Effectiveness of Passive Adaptation Measures Against Climate Change for Buildings in Hot, Humid and Desert Climate

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Declaration

I certify that this research work titled *"Effectiveness of Passive Adaptation Measure against Climate Change for Buildings in Hot, Humid and Desert Climate."* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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Abstract

Due to climate change, the energy demand of buildings for cooling and heating are changing considerably. Besides, it is also adversely impacting the energy efficiency & thermal comfort of the present building stock. Passive design measures for buildings or Passive climate change adaptation measures (PCAMs) can be extremely useful in reducing and mitigating its negative effects. In this study, various PCAMs were used to analyze its efficacy in minimizing the energy consumption of a detached house or villa in the Kingdom of Saudi Arabia (KSA) with its hot, humid and desert climate. However, the uniqueness of this research lies from its emphasis on the usage of numerous types of Phase Change Materials (PCM) to reduce the consumption of energy. Besides the effect of green roof with variable Leaf Area Index, white paint (Short Wave Reflectivity) and natural ventilation on the villa's energy consumption is also studied. Through these PCAMs up to 21.2 % reduction in total energy consumption, 31.2% reduction in cooling demand, and 34.7 % decrease in heating load can be achieved.

Key Words: *Climate Change, Passive climate change adaptation measures, Phase Change Material*

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

The effect of climate change not only involves rising temperature but also rising sea levels, extreme weather occasions, shifting of wildlife populations and habitats to different locations [1-3], and a range of other negative impacts which includes: (i) cooling and heating energy demand for buildings (ii) energy efficiency and thermal comfort for the building stock

To cater to these heating and energy cooling demands and subsequent residents' thermal comfort, it would become imperative to install more active cooling and heating systems. However, this will further increase the climate change hazards as more burning of fossil fuels, excessive carbon dioxide emissions would take place. Therefore, to overcome unpredictable temperatures and climate change impacts, effective policies and strategies are required to be employed across the globe to get a better eco-friendly environment for thermal comfort for the residents.

1.2 PASSIVE ADAPTATION MEASURES

The Passive adaptation measures or Passive climate change adaptation measures (PCAMs) is one of the many successful strategies that can be extremely useful in reducing and mitigating the negative effects of climate change. Passive adaptation measures are those measures that ensure that no active energy is used when these measures are applied [4]. It is referred normally to adaptation measures for a building's indoor environment. [5]. Passive adaptation measures will reduce the energy consumption of buildings and maintain indoor comfort.

1.3 CLIMATE CHANGE AND KSA

The Kingdom of Saudi Arabia (KSA) is vulnerable to climate change. The building sector, in particular, is immensely under the radar of this threat as the rise of atmospheric temperature will soar up the cooling demand of the buildings to keep its occupants comfortable. The gradual rise of temperature due to climate change will not only disturb the thermal comfort of the occupants but in pursue of achieving this thermal comfort, an increase in energy consumption will also be likely to happen.

1.4 HOT, HUMID AND DESERT CLIMATE

The climate of the Kingdom of Saudi Arabia (KSA) is described as hot, humid & desert. Riyadh, the financial capital of Saudi Arabia has a hot and desert climate. Summers are extremely hot with an ambient average temperature around 44^0C and maximum outdoor temperature may surpass 55^0C. Winter, which happens for a few months, is considered cold with a minimum temperature of 5^0C. Jeddah, another important city of KSA, has a hot and humid climate with temperature range 45-50^0C in the afternoon and 35 ^{0}C at night. The Winter season is often for a few days and is normally mild with the temperature reaching up to 8-10^0C.

1.5 ENERGY CONSUMPTION OF BUILDINGS IN KSA

Over a decade, the peak demand for electricity of buildings has increased by 83% to touch around 40GW. [6]. The residence sector consumes about 50% of electricity in which air conditioning is accountable for over 65% of total energy consumption. [7]. Owing to the ever-increasing population and extreme temperatures conditions, KSA has planned to expand the electric generation to 125 GW by 2025, which would be considered the largest expansion of electricity generation for the Middle East [8]. This will, in turn, cause expansion of air conditioning usage in buildings leading to (a) higher energy consumption (b) peak energy demand increase (c) environmental related issues especially global warming and depletion of the ozone layer. (d) indoor air quality problems. [9]

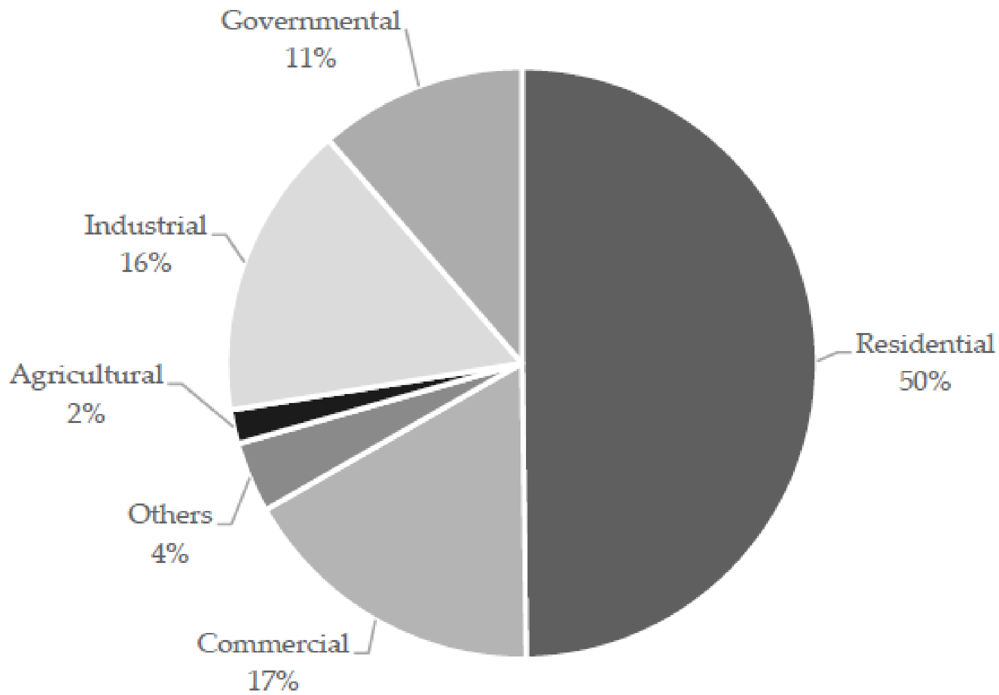


Figure 1 - Fuel Breakdown:

As a result, passive adaptation measures are necessary to lessen energy consumption and maintain indoor comfort.

1.6 OBJECTIVE

The objective of this research is to use these passive adaptation measures in a residential building of KSA to analyze its efficacy in minimizing energy consumption with its hot, humid and desert climate. Previously, various researchers have applied numerous types of passive measures on diverse type of buildings including this under-study residential villa. However, the uniqueness of this research lies from its emphasis on the usage of numerous types of Phase Change Materials (PCM) to reduce the consumption of energy. Besides the effect of green roof with variable Leaf Area Index, white paint (Short Wave Reflectivity) and natural ventilation on the villa's energy consumption will also be studied.

CHAPTER 2: LITERATURE REVIEW

Many studies have been conducted in the past to study the effect of the application of passive measures on different and diverse types of buildings in different climatic conditions around the world. Alaidroos et al. [10] developed a prototype residential building in the Kingdom of Saudi Arabia for energy conservation measures. The energy conservation measures for the building involved in his research were (i) insulation of the walls, (ii) insulation of the roof, (iii) window area, (iv) window glazing, (v) window shading, and (vi) thermal mass. Al-Hadrami et al. [11] analyzed the thermal performance of diverse types of locally available bricks for the residential building. Ahmad et al.[12]studied the insulation properties of masonry materials for residential buildings and their effect on the energy load. The effect of thermal mass and surface solar absorptivity on the thermal performance of walls was critically studied by Al Sanea et al. [13,14].

Proper insulation of the roofs & walls aided in reducing the peak cooling load & annual energy consumption by more than 24% and 28% respectively [15,16]. Thermal insulation material's performance is mainly determined by its respective thermal conductivity(k) which itself depends on porosity, density, moisture content and mean temperature difference. [17,18]. Not only that Al-Ghamdi et al. [19] research showed that floor insulation had an effect on the building's electric energy consumption.

