Effectiveness of Passive Measures on Energy Efficiency and Carbon Production of Commercial Building in Various Climate Zones

By

Rohan Hussain

(Registration No: 330573)

Department of Mechanical Engineering

School of Mechanical and Manufacturing Engineering

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

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Rohan Hussain

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Supervisor: Dr. Zaib Ali

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1. Name: Waqas Khalid Signature:

2. Name: Abdullah Jamil Signature:

Supervisor: Zaib Ali Signature:

Date: 08 - Oct - 2024

Head of Department

08 - Oct - 2024

Date

COUNTERSINGED

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Student Name: Rohan Hussain Signature: ________________

Examination Committee:

a) External Examiner 1: Name Signature: ________________

(Designation & Office Address)

Dr Waqas Khalid, SMME NUST

b) External Examiner 2: Name Signature: ________________

(Designation & Office Address)

Dr Abdullah Jamil, SMME NUST

Supervisor Name: Dr. Zaib Ali Signatu ________________

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ABSTRACT

Climate change poses a significant threat, resulting in rising global temperatures and increased energy demands. Commercial buildings, being substantial consumers of energy, are at the forefront of this challenge. This research addresses a critical gap in the literature, which lacks comprehensive studies on the long-term efficacy of passive design strategies under both current and future climate conditions, particularly in the context of rapidly urbanizing regions like Pakistan. This study investigates the role of passive design measures in enhancing the energy efficiency of commercial buildings and reducing carbon emissions across different climate scenarios. Using building energy simulations for a commercial structure, the research explores the effectiveness of various insulation materials, including expanded polystyrene, extruded polystyrene (XPS), and bio-phase change materials (BioPCM), under present and future climate conditions projected for 2050 and 2080. Results demonstrate that expanded polystyrene applied on the roof and polyurethane foam on the walls provide the highest energy savings, achieving reductions of 21.9% in current climates, 15.1% by 2050, and 9.1% by 2080. Additionally, a 20% reduction in carbon emissions was observed. When applied to Karachi's climate, these passive measures yielded an 18.88% reduction in energy consumption, indicating their broad applicability. The study emphasizes the potential of passive strategies in achieving Net Zero Carbon goals and promoting sustainable development.

Keywords: passive methods, passive design measures, net zero carbon, building energy simulation, climate change, sustainable

CHAPTER 1: INTRODUCTION

The global focus on reducing energy consumption and minimizing carbon emissions has intensified in recent years, particularly in the built environment. Commercial buildings, as significant energy consumers, contribute substantially to greenhouse gas emissions. Improving energy efficiency in such buildings has therefore become a priority for mitigating climate change. Passive design measures, which rely on the building's architecture and environmental context rather than mechanical systems, offer a sustainable approach to enhancing energy efficiency. These measures include natural ventilation, thermal mass, solar shading, and optimized building orientation, among others.

The effectiveness of passive design strategies, however, varies depending on the climatic zone in which the building is located. Different climates present unique challenges and opportunities for energy conservation and carbon reduction. For instance, cooling demands are more prominent in hot climates, while heating efficiency is critical in colder regions. This paper explores the effectiveness of various passive measures in improving energy efficiency and reducing carbon production in commercial buildings across diverse climatic zones. By understanding how these measures perform in different environments, architects and engineers can optimize building designs to achieve both energy savings and environmental sustainability.

1.1 PASSIVE MEASURES

Passive measures in building design refer to strategies that enhance a building's energy efficiency without relying on mechanical systems like heating, ventilation, and air conditioning (HVAC). These measures use the building's architectural features, materials, and environmental conditions to regulate temperature, provide natural lighting, and improve comfort. They are designed to work in harmony with the local climate, reducing the need for artificial energy use and thereby minimizing carbon emissions.

1.2 CLIMATE CHANGE IN THE PERSPECTIVE OF LAHORE, PAKISTAN

Lahore, the capital city of Pakistan's Punjab province, is one of the most densely populated and rapidly urbanizing cities in South Asia. Like many cities in developing countries, it is increasingly vulnerable to the impacts of climate change. The city's geographical location, socioeconomic factors, and rapid industrialization all contribute to how it experiences climate change.

1.2.1 RISING TEMPERATURES

One of the most apparent effects of climate change in Lahore is the rise in average temperatures. Over the past few decades, the city has been experiencing more frequent and prolonged heatwaves, with summer temperatures often exceeding 45°C (113°F). The increasing heat is exacerbated by the urban heat island effect, where concrete structures and asphalt absorb and retain heat, making urban areas significantly warmer than surrounding rural regions.

This rise in temperature impacts not only public health—causing heat-related illnesses like dehydration, heatstroke, and respiratory issues—but also increases energy demand, as more people rely on air conditioning for cooling. The higher demand for energy leads to greater consumption of fossil fuels, further contributing to carbon emissions and worsening climate change.

1.2.2 IMPACT ON BUILDING ENVIRONMENT

As temperatures increase due to global warming, buildings face greater challenges in maintaining thermal comfort. Higher temperatures lead to increased reliance on air conditioning and other cooling systems, which can drive up energy consumption. In hot regions, buildings may require more energy-efficient designs to cope with prolonged heatwaves, while maintaining comfort for occupants.

Moreover, in cities, where concrete and asphalt absorb and retain heat, the urban heat island effect exacerbates the impact of climate change. This makes cooling even more critical, putting additional strain on building energy systems.

Prolonged exposure to heat can degrade materials used in construction, such as roofing, insulation, and façades, reducing their lifespan and increasing maintenance costs.

1.3 NET ZERO CARBON

Net Zero Carbon is a concept aimed at balancing the amount of carbon dioxide (CO_2) emitted into the atmosphere with an equivalent amount of CO_2 removed, resulting in no net increase in global carbon emissions. This is an essential goal in addressing climate change and limiting global warming to 1.5°C or 2°C, as outlined by international agreements such as the Paris Agreeme1.nt. Achieving net zero carbon requires significant reductions in greenhouse gas (GHG) emissions across all sectors, as well as efforts to capture and store or offset any remaining emissions.

1.3.1 OPERATIONAL CARBON EMISSIONS

These are emissions resulting from the energy used in a building during its operation. This includes heating, cooling, lighting, appliances, and other electrical uses. The primary goal is to reduce these emissions through energy-efficient technologies and renewable energy sources.

1.3.2 ENERGY EFFICIENCY

Implementing energy-efficient design strategies is the first step toward achieving net zero. This includes optimizing insulation, improving building envelopes, using energy-efficient windows, and installing energy-efficient HVAC systems. Passive design strategies that maximize natural light, ventilation, and thermal mass can also significantly reduce energy demand.

1.4 OBJECTIVES

The objectives of this research are as follows:

- To investigate the applicability of passive cooling measures on the proposed building.
- Compute the climate data incorporating future climate change and perform building energy simulation on base case scenario and when proposed interventions are applied.
- Evaluate the results of both scenarios and compute the energy variation between both.
- Evaluate the effect towards achieving Net Zero Carbon.

CHAPTER 2: LITERATURE REVIEW.

2.1 REVIEW OF LITERATURE

[1] performed an analysis on a 1-BHK vernacular house in North-East India. The location has summer and winter temperatures ranging between 31-39 degree-Celsius and 20-30 degree-Celsius respectively with relative humidity greater than 75 % and just under 90 %. The model was developed in DesignBuilder and simulations were carried out through its EnergyPlus module while also verifying the results experimentally. The passive strategies that were investigated include optimization of wall construction details, varying orientation of the house, shading, roof construction detail, window to wall ratio (WWR), window glazing and type of ventilation. The results indicate that the best combination of passive methods is obtained by using a wall which is externally bonded with paraffin layer, installing false ceiling along with double blue 6 mm glazing with air in between and 1.5 m overhang for shading, A WWR of 0.32 and orientation of the site being 167 degrees from North in the clockwise direction. This indicates that best orientation lies somewhere in the South-East direction. The orientation minimizes lighting loads and is best for utilizing solar heat during winters. These passive measures significantly reduced the cooling load by approximately 51 % while also reducing carbon-dioxide emissions by almost 30 %.

Another study conducted by [2] focused on simulating a three-story commercial building in different cities in China which could serve as templates for different climatic zones across the country including the relatively colder areas, hotter areas and also those which have either warmer winters or colder winters. The investigation primarily focuses on using polymer-based coatings on roofs and walls along with window glazing to improve thermal comfort. The polymer in question is poly(vinylidene fluoride-cohexafluoropropene) ($P(VdF\text{-}HFP)_{HP}$) which is structurally porous and demonstrates remarkable cooling characteristics and is also feasible for manufacturing on a large scale. For roof improvement, a comparison between typical white paint and polymer based white paint is carried out along with using polymer based radiative red and yellow paint coatings for walls. In addition to that windows using insulated green low e glass and insulated clear grey glass with double glazing were compared as well. The study concludes that the polymer based white roof paint is more suitable with yellow wall coating being also more beneficial. Both the selected roof and wall improvements resulted in below ambient temperatures 40 % and 15 % of time respectively. Moreover, the insulated clear grey glass prevented the transmissibility of solar energy by approximately 54 %. Energy cost savings are on average $1200 per year in hot cities while the average for colder cities is about $1100 per year.

[3] investigated the application of a PCM based passive cooling solution on a residential building comprising of a single room located in Jaipur, India. The city has hot summers and consists of mild winter temperatures. Average temperature during the summer is around 30 degree-Celsius and during winters it is approximately 16 degree-Celsius. The PCM used is called HS 24 which has a phase change temperature of 24 degree-Celsius. The PCM was applied in encapsulated form between the external and internal face of the walls. The simulation was carried out in EnergyPlus and results of non-PCM and PCM integrated building were compared. The study examined temperature variation throughout the year with temperature drop in May being almost 9 degree-Celsius. The PCM integrated building was able to maintain the thermal comfort temperature of 27 degree-Celsius whereas the non-PCM integrated building allowed temperature to rise up to 36 degree-Celsius.

The application of Bio-PCMs along with evaluating the effect of cool roof paintings, aluminum roof and autoclave aerated concrete (AAC) block walls was investigated by [4]. These measures were employed in portable cabins which were then simulated. The results showed that cool roof painting caused energy saving of approximately 3 % whereas aluminum roof reduced energy savings by around 2 %. In warmer days however the marginal variation even caused rise in air conditioning requirement in some instances. Bio-PCMs were used in the category Type 1270. These PCMs were applied to the interior side of walls and roof. The results indicate that almost 20-23 % reduction in energy was observed in the desert climates of Kuwait and Australia but a remarkable reduction of 50 % was observed in South India. AAC block walls also improved savings in cooling which were on average around 35 %.

[5] carried out a simulation on a radiant cooling system installed under the concrete floor of a house with forced ventilation occurring under the floor. The said house is in Indonesia where maximum temperature recorded reaches 30 degree-Celsius. Ventilation is achieved by installing louvres under the floor with fans on both sides thereby creating a tunnel under the floor with the PCM layer on its roof. At night the tunnel is opened on both sides and the fans allow the cool night air to enter it. Heat exchange takes place where the high temperature PCMs are cooled. The PCM layer is then ready to absorb heat in the daytime and allow reduction in temperatures. This procedure is facilitated by natural ventilation in the house during daytime. The PCM used is paraffin which is in the form of aluminum encapsulation and is attached on the backside of the floor panels. This system was evaluated both through simulation and an experimental approach and it was concluded that thermal comfort was achieved around 69% of tie throughout the year.

[6] conducted an analysis of two-story office building and simulated it in eighteen different cities in India having maximum average temperatures of around 30 degree-Celsius. The passive measures employed include using roof and wall insulations, single- and double-layer glass, and using optimum site orientation and window-to-wall ratio. The insulation material used in roof insulation was expanded polystyrene whereas for wall insulation, fiberglass and polyurethane foam were used. The results showed that insulation applied to the external side of the wall or in the middle of the wall was most beneficial. Moreover, the insulation thickness required is approximately 140 mm and 100 mm for roof and wall respectively. In addition to that relationship between the passive measures was also studied. It was found that roof insulation thickness is not dependent on window-to-wall ratio and site orientation. However, for wall insulation, marginal variation was observed in energy requirement and showed that insulation thickness requirement decreases with increase in window-to-wall ratio. For window types, the best results were obtained by using double-layer green 6 mm/13 mm air windows. The investigation also studied the correlation between the application of reflective coating on walls and roof with insulation thickness. The study concluded that there was no relation between insulation thickness and reflective coating for walls but for the roof, insulation thickness reduced to less than 10 mm in most climatic regions whereas in colder areas the requirement was around 25 mm. In addition to that, the material best suited was polyurethane for no

reflective coating scenario and fiberglass with reflective coating. The analysis concluded that around 10 % to 30 % energy requirement was reduced for HVAC.

The integration of PCMs in walls was also studied by [7]. A single room with a clear double-glazed window was simulated. The PCMs used in the analysis are variants of paraffin, namely the Rubitherm RT-HC used in aluminum encapsulated form. The PCM was placed in internal and external configuration and results were obtained for the entire year. Internally, it was placed between the brick layer and the gypsum board layer. The site location is in Benguerir, Morocco which has an average daily maximum temperature of 41 degree-Celsius in summer and around 8 degree-Celsius in the winter. PCM integration was studied in single layer and triple layer configurations. The best PCM was found to be RT-28 HC and the optimum thickness was computed to be 1.5 cm with both cooling and heating requirement decreased by around 14 %. With respect to location, PCM placed on the external side was beneficial in winters whereas PCM placed on the inside layer was suitable for cooling. Moreover, PCM placed on the South wall demonstrated better results as compared to other walls. The triple-layer PCM provides the best results with the configuration being RT21-RT25-RT28 HC with an annual energy saving of approximately 15 % and a break-even period of thirteen years.

[8] has studied the use of glass coatings and energy storage cement to reduce energy usage. The specific compounds used are $Cs_xWO_3@TiO_2$ coated glass (CG) and polyethylene glycol (PEG)/halloysite nanotubes (HNTs) energy storage cement (CP/F). A residential room was used in the simulation. Two different locations were used for the simulation namely Hong Kong and Changsha. Both cities exhibit maximum summer temperatures of 30 degree-Celsius and 34 degree-Celsius respectively whereas the winter temperatures are 19 degree-Celsius and 8 degree-Celsius respectively. The results show that the glass coating blocked 90 % infra-red radiation while also allowing 80 % light to pass through. The combination of both measures yielded better results than if they were used separately by decreasing the indoor room temperature by up to 10 degree-Celsius and temperature difference up to 7 degree-Celsius. The break-even period of this combination is seven years for Changhsa and five years for Hong Kong.

