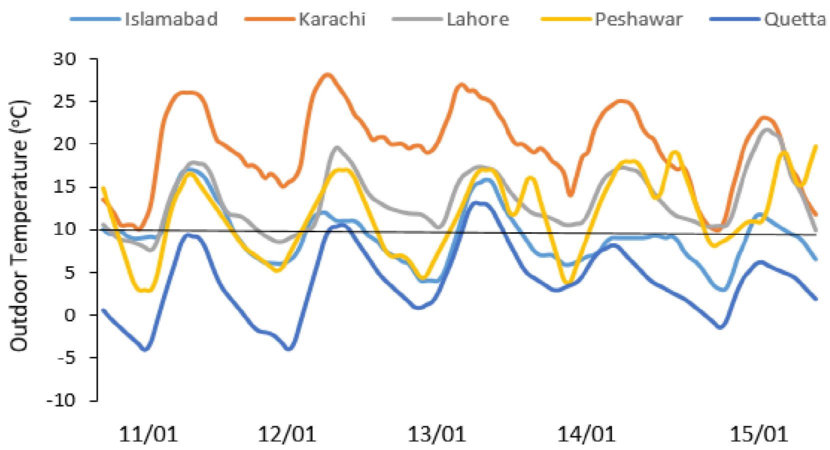


FIGURE 3.10: Outdoor Temperature Profiles for one week of Winter Season

The hourly outdoor temperature given in these weather files is shown for one week of June in summer season and for one week of January in winter season in Figure

3.9 and 3.10. It can be seen that Peshawar has highest outdoor temperatures as summer are very warm in Peshawar and Quetta has lowest temperatures in the month of June as summer starts in May in Quetta. In January, Quetta and Islamabad has lowest temperature and Karachi has highest outdoor temperatures as winters are shortest in Karachi. Simulations are iterated for all these cities separately to find optimal PCM in Pakistan climate.

TABLE 3.7: Number of Years used for TMY Formulation [63]

Cities	Number of Years
Karachi	44
Lahore	36
Islamabad	33
Peshawar	27
Quetta	13

3.8 Numerical Modeling

EnergyPlus software considers walls of thermal zone as a control volume (CV) and apply heat balance on interior and exterior sides as shown in Figure 3.11 to calculate energy consumption in CV. All heat transfers are calculated separately by EnergyPlus user user defined input and then heat balance is applied.

The conduction heat transfer flux in walls is calculated using Fourrier's law given in equation 1, where k is the thermal conductivity of the material and ΔT is a temperature gradient. The rate of convective heat transfer is calculated using Newton's Law of Cooling given in equation 2, where h is convective heat transfer coefficient, Ts is surface temperature and $T\infty$ is the temperature of the fluid. Similarly, rate of radiation heat transfer is calculated using Stephen Boltzman Law given in equation 3 where ϵ is emissivity, a radiative property of material, σ is Stephen Boltzmann constant ($\sigma = 5.67 \times 10^{-3} W.m^{-2}.K^{-4}$).

$$q" = -K\Delta T \tag{1}$$

$$q" = h(T_s - T_\infty) \tag{2}$$

$$q" = \epsilon\sigma(T_s^4 - T_\infty^4) \tag{3}$$

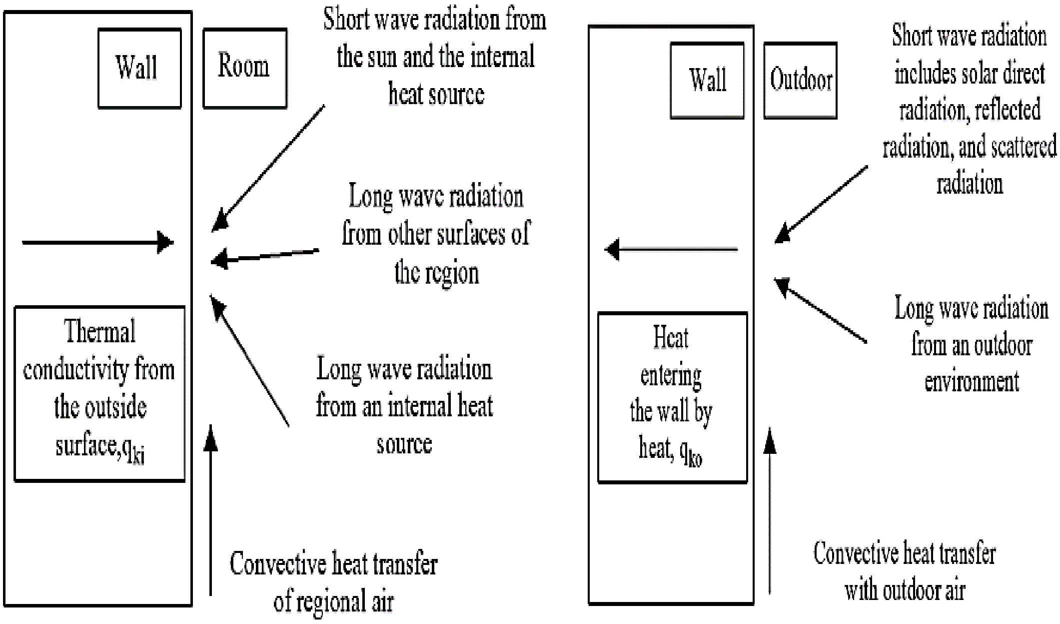


FIGURE 3.11: Heat Balance Schematic Diagram for Control Volume [60]

The EnergyPlus software requires heat transfer solution algorithms and the number of time steps per hour to calculate conduction, convection and radiation heat transfer layer by layer using these laws. The conduction heat transfer is generally solved by conduction transfer function (CTF) algorithm given in EnergyPlus due to its simple and quick solution in one dimension. But it can not be used in this study as it calculates conduction heat transfer from materials having constant thermal properties. The conduction finite difference (CondFD) solution algorithm will be used in this study to calculate energy consumption when PCMs are incorporated in the building using hourly weather data. The time step of the simulation is set to 3 minutes initially as suggested by Tabares-Valesco et al.[47].

3.8.1 Conduction Finite Difference (CondFD) Algorithm

The conduction finite difference algorithm is integrated with EnergyPlus to overcome the limitations of conduction transfer function solution algorithm such as its inability to solve the interior of a material having variable properties such as PCM [64]. The CondFD algorithm can calculate heat transfer for the interior of a material having different properties in solid and liquid phases by allowing calculations at internal nodes [60]. Two solution schemes option is available with CondFD model in EnergyPlus, a Crank-Nicholson scheme also referred to as semi-implicit second order in time and fully implicit first order in time. According to Versteeg, although semi-implicit Crank-Nicholson scheme is second order in time and more accurate and stable for all time steps results of this scheme are non-bounded sometimes and physically unrealistic [65]. Therefore, a fully implicit scheme is used in this study because of its robustness and stability over time. The model heat transfer equation for the fully implicit scheme is given below [60].

$$C_p \rho \Delta X \frac{T_i^{j+1} - T_i^j}{\Delta t} = K_W \frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta X} + K_E \frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta X} \tag{4}$$

$$K_W = \frac{K_{i+1}^{j+1} - K_i^{j+1}}{2}$$

$$K_E = \frac{K_{i-1}^{j+1} - K_i^{j+1}}{2}$$

Where C_p is the material specific heat, ρ is the material density, ΔX the finite difference layer thickness, T is node temperature and Δt is the time step. Similarly, K_w is the thermal conductivity for the interface between nodes i and $i+1$, and Ke is the thermal conductivity for the interface between the nodes i and $i-1$. The subscript and superscript i is the for the node being modeled and $i+1$ is for the adjacent node to the interior of construction and i–1 is for an adjacent node in the exterior of the construction. Likewise, $j+1$ is a new time step and j is the previous time step.

EnergyPlus uses four different nodes with both schemes as shown in Figure 3.12 which are interior surface node, interior node, material interface node and external surface node. Grid for each material given in construction such as in Table 3.1 are defined, material interface nodes and other 3 nodes are established for all material. Then equation one is solved at each node and for each material. In CondFD model, surface discretization is done using equation 5 [60] which divides all surfaces automatically. Here c is space discretization constant, $\propto$ is thermal diffusivity of a material and Δt is time step selected.

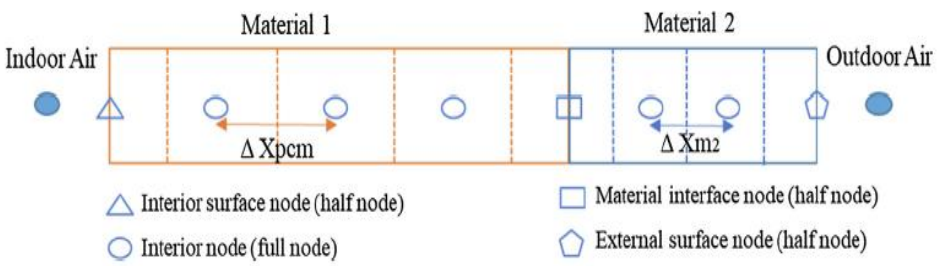


FIGURE 3.12: Node description for Conduction Finite Difference Model [60]

$$\Delta x = \sqrt{c \propto \Delta t} = \sqrt{\frac{\propto \Delta t}{F_o}} \tag{5}$$

The specific heat of the materials with hysteresis such as PCM is dependent on the current state and the former state because it has to model the hysteresis phenomenon between the melting and freezing processes [60]. Using Equation 2, CondFD model discretizes the building envelop such as wall and roof using thermal diffusivity of materials and given time step. EnergyPlus uses space discretization constant default value of 3 which is inverse of Fourier number given in equation 6. This default value of 3 is used to fulfill the stability requirements of CondFD model which requires Fourier number should be less than 0.5 or space discretisation value should be greater than 2 for explicit mode. But as we are considering implicit scheme with CondFD method, the discretization constant does not need to be 3 and can be set arbitrarily because the implicit scheme does not have to meet any specific stability [60]. It was suggested by Tabares–Velasco et al. that space discretization constant should be selected between 0.3 and 0.5 for hourly performance analysis of PCMs and similarly time step should be chosen less than 3 minutes [47]. In this research study, a time step of 1 minute and space discretization constant of 0.3 is selected to simulate phase change materials in building envelopes.