2.1 ADAPTATION MEASURES

Phase change materials (PCM) are considered as smart materials that are implemented as thermal regulators for buildings because it helps to link the gap between 'when the energy is available' and 'when it is required for cooling, heating and enhancing the comfort & quality of the residential spaces [20]. Numerous research has taken place to study the impact of phase change materials (PCMs) on buildings roofs. [21-24]. Saxena et al. investigated the effect of embedding PCM materials into bricks to improve the indoor environment of the buildings. Experimental testing was conducted during peak summertime when temperatures exceeded 45^{o} C during a normal day. The results indicated that the temperature got reduced between 5~ 9.5°C across the embedded bricks with PCMs as against to the ordinary bricks without embedded phase change materials. [25]. Also, Eddhanak-Ouni et al. research resonated with the previous study which had deduced that Phase Change Material incorporated in the cementitious materials boosted the thermal qualities of the building [26]. Yoo et al. surveyed the thermal performance of bio-composites formed by mixing coffee wastes with PCM materials. The findings revealed that the usage of Biocompatible PCM by-products enhanced the thermal properties of the residence and was ecologically friendly. [27].

Santamouris et al. [28] showed that the application of green roofs lessened the average overall ambient temperature from 0.4~2.8. ° C. An experiment study conducted by Peng et.al recorded a maximum daily temperature decline of around 5 °C and cooling load savings of 0.89 kWh/m^2 on a sunny day and 0.55~0.57 kWh/m^2 on a normal cloudy day. [29]. In an experiment by Hodo-Abalo et al., a green roof was implemented for energy savings and concluded that by varying (changing) the Leaf Area Index (LAI), solar penetration flux was reduced & in the summers the indoor conditions got cooler [30].

Luo, M et al. [31] analyzed the positive effect of implementing natural ventilation to improve the thermal comfort of the building. Much research has been conducted where the mixed mode of ventilation i.e. combination of natural ventilation from operable windows (automatically controlled or manually controlled) and Heating, Ventilation and Air Conditioning Systems (HVAC). In these researches, natural ventilation strategies coupled with schedules for these HVAC systems were designed in such a way to ensure thermal comfort, better air quality and minimization of energy consumption due to the mechanical cooling. [32- 34].
In similar researches by [35-40], it is apparent that the energy consumption of a residential or commercial building can be lessened through the implementation of passive climate adaptation means.

Akbari et al. [41] revealed that the application of white paint on buildings roofs does increase the emissivity & reflectivity of the roof's surface, which resulted in a lower surface temperate as compared to general roof surfaces. He also concluded that these type of roofs are quite effective at cooling in the summer conditions since these roofs abate solar heat gain. However, they increase the heating load in winters causing a negative effect for this passive measure.

This study is made unique since no research work has been done previously to investigate the effect of various types of PCMs (difference in thickness and melting points) in reducing the energy load of the residential building of KSA which has a hot, humid and desert climate. Also, the effect of green roof with varied LAI, natural ventilation and short wave reflectivity (white paint) is also investigated Besides, the research is significant as it demonstrates, through software simulation, how passive measures especially PCMs can be an extremely effective solution to promote building's energy efficiency.

CHAPTER 3: METHODOLOGY

In the current study, the same prototype residential building has been used as a base case for further application of Passive building design measures in Riyadh which is the capital and financial hub of the Kingdom of Saudi Arabia. Through the application of these passive measures, change in (annual) cooling load, heating load and change in total energy load are found out. The novelty of this research lies from its emphasis on the application of numerous types of Phase Change Materials (PCM) Besides, the effect of green roof with variable Leaf Area Index, white paint (Short Wave Reflectivity) and natural ventilation on the villa's energy consumption is also studied. The software used in this research was DesignBuilder which is considered and recognized as the most comprehensive and powerful graphical user interface for EnergyPlus. EnergyPlus is an in-built dynamic simulation engine that helps in generating performance data. Further details regarding this software would be discussed later in this chapter.

The scheme of methodology would be described through each step, which was required in this research.

3.1 STEP-1

In the first step, the residential villa understudy was designed in Design Builder using various construction and simulating parameters. The weather file of Riyadh was selected. Through software simulations, the results of the comparison between the actual energy consumption of the under-study residential villa in Riyadh (KSA) with the energy output of the simulation were found out to validate the results of the software.

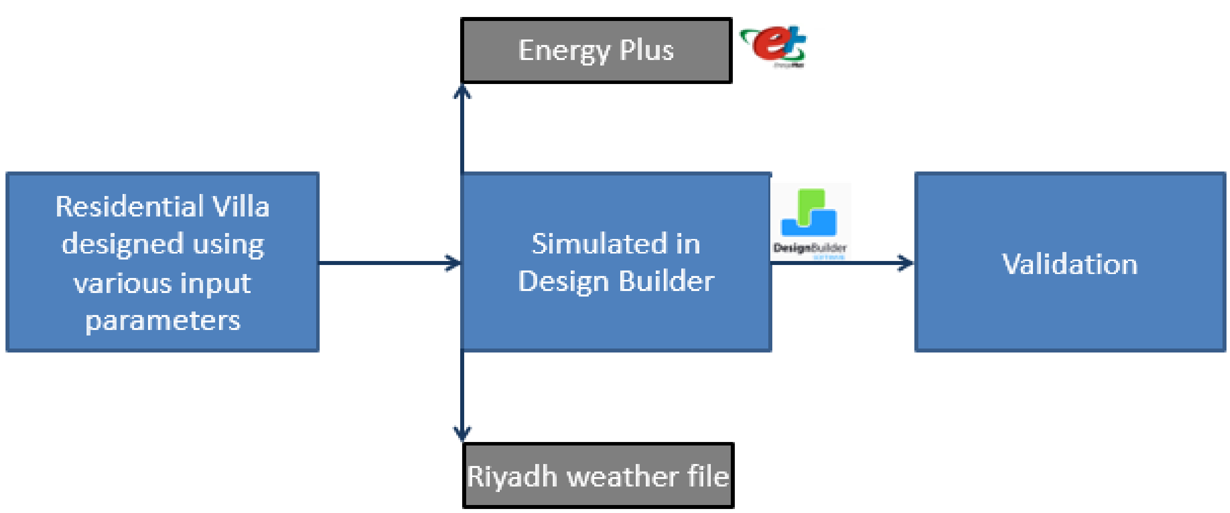


Figure 2 - Flow Diagram :Step-1

3.1.1 Construction and Simulation Parameters

Table-1 gives an overview of various input parameters for the construction of this residential villa. This villa had 2 floors. The total floor area was 525m^2. The walls of the villa consisted of 3 layers. The outer layer which was exposed to the outside ambient condition was 20mm plaster. The middle layer was a 150mm concrete hollow block and the inside was 20 mm plaster. Similarly, the roof was constructed with an outside layer of 10 mm built-up roofing, a middle layer of 200 mm concrete roof slab, and an inside layer of 13 mm plaster. Window-to-Wall (WWR) ratio was kept to 13%.

Split DX was the HVAC system with thermostat settings of 72^0 F (equivalent to 22.2 ^{0} C) for heating and 76^0 F (equivalent to 24.4 ^{0} C) for cooling. In this type of HVAC, the compressor and condenser are placed outside the building while the evaporator and fans are positioned inside. Air Infiltration value was kept at 0.8 ACH (Air Changes per Hour). This villa is occupied by 6 people. The age and sex of the occupants do not affect the outcome of the results. Lighting Power Density (LPD) was kept at 4.0 W/m^2 and Equipment Power Destiny (EPD) was 3.5 W/m$^{2.}$ LPD denotes the load consumed by any type of lighting equipment in a defined boundary area or watts per square meter of the lighting equipment. By dividing the total lighting load by the concerned area, LPD can be calculated. Similarly, EPD represents the load consumed by any equipment/appliance in any defined boundary area or watts per square meter of any appliance. It can be obtained by dividing the total equipment load by the respective area.