A residential building in Kerala, South India has been considered by [9] with the climate being mostly warm and humid making summers uncomfortable. The dry bulb temperature ranges from 25-30 degree Celsius and relative humidity is around 75 %. The passive ECMs (energy conservation measures) studied include using energy efficient bricks, insulating plaster, embedded roof and wall insulations, cool roof painting, green roofs and PCMs installed in walls and roof. Simulation results show that AAC has the lowest U value and specific heat capacity hence its energy saving potential is substantial as compared to other energy efficient bricks. Applying insulating plaster on both sides can reduce energy usage by 4.6% however, cost becomes a factor to examine. All embedded insulations have shown approximately equal energy saving potential. Reflective white paint shows better performance. 700 mm soil bed shows energy savings of approximately 7.39%. PCM under wall and roof shows saving of approximately 6 %.

[10] performed a simulation, evaluating the effectiveness of retrofitting measures in a one-story single-family house having a floor area of 155 m2 in Jordon. Temperatures reach up to a maximum of 31 degree-Celsius in the summer. A comparison was carried out by first examining the base case scenario and the results by applying different retrofitting measures. Subsequently, the load reduction and affordability of the proposed measures was checked. The results indicate that roof and wall insulation through polystyrene films produced the best reduction in cooling ranging from approximately 6% to 13%. The economic analysis shows that by using these retrofitting measures, energy usage becomes affordable for at least 83%-85% of Jordanian households and the measures are affordable for around 73% to 78% people. However, the initial capital cost is a concern which can be overcome by government support through financing programs.

[11] retrofitted a garment factory in Bangladesh by employing passive cooling techniques on the factory’s rooftop. The measures consisted of using a green roof, shaded roof and an insulated roof and compared it with the baseline scenario of a concrete roof. The results showed an average decrease of 2 degree Celsius with the shaded roof showing the greatest decrease of 1.9 degree Celsius.

[12] evaluated the placement of PCMs to achieve the best thermal comfort. In this regard, a typical office building was selected in Zhenghzou, China with a maximum summer temperature of 32 degree-Celsius and winter temperature of 6 degree-Celsius and the proposed placements were studied. Paraffin was selected as the PCM in this simulation. The results indicate that placing PCMs on external walls and roof provides the greatest cooling effect. It also concludes that if the same mass of PCM is considered then the greatest effect is observed by placing PCM layer on the roof. The reduction rate of uncomfortable hours can range from 24% to 40%.

[13] has analyzed the integration of PCM and EPS insulation in single wall (SW) buildings and double wall (DW) buildings. The analysis has been carried out for a residential building located in Tunisia. Tunisia is a region characterized by maximum summer temperature of 32 degree-Celsius. In addition to passive measures, a heat pump has also been used for air conditioning. The PCM used is the Infinite R which is used in a variety of applications commercially. The study concluded that the double wall is much more energy saving tha the single wall due to its high thermal resistance. If using both EPS insulation and PCM, the thickness of EPS can be decreased as PCM has greater energy saving potential. The most suitable thickness of EPS insulation is 6 cm. It is also stated that using two PCM layers in double wall configuration is far better than using a single layer. Energy reduction is around 73 % for single wall and 76 % for double wall.

[14] has investigated the benefit of natural ventilation only in a 9-story apartment building divided into seven thermal zones located in Belgium. Single sided ventilation and cross ventilation have been studied with thermal comfort being achieved 66% in single sided and 79% with cross ventilation.

[15] carried out an experimental study to determine the cooling effect of using PCM layer on the inside layer of the roof and walls. The PCM material salt hydrate SP24E (Rubitherm) is encapsulated in Compact Storage Module (CSM) aluminum plates (dimensions: 40 × 30 × 15 mm and weight: 2 kg). The experiment incorporated an active ventilation fan during nighttime to cool the PCM which would then be melted by storing heat during the daytime. The results indicate that the proposed system is adequate for

ambient temperatures ranging from 30 degree Celsius to 35 degree-Celsius which is suitable for Mediterranean summer conditions but may fail in subtropical humid climate consisting of occasional heatwaves. The fan used to cool the PCM during nighttime may also add to the operational costs of the system and will need to be studied before implementation.

[16] reviewed the application of passive techniques in residential buildings. Several passive measures were investigated out of which six measures were deemed to be the most effective especially in hot and humid climates. These measures included enhancing the thermal resistance properties of exterior walls, roofs, window glazing, shading, and using optimum cross ventilation. Using roof insulation with high thermal resistance can reduce colling load by approximately 30 % and combining it with using reflective paint having low emissivity and shading can further decrease it up to 36 %. Furthermore, roof shape is also a contributing factor with a vault shaped roof reducing cooling demand by 26 %. Wall insulation is a critical factor in hot and humid climates and similar insulation characteristics as used in the roof are required. Using reflective glazing, low E glass and double pane windows can help in reducing heat gained through solar radiation and contribute to 45 % decrease in energy use. All these passive measures combined can reduce overall cooling load by up to 65 %.

[17] carried out a review of existing passive methods from a technical and financial aspect as well. For thermal insulation, it is preferable to install it on external walls of buildings. The best material for this purpose was found to be XPS resulting in around 15 % decrease in HVAC load and a break-even period of approximately two years with an ROI of 28 %. By using PCMs inside walls and roof insulation, an average 5 % decrease in energy requirements was observed in five cities of Iran where the maximum summer temperature rises to 38 degree-Celsius. The optimum thickness of PCM has been found to be 10 mm with a melting point temperature range between 21-26 degree-Celsius. The payback period is approximately sixteen years, which is considerably higher than other measures due to its high capital cost.

[18] has performed a review on the possibility of using Radiative Sky Cooling (RSC) on building roofs and investigating its impact on building energy performance. The review showed that on average RSC can provide cooling of about 40 W/square-metres which is relatively low and as roof area is significantly less, it is essential that RSC be deployed on building facades as well to extend its area. Moreover, RSCs can provide a temperature reduction of up to 3 degrees-Celsius and hence it is necessary that RSC be integrated with other passive or active cooling systems for greater effect.

A review of passive measures based on different types of climates was carried out by [19]. Climates were classified into the following categories: Type A (Tropical), Type B (Arid), Type C (Temperate), Type D (Cold), Type E (Polar), Type H (Highland). For Type C, PCM insulation is recommended in the inner wall and under the floor as well. It is also stated that PCM insulation alone poses problems due to overheating issues and hence should be used in conjunction with natural ventilation.

2.2 SELECTION OF BUILDING TYPE

With reference to the literature reviewed in the preceding section, it is found that most of the studies have been performed in residential or office buildings with the latter being in the majority. Moreover, several studies focus on simulating only single rooms whereas it is essential that a complete building unit should be studied to investigate the effect of passive methods on thermal comfort. Therefore, it is concluded that a commercial building can be studied which would provide a novel area of investigation and such research would be valuable in the sense that it would encourage use of passive methods in commercial applications.

2.3 SELECTION OF PASSIVE METHOD

The most commonly used passive cooling methods include using PCMs, roof insulation, wall insulation, and window glazing. These practices can be employed in our chosen building type and its effects can be studied. It is also highlighted that these methods would have to be used in conjunction with active cooling methods and as such a chillerbased HVAC system can be used. Hence, the reduction in cooling load requirement can also be studied because of using passive measures which would ultimately reduce the size of the system. For PCMs, the most common PCM has been observed to be paraffin. In the proposed study a selection of materials can be studied other than paraffin and effects can be compared. In roof and wall insulation, it has been preferable to use double insulation and even for single insulation layer, it has been found that it is better on external surface of the wall. Double glazing windows is found to be much better than single glazing, however cost considerations in glazing and PCM based methods will have to be taken into account.

2.4 NET ZERO CARBON

[20] has presented an assessment of a residential Net-Zero building in Albania. A combination of passive and active interventions were proposed and assessed. The scenarios are stated as follows:

- Wall Insulation resulting in combined U Value of 0.380 W/m2.K
- Roof Insulation resulting in combined U Value of 0.350 W/m2.K
- 5.5 kW Solar PV Installation

The assessment yielded favorable results when the passive measures were combined with on site solar photovoltaic installation. The results indicated that the proposed measures would result in the building towards moving 80% towards the goal of Net-Zero Building.

[21] performed a case study on a one-story construction located in the Research and Development Framework in Benguirr, Morocco. The climate is characterized as hot and semi-arid. The building was analyzed in its base case scenario and proposed scenario to evaluate the goal of moving towards Net-Zero. Therefore, polyurethane insulations were used in both roof and walls in addition to using red brick for exterior walls and compression slabs, concrete and bitumen for roof. The corresponding U values are 0.44 W/m2.K and 0.52 W/m2.K respectively. The same was combined with a 3.3 kW Solar PV system to offset the annual embodied and operational carbon emissions.

[22] studied a residential villa situated in the southeast of Kerman, Iran. The region has hot and dry summers and hence it is similar to climatic conditions of Pakistan. A number of wall insulations were considered including glass wool insulation, polyurethane foam and stone wool insulation. Polyurethane foam presented the most favorable results showing a 33.70% decrease in energy consumption. The remaining energy offset was achieved by installing a wind turbine.

[23] conducted a case study on a high-rise building Costain House located in Manchester, UK. It is a three-floor modern office building block, consisting of multiple offices and conference rooms. The U Value of the external wall and roof is 2.45 W/m2.K. The proposed interventions of covering the roof with sheep wool (thickness 0.15 m) and installing insulation board (thickness 0.7 m) result in reducing the U Value to 0.251 W/m2.K and 0.256 W/m2.K respectively contributing to the goal of net zero in this building along with renewable options as well.

[24] reviewed the designs of several buildings in different climatic conditions thereby drawing a comparison between their initial states and proposed passive measures that are applicable for achievement of net-zero emissions. The research outlines the proposed construction details of exterior walls, roof and partition walls describing their cross sections with their used materials and corresponding U-Values which are 0.330 W/m2.K, 0.180 W/m2.K and 1.570 W/m2.K respectively for temperate regions. Pakistan has a temperate climate and hence the measures employed in this study can be investigated as well. The measures used resulted in an energy use reduction of up to 35% in the temperate region.

[25] performed a case study on a four-story office building which is an office for the University of Tehran Science and Technology Park (UTSTP) located in Tehran, Iran. Iran has a dry-summer subtropical climate with mean summer temperature of 31.5 degree-Celsius. Aerogel is applied in the external wall with thickness 40 mm along with using Bio-PCM 91 having thickness of 14 mm. The PCM case is simulated for it being installed in the outer and inner layer of the wall. The aerogel insulation reduced heating and cooling loads by 22.9% and 3.05% respectively and carbon emissions by 5.39%.

CHAPTER 3: METHODOLOGY

The building under study is an office building complex consisting of three separate buildings namely, Engineering, Operations and CEO Office. This building has been modelled in the base case scenario for applicability of passive design measures in the climate of Lahore, Pakistan where it is located. By applying passive design measures, significant reduction in energy usage, resulting in decreasing the cooling load and heating load thereby leading to a more comfortable environment for its occupants.

The application of passive measures not only contributes to the reduction in energy demand but also plays an essential part in lessening the greenhouse effect. This is because, by using passive design measures, we lower the energy consumption of the active cooling and heating systems already installed in the building which leads to decreased carbon dioxide production. The novelty in this research is that the application of passive measures has been studied with respect to effect on carbon dioxide production along with evaluating the effectiveness of passive design measures in future climate change scenarios of 2050 and 2080 in addition to simulating the same building in a different climatic zone of Karachi.

This work therefore investigates the application of passive design measures individually on the building. The most effective interventions are then determined through this procedure. Subsequently, the interventions are applied on the building by taking into consideration, the goal of achieving Net Zero Carbon emissions. The interventions selected to model the Net Zero Carbon building by keeping the Thermal Transmittance (U-Value) approximately 0.2 – 0.3 W/m2.K as evident from the existing literature. The Net Zero Carbon building is then simulated in 2050 and 2080, and results evaluated. Moreover, the same building is simulated in Karachi so that the impact of passive measures on a different climate can be studied as well. Conclusively, the energy reduction in each case is studied and results discussed.

3.1 BUILDING COMPLEX GEOMETRY AND INPUT PARAMETERS

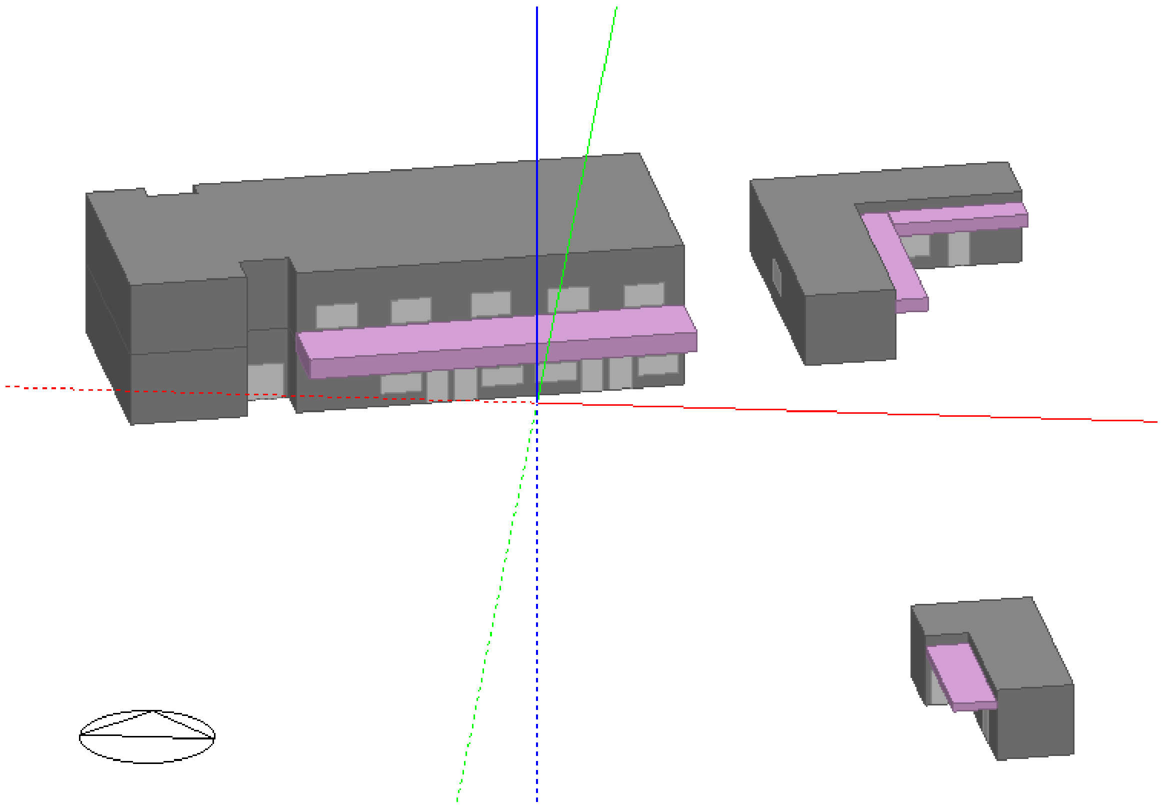

Figure 3.1.1: Office Complex Layout

Engineering	
Parameter	**Description**
Building Type	Office
No. of Floors	G+1
Total Floor Area	
Wall Construction	0.6 in Cement Plaster Mortar - 10 in Brick - 0.6 in Cement Plaster Mortar
Roof Construction	0.7480 in Asphalt - 0.5120 in Fiberboard - 2.920 in Cast Concrete
Glazing	Single Clear with Aluminum Frames
Air Infiltration	0.7 ACH
No.of Occupants	Variable
Lighting Power Density	0.025 W/ft^2
Equipment Power Density	1.0935 W/ft^2
Cooling Set Point	75.2 F (24 degree Celsius)
Heating Set Point	71.6 F (22 degree Celsius)
Air Conditioning System	Split Air Conditioners
Heating and Cooling Period	As per defined schedules of each zone