$$F_o = \frac{\propto \Delta t}{\Delta x^2} \tag{6}$$

The temperature at each node has to be updated in each iteration in the implicit scheme, therefore by calling innermost solver Guass-Seidell iteration loop for each surface present in constructions, the temperatures at new nodes are updated [60]. Similarly, enthalpies at each node are updated during each iteration and further used to calculate variable specific heat at each node for PCM simulations [60]. Previous versions of EnergyPlus define PCM using enthalpy-temperature values taken from PCM Enthalpy-Temperature curve under Material Property: PhaseChange object and use equation 7 for this specific heat calculation [60].

$$C_p = \frac{h_{i,new} - h_{i,old}}{T_{i,new} - T_{i,old}} \quad (7)$$

But this approach of defining PCM has one limitation, it can define PCM with one temperature-enthalpy curve and hysteresis occur during PCM simulation can not be considered which cause accuracy issues in simulation results [66]. A new object Material Property: Phase Change Hystersis is added by EnergyPlus to address this issue in the new version. As EnergyPlus V9 is used in this study to define the properties of PCM under Phase Change Hystersis object, the C_p at each step is calculated using equation 8 [60].

$$C_p = f(Ti_{new}; Ti_{prev}; PhaseState_{new}; PhaseState_{prev} \quad (8)$$

The phase change hysteresis model need values of density, specific heat and thermal conductivity for both solid and liquid phase. These properties of all phase change material are already given in Table 3.3.

3.8.2 Interior/Exterior Convection

EnergyPlus uses different correlations to find heat transfer coefficient for interior and exterior surface convection as given in Table 3.7. The TARP default convection model developed by Walton is used to model interior surface convection in this study. Walton derived this algorithm directly derived from ASHRAE handbook [59]. It correlates the convective heat transfer coefficient with surface orientation and temperature gradient between zone air temperature and surface temperature to as shown in Table 3.8. The zone indoor temperatures are governed by the user given setpoint and setback temperature as given in Table 3.8 for this study. The DOE-2 default convection model for outside surface convection coefficient is used in this study. The DOE'-2 algorithm is a combination of MoWiTT model used for smooth surface convection calculations and BLAST mode which is used to convection coefficient for less smooth surfaces [60].

TABLE 3.8: Convective Heat Transfer Coefficient Coorelations [60]

Interior surface	**Correlations**	**Exterior surface**	**Correlations**
TARP*	$a\|\Delta T\|^{0.33}$	DOE-2*	$\{(a(\Delta T)^{1/3})^2+(bUc)^2\}^{1/2}$
Simple	a	SimpleCombined	$a+bU+cU^2$
CeilingDiffuser	$a+b*ACH^c$	TARP	$2.537W_fR_f(PU/A)^{1/2} + a\|\Delta T\|^b$
Adaptive_default	AutoSelected	MoWiTT	$\{(a(\Delta T)^{1/3})^2+(bUc)^2\}^{1/2}$
Adaptive_modified	$ASHRAE_{vertical}$	Adaptive_default	AutoSelected
	Walton Stable Or Tile	Adaptive_TARP	TARPWindward+TARPLeeward+ClearRoof
	Walton Unstable Or Tile	Adaptive_MoWiTT	MoWiTTWindward+MoWiTT Leeward+ClearRoof
ASHRAEvertical	$3.1\|\Delta T\|^{33.0}$,	Adaptive_DOE2	DOE2Windward+DOE2Leeward+ClearRoof
AlamdariHammond	$0.6\{\|\Delta T\|/Dh^2\}^{1/5}$	Adaptive_Emmel	EmmelVertical+EmmelVertical+EmmelRoof
AwbiHatton	$a\|\Delta T\|^b/Dh^c$	Adaptive_Blocken	BlockenWindward+ EmmelVertical+EmmelRoof
FohannoPolidon	$a\{\|\Delta T\|^b/H\}^{1/4}$, OR be $0.0467H_{\|\Delta T\|}0.316$	NusseltJurges	5.8+3.94U
		Mcadams	5.7+3.8U
		Mitchell	$8.6U^{0.6}/L^{0.4}$
		Emmel	aU^b

* Default models used in EnergyPlus

3.8.3 Shortwave/Longwave Radiations

The radiation heat flux in EnergyPlus is calculated using Stephen Boltzman Law as already discussed. The surface temperature, sky temperature and ground temperatures are considered for exterior and interior long wave radiations [60]. The sky temperature are calculated using data from weather files using in EnergyPlus simulation whereas ground temperature are taken equivalent to outdoor temperature given in weather file. Moreover, the emmisivity of material is used.
The longwave radiation heat flux in interior of thermal zone is also calculated using same procedure. The shortwave radiation heat flux is subjected to tilt angle of surface, material of surface, location and climate conditions considered [60]. All these parameter are considered by EnergyPlus to calculate shortwave radiation heat flux.

3.9 Thermal Insulation in Modern Houses

In recent years, the trend of using thermal insulations has been observed in the construction of modern houses of Pakistan especially for roof insulation to meet Pakistan building code requirements. The thermal properties of four different types of common insulation are considered in this study are given in Table 3.9.

Table 3.9: Properties of Insulations

Insulations	**Conductivity (W/mK)**	**Density (kg/m^3)**	**Specific Heat (J/kgK)**
Expanded Polystyrene	0.039	35	1250
Extruded Polystyrene	0.037	40	1700
Fiber Glass	0.043	150	700
Polyurethane Foam	0.021	30	1500

The thickness of these insulations is set to meet U-Value criteria given for walls and roof by Building code of Pakistan [7] as shown in Table 3.10. The best insulation is selected based on maximum energy saving by applying it in base case house. Further, the energy-saving from best insulation and optimal PCM are compared.

Table 3.10: Construction with Insulations

Name	**Constructions (Outside to Inside)**	**U-Value [W/m^2-K]**	**BCP-2011 U-Value [W/m^2-K]**
Walls	Plaster, Brick, Insulation, Plaster	0.56	0.57
Roof	Plaster, Bitumen, RCC Slab, Insulation, Plaster	0.44	0.44
Floor	Cement Mortar, Concrete, Aggregate, Sand, Earth/Soil	2.2	
Windows	Single Glazed	5.8	
Door	Plywood	2.56	

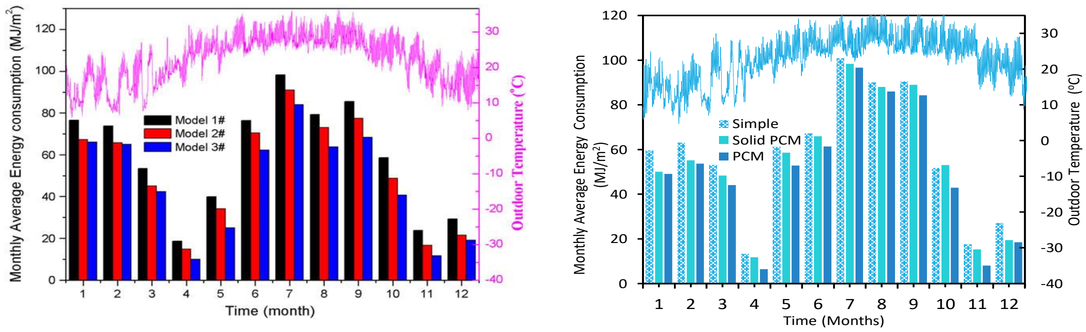
Chapter 4

Results and Discussions

4.1 EnergyPlus Model Validation

A numerical study conducted by Ji et al. [9] is validated initially for EnergyPlus model verification used in this study. The authors numerically assessed the energy performance of an ideal cabin having dimensions of $3m \times 3m \times 2.8m$ whereas concrete is used in construction of walls, roof and floor. The simulations are performed for Guangzhou city, China using phase change materials. The monthly average energy consumption of simple model is assessed with solid PCM (Model 2), PCM (Model 3) and without PCM (Model 1). The same model is developed using model setup and boundary conditions given in research study. The standard available weather file of Guangzhou city is used to perform the simulation. The result of EnergyPlus simulation shown in Figure 4.1(b) is in good agreement with the result of the research study shown in Figure 4.1(a). It has been observed that the trend of monthly energy consumption for all 3 models from current methodology compares well with results of literature however, some variation in magnitude of the values is observed.

This discrepancy is due to fact that weather data file used in the literature and in current simulations are different. The IWEC weather data gathered by ASHRAE [67] is used in both simulations, however the author used latest weather data IWEC2 collected for 12 to 25 years from 1983-2008 which is not freely available in EnergyPlus data library. This study use freely available IWEC data which is available with EnergyPlus software. The IWEC data are formed in 2001 whereas IWEC2 weather data file are formed in 2008. Therefore variations in weather data are seen in this validation.

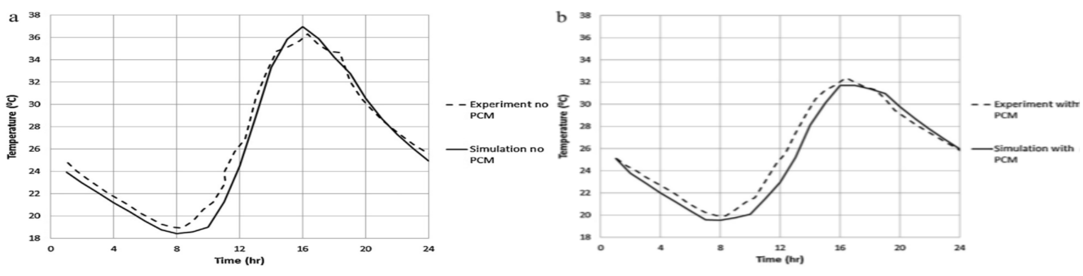


(a): Literature Results [9]

(b): EnergyPlus Results

FIGURE 4.1: Literature Results & EnergyPlus Results

Moreover, the algorithms used in EnergyPlus are also validated by many researchers with experimental results. Alam et al. [15] validated the experimental zone simulated temperature with and without PCM with a numerical model which shows great agreement as shown in Figure 4.2(a) and 4.2(b). Similarly,Al-Janabi and Kavgic [68] validated the EnergyPlus algorithms by defining PCM in two different ways, using temperature enthalpy values and considering hysteresis and compared results with actual values. Authors concluded that both models results are in good agreement with experimental values and PCM should be defined with hysteresis. Hence, it is concluded that EnergyPlus simulations can be used in the evaluation of the thermal performance of building envelopes and model used in this study is also supported by the literature.