The presence of the occupants in the villa was maintained through a 24hrs schedule which is presented in Table-2. Likewise, the same duration schedule for Lighting and appliances are also given in the same table. Occupancy (1-8 hrs, WD-100%, WEH-100%) is described as all occupants were present in the villa from 1 am to 8 am on weekdays (Sunday-Thursday) and on weekends (Friday-Saturday). Similarly, Lighting (8-14 hrs, WD- 20%, WEH- 20%) means that from 0800 to 1400 hrs, 20% of Lighting was consumed in the weekdays and weekends. Also, Appliances (22-24 hrs, WD- 10%, WEH- 10%) is defined as 10 % of all the appliance are being used from 2200 hrs to 2400 hrs in weekdays and weekends

Model	Villa
Number of Floors	2
Total Floor Area	525 m^2
Wall Construction	20 mm plaster outside + 150 mm concrete hollow block + 20 mm plaster inside
Roof Construction	10 mm built-up roofing + 200 mm concrete roof slab + 13 mm plaster inside
Glazing	Single Clear with Wood Frames
Window-to-Wall Ratio (WWR)	13%
Air Infiltration	0.8 ACH
Number of Occupants	6
Lighting Power Density	4.0 W/m^2
Equipment Power Density	3.5 W/m^2
Domestic Hot Water	11.4 L/person/day
Cooling Set Point	720 F (22.2 0 C) for heating and 760 F(24.4 0 C) for cooling
HVAC System	Cons. Volume DX air cooled A/C with electric heating
Energy Efficiency Ratio (EER)	7.5
Heating & Cooling Period	24 h/day

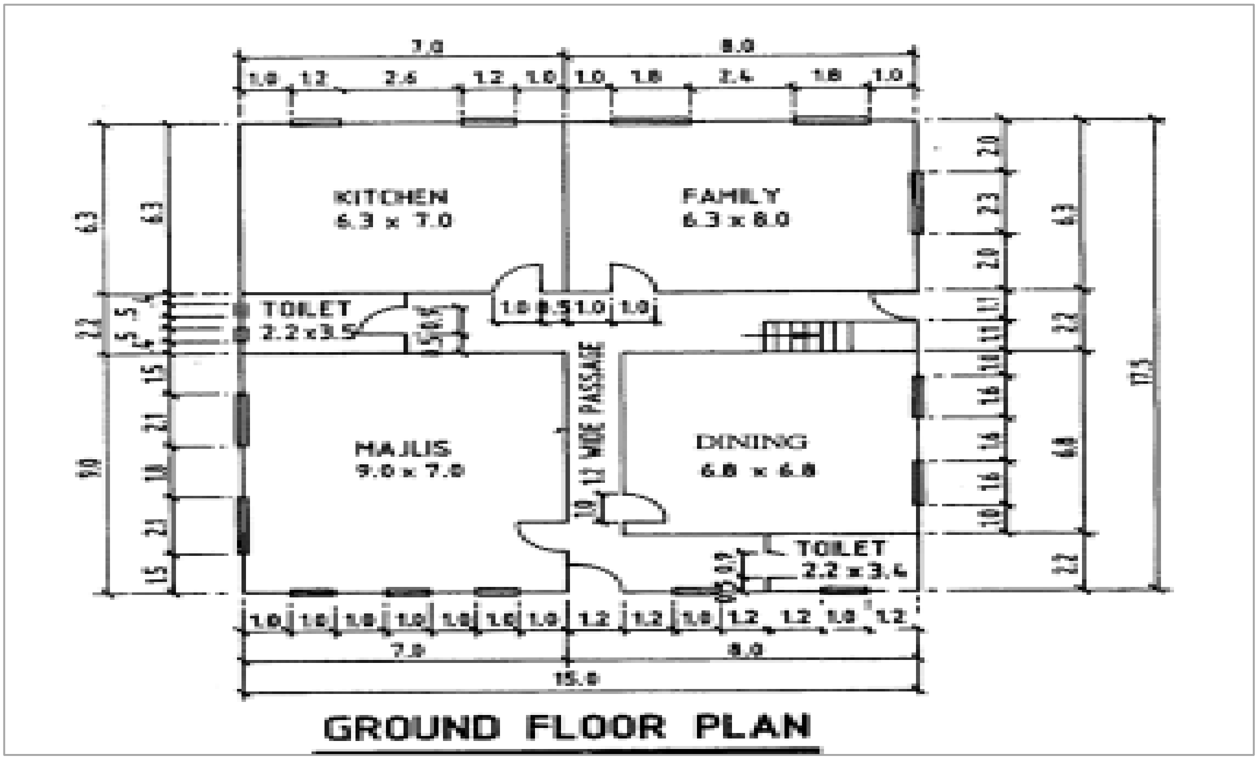
Table 1- Specifications for the Building Construction- Base Case (Residential Villa)

Typical Schedules	Hours	WD (Sun-Thu)	WEH (Fri-Sat)
Occupancy	1-8 8-14 14-22 22-24	100% 50% 80% 100%	100% 60% 70% 100%
Lighting	1-8 8-14 14-22 22-24	5% 20% 60% 5%	5% 20% 60% 5%
Appliances	1-8 8-14 14-22 22-24	20% 30% 60% 10%	20% 30% 70% 10%

Table 2 - Typical Schedule for Occupancy , Lighting and Appliances

3.1.2 Floor Plan of Residential Villa

Moncef et al. had taken all the construction & simulating parameters and the floor plan of the residential villa from [12]. The floor plan for the villa can be seen in Figure (3)



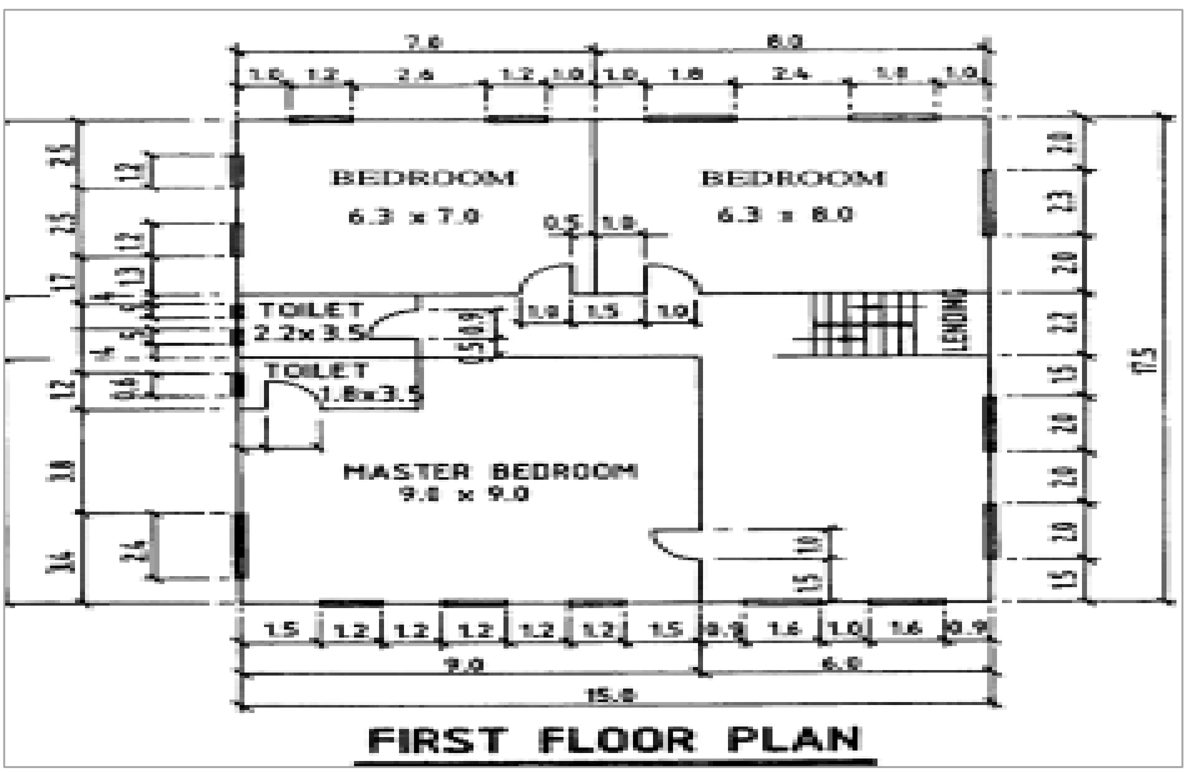


Figure 3 - Floor Plans (Ground + First Floor) for the residential villa: Source[12]