Table 3.1.1: D&E Building Construction and Input Parameters

Operations	
Parameter	**Description**
Building Type	Office
No. of Floors	Single Storey
Total Floor Area	
Wall Construction	0.6 in Cement Plaster Mortar - 10 in Brick - 0.6 in Cement Plaster Mortar
Roof Construction	0.7480 in Asphalt - 0.5120 in Fiberboard - 2.920 in Cast Concrete
Glazing	Single Clear with Aluminum Frames
Air Infiltration	0.7 ACH
No.of Occupants	Variable
Lighting Power Density	0.025 W/ft^2
Equipment Power Density	1.0935 W/ft^2
Cooling Set Point	75.2 F (24 degree Celsius)
Heating Set Point	71.6 F (22 degree Celsius)
Air Conditioning System	Split Air Conditioners
Heating and Cooling Period	As per defined schedules of each zone

Table 3.1.2: OPS Building Construction and Input Parameters

CEO Office	
Parameter	**Description**
Building Type	Office
No. of Floors	Single Storey
Total Floor Area	
Wall Construction	0.6 in Cement Plaster Mortar - 10 in Brick - 0.6 in Cement Plaster Mortar
Roof Construction	0.7480 in Asphalt - 0.5120 in Fiberboard - 2.920 in Cast Concrete
Glazing	Single Clear with Aluminum Frames
Air Infiltration	0.7 ACH
No.of Occupants	Variable
Lighting Power Density	0.025 W/ft^2
Equipment Power Density	1.0935 W/ft^2
Cooling Set Point	75.2 F (24 degree Celsius)
Heating Set Point	71.6 F (22 degree Celsius)
Air Conditioning System	Split Air Conditioners
Heating and Cooling Period	As per defined schedules of each zone

Table 3.1.3: CEO Building Construction and Input Parameters

Design & Engineering Building		
Block No. 1 (Ground Floor)		
Zones 1 to 5 (Director Offices)		
Typical Schedules	**Hours**	**Working Days (Monday to Friday)**
Occupancy	9:30 to 10:30	100%
	16:00 to 18:00	100%
Zones 6 (Deputy Director Audit)		
Typical Schedules	**Hours**	**Working Days (Monday to Friday)**
Occupancy	09:00 to 17:00	100%
Zone 7 (Kitchen)		
Typical Schedules	**Hours**	**Working Days (Monday to Friday)**
Occupancy	09:00 to 12:00	25%
	13:00 to 14:00	25%
	16:00 to 17:00	25%
Zone 8 (Conference Room)		
Typical Schedules	**Hours**	**Working Days (Monday to Friday)**
Occupancy	10:30 to 12:00	60%
	16:00 to 17:00	40%
Zone 9 (Prayer Room)		
Typical Schedules	**Hours**	**Working Days (Monday to Friday)**

Occupancy	13:15 to 13:45	25%
	15:30 to 16:00	25%
For Winter	17:00 to 17:30	25%
Block No. 2 (First Floor)		
Zone 1 to 12 (Assistant Director and Deputy Director Offices)		
Typical Schedules	**Hours**	**Working Days (Monday to Friday)**
Occupancy	09:00 to 09:30	100%
	09:30 to 10:00	67%
	10:00 to 12:00	100%
	16:00 to 18:00	100%

Operations Building		
Block No. 1 (Ground Floor)		
Zones 1 to 4 (Operations Staff Offices)		
Typical Schedules	**Hours**	**Working Days (Monday to Friday)**
Occupancy	09:00 to 12:00	100%
	16:00 to 17:00	100%
Zone 5 (Kitchen)		
Typical Schedules	**Hours**	**Working Days (Monday to Friday)**
Occupancy	09:00 to 12:00	25%
	13:00 to 14:00	25%
	16:00 to 17:00	25%

CEO, COO Offices		
Block No. 1 (Ground Floor)		
Zones 1 to 2 (CEO & COO)		
Typical Schedules	**Hours**	**Working Days (Monday to Friday)**
Occupancy	09:30 to 12:00	100%
	15:00 to 17:00	100%
Zone 5 (PSO to CEO)		
Typical Schedules	**Hours**	**Working Days (Monday to Friday)**
Occupancy	09:30 to 12:00	100%
	12:00 to 13:00	67%
	14:00 to 15:00	67%
	15:00 to 16:00	100%

Table 3.1.4: Occupancy Data and Schedule

3.2 SIMULATION WEATHER DATA FILE

The EPW (EnergyPlus Weather) file is a standardized format used to provide climate data for building energy simulation tools like EnergyPlus, DesignBuilder, and other building performance modeling software. It contains detailed hourly weather information that represents typical meteorological conditions over a year for a specific location.

EPW files contain information pertaining to Dry Bulb Temperature, Dew Point Temperature, Relative Humidity, Solar Radiation, Wind Speed and Direction, Atmospheric Pressure, Precipitation and Cloud Cover. These files provide wearher modeling information for each hour of the year and consider a Typical Meteorological Year (TMY) consisting of average weather patterns rather than using extremes. This approach enables much more accurate weather modeling for use in simulations. Moreover, EPW files are specific to each location considering historical weather patterns.

To develop future climate change weather data files for 2050 and 2080, the software 'Future Weather Generator' developed in collaboration between the Association for the Development of Industrial Aerodynamic, University of Coimbra and the Centre for Environmental and Marine Studies, University of Aveiro.

The software develops future weather data files by morphing the currently available EPW files into 2050 and 2080 scenarios. Two parameters are essential in understanding future climate change namely the Shared Socioeconomic Pathways (SSP) and the radiative forcing that is forecasted at the end of this century. The SSP scenarios are elaborated as follows:

SSP 1: This scenario describes a sustainable and environmentally friendly future where the focus is on human well-being, significant reduction in income disparities and minimizing the usage of finite energy resources and preserving natural resources.

SSP 2: This is the 'Middle of the Road' scenario where the future is predicted by extrapolating from current and past global trends. Income disparity is present along with a minimum divergent behavior between states. Population growth is modest with environmentally friendly initiatives lacking somewhat.

SSP 3: A rise in nationalism and decrease in multilateralism is observed with growing income disparities. The world becomes focused on realist ideology keeping security considerations at the forefront rather than investments in innovation and technology.

SSP 4: High level of disparity between developed and developing states with environmentally friendly measures being implemented at local levels rather than a concerted national or global level effort.

SSP 5: A fossil fuel consumption-based future where increasing social and economic growth comes at the cost of greater exploitation of fossil fuel resources.

Radiative forcing refers to the change in energy balance at the Earth's surface. It is measured in W/m2 where a positive value means that greater heat is being trapped due to the greenhouse effect. This radiative forcing is combined with the SSP scenarios to estimate the rise in temperatures in each situation. The combination of both SSP and radiative forcing results in the following four parameters:

SSP 585: Radiative forcing of 8.5 W/m2 by the year 2100.

SSP 370: Radiative forcing of 7 W/m2 by the year 2100.

SSP 245: Radiative forcing of 4.5 W/m2 by the year 2100.

SSP 126: Radiative forcing of 2.6 W/m2 by the year 2100.

The following figure shows the graphical representation of these parameters:

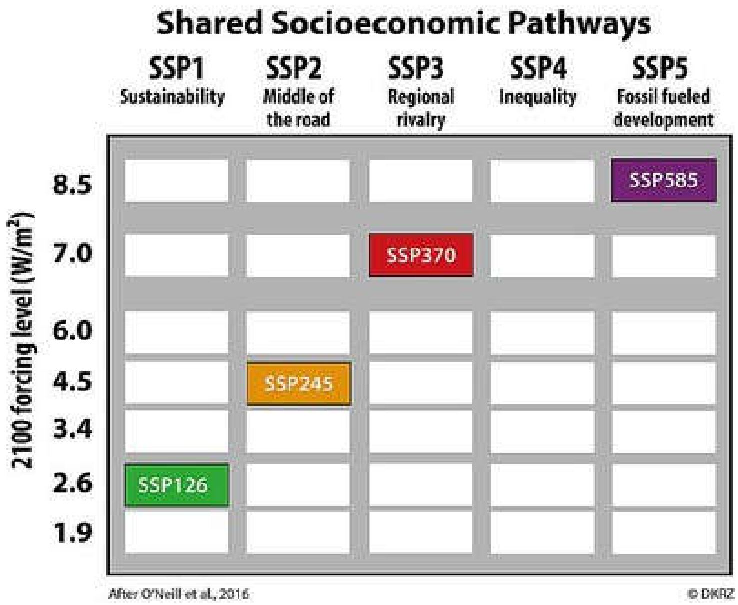

Figure 3.2.1: Graphical Representation of SSP Scenarios

Hence, the SSP 245 scenario is used to develop future weather data files as it represents a moderate outlook into the future. The remaining scenarios refer to an extreme picture and for research purposes, it is much better to use a balanced outlook catering to an average of extreme situations.

3.3 SOFTWARE USED IN BUILDING ENERGY SIMULATION

DesignBuilder is a software program that helps people design and analyze buildings to make them more energy efficient. It has a friendly interface that lets users create building models and see how different designs affect energy use, lighting, and comfort inside the building. It also uses another powerful program called EnergyPlus to do more detailed calculations.

DesignBuilder allows researchers to perform a complete building energy simulation by modeling buildings using actual construction materials used in the building together with applying both active and passive systems in addition to incorporating real weather data specific to the location of the building. Moreover, occupancy and operation schedules are also used as input parameters together with lighting level, equipment energy consumption and gas consumption data to ensure that all essential functions in the building are modelled.