(a): EnergyPlus Validation without PCM

(b): EnergyPlus Validation with PCM

FIGURE 4.2: EnergyPlus Validation with & without PCM

4.2 PCM Integration in Building Envelope

The effect of PCM integration on base case building heating and cooling energy consumption is investigated. A 10 mm layer of PCM (SP21EK) is initially applied on the interior side of the walls and roof of the base case single room house. Different simulations are conducted with and without PCM for different cities of Pakistan and the result of these simulations are shown in Figure 4.3.

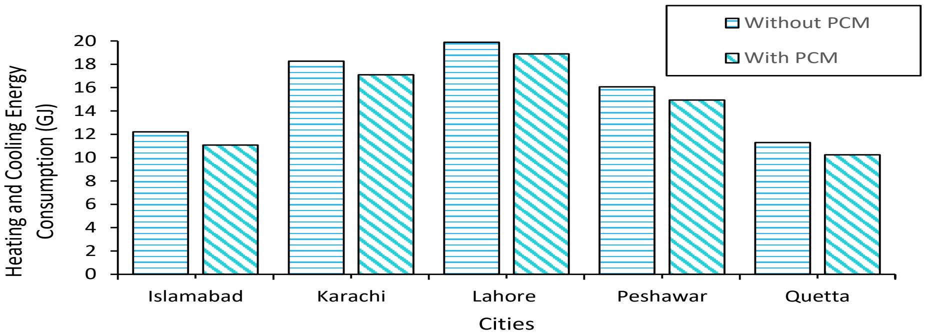


FIGURE 4.3: Heating and Cooling Energy Consumption in Different Cities

Lahore has the highest 19.9 GJ total average heating and cooling consumption without PCM and Quetta has minimum 11.3 GJ consumption without PCM among 4 selected cities. The total energy consumption in Islamabad city is 12.21 GJ, 16.06 GJ in Peshawar and 18.26 GJ in Karachi. The PCM integration in building envelopes reduce the total average energy consumption of Islambad and Quetta by 9% as shown in Figure 4.3. Similarly, 5% saving is achieved in Lahore, 7% in Peshawar and 6% in Karachi city. Therefore, it is concluded that PCM can reduce building energy consumption if used in building envelopes of these cities.

4.3 Optimal Phase Change Material Selection

A comparison of integration of 15 different PCMs in base case house is done for all 5 selected cities to select an optimal PCM that can be used in all these cities. For this purpose, a 10 mm layer of all these PCMs having melting temperatures between 18 °C to 25 °C is integrated on the interior side of exterior walls and roof of base case house and dynamic energy simulations are performed for each city. Figure 4.4 to 4.8 indicates that all PCMs show annual energy savings for all cities. In Figure 4.4, CrodaTherm24, SP25E2, SP24E shows maximum annual energy saving of 14%, 13% and 11% respectively in Islamabad whereas all other PCM shows 6% to 8% savings except CrodaTherm24W which shows the lowest saving of 4%.

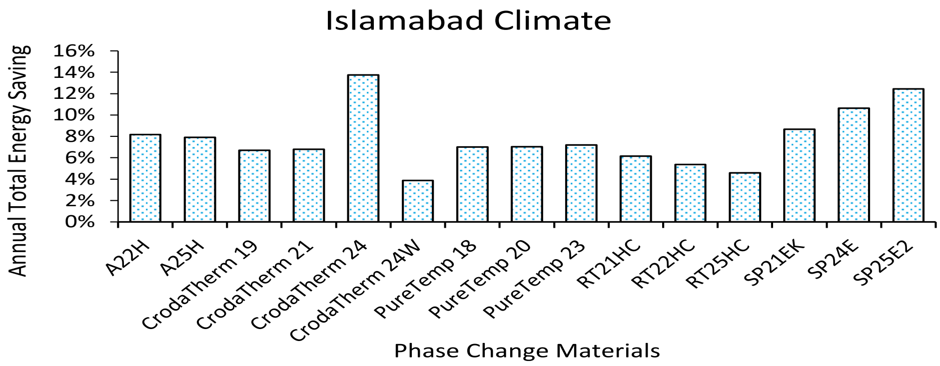


FIGURE 4.4: Behaviour of different PCMs in Islamabad

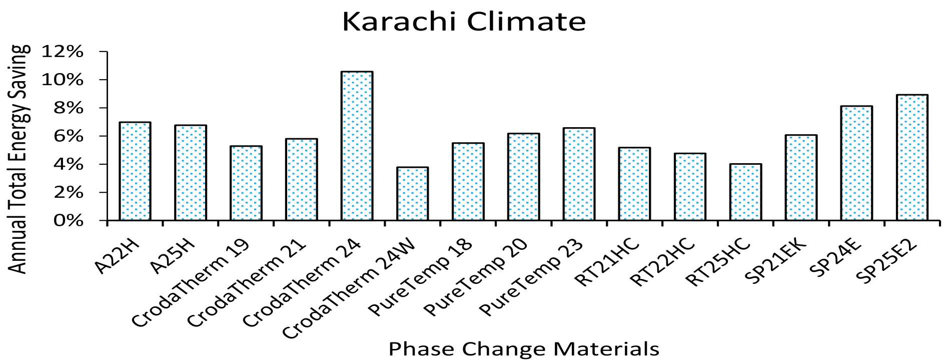


FIGURE 4.5: Behaviour of different PCMs in Karachi

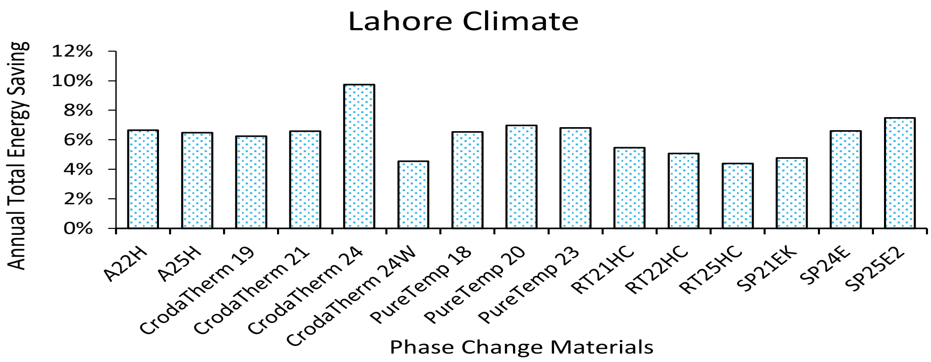


FIGURE 4.6: Behaviour of different PCMs in Lahore

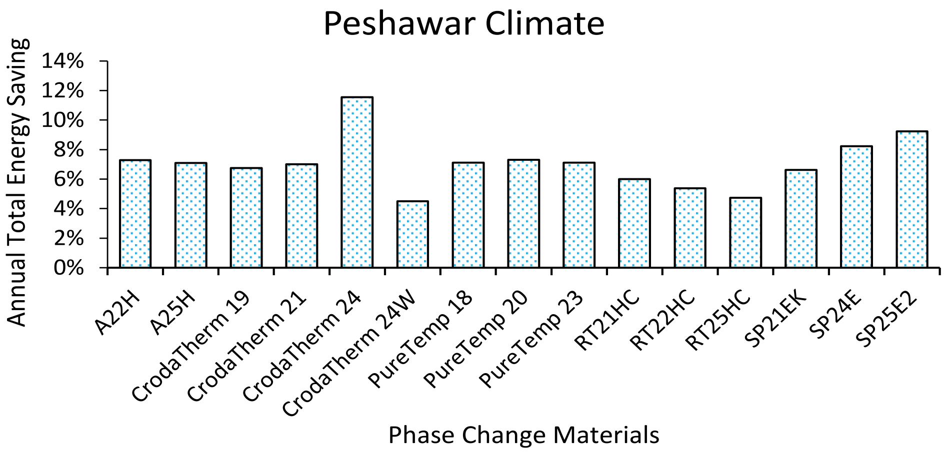


FIGURE 4.7: Behaviour of different PCMs in Peshawar

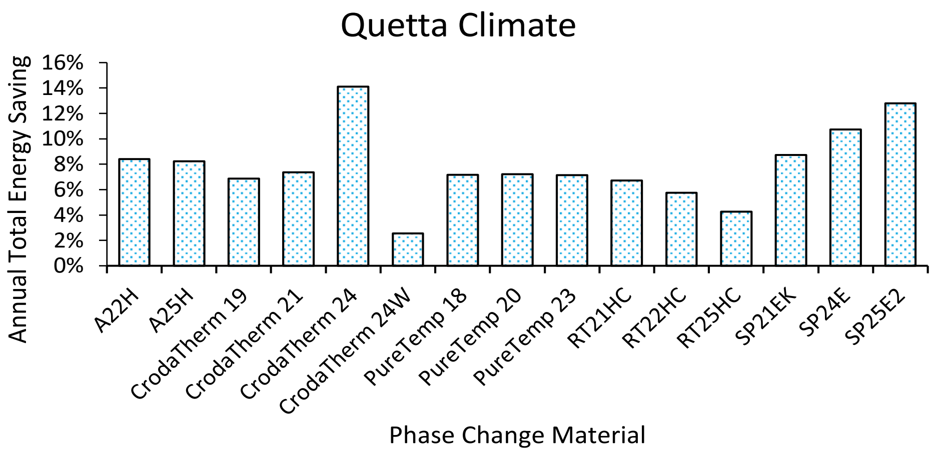


FIGURE 4.8: Behaviour of different PCMs in Quetta

Similarly, CrodaTherm24, SP25E2, SP24E save 11%, 9% and 8% energy annually in Karachi as shown in Figure 4.5. Remaining PCMs show an annual saving of 4% to 8%. The same performance of CrodaTherm24, SP25E2 and SP24E shows highest annual energy saving for the climates of all other cities namely, Lahore, Peshawar and Quetta in Figure 4.6, Figure 4.7 and Figure 4.8. On the other side, CrodaTherm24W and RT25HC show minimum energy savings in all 5 selected climates. It is also noticed that PCM having a melting temperature of more than 24 °C show more savings as it is complying with a cooling set point temperature of 25 °C. Maximum energy consumption in Pakistan is for cooling purpose therefore maximum savings have resulted when PCM having melting temperatures of 24 °C and 25 °C are chosen. All these 3 PCMs having maximum saving are bio-based organic PCMs can be installed in building envelopes to reduce average annual consumption. But if we compare the behaviour of these PCMs based on maximum annual energy saving, CrodaTherm24 has the highest saving in all cities.