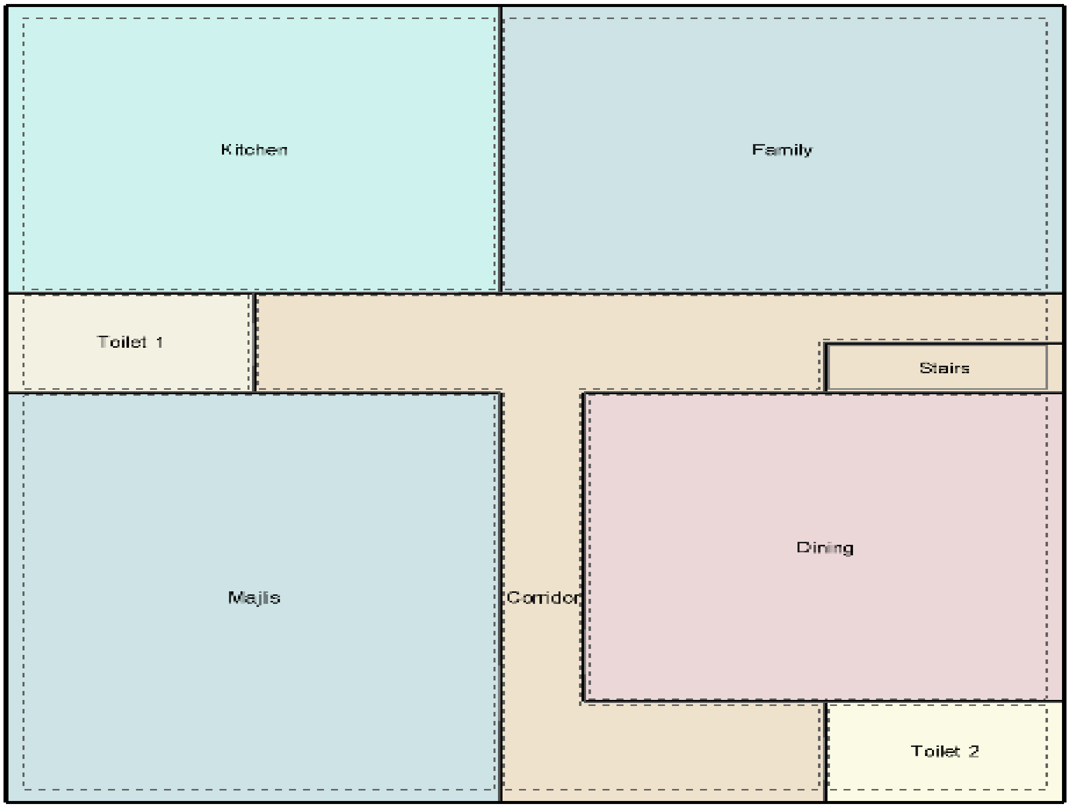


Figure 4 - Ground Floor Plan - Design Builder

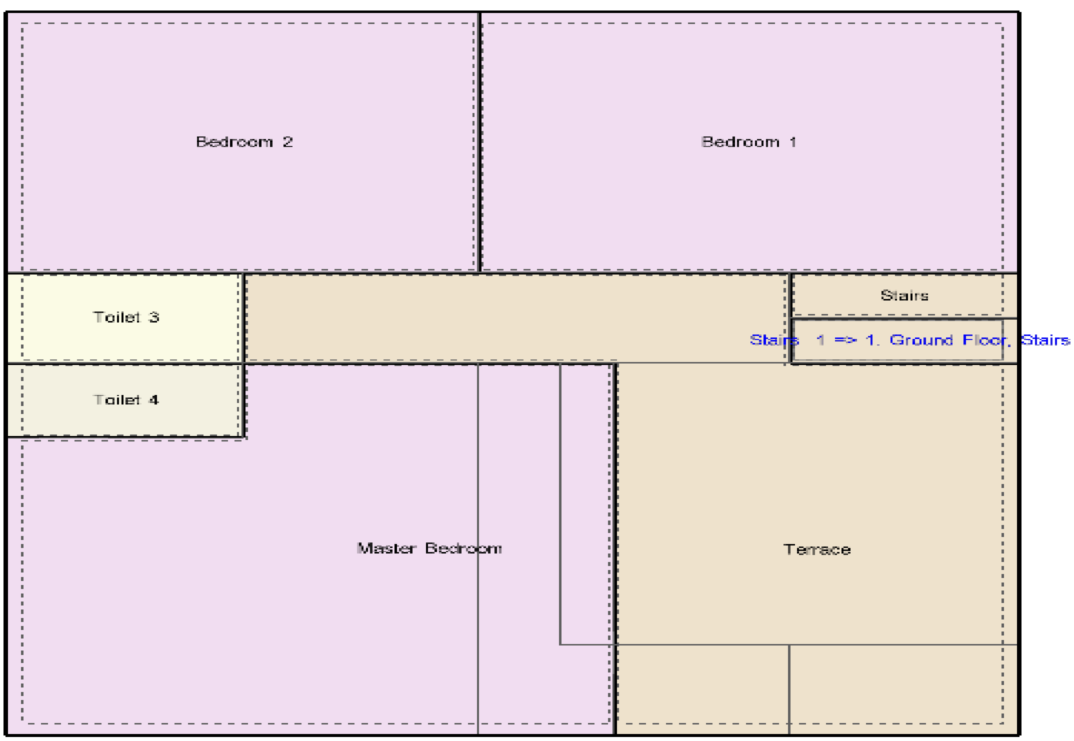


Figure 5 - First Floor- Design Builder

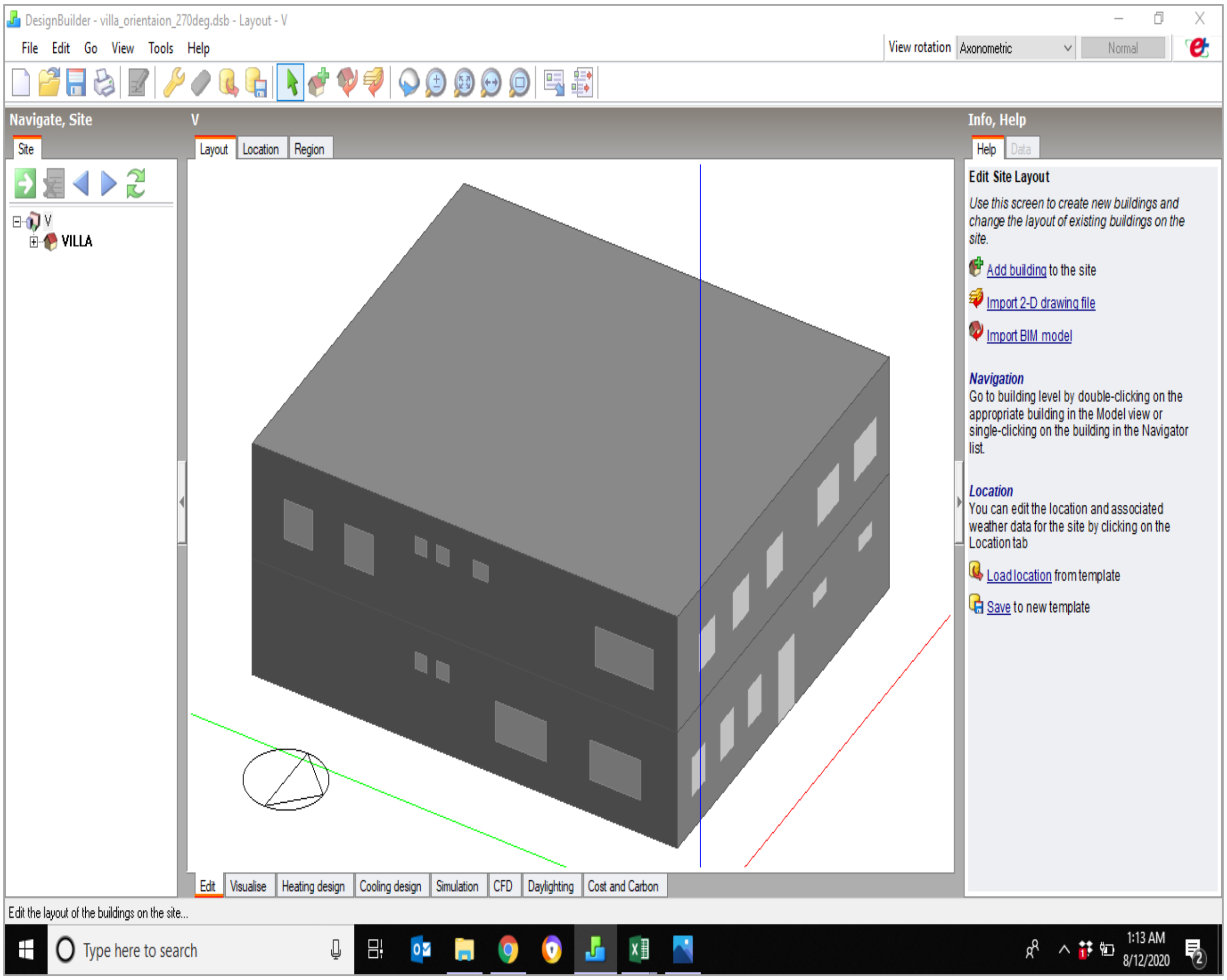


Figure 6 - Screenshot of Residential Villa-Design Builder

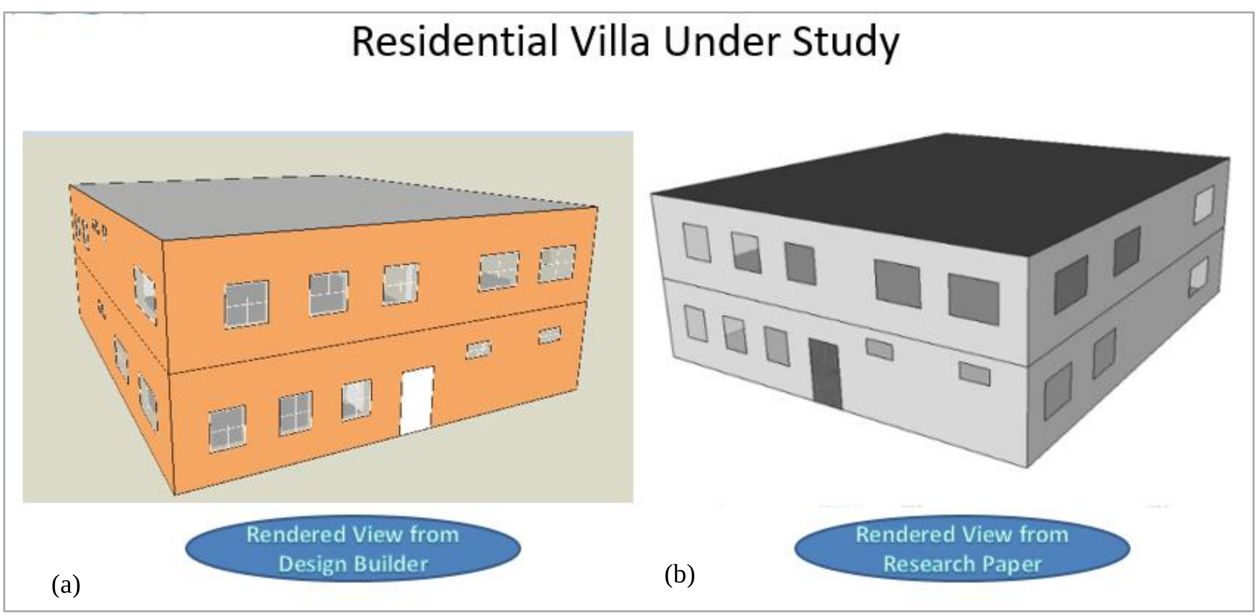


Figure 7 - Rendered view of the villa – (b) [12]

3.1.3 Weather Data File

The weather data file used in this energy simulation is Energy Plus Weather (EPW) data file which is usually based on Typical Meteorological Year (TMY). TMY is a collation of selected and certain weather data for an exact location (in this case Riyadh and later Jeddah), listing hourly values of temperature, humidity & precipitation, sunshine, wind velocity and air pressure for a one-year period.

TMY model is based on Filkenstein-Schafer (FS) method [42], a statistical method selecting the twelve months with each month of the year considered "typical" by various weather parameters as mentioned above. Normally the weather data for 30 years is recorded by TMY to generate the EPW weather file [43].

3.1.4 DesignBuilder Software