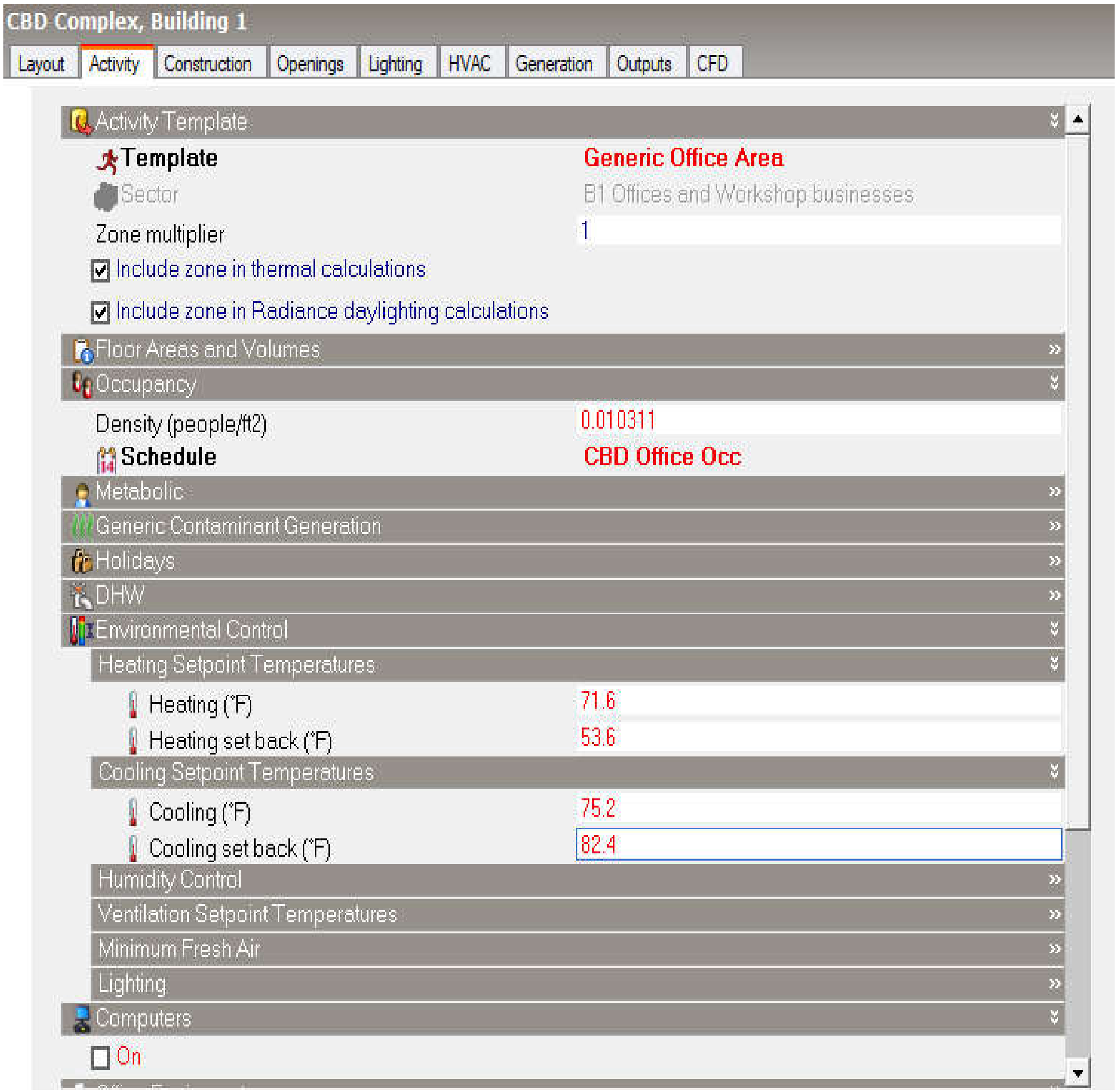

Figure 3.3.1: Activity Data in DesignBuilder

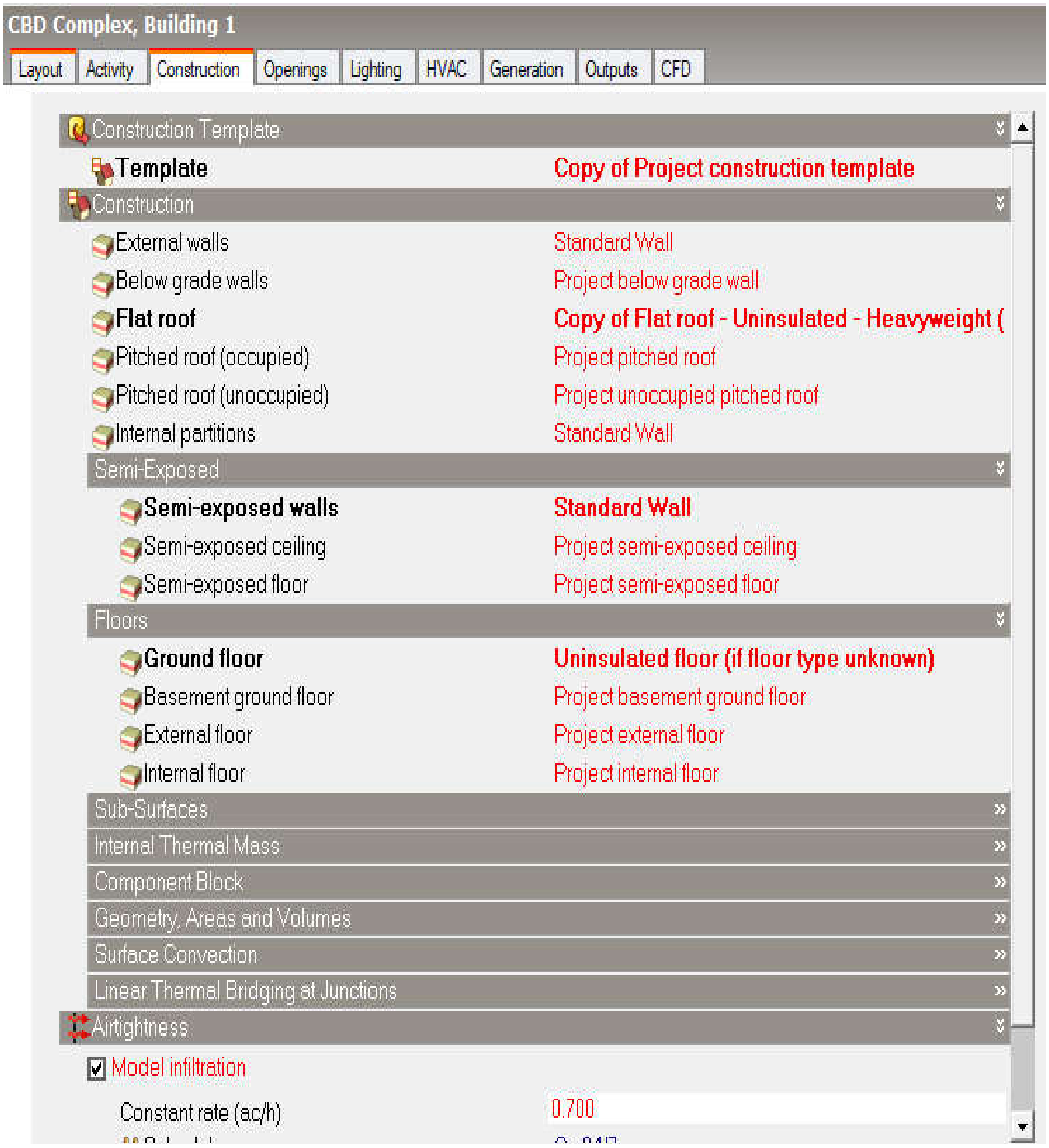

Figure 3.3.2: Construction Details in DesignBuilder

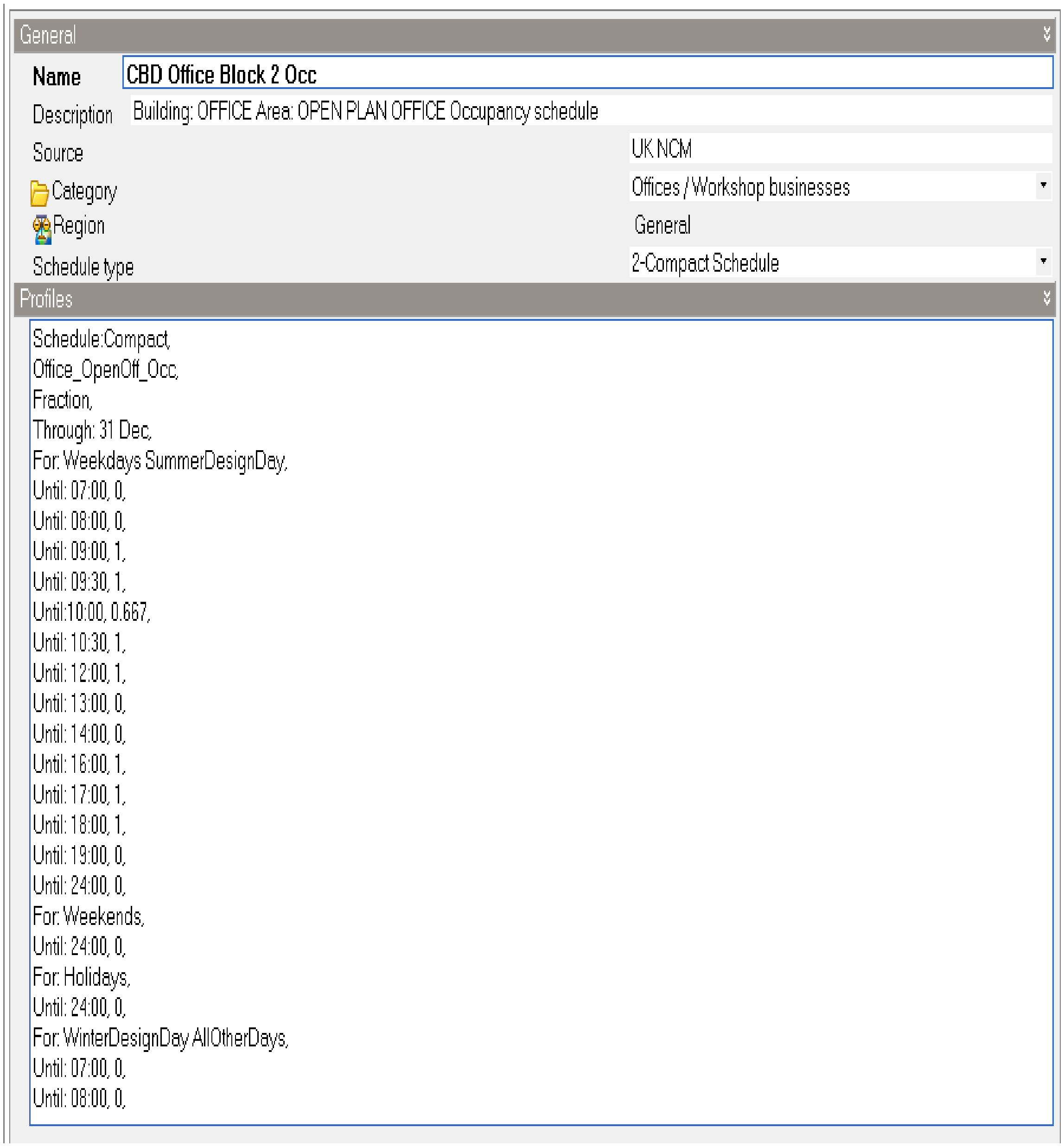

Figure 3.3.3: Occupancy Schedule in DesignBuilder

3.4 VALIDATION

The annual energy profile of the subject office building was obtained, and the building was modelled in base case scenario with its actual construction conditions. The base case construction details have been described in Tables 3.1.1, 3.1.2 and 3.1.3. The simulation was conducted in the current climate on the building's real location. The results of the validation are shown in the following figure:

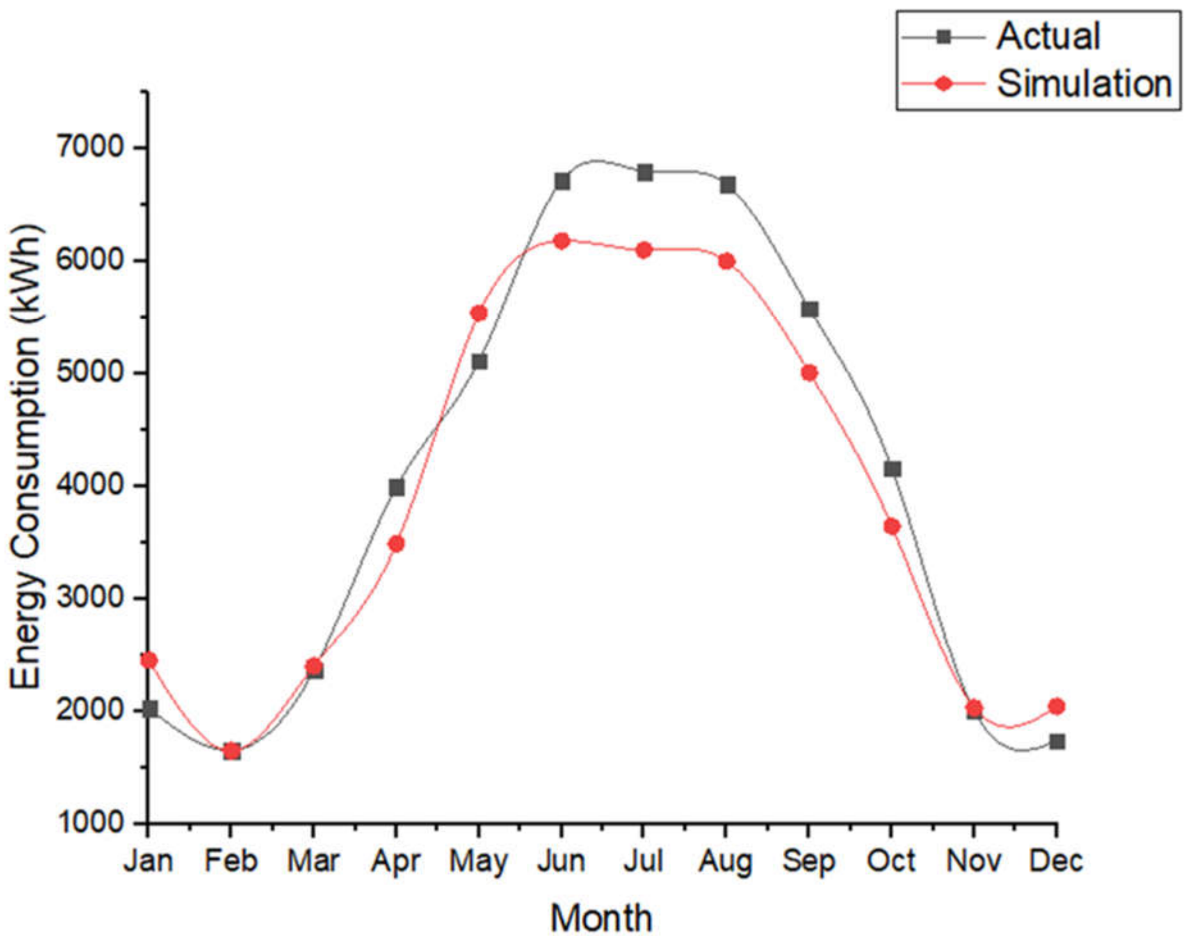

Figure 3.4.1: Validation between Actual and Simulation Results

The above graph indicates a close symmetry between the actual and simulation results thereby assuring that the model developed for the simulation is close to the actual conditions. The average variation is 7.8% with the results of the simulation being lesser than the actual. This can be attributed to the simulation not accounting for real time variability of usage patterns among the occupants of the building. However, the tolerance remains well below 10% showing results within acceptable limits.

3.5 PASSIVE METHODS

The passive strategies employed can be categorized as follows:

- **Roof Insulation**
  a) XPS (3.14 in External)
  b) Expanded Polystyrene (5.510 in External)
  c) BioPCM M182/Q25 (2.92 in External)
- **Wall Insulation**
  a) Polyurethane Foam (3.93 in External)
  b) BioPCM M182/Q25 (2.92 in External)

In the first step, each intervention is applied separately to the building ad simulation is performed to evaluate the effectiveness of these measures by noting the reduction in energy usage. The thickness of each insulation has been validated from the literature and care has been taken to use those thicknesses which have already been used for buildings in similar climate.