From this comparison of the performance of PCMs in different cities, it is concluded that CrodaTherm can be selected as optimal PCM for installation in building envelopes of Islamabad, Karachi, Lahore, Peshawar and Quetta. It can save 14% annual energy in Islamabad, 11% in Karachi, 10% in Lahore, 12% in Peshawar and 14% in Quetta. A slight decrease in energy saving is observed in hot climates although it shows maximum saving in hot climates as well. CrodaTherm24 is a biobased organic PCM has melting temperature of 24 °C, freezing temperature of 21° C and latent heat of 183KJ/kg. Although the latent energy of Crodatherm24 is comparable with other PCMs, it is observed that its specific heat is lowest among other PCMs which means it needless energy for phase change. Its melting temperature is also close to indoor thermostat set temperature, therefore it phase changes in CrodaTherm24 are quick which make it most suitable PCM in all climates of Pakistan.It will be used in further study as an optimal phase change material.

4.4 Parametric study of Phase Change Materials

Different literature studies concluded that there are several parameters which are influencing the thermal performance of PCMs when implemented in building envelopes. The optimal PCM found in the previous section will now be installed in base case house for evaluating the effect of different PCM parameters such as PCM thickness, PCM installation location on heating and cooling energy consumption of buildings. Parameters of PCM are varied in each simulation and dynamic energy performance of building envelopes are investigated in detail for identifying optimum location and layer thickness of the PCM. The parametric study will be done for one climate i.e. Islamabad as the purpose of this study is to find the best installation location of PCM and its thickness.

4.4.1 PCM Placement in Walls and Roof

The different positions of the PCM layer in walls and roof are assessed to investigate their effect on the annual energy performance of the building. For this purpose, 4 different positions for placement of PCM layer in walls are considered. In the first configuration, PCM layer of 10 mm is placed on the internal side of wall construction of base case house, then placed after plastering in Wall B, placed after brick in Wall C and placed in the most external side of construction in Wall D as shown in Figure 8. The percentage of energy-saving for all these wall configurations is shown in Figure 4.9. It shows that PCM shows maximum total energy saving of 6.04% in Wall A configuration when placed on the internal side of construction and minimum total energy saving of 5.5% annually when placed on the external side of wall construction exposed to an outdoor environment.

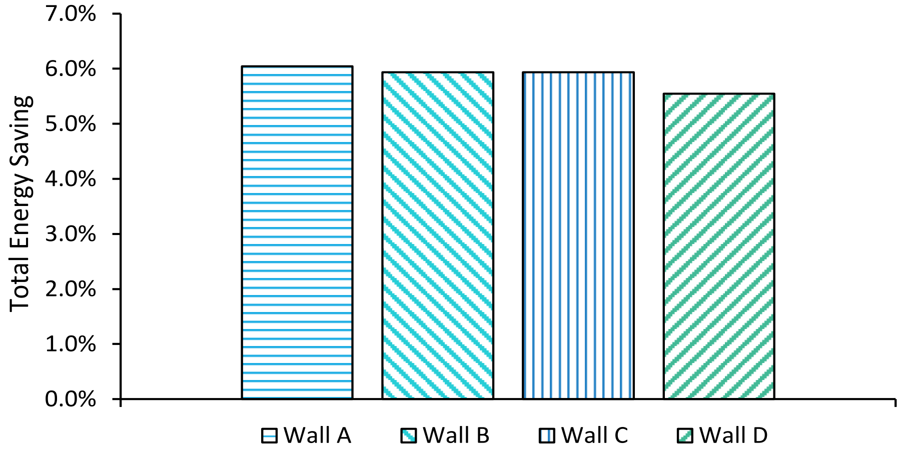


FIGURE 4.9: PCM layer Placement in Walls

Similarly, 4 different roof configurations are considered shown in Figure 3.5 in which the PCM layer of 10 mm is placed at 4 different positions in roof construction. In Roof A, PCM layer is placed on the internal side of roof construction, then placed after Bitumen layer in Roof B, place after RCC Slab in Roof C and finally placed on most external of roof construction. The total energy consumption saving from all these placements are calculated by running dynamic energy simulations annually in EnergyPlus. The simulation results given in Figure 4.10 shows that Roof A configuration has maximum energy consumption saving of 8.55% when

PCM layer is placed on the internal side of construction and has lowest saving of 7.14% when placed on the external side of construction in Roof D configuration.

Hence, both roof and walls indicate the same behaviour that PCM layers should be installed on the internal side of the walls and roof of buildings built in climates of Pakistan. It is concluded from this section that Wall A and Roof A are the best configurations as shown in Figure 4.11. This PCM placement in walls and roof is used in further analysis as both these configurations show maximum total energy consumption saving of 6.04% in walls and 8.55% in roof.

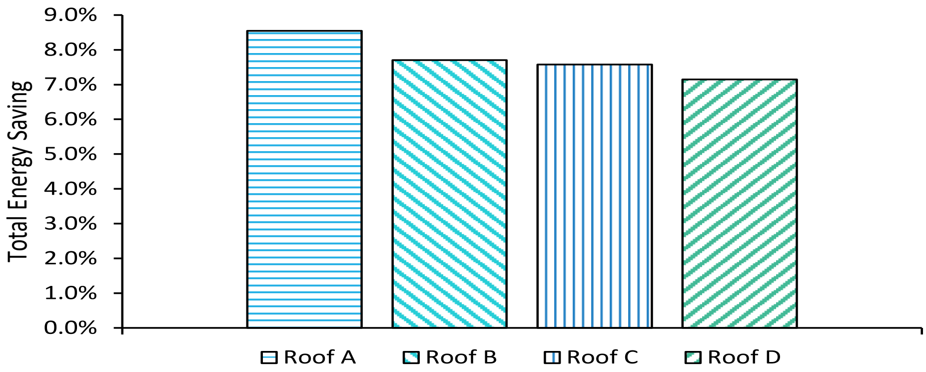


FIGURE 4.10: PCM layer Placement in Roof

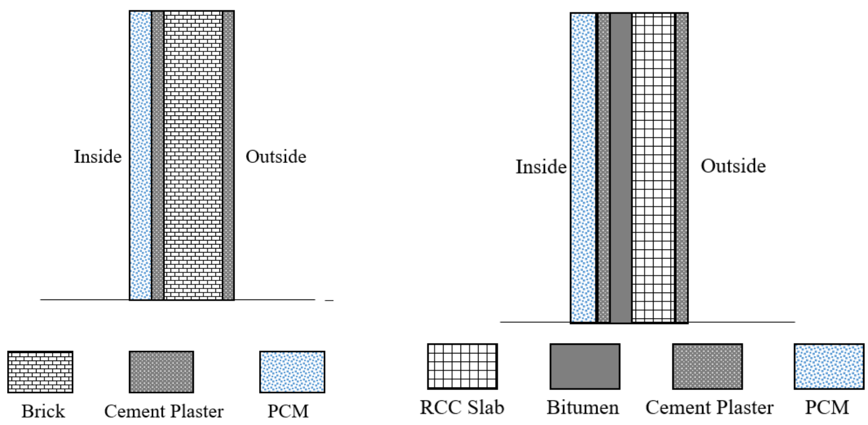


FIGURE 4.11: Best Loction for PCM Placement a) Walls b) Roof

4.4.2 PCM Thickness

The latent energy stored in PCM is directly related to the volume of PCM used. The energy stored in PCM increase when more volume of PCM used but it is also expected that energy stored might start decreasing when there is a limited amount of energy available in building envelope to be stored by PCM. Moreover, if a large volume of PCM is installed in the building envelope, it increases cost as well as reduce economic feasibility.The effect of PCM layer thickness on total building energy consumption, cooling and heating energy consumption is investigated in this section by varying the thickness of the PCM layer from 10 to 100 mm. The thickness of the PCM layer installed in the internal side of walls and roof of the building envelope of base case house is varied with an increment of 10 mm in each dynamic building energy simulation.

In Figure 4.12, simulations result shows that overall saving in total energy consumption is increasing when PCM layer thickness increases. The energy-saving of 14% is achieved with 10 mm layer, 22% with 20 mm layer, 28% with 30 mm, 33% with 40 mm PCM layer and so on as shown in Figure 4.10. It is also seen that upto 50 mm, the significant increase in energy saving is seen with the slope of 0.0062 whereas after after 50 mm, saving in energy is not substantial as the slope reduces to 0.0032 decreasing by 50%.