The simulation software used in this research for modeling energy consumption of the buildings is DesignBuilder (Version 6.1.6.008). The main features of this software lie in its extremely user-friendly & comprehensible interface with its vast range of performance data due to which it can make available information like annual energy consumption, temperature variations throughout the year and properties of HVAC components. [44]. Four types of energy simulations are emphasized by this software: (a) cooling systems simulation, (b) heating systems simulation (c) energy performance indicator simulation and (d) real weather data simulation.

The simulation engine, EnergyPlus, which is well integrated within any DesignBuilder, runs all the essential and necessary calculations associated with the energy model of any type of building stock and reports all the results within the interface of the DesignBuilder

In the user interface of this DesignBuilder software, there are many types of templates that are accessible like construction templates, schedule templates, etc. Figure 8-10 shows the occupancy schedule taken in this research (see Table-2). All the required values (percentage) used in the formulation of this schedule have been included. Similarly, the schedule regarding the usage of appliances is shown from Figure11-13.

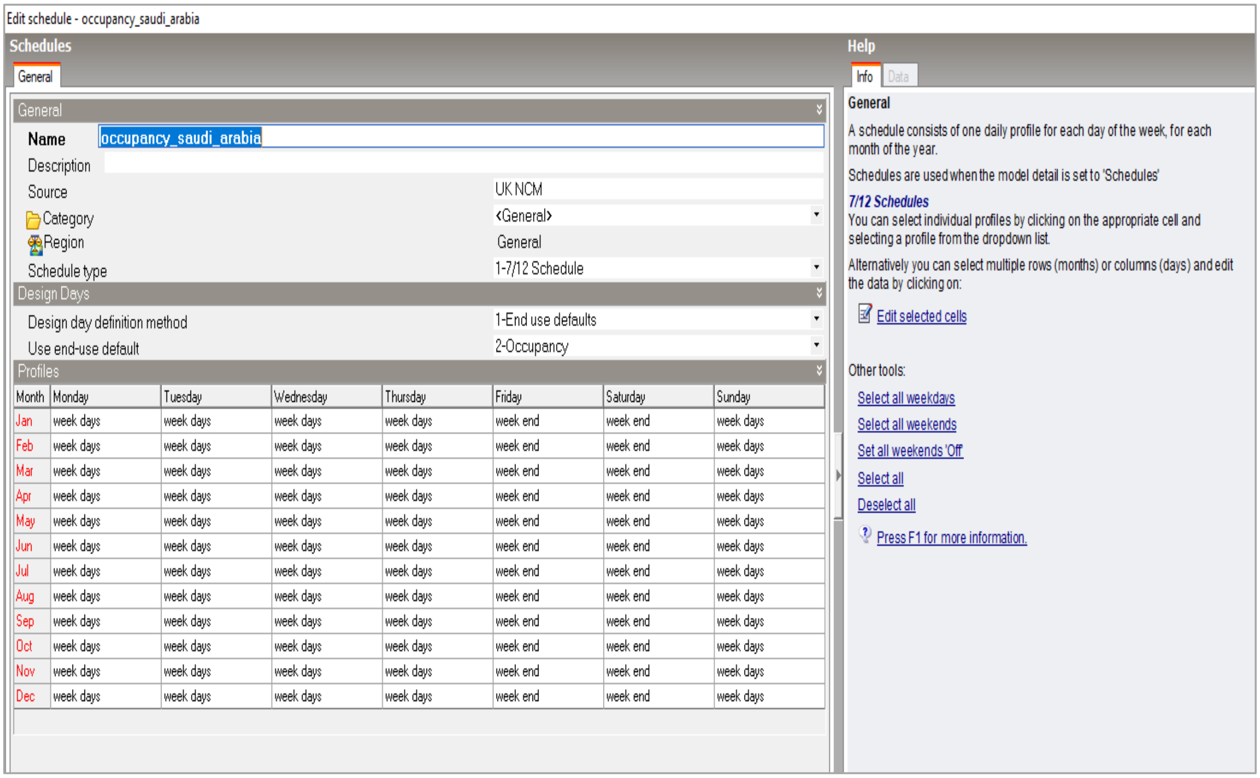


Figure 8 - Occupancy Schedule-(DesignBuilder)