The wall and roof cross sections of each intervention are shown in the following figures:

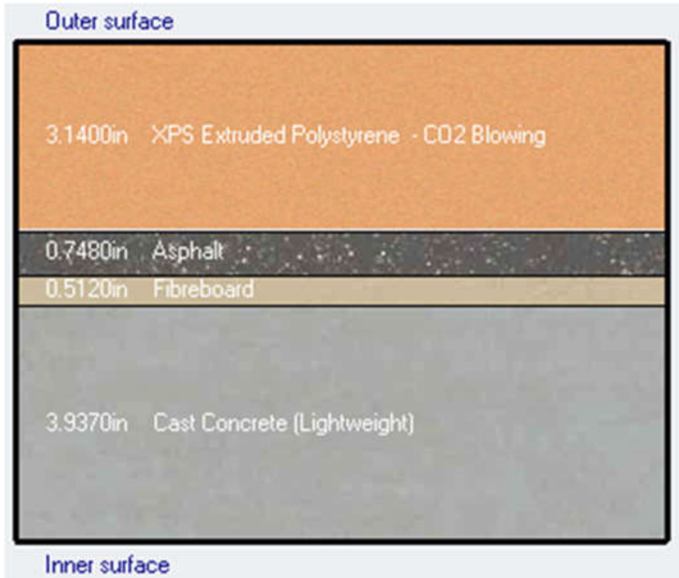

Figure 3.5.1: Roof Insulation XPS

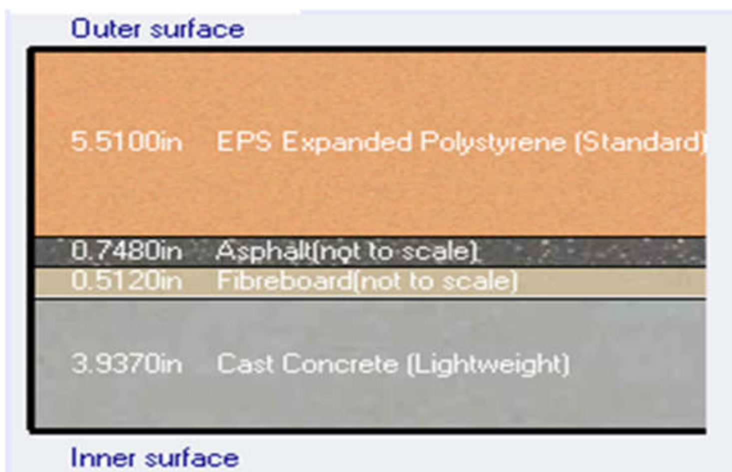

Figure 3.5.2: Roof Insulation EPS

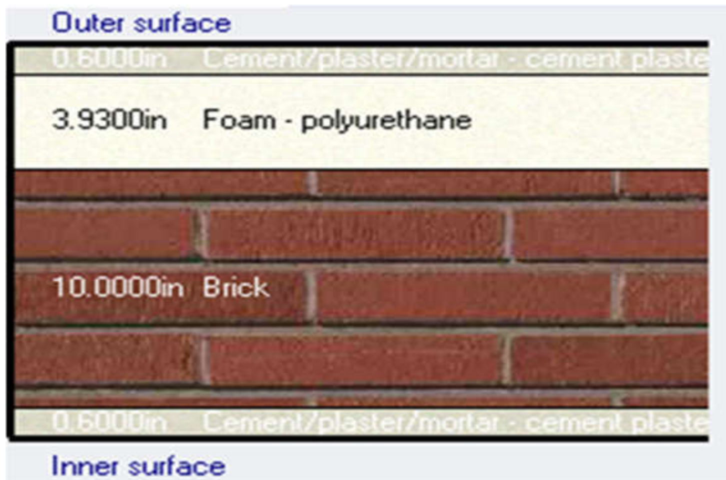

Figure 3.5.3: Wall Insulation Polyurethane Foam

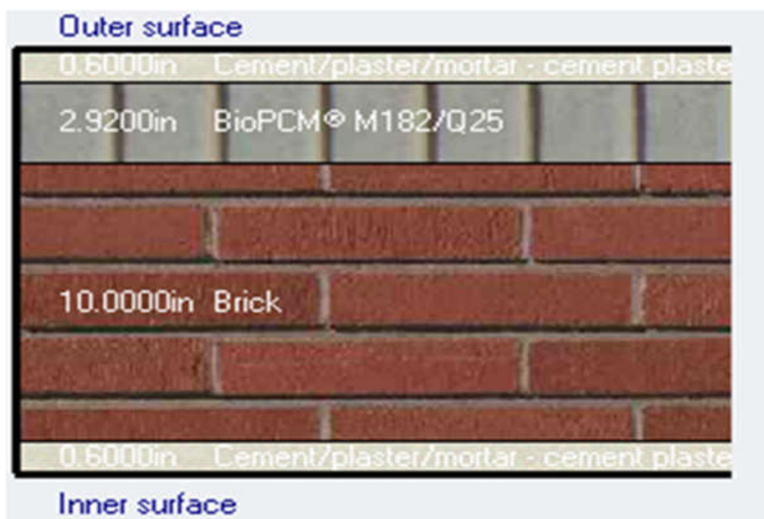

Figure 3.5.4: Wall Insulation BioPCM

3.6 DETERMINATION OF MOST EFFECTIVE PASSIVE METHOD TO CONTRIBUTE TO THE GOAL OF NET ZERO CARBON EMMISSIONS

The afore-mentioned individual interventions, when applied separately result in considerable energy savings. A comparison is made to determine the most effective solution in all these interventions to determine which passive method shall be most useful for Lahore's climate. It is important to note that in addition to studying the energy reduction from the application of these passive measures, our aim is to also study the reduction in carbon dioxide emissions during the operational cycle of the building and to evaluate which of these measures would be most effective in contributing towards Net Zero Carbon emissions. As mentioned in the literature review, previous research has been done by keeping the U-Values of walls and roof between 0.2 to 0.3 w/m2.K by applying suitable measures. Our goal will be to achieve this thermal transmittance through passive measures. Therefore, a building dubbed as the Net Zero Carbon Building (NZB) was modeled and its energy usage change and carbon dioxide emissions were noted.

3.7 SIMULATION OF THE NZB BUILDING IN 2050 AND 2080 CLIMATE CHANGE SCENARIOS

The weather data files developed for 2050 and 2080 were used in DesignBuilder to conduct the simulation in future climate change scenarios. A comparison is made between the effectiveness in reducing energy usage between the current climate and future climates. Moreover, the change in carbon dioxide emissions is also noted.

3.8 BUILDING ENERGY SIMULATION IN CLIMATE OF KARACHI

The climate of Karachi is characterized by long and hot weather with daytime temperatures reaching up to 40degree-Celsius with a high level of humidity. Winters are mild where temperatures rarely drop below 10 degree-Celsius. In comparison, Lahore has extreme heatwaves with temperatures sometimes rising beyond 40 degree-Celsius. However, there is less humidity than in Karachi. Winter temperatures are significantly low with the onset of seasonal fog as well with temperatures sometimes dropping to 5 degree-Celsius.

This difference in climate makes it essential to evaluate the effects of these passive measures on a different climate so that our work can serve to encompass a wide range of possibilities. Therefore, by using the weather data file of Karachi, the simulation is performed and energy reduction observed on the NZB Building.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 INDIVIDUAL PASSIVE INTERVENTIONS

4.1.1 ROOF INSULATION XPS

Description	Value
Total Base Simulation Annual Energy Consumption (kWh)	46,560.65
Total Roof Insulation XPS Annual Energy Consumption (kWh)	42,244.51
Wall U-Value (Base) (W/m2.K)	1.8
Roof U-Value (Base) (W/m2.K)	1.5
Roof U-Value (XPS) (W/m2.K)	0.3
% Reduction in Energy Usage	9.3
% Reduction in U-Value	78.3

Table 4.1.1: Energy Consumption and U Value Comparison between Base Case and XPS Roof Insulation

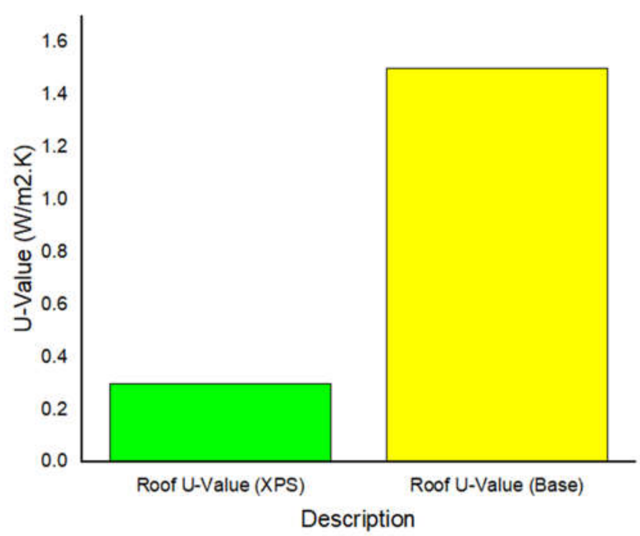

Figure 4.1.1: U Value Comparison Base Case and XPS

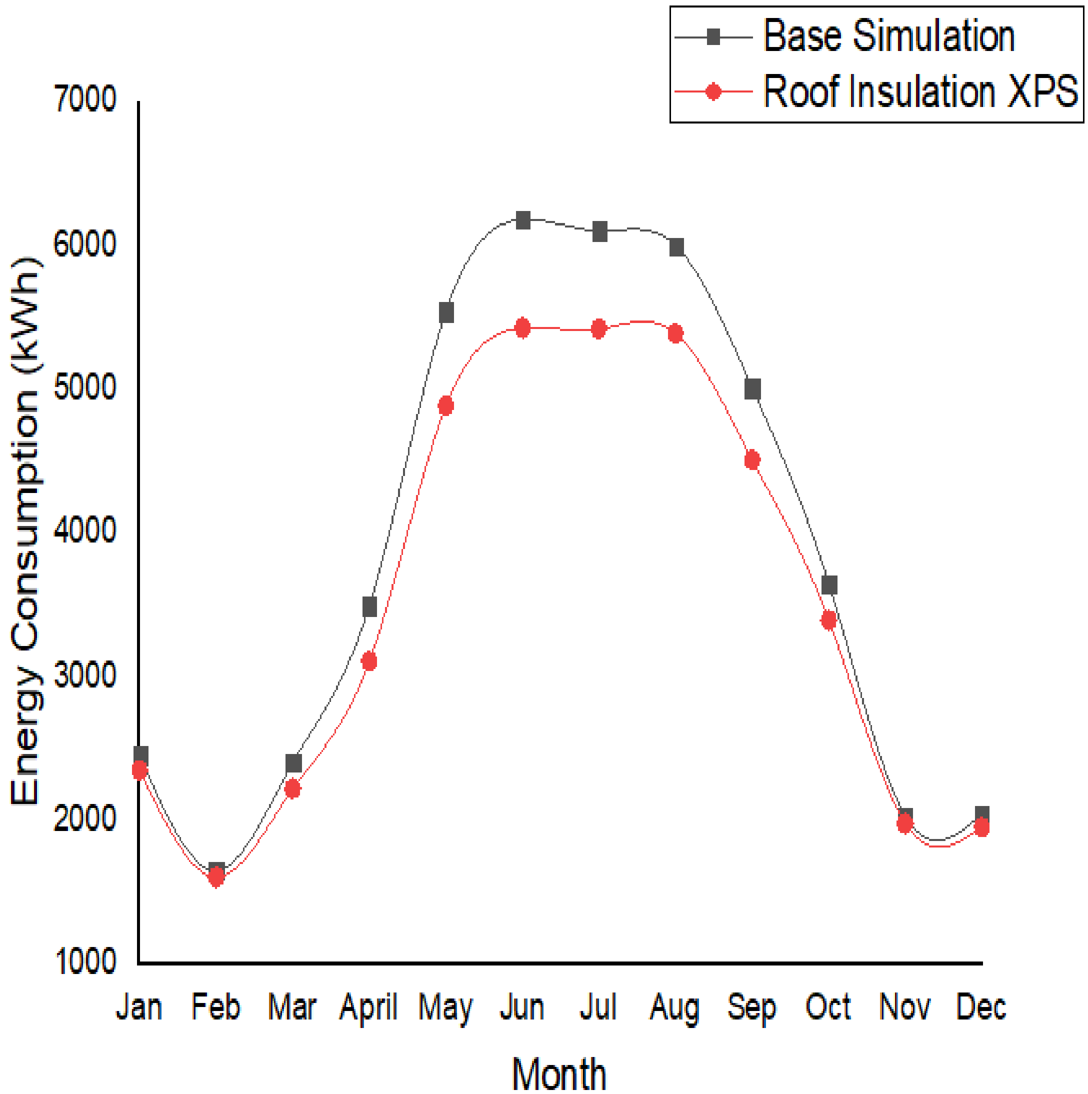

Figure 4.1.2: Annual Energy Consumption Profile between Base Case and XPS Roof Insulation

4.1.2 ROOF INSULATION EXPANDED POLYSTYRENE

Description	Value
Total Base Simulation Annual Energy Consumption (kWh)	46,560.65
Total Roof Insulation EPS Annual Energy Consumption (kWh)	42,032.03
Wall U-Value (Base) (W/m2.K)	1.8
Roof U-Value (Base) (W/m2.K)	1.5
Roof U-Value (Expanded Polystyrene) (W/m2.K)	0.2
% Reduction in Energy Usage	9.7
% Reduction in U-Value	84.6

Table 4.1.2: Energy Consumption and U Value Comparison between Base Case and EPS Roof Insulation