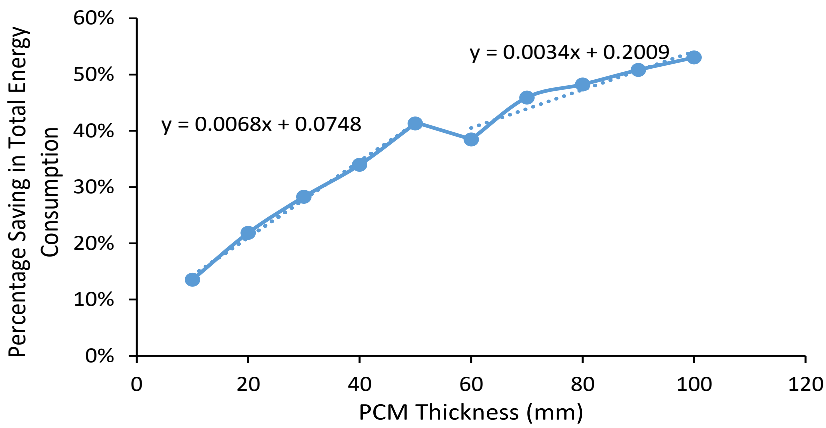


Figure 4.12: Effect of PCM thickness on Total Energy Consumption

Figure 4.13 shows the saving in cooling energy consumption with varying PCM layer thickness and same trend of increase as in total consumption is seen. A maximum of 6.6 GJ cooling energy can be saved with 100 mm PCM layer and a minimum of 1.5 GJ cooling energy can be saved with 10 mm PCM layer. The saving in heating energy consumption with changing PCM layer thickness is shown in Figure 4.14. The maximum heating energy saving of 0.61 GJ is achieved at 50 mm thickness, therefore no effect of increasing PCM thickness on heating energy consumption saving after 50 mm has been observed. It is concluded from this section that optimum PCM layer thickness should be chosen as 40 mm as upto this thickness, significant effect on overall energy saving as well as heating and cooling energy consumption saving is achieved.

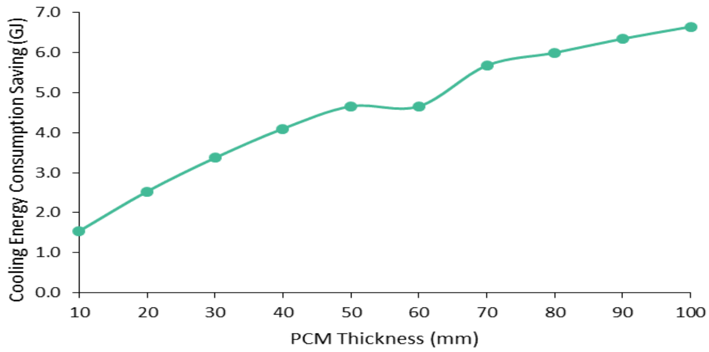


FIGURE 4.13: Effect of PCM thickness on Cooling Energy Consumption Saving

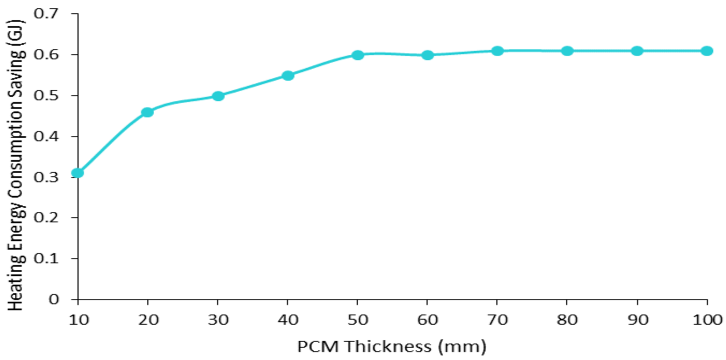


FIGURE 4.14: Effect of PCM thickness on Heating Energy Consumption Saving

4.5 Climates effect on PCM Integration

The effect of climates on monthly and annual energy consumption with the integration of optimal PCM is investigated in this section. The base case house is analyzed in all 5 selected climates of Islamabad, Karachi, Lahore, Peshawar and Quetta. Using the results of parametric analysis, a 40 mm PCM layer is added on internal sides of walls and roof construction of base case house. The dynamic energy simulation with all these parameters selected is performed with different climates data. All these simulations are performed for 12 months with a times step of 1 minute.

The monthly heating and cooling consumption of Islamabad city with and without PCM are shown in Figure 4.15. It can be seen in Figure 4.15(a) that PCM reduce the cooling energy consumption n all months. Furthermore, cooling energy consumption in the peak month of summer season June is 2.3 GJ for base case single room house which is reduced to 1.63 GJ with the use of PCM. Figure 4.15(b) shows that similarly to cooling energy consumption, heating energy consumption in Islamabad city is also decreasing with the integration of PCM in building envelope. In peak month of winter season January,the heating energy consumption of 0.3 GJ and drop to 0.04 GJ when PCM is installed. Hence, CrodaTherm24 PCM can be used in building envelopes of Islamabad to reduce the building energy consumption.

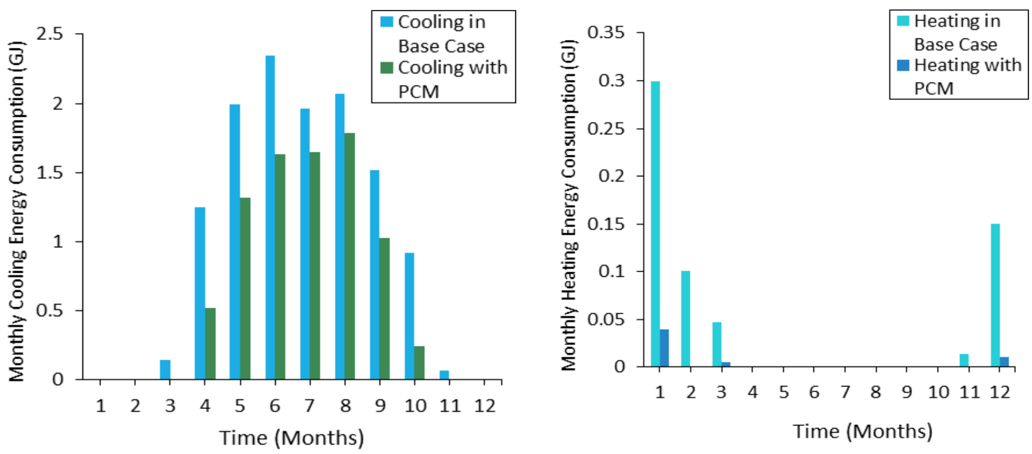


Figure 4.15: Monthly Energy Consumption in Islamabad
(a) Cooling (b)Heating

Figure 4.16 presents the monthly heating and cooling energy consumption of the base case house in Karachi city with and without the implementation of PCM. The substantial decrease in cooling energy consumption is seen in all month of summer shown in Figure 4.16(a). The highest cooling consumption of 2.8 GJ in the month of June is reduced to 2.4 GJ showing saving of 14% cooling energy. Whereas heating consumption in Karachi is not reduced by PCM, it increases with the use of PCM as shown in Figure 4.16(b). Therefore, PCM cannot be recommended in the winter season of Karachi with designed parameters. It needs further optimization before implementation in building envelopes of Karachi.

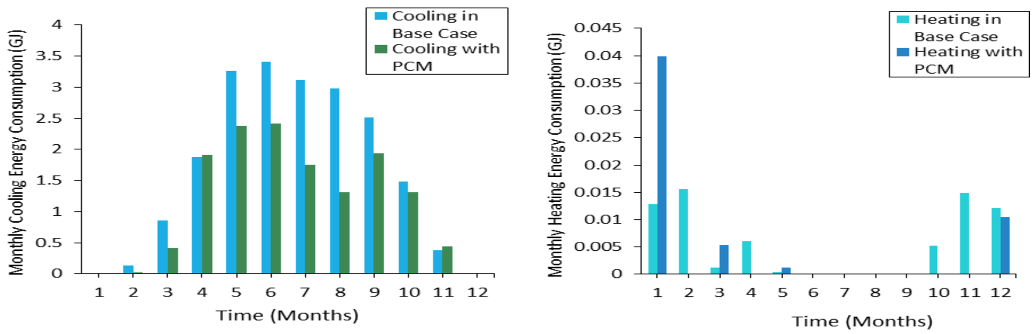


FIGURE 4.16: Monthly Energy Consumption in Karachi
(a) Cooling (b) Heating

The monthly heating and cooling consumption in Lahore city for base case house are shown in Figure 4.17. The cooling consumption in summer peak month June decreases from 3.4 GJ to 2.8 GJ when PCM is installed in the building envelope shown in Figure 4.17(a). Similarly, in July and August,a significant decrease of 0.48 GJ and 0.45 GJ is seen with the use of PCM. Lahore city has a hot climate, heating demand is less in this city having maximum heating consumption of 0.01 GJ, but use PCM reduces heating consumption to zero. Therefore,the use of CrodaTherm24 PCM in building envelope of Lahore is recommended.

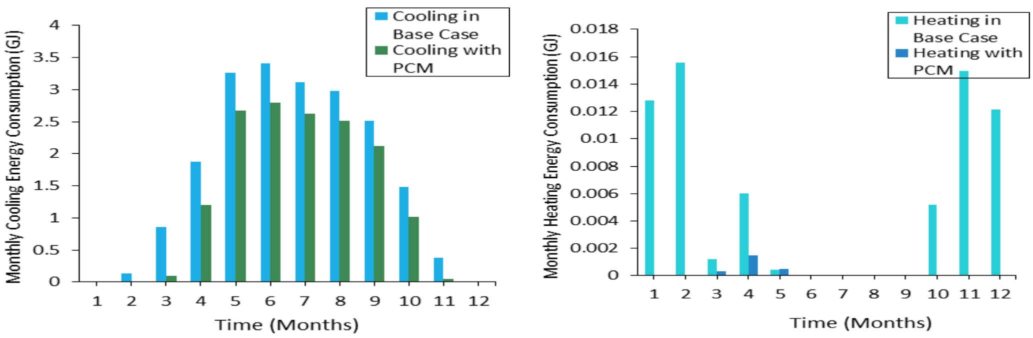


FIGURE 4.17: Monthly Energy Consumption in Lahore (a) Cooling (b) Heating

The monthly heating and cooling energy consumption in base case house with and without PCM for Peshawar city are shown in Figure 4.18. The cooling consumption decreases with the use of PCM as shown in Figure 4.18(a). The peak cooling energy of 3.2 GJ is consumed in July and reduces to 2.7 GJ when PCM is implemented showing a saving of 0.5 GJ. The heating consumption is also reduced with the use of PCM in all months of the winter season as shown in Figure 4.18(b). The maximum heating consumption of 0.36 GJ is observed in Peshawar in the month of January which is the coldest month of the winter season. The saving of 0.15 GJ is achieved in this month when the base house is simulated with PCM. In other months, PCM installation reduces heating consumption to zero. From these results, it is concluded that PCM should be used in building envelopes of Peshawar city to reduce the building energy consumption.