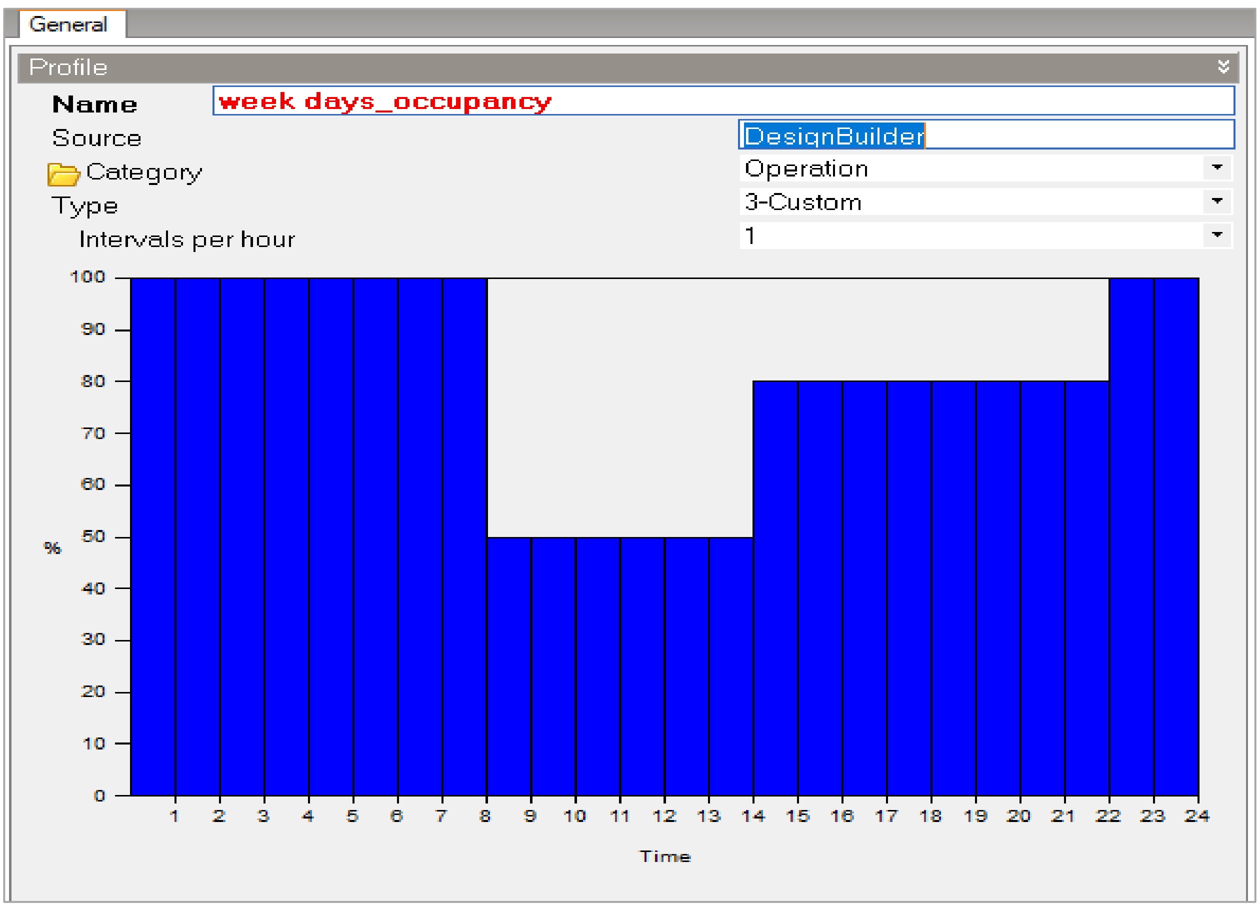


Figure 9 - Occupancy Schedule, Weekdays (DesignBuilder)

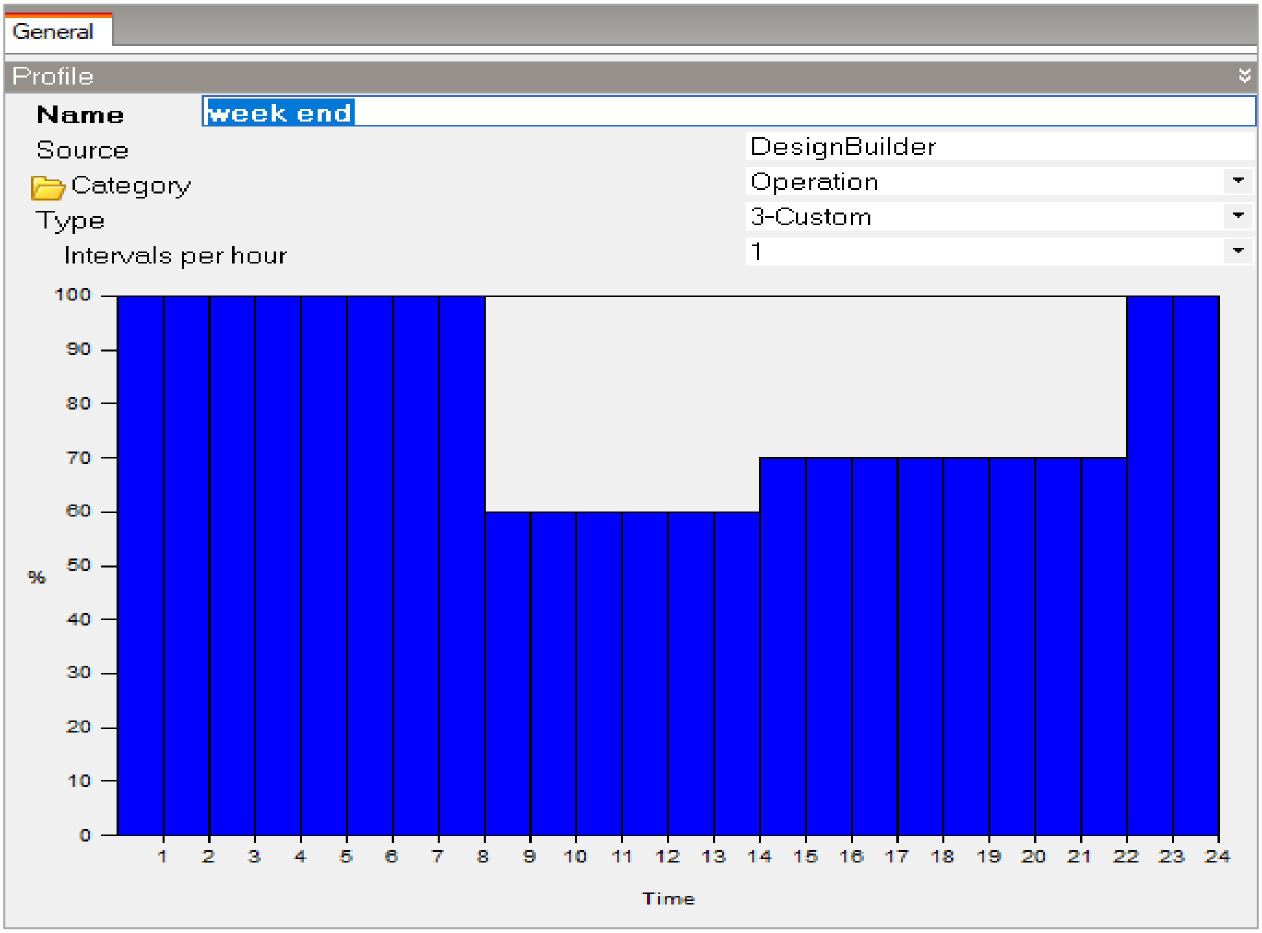


Figure 10 - Occupancy Schedule, Weekends (DesignBuilder)

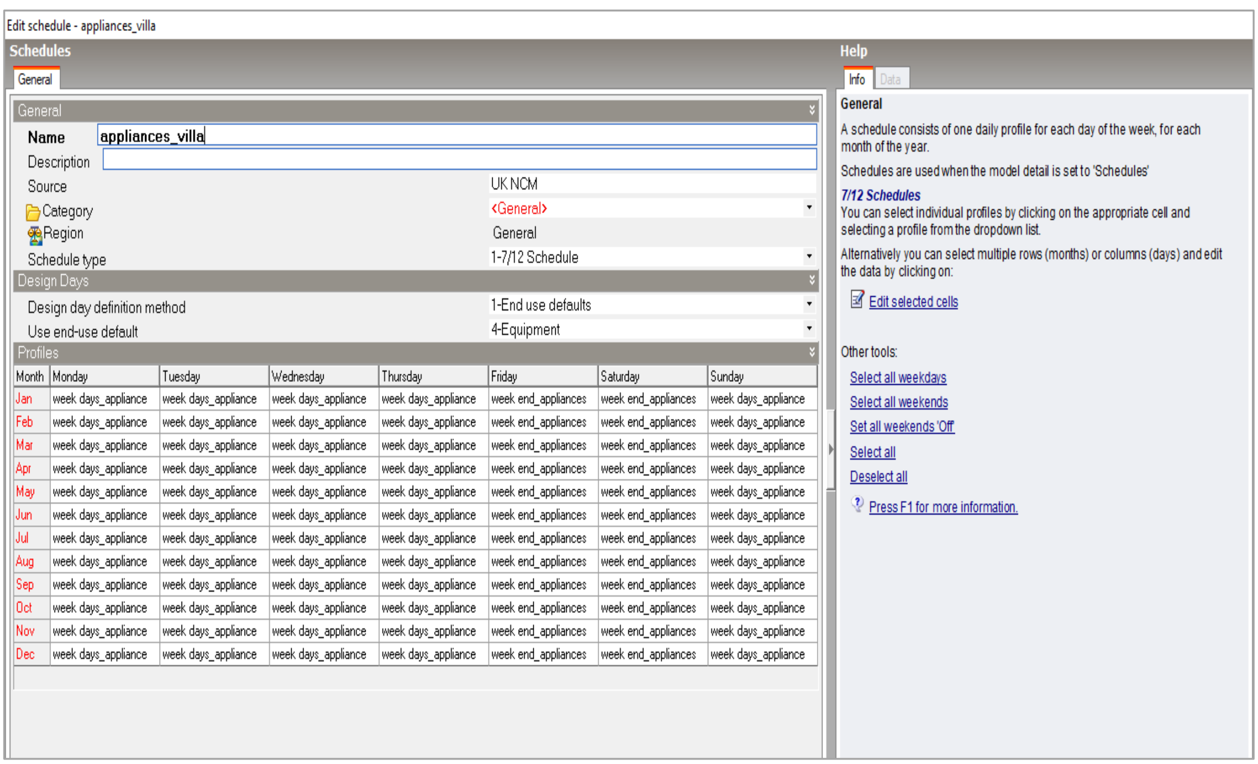


Figure 11 - Appliances Schedule-(DesignBuilder)