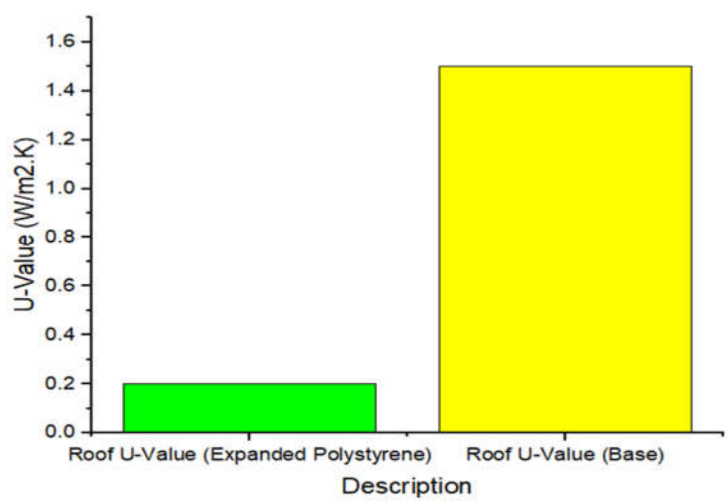

Figure 4.1.3: U Value Comparison Base Case and EPS

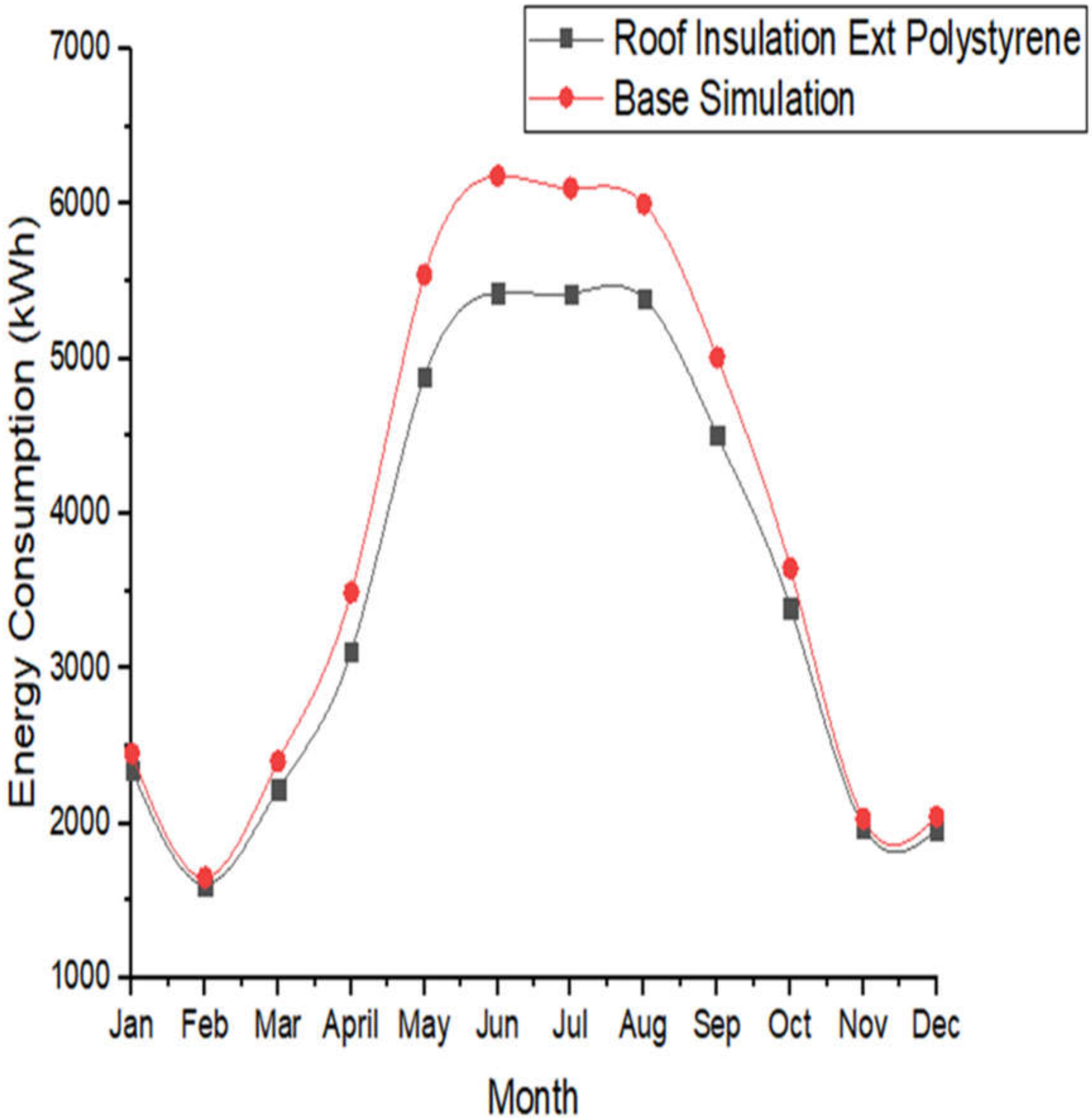

Figure 4.1.1: Annual Energy Consumption Profile Base Simulation and EPS

4.1.3 WALL INSULATION POLYURETHANE FOAM

Description	Value
Total Base Simulation Annual Energy Consumption (kWh)	46,560.65
Total Wall Insulation Annual Energy Consumption (kWh)	42,743.38
Wall U-Value (Base) (W/m2.K)	1.8
Wall U-Value (Polyurethane) (W/m2.K)	0.2
Roof U-Value (Base) (W/m2.K)	1.5
% Reduction in Energy Usage	8.2
% Reduction in U-Value	86.2

Table 4.1.1: Energy Consumption and U Value Comparison between Base Case and Polyurethane Foam Wall Insulation

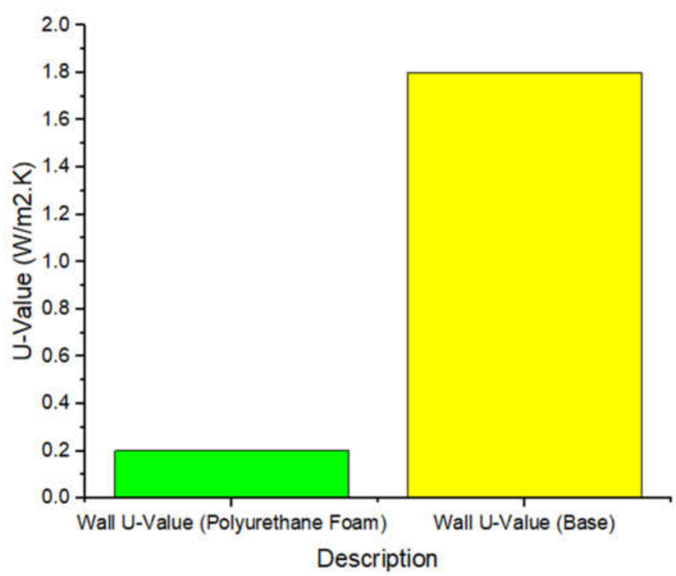

Figure 4.1.1: U Value Comparison Base Case and Polyurethane Foam

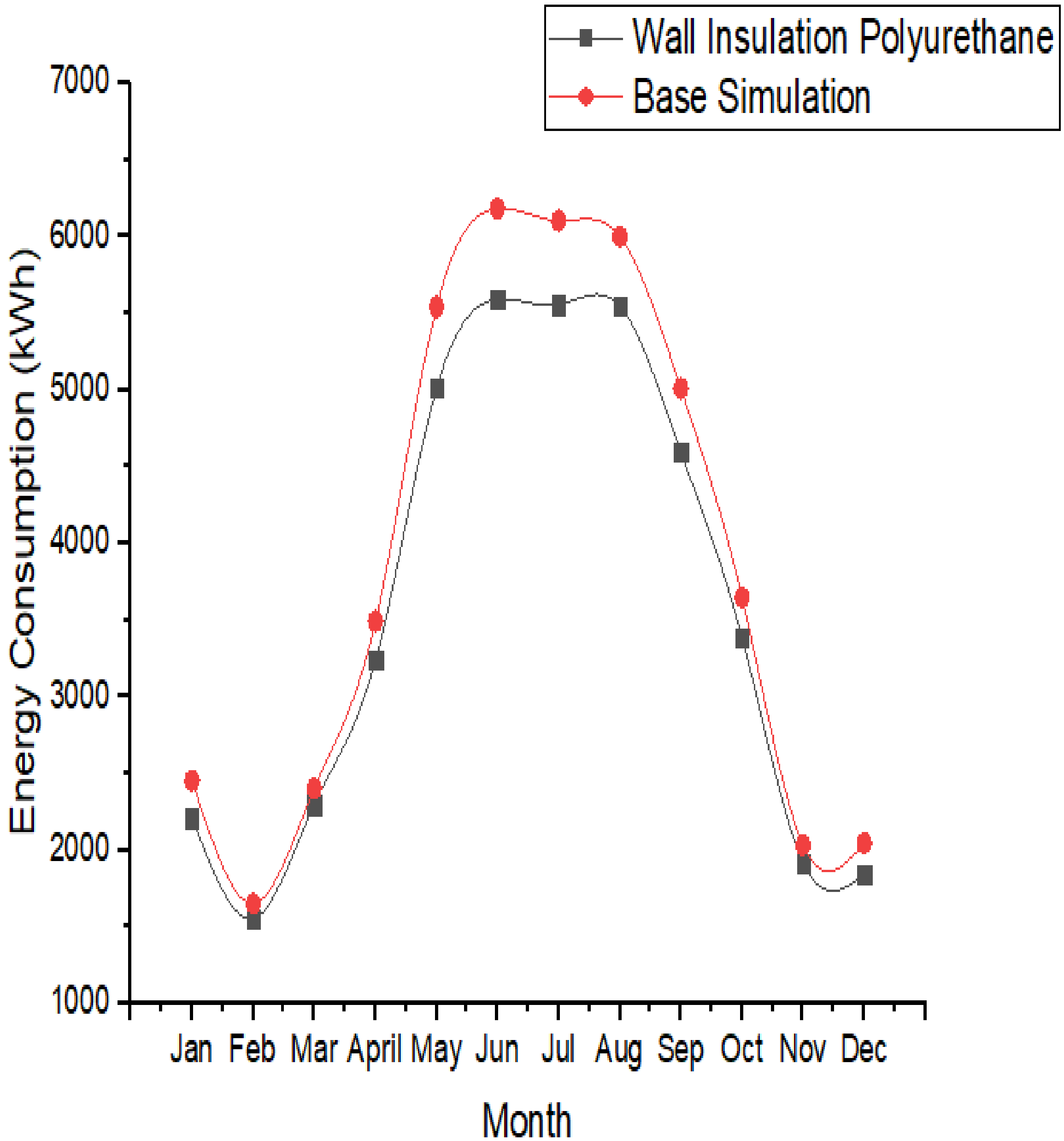

Figure 4.1.2: Annual Energy Consumption Profile Base Simulation and Polyurethane Foam

4.1.4 WALL INSULATION BIOPCM M182/Q25

Description	Value
Total Base Simulation Annual Energy Consumption (kWh)	46,560.65
Total Wall Insulation Annual Energy Consumption (kWh)	44,678.53
Wall U-Value (Base) (W/m2.K)	1.8
Wall U-Value (BioPCM) (W/m2.K)	1.1
Roof U-Value (Base) (W/m2.K)	1.5
% Reduction in Energy Usage	4.0
% Reduction in U-Value	39.7

Table 4.1.1: Energy Consumption and U Value Comparison between Base Case and BioPCM Wall Insulation

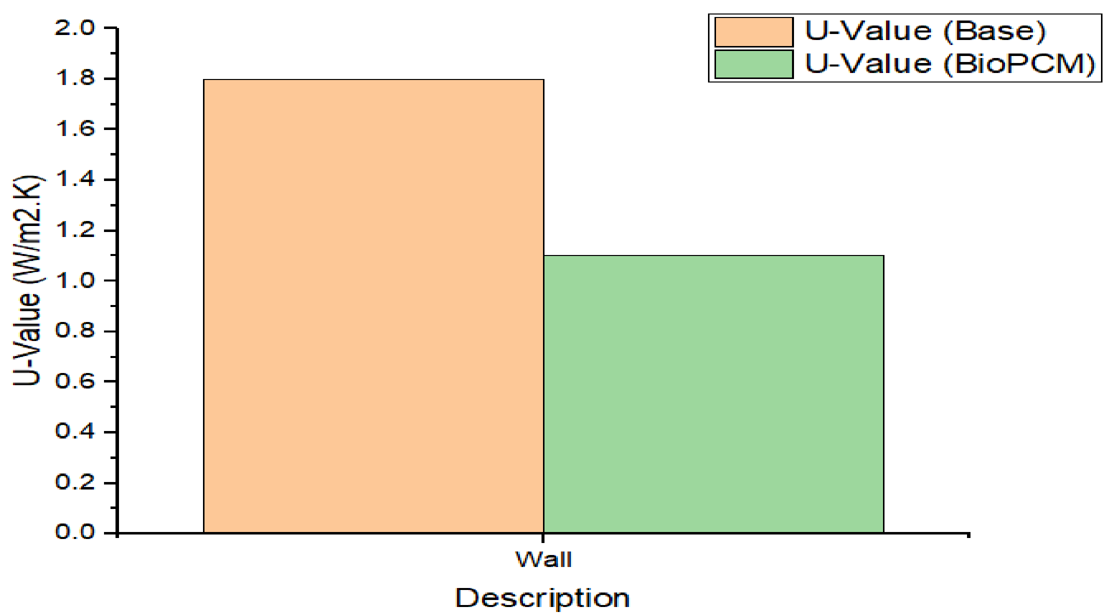

Figure 4.1.3: U Value Comparison Base Case and BioPCM Wall Insulation

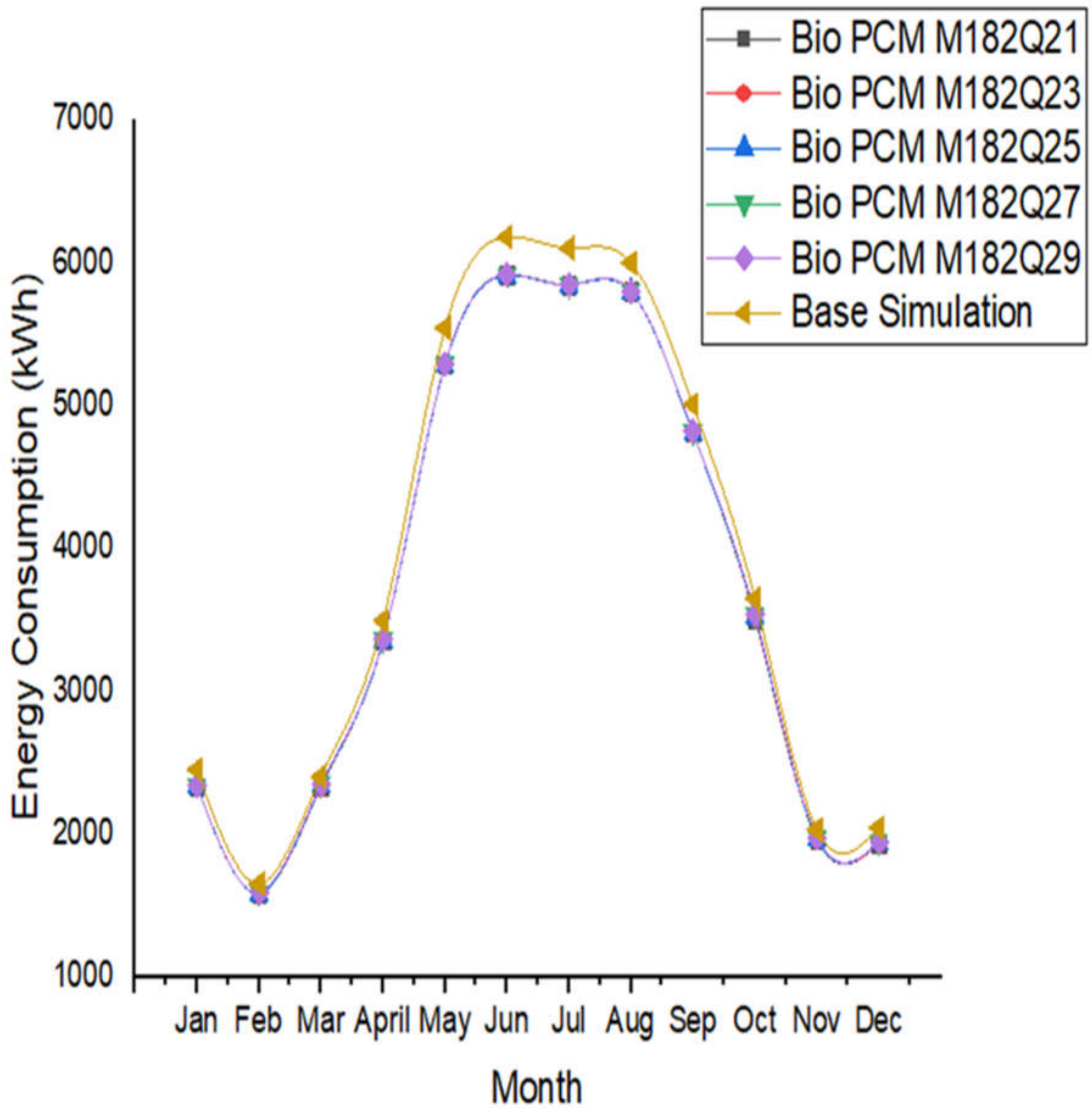

Figure 4.1.4: Annual Energy Consumption Profile Base Simulation and BioPCM Wall Insulation