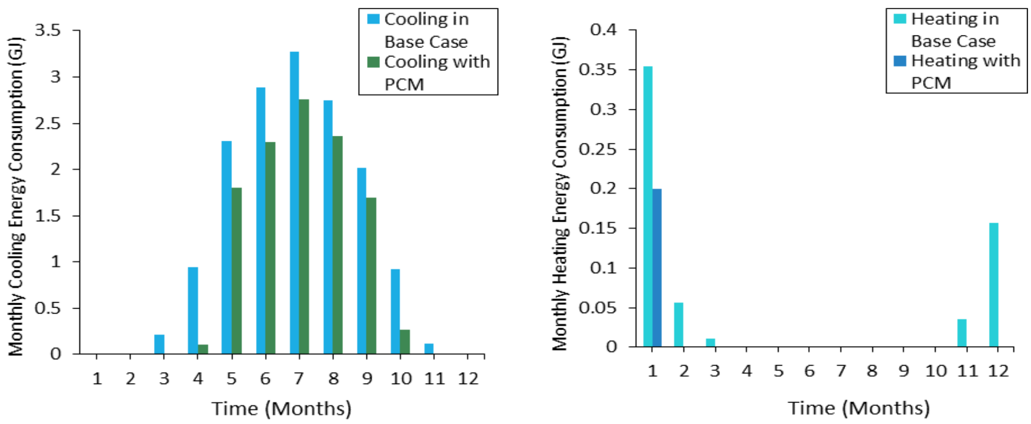


FIGURE 4.18: Monthly Energy Consumption in Peshawar
(a) Cooling (b) Heating

Finally, the monthly cooling and heating energy consumption of Quetta city is analysed. From selected five cities, Quetta has relatively cold climates. It is shown in Figure 4.19(a) and 4.19(b) that the use of PCM decreases the cooling and heating consumption in all months of summer and winter season. The heating consumption in December and January is 0.9 GJ and 0.7 GJ, whereas with the use of PCM in building envelope of Quetta 0.28 GJ energy can be saved in January and 0.15 GJ energy can be saved in January. Thus, the use of PCM is recommended in building envelope of Quetta.

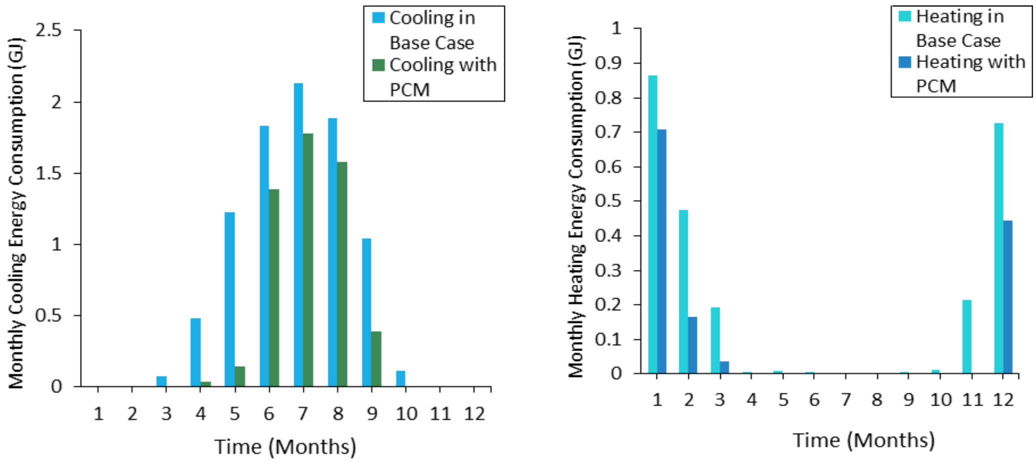


FIGURE 4.19: Monthly Energy Consumption in Quetta (a) Cooling (b) Heating

Figure 4.20 to 4.24 shows the total heating and cooling energy consumption in Islamabad, Karachi, Lahore and Peshawar and Quetta for 12 months. It can be seen in all figures that the total energy consumption is decreasing significantly in all months. The average monthly total heating and cooling energy consumption of Islamabad city reduces from 1.01 GJ to 0.68 GJ which is a significant decrease. Likewise, the average monthly energy consumption of Karachi and Lahore city are decreases from 1.54 GJ to 1.16 GJ and 1.67 GJ to 1.26 GJ. Whereas monthly energy consumption of Peshawar city shows a reduction of 0.39 GJ from 1.34 GJ to 0.95 GJ. The Quetta city shows 40% saving in annual energy consumption as the average energy consumption of Quetta is decreased from 0.94 GJ to 0.55 GJ.

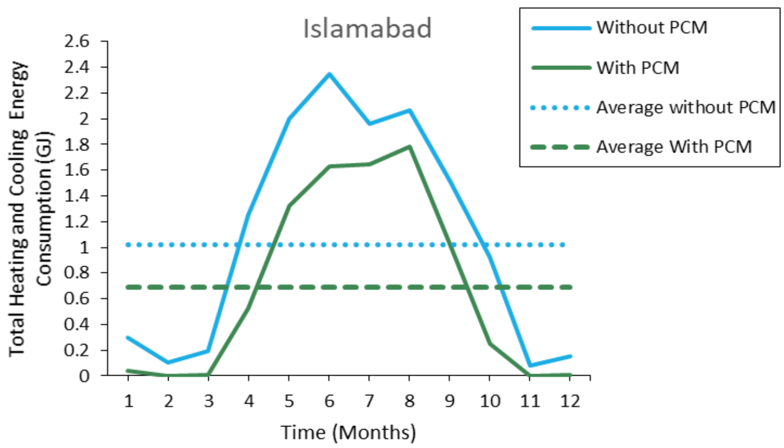


FIGURE 4.20: Total Energy Consumption in Islamabad

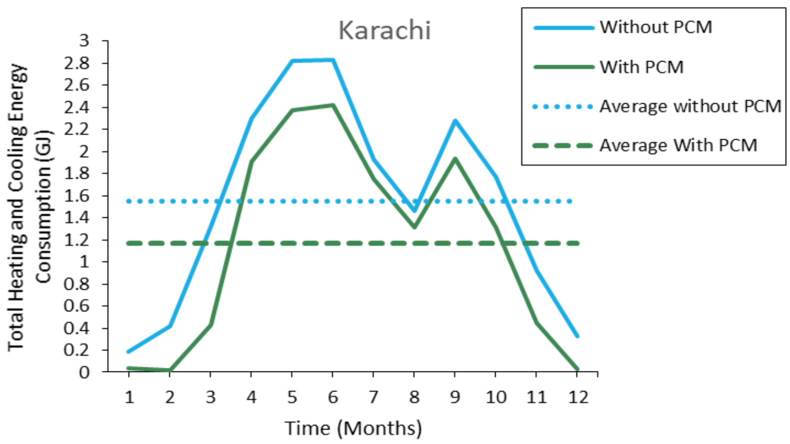


FIGURE 4.21: Total Energy Consumption in Karachi

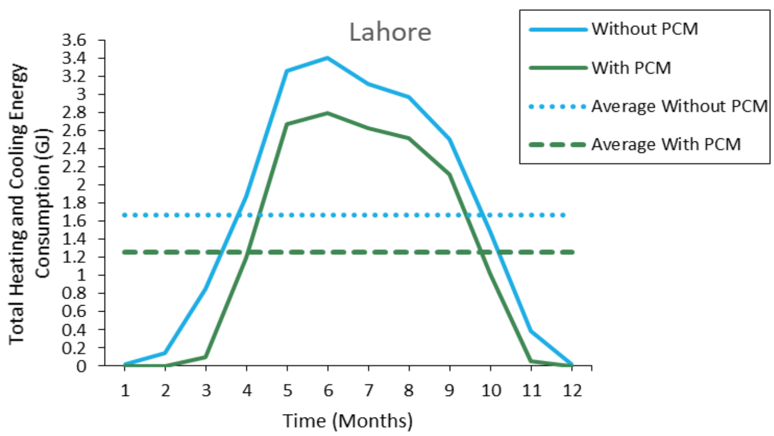


FIGURE 4.22: Total Energy Consumption in Lahore

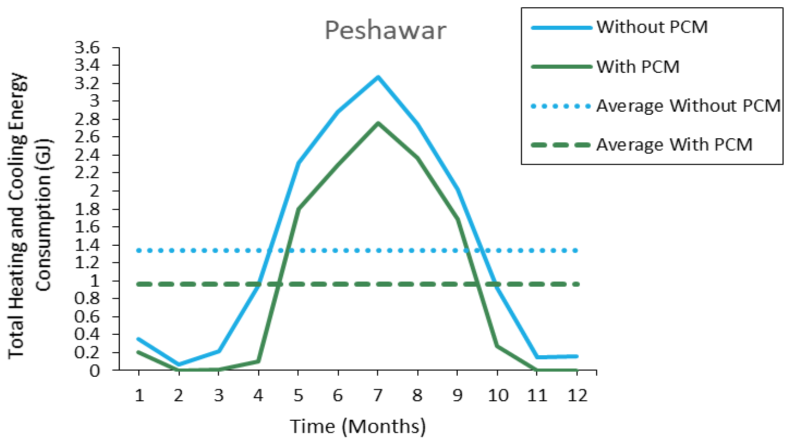


FIGURE 4.23: Total Energy Consumption in Peshawar

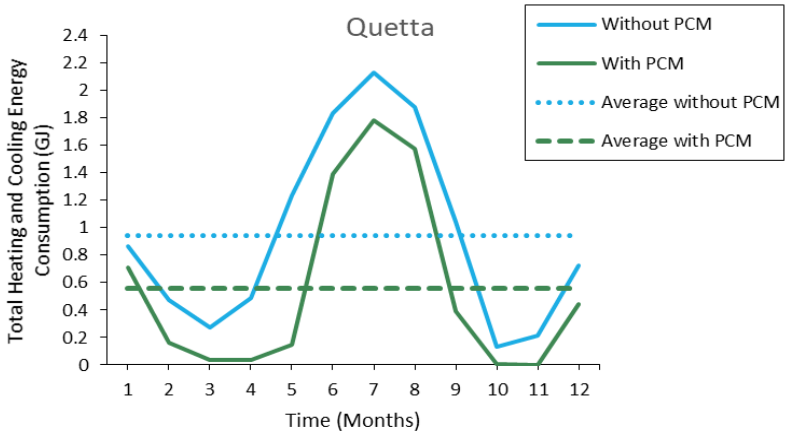


FIGURE 4.24: Total Energy Consumption in Quetta

The effect of PCM integration in building envelopes of 5 different climates is analysed in this section and it is concluded that reduction in energy consumption with the use of PCM might vary but PCM integration shows a significant reduction in total heating and cooling energy consumption. PCM integration is recommended in all climates as significant saving in total energy consumption can be achieved with the use of PCM.