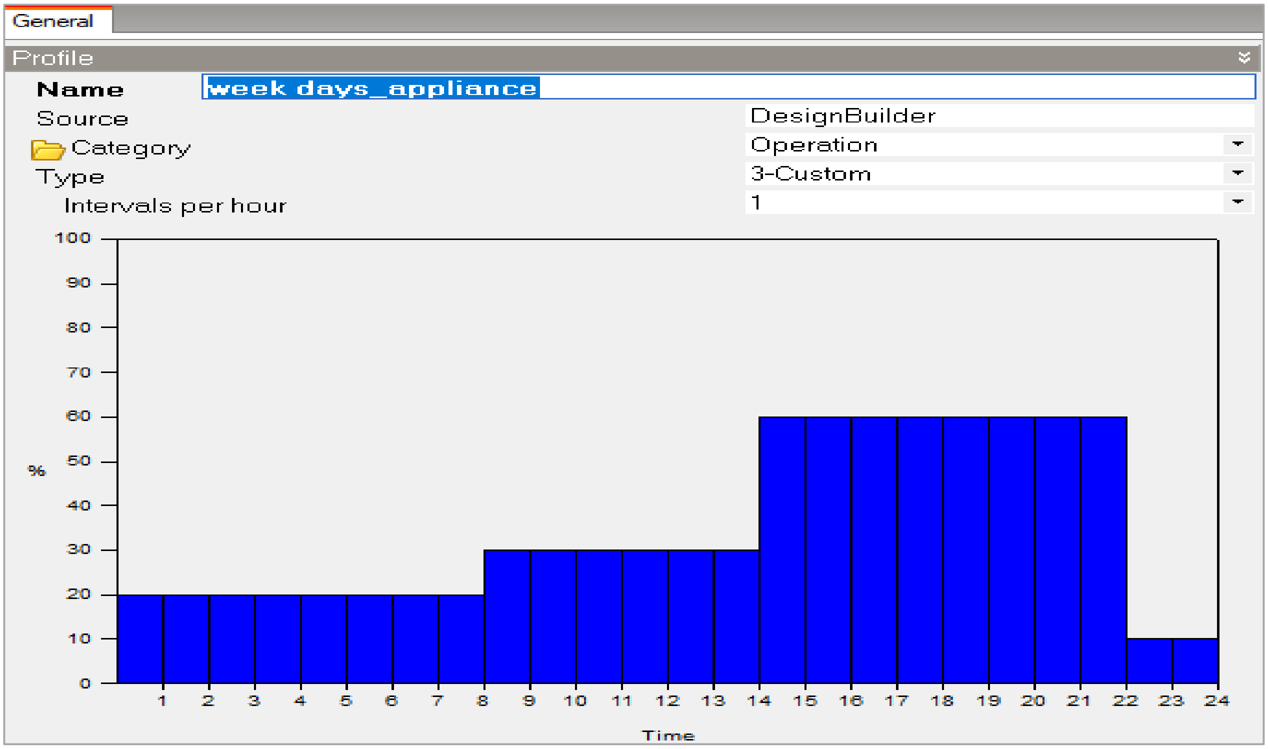


Figure 12 - Appliances Schedule, Weekdays (DesignBuilder)

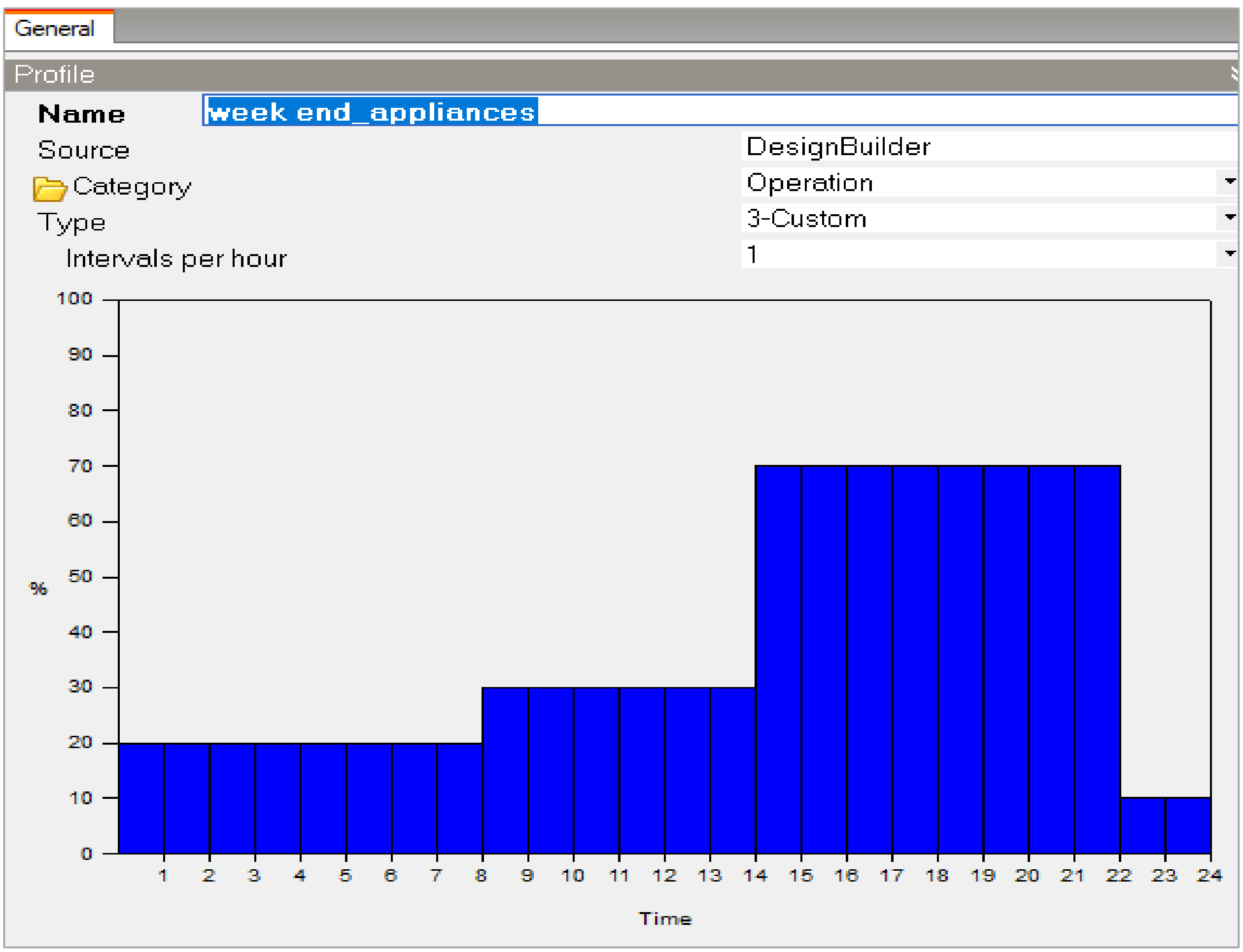


Figure 13 - Appliances Schedule, Weekends (DesignBuilder)

3.2 STEP-2

After the validation of simulation results in the first step, passive measures were applied to the base case. The first passive measure was the macro encapsulation of Phase Change Material of different Melting Points and thickness. Once applied, energy simulations were again carried out to determine the change in cooling load, heating load and total energy consumption.