4.1.5 ROOF INSULATION BIOPCM M182/Q 25

Description	Value
Total Base Simulation Annual Energy Consumption (kWh)	46,560.65
Total Roof Insulation BioPCM Annual Energy Consumption (kWh)	44,751.13
Wall U-Value (Base) (W/m2.K)	1.8
Roof U-Value (Base) (W/m2.K)	1.5
Roof U-Value (BioPCM) (W/m2.K)	1.0
% Reduction in Energy Usage	3.9
% Reduction in U-Value	36.4

Table 4.1.2: Energy Consumption and U Value Comparison between Base Case and BioPCM Roof Insulation

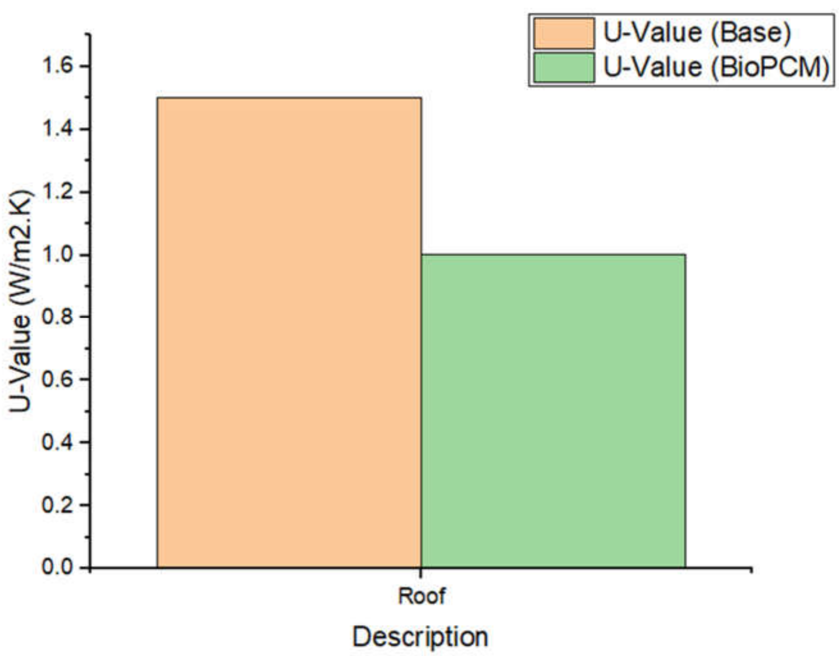

Figure 4.1.5: U Value Comparison Base Case and BioPCM Roof Insulation

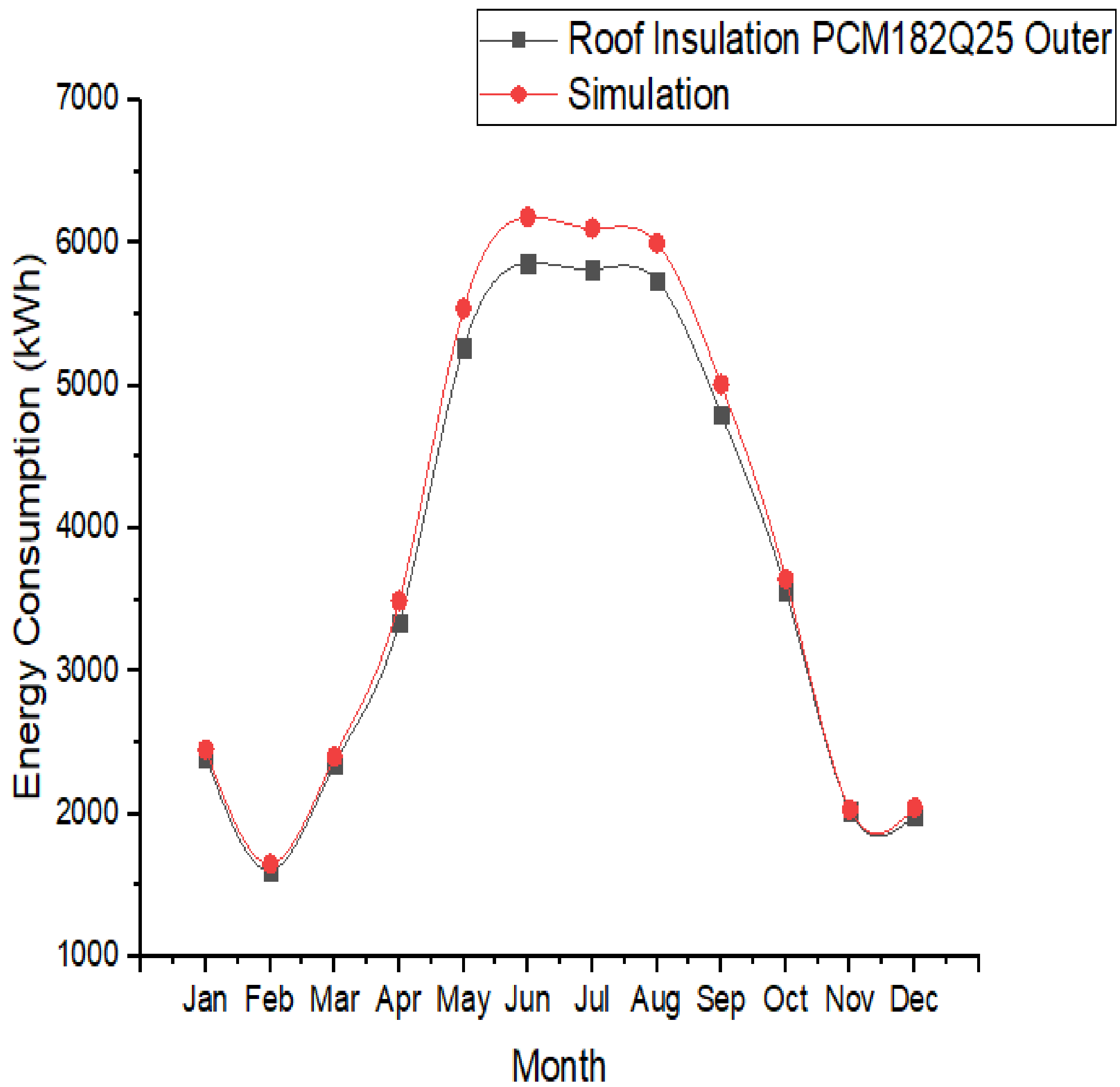

Figure 4.1.6: Annual Energy Consumption Profile Base Simulation and BioPCM Roof Insulation

4.2 INTERVENTIONS FOR NET ZERO CARBON BUILDING

4.2.1 CURRENT CLIMATE SCENARIO

Description	Value
Total Base Simulation Energy Consumption (kWh)	46,560.65
Total Net Zero Carbon Building Energy Consumption (kWh)	36,376.93
% Reduction in Energy Usage	21.9

Table 4.2.1: Energy Reduction of NZB in Current Climate Scenario

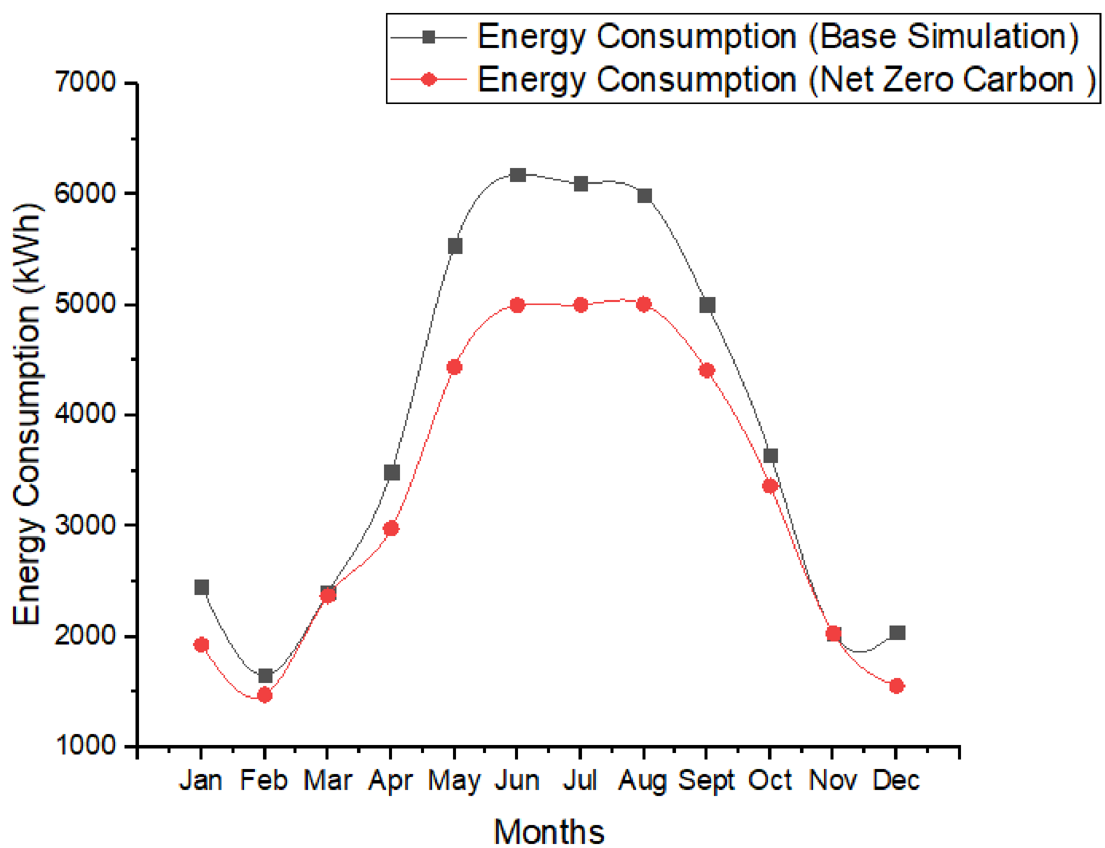

Figure 4.2.1: Annual Energy Use Reduction for NZB in Current Climate Scenario

4.2.2 2050 CLIMATE SCENARIO

Description	Value
Total Base Simulation Energy Consumption (kWh)	46,560.65
Total Net Zero Carbon Building Energy Consumption (kWh)	39,550.87
% Reduction in Energy Usage	15.1

Table 4.2.2: Energy Reduction of NZB in 2050 Climate Scenario

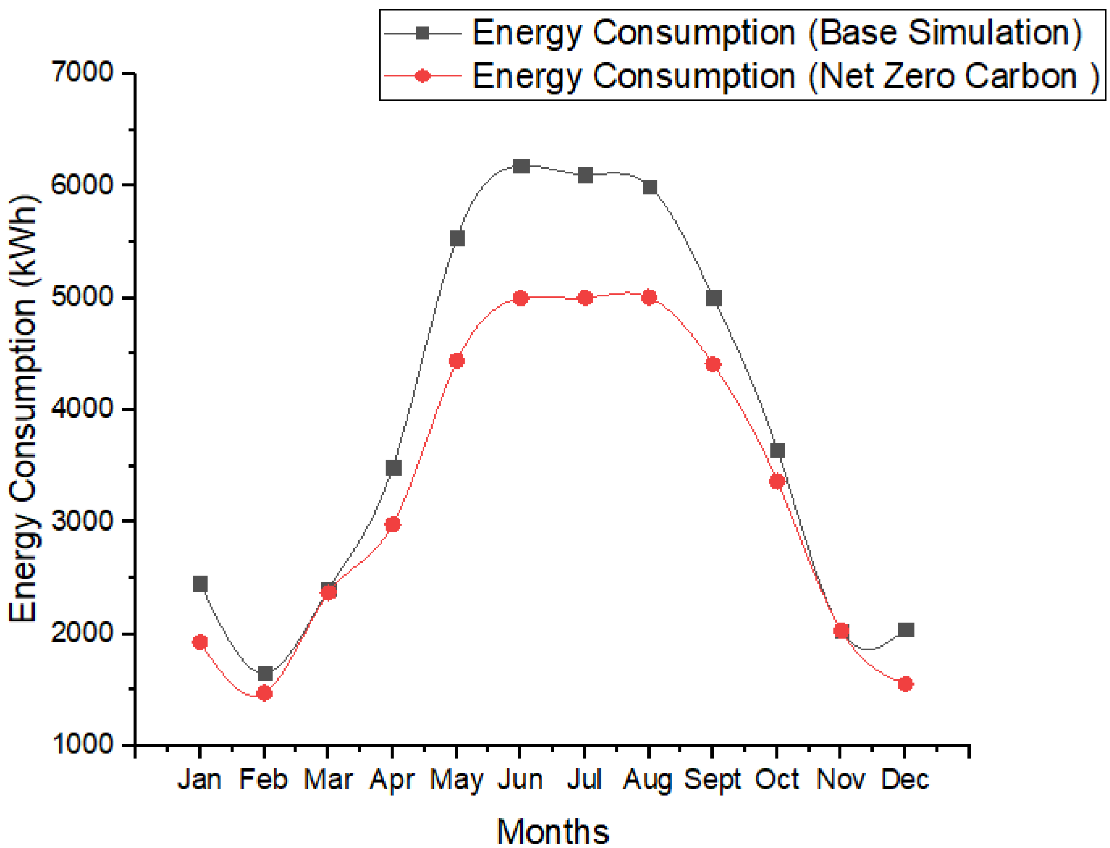

Figure 4.2.2: Annual Energy Use Reduction for NZB in 2050 Climate Scenario

4.2.1 2080 CLIMATE SCENARIO

Description	Value
Total Base Simulation Energy Consumption (kWh)	46,560.65
Total Net Zero Carbon Building Energy Consumption (kWh)	42,329.34
% Reduction in Energy Usage	9.1