4.6 PCM Integration in Multizone Residential House

Similar to basecase house, a 40 mm layer of optimal PCM CrodaTherm24 is installed on internal side of external walls and roof of multizone single storey house and building energy consumption is evaluated by performing simulations in selected five cities. Figure 4.25 shows that total heating and cooling energy consumption of this multizone house declined in all 12 months when simulated with weather data of Islamabad and average monthly heating and cooling energy consumption reduces from 1.75 GJ to 0.97 GJ with an annual energy saving of 45%. Figure 4.26 shows similar trend of reduction in total heating and cooling energy consumption in same house when it is simulated in remaining four cities Karachi, Lahore, Peshawar and Quetta for 1 year. In Karachi, average monthly energy consumption reduces from 2.66 GJ to 1.72 GJ with an annual energy saving of 35%. Similarly, the average monthly energy consumption reduces from 3.09 GJ to 2.08 GJ in Lahore, 2.45 GJ to 1.60 GJ in Peshawar and 1.63 GJ to 0.82 GJ in Quetta with an annual energy average of 32%, 35% and 50% respectively.

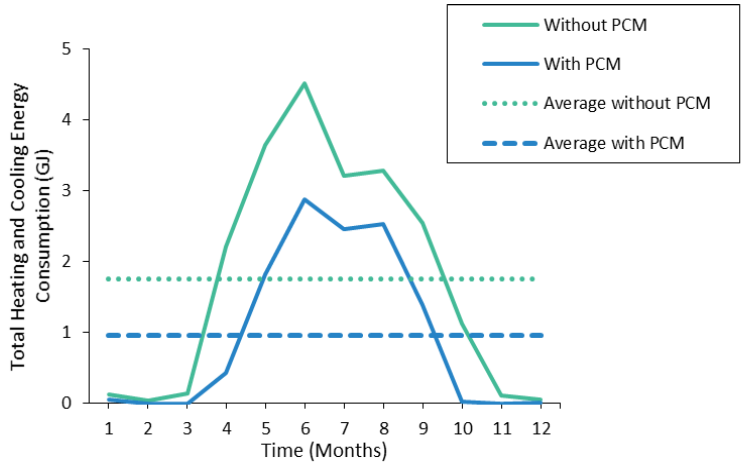


Figure 4.25: Total Energy Consumption in Islamabad in Single Storey House

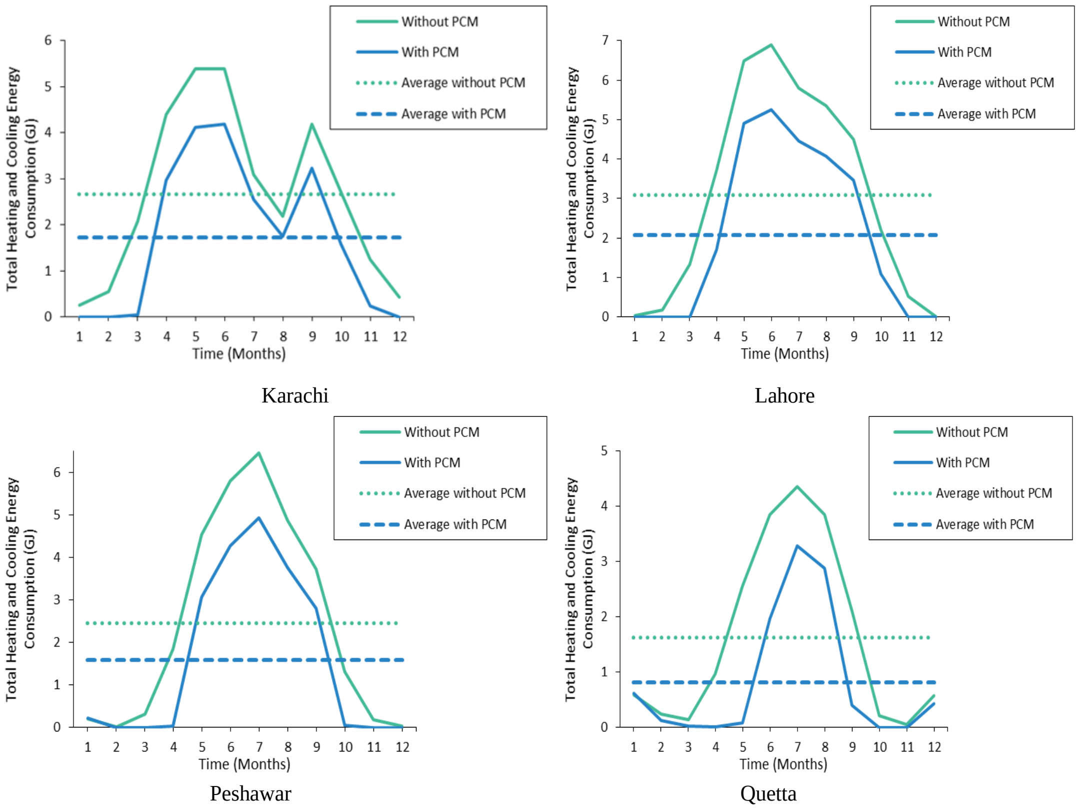


Figure 4.26: Total Energy Consumption in different cities in Single Storey House

Then a 40 mm layer of optimal PCM CrodaTherm24 is installed on the internal side of external walls and roof and building energy of this multizone two storey house to perform simulations in all five selected cities. The result of simulations for all cities are presented in Figure 4.27 showing that total heating and cooling energy consumption decreases with the use of PCM in all 12 months.

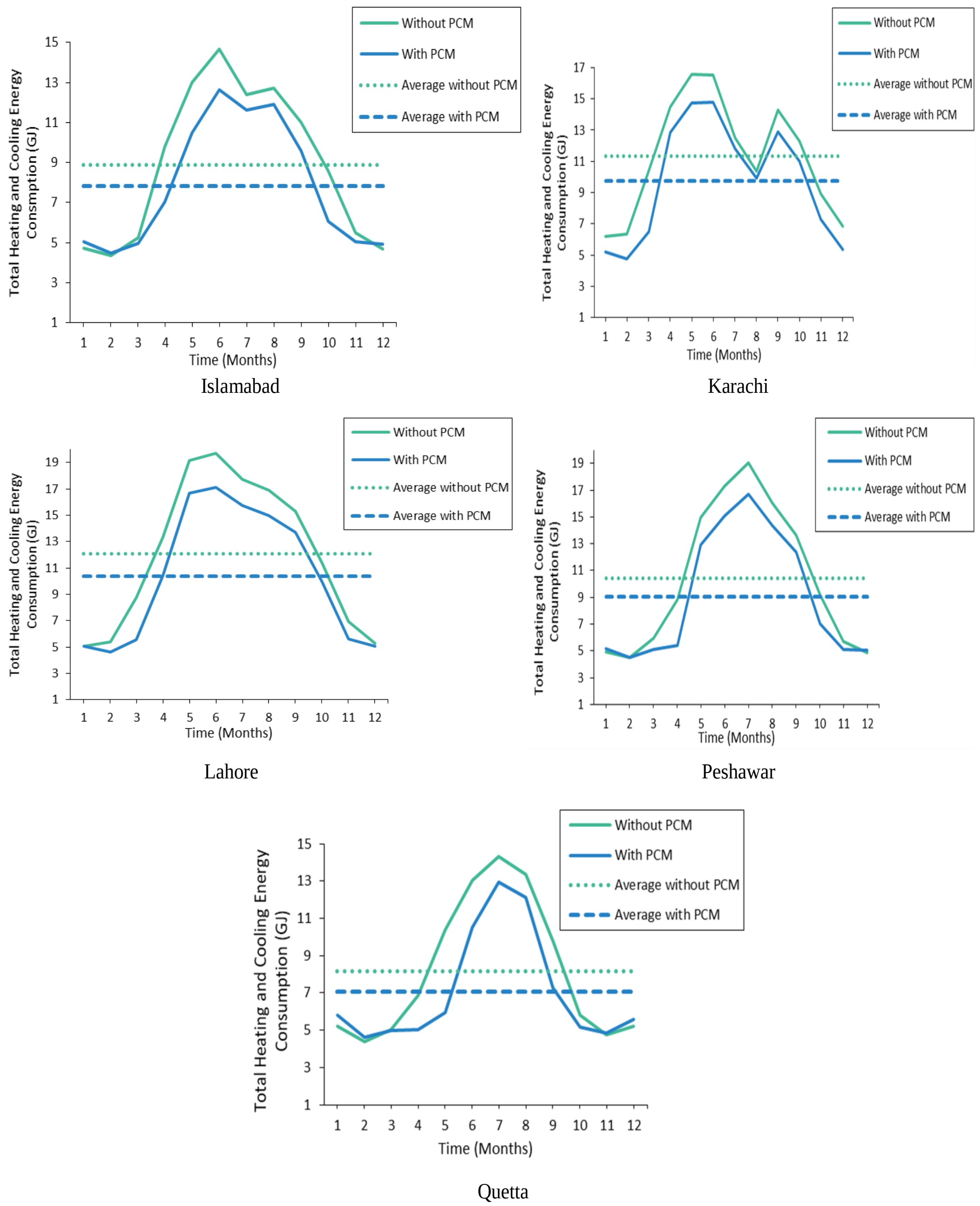


FIGURE 4.27: Total Energy Consumption in different cities in Two Storey House

The monthly average heating and cooling energy consumption in Islamabad reduces from 9 GJ to 7.8 GJ with an energy saving of 12% whereas in Karachi, it decreases from 11.3 GJ to 9.7 GJ showing annual energy saving of 14%. Similarly, annual energy saving of 13% is observed in Lahore, 13% in Peshawar and 14% in Quetta and monthly average energy consumption drops from 12.1 GJ to 10.5 GJ, 10.4 GJ to 9 GJ and 8.1 GJ to 7 GJ in Lahore, Peshawar and Quetta respectively.