Table 4.2.3: Energy Reduction of NZB in 2080 Climate Scenario

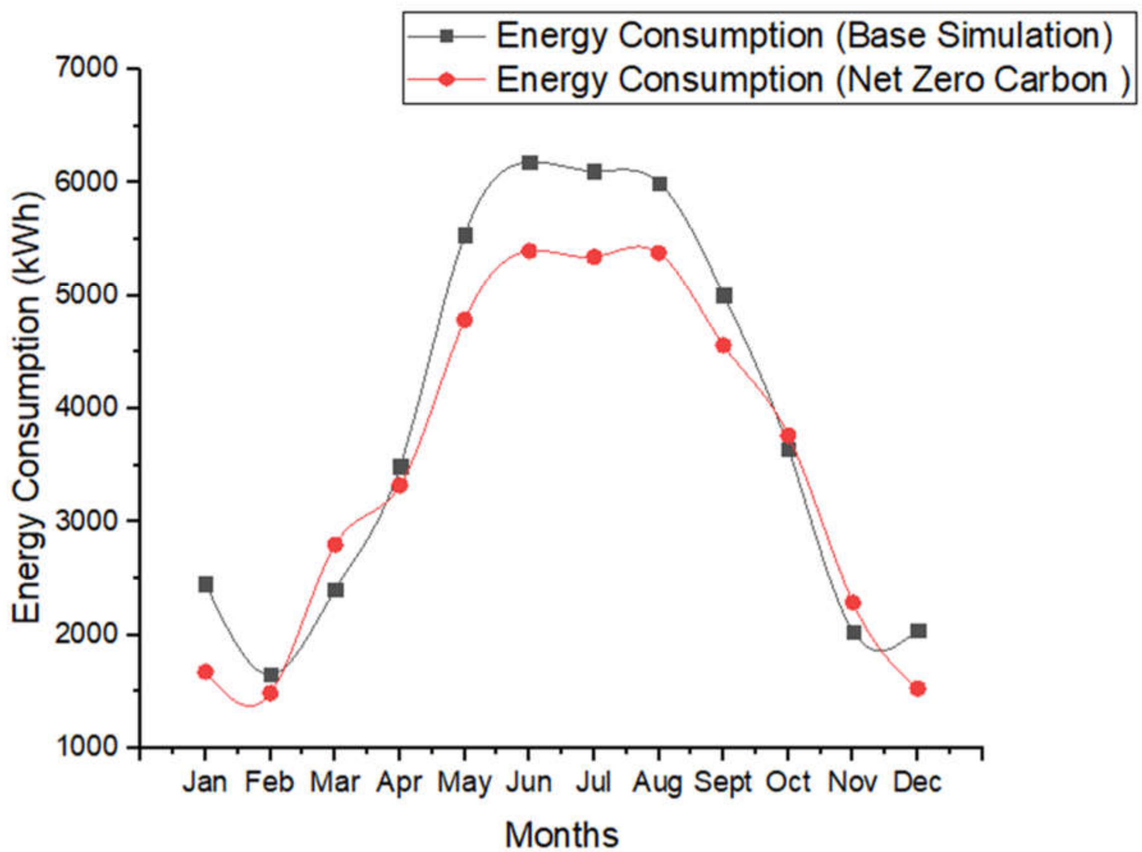

Figure 4.2.3: Annual Energy Use Reduction for NZB in 2080 Climate Scenario

4.3 NET ZERO CARBON BUILDING CARBON PRODUCTION

Scenario	Annual CO2 Production (kg)
Base Case	28239.9
Net Zero Carbon Building (Current)	22063.3
Net Zero Carbon Building (2050)	19385.0
Net Zero Carbon Building (2080)	20742.6

Table 4.3.1: CO2 Production Comparison in Base Case, 2050 and 2080 Scenarios

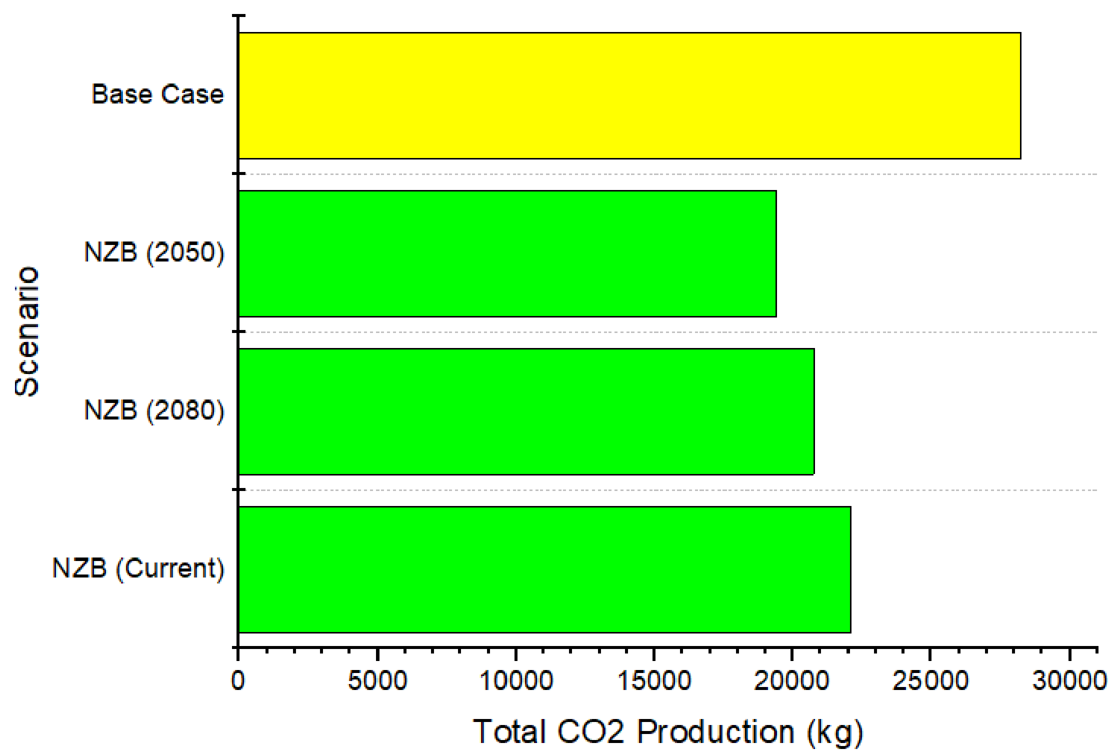

Figure 4.3.1: CO2 Production in Base Case, 2050 and 2080 Scenarios

4.4 NZB BUILDING IN KARACHI

Description	Value
Total Base Simulation Energy Consumption (kWh)	45,542.56
Total Net Zero Carbon Building Energy Consumption (kWh)	36,940.19
% Reduction in Energy Usage	18.88

Table 4.4.1: Energy Reduction of NZB in Karachi

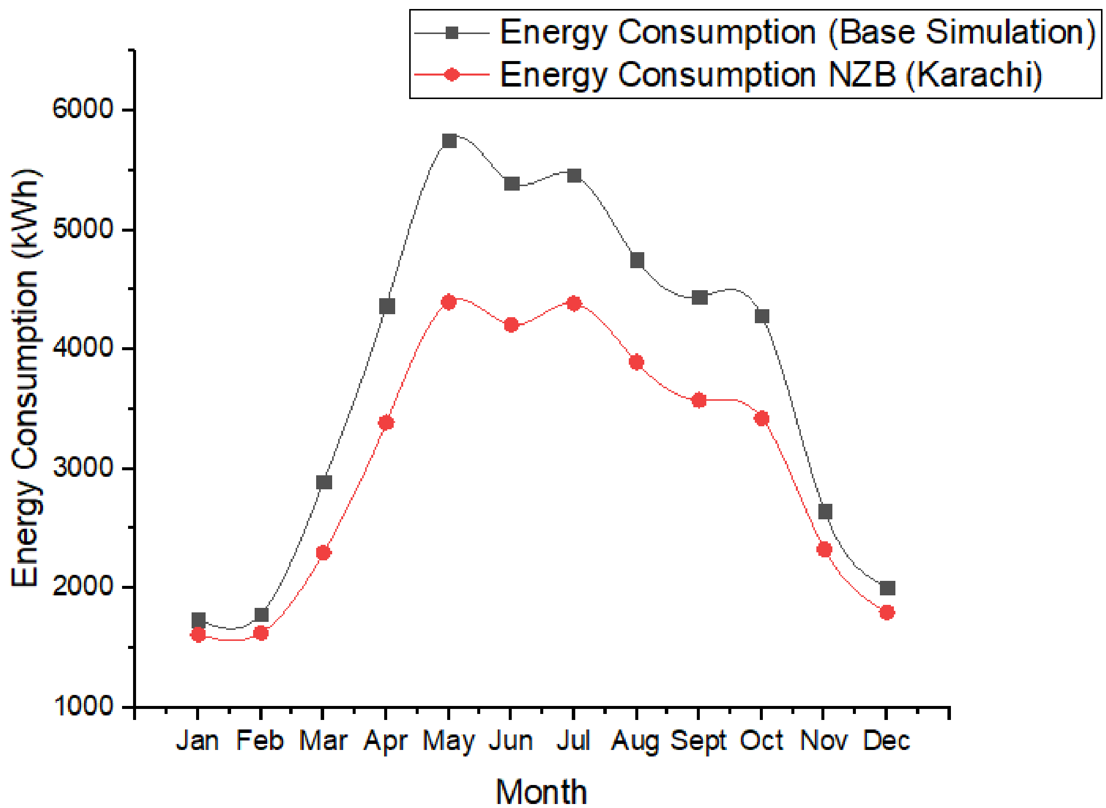

Figure 4.4.1: Annual Energy Use Reduction for NZB in Karachi

4.5 DISCUSSION

As demonstrated in the preceding sections, the building energy simulations have been conducted on the scenarios and their results plotted graphically and in tabular form. Individually, expanded polystyrene shows the most promising results as roof insulation with a 9.7% reduction in energy usage whereas XPS insulation decreases energy use by 9.3%. For roof insulation, BioPCM showed the least effective outcome resulting in energy savings of 3.9% only.

The reason for PCM showing the least effective results can be attributed to the fact that PCMs change phase at a specific temperature. The PCM used has a phase change temperature of 25 degree-Celsius which was found to be the most beneficial among other PCMs with different phase change temperatures. However, it is important to note that the temperature may have remained well below or above the phase change temperature which is why PCM was not very effective. In contrast expanded polystyrene and XPS do not change phase, rather they slow down heat transfer, hence they can work across a wide range of temperatures rather than being limited by phase change temperature only.

For wall insulation, results are similar with polyurethane foam being more energy efficient than BioPCM resulting in energy saving of 8.2% and 4% respectively. Hence, the above discussion stipulates that the Net Zero Carbon building simulation should be carried out by applying thermal insulation together on wall and the roof. Therefore, to achieve the Net Zero Carbon goal, polyurethane foam is applied on wall and expanded polystyrene is applied on the roof.

The above-mentioned interventions reduce the U-Value of the walls and roof to 0.2 W/m2.K from 1.8 W/m2.K and 1.5 W/m2.K respectively resulting in 86.2% and 84.6% reduction in U-Values. The corresponding energy savings amount to 21.9% for the NZB building in the current climate scenario. These results indicate that the Net Zero Carbon approach is much more beneficial in reducing energy consumption thereby making operations of the building easier.

To provide further validation of our results, the same building was simulated in Karachi and its results indicate energy saving of 18.8%. This shows that our passive measures can be used up to some extent in a different climate as well. Further research can be carried out to optimize these results.

The NZB building is subsequently studied in 2050 and 2080 climate change scenario. The results indicate that the effectiveness of these passive measures decreases over time to 15.1% and 9.1% respectively. This can be due to increased temperature rise of up to 2.7 degree-Celsius in the simulated scenario resulting in higher temperatures in the future due to additional radiative forcing. Further studies can be conducted to optimize the material types and thicknesses to better optimize them for the future.

The effectiveness of these passive measures is also studies with respect to reducing carbon dioxide emissions. The results show a 20% decrease in carbon dioxide emissions when these measures are applied. Therefore, as these are passive measures and do not involve the operation of active systems, significant carbon dioxide emissions have decreased. This suggests that passive measures are instrumental in combating the greenhouse effect and the effects of climate change.

CHAPTER 5: CONCLUSION AND FUTURE RECOMMENDATION

This study confirms the substantial energy-saving potential of passive design strategies in commercial buildings, particularly in achieving Net Zero Carbon emissions. Expanded polystyrene and polyurethane foam, when applied to the building's roof and walls, demonstrated the most effective reductions in energy use and carbon emissions across varied climatic scenarios. While these measures significantly reduce energy consumption under current conditions, their effectiveness diminishes slightly in future climate projections for 2050 and 2080, likely due to rising temperatures. In particular, energy savings reduced from 21.9% in the current climate to 15.1% in 2050 and 9.1% by 2080, emphasizing the need for adaptive strategies to cope with future climate scenarios.

A key finding is the adaptability of these interventions to different environmental contexts, as seen with the 18.88% energy reduction achieved in Karachi's humid climate. This suggests that passive measures are not only applicable across diverse climates but also hold promise in mitigating the impacts of climate change in both hot and humid, and hot and dry regions.

The research highlights the importance of integrating passive measures into building design as part of a broader strategy to achieve sustainability and Net Zero Carbon emissions. However, to optimize long-term benefits, a holistic approach must consider local climate compatibility, economic feasibility, and future climate projections. Procurement and operational costs associated with implementing passive measures must be weighed carefully to ensure that they deliver both environmental and economic benefits.

Future work should focus on combining passive strategies with smart technologies like adaptive ventilation systems, daylight sensors, and intelligent building management to further enhance performance. Moreover, research on material innovation, such as more efficient phase change materials (PCMs) and better insulation solutions, could offer new pathways for energy savings. Integrating renewable energy sources, such as Building-Integrated Photovoltaics (BIPV), could also complement passive strategies, helping buildings to further offset carbon emissions and meet the goals of energy-efficient urban development.

Conclusively, the results underline the importance of passive measures in mitigating the greenhouse effect and reducing operational energy consumption. With proper integration into building design, these measures can provide both immediate and long-term sustainability benefits, aligning with global efforts to combat climate change and build resilient urban infrastructures.

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