Although both of these houses has same construction materials, location and orientation but number of windows and door, internal loads and schedule profile are different in each house.
The saving in energy consumption is also different in both houses and maximum energy saving is observed in single storey house comprises of only bedrooms and drawing room. It is also observed that simulation results of one specific house can not be applied on all houses of that particular climate.
Two storey house also involve a living room which is utilized by individuals of house most time of the day. Use of PCM will reduce energy consumption in all types of buildings as represented by multizone house when simulated in different climates, the amount of savings might vary.

4.7 Comparison of PCM and Thermal Insulation

The four selected insulations are applied separately in building envelope to select the best insulation in terms of annual energy saving. The dynamic energy simulation is performed for all insulations separately.
The 26% annual energy can be achieved with Polyurethane Foam whereas fiber glass and extended polystyrene can save 27% annual energy consumption as shown in Figure 4.28.
The annual energy saving of 28% can be achieved with expanded polystyrene insulation which is maximum, therefore expanded polystyrene is selected as optimal insulation for base case house simulated in Islamabad city only.

As already discussed, the thickness of expanded polystyrene is adjusted to meet U value criteria recommended by the government of Pakistan. The layers of optimal

PCM having same thickness of insulation are applied on the internal side of the walls and roof.

The use of insulation in building envelopes show total annual energy saving of 28% as compared to 44% with PCM when the same layer thickness is used as shown in Figure 4.29.

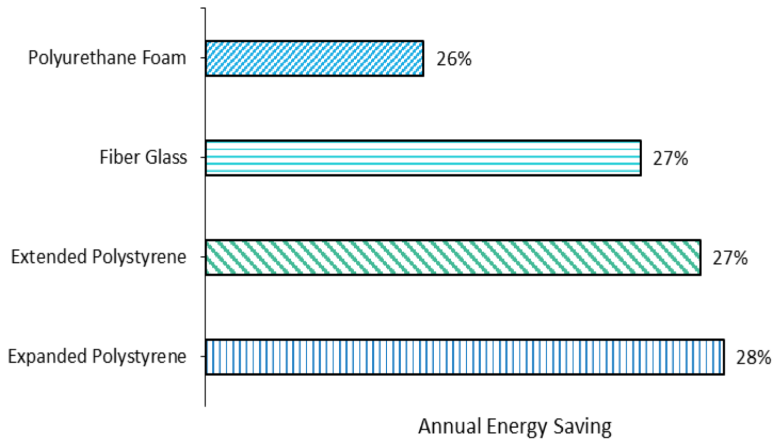


FIGURE 4.28: Percentage of Energy Saving with different Insulations

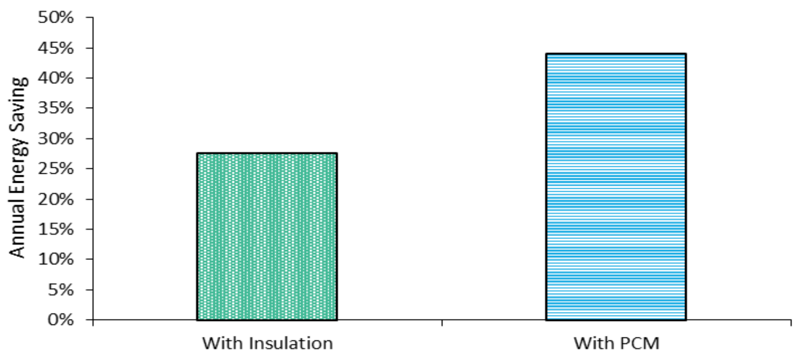


FIGURE 4.29: Energy Saving with Insulation and PCM

The percentage reduction in total heating and the cooling energy consumption is evaluated for PCM and insulation and compared with the base case house when no insulation layer or PCM layer is used. Figure 4.30 shows the dynamic energy simulation results consisting of total heating and cooling consumption. It can be seen that energy consumption is less with PCM as compared to optimal insulation. Moreover, if a layer of PCM with less thickness is installed, energy savings greater than insulations are achieved. Figure 4.9 already explained in Section 4.4.2 shows that's with 25 mm to 30 mm layer of PCM, approximately 30% saving in total heating and cooling energy consumption is achieved.

This suggested that PCM can save more energy with less volume if their installation is optimized. Besides, another factor thermal transmittance U-value of insulations and PCM is also considered. The U-value calculated for wall and roof with insulation is 0.56 W/m^2-K and 0.44 W/m^2-K meeting building code requirements suggesting the value of 0.57 W/m^2-K for wall and 0.44 W/m^2-K for the roof. However, the U-value for wall and roof with the PCM layer is calculated as 1.92 W/m^2-K and 2.06 W/m^2-K. Although the thermal transmittance values with PCM layer are higher but energy saving is also higher.

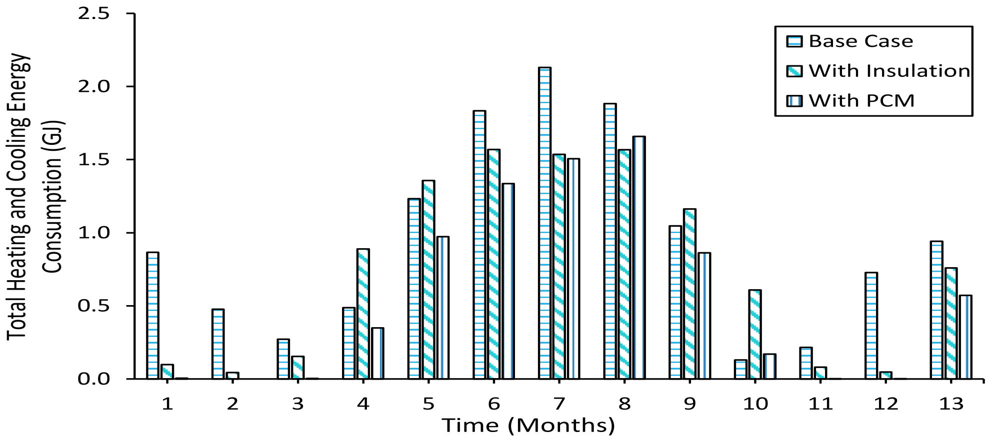


FIGURE 4.30: Comparison of Insulation and PCM

Chapter 5

Conclusions

Energy crises is one of the most burgeoning issue of present era due to increasing level of population, industrialization and urbanization. The key focus area of this research project is increasing need of energy in residential sector, specifically for heating and cooling purpose. A number of methods are under research to address this phenomenon, use of Phase Change Materials (PCM) in building envelops of residential building is one of the effective method as compared to traditional insulations. Therefore, the implications of PCM is investigated in this study considering different climate conditions in five cities of Pakistan with the help of numerical models. EnergyPlus, a building simulation software, is used to evaluate heating and cooling energy consumption by using *CondFD, TARP and DOE-2* algorithms. The heat addition by conduction, convention and radiation are measured in $4 \times 4 \times 3$ base case house, while using the traditional construction materials commonly used in residential building in Pakistan. Moreover, the internal loads such as occupants, lights and equipment are added in base case house and ideal HVAC system is used to maintain indoor temperature. A number of dynamic energy simulation are performed with varying parameters to calculate the amount of heating and cooling energy consumption to maintain the indoor comfort temperature. Then a PCM layer is added in this room to evaluate its effects on energy consumption and results showed 8% to 9% saving.

Furthermore, the implications of 15 different PCMs for energy saving are also investigated by performing simulations in different cities i.e. Islamabad, Karachi, Lahore, Quetta and Peshawar to find optimum PCM. Results suggest that Crodatherm24 with a melting temperature of 24 °C and 183 KJ/kg latent energy is an optimal PCM that can be used in these 5 cities for saving heating and cooling energy consumption. A maximum saving of 14% with CrodaTherm24 for the base case house is achieved in Islamabad and Quetta city and 11 to 12% in Karachi, Lahore and Peshawar. Different parameter of PCM such as thickness, placement in walls and roof are also considered to examine the their effect on total energy saving. It is found that building energy consumption can be reduced if PCM is placed on inner sides of walls and roof of building envelops built in Pakistan. The thickness of the PCM layer has direct relation with energy-saving, an optimum thickness of 40 mm should be used.

Lastly, when CrodaTherm24 PCM layer with optimal thickness of 40 mm is applied as inner most layer of external walls and roof in a traditional single storey multizone house, maximum energy saving of 50% can be achieved in total heating and cooling consumption in Quetta and similarly, 45% in Islamabad, 35% in Karachi and Peshawar and 32% in Lahore. Furthermore, energy saving of 14% can be achieved in Karachi and Quetta, 13% in Lahore and Peshawar and 12% in Islamabad in multizone two storey with the use of optimal PCM in building envelope. The amount of energy saving in total heating and cooling energy consumption of two storey house is less as compared to single storey house as two house involve higher internal loads as well as extra living area with high infiltration rate. Moreover, PCM is placed in only external building envelope not in ceiling which causes less amount of energy saving.

As the study has shown the positive impacts of PCM and its suitability for different weather conditions in Pakistan, recommendations are made for future research.

- Future research is needed to assess the effect of other parameters of PCM i.e. thermal conductivity and transition temperature on energy consumption of building.
- Economic feasibility of implementation of PCM in building enevelops must be measured to assess the practiability.

- A comparative study of PCM with traditional material is needed to assess its cost effectiveness in long term.

- Future research is required to assess the effect of PCM thickness on energy saving when it varies between 50 mm to 70 mm.

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