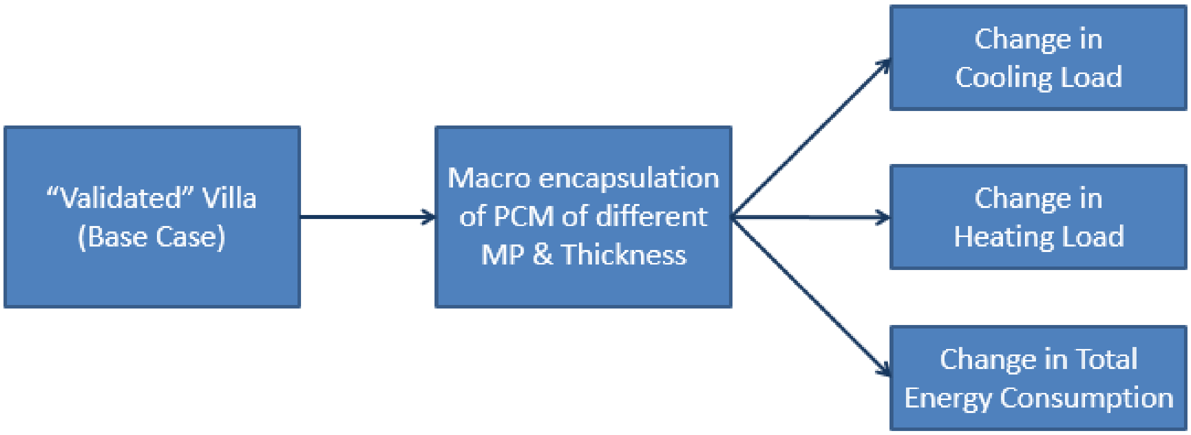


Figure 14 - Flow Diagram: Step -2

3.2.1 Application of Phase Change Materials (PCMs)

PCMs are smart materials that absorbs, stores, and releases a large amount of energy as latent heat at known and expected temperatures. [45] One purpose of developing new smart construction materials is their capability to respond to their environmental changes in a favorable and positive way, unlike its predecessors, such as stone, wood and concrete. [46]

There are 3 processes that can be affiliated with the PCMs: The PCMs may have Solid-Liquid, Solid-Solid, or Solid-Gas transition. The Solid-Gas transition enthalpy is extremely high. This enormous enthalpy results in some application difficulties, like high pressure and volume variation during phase transition. The Solid-Solid transition has significantly lower energy storage capacity. The Solid-Liquid transition doesn't present high volume and pressure variation therefore it is preferred over the other two (Solid-Solid, Solid-Gas transition) [47,48,49]. PCMs can be either, organic (food grade by-products[Bio], paraffin etc), inorganic (hydrated and metal salts) and eutectic (a combination of both organic and inorganic) [50].

In this study, Bio-PCMs were macro-encapsulated in a sheet and then were incorporated in the walls and roof of the residential villa. 05 different PCMs were selected for the study, each one with unique melting points [(Q29, Q27, Q25, Q23, Q21) representing the melting temperature of (29°C, 27°C, 25°C, 23°C, and 21°C respectively). For each case, 04 different thickness along with its relevant Energy Storage Capacity (ESC) were considered [(M182 –ESC 182 BTU/ft^2, thickness of 74.2mm); (M91 – ESC 91 BTU/ft^2, thickness of 37.1 mm); (M51 – ESC 51 BTU/ft^2, thickness of 20.8 mm) and (M27 – ESC 27 BTU/ft^2, 11.2mm thickness).

The combination of the earlier mentioned parameters resulted in **20** diverse and unique variations. For further understanding of the readers, "M" represents Energy Storage Capacity of the PCM. M27 represents a PCM with an ESC of 27 BTU/ft^2.In SI units this is 306.6 kJ/m^2 i-e it can store and subsequently release 306kJ of energy in 1m^2 of its area. Definitely higher the value of M, the higher would be its thickness. Further details regarding the PCMs are given in Table-3

PCM	MP (°C)	Thickness (mm)	Energy Storage Capacity	
			(BTU/ft^2)	(kJ/m^2)
M27_Q21 M27 _Q23 M27 _Q25 M27 _Q27 M27 _Q29	21 23 25 27 29	11.2	27	306.626
M51 _Q21 M51 _Q23 M51 _Q25 M51 _Q27 M51 _Q29	21 23 25 27 29	20.8	51	579.183
M91_Q21 M91 _Q23 M91 _Q25 M91 _Q27 M91 _Q29	21 23 25 27 29	37.1	91	1,033.44
M182 _Q21 M182 _Q23 M182 _Q25 M182 _Q27 M182 _Q29	21 23 25 27 29	74.2	182	2,066.89

Table 3 - Properties of PCMs

Figure 14 shows the 3 layers of the walls and roof of the base case without the application of PCM sheets. In subsequent Figures, the positioning of PCM layer sheet would be visible for the readers. All 20 variations are not possible to be displayed in these figures. However, PCMs with different values of “M” would be presented to have a clear understanding of the thickness and amount of space occupied by the macro encapsulated PCM or layer of a sheet of PCMs

(A)	**BASE CASE**
	
ROOF OF THE RESIDENTIAL VILLA	**WALL(S) OF THE RESIDENTIAL VILLA**

Figure 15 - Base Case w/o PCM

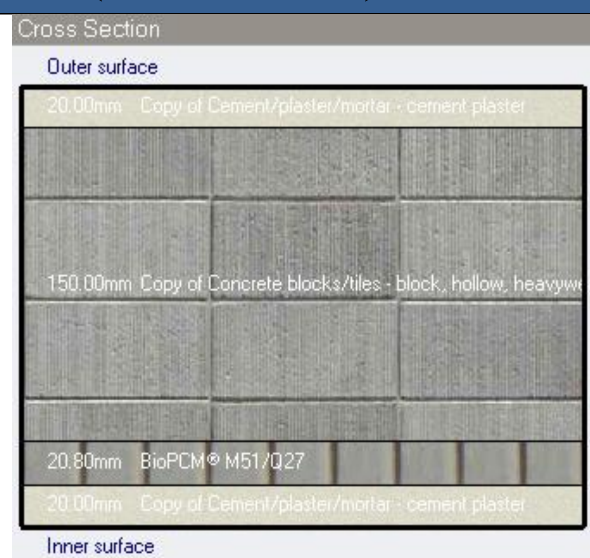
Figure 15 shows the layer of PCM (M: 27) with a thickness of 11.20 mm is incorporated in the residential villa’s walls and roof. It is layered closer to the inner surface for both walls and roof. Likewise, Figure 16-18 presents the layer of PCM with different ‘M’ is encapsulated. It can be clearly seen, and as discussed earlier, that as the value of ‘M’ increases, so does the thickness of the layer increases. Besides this layer would occupy more space in the walls and the roof.

(B) Layer of PCM with “M”=27 (thickness:11.20mm)

ROOF OF THE RESIDENTIAL VILLA	WALL(S) OF THE RESIDENTIAL VILLA

Figure 16 - PCM with M:27

(C) Layer of PCM with “M”=51 (thickness:20.80mm)

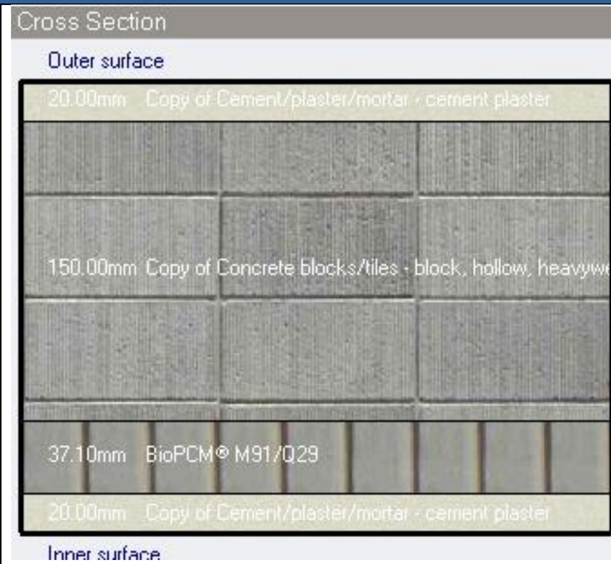


ROOF OF THE RESIDENTIAL VILLA	WALL(S) OF THE RESIDENTIAL VILLA

Figure 17 - PCM with M:51

(D) Layer of PCM with “M”=91 (thickness:37.10mm)

ROOF OF THE RESIDENTIAL VILLA



WALL(S) OF THE RESIDENTIAL VILLA

Figure 18 - PCM with M:91

(E) Layer of PCM with “M”=182 (thickness:74.20mm)

ROOF OF THE RESIDENTIAL VILLA

WALL(S) OF THE RESIDENTIAL VILLA

Figure 19 - PCM with M:182

3.3 STEP-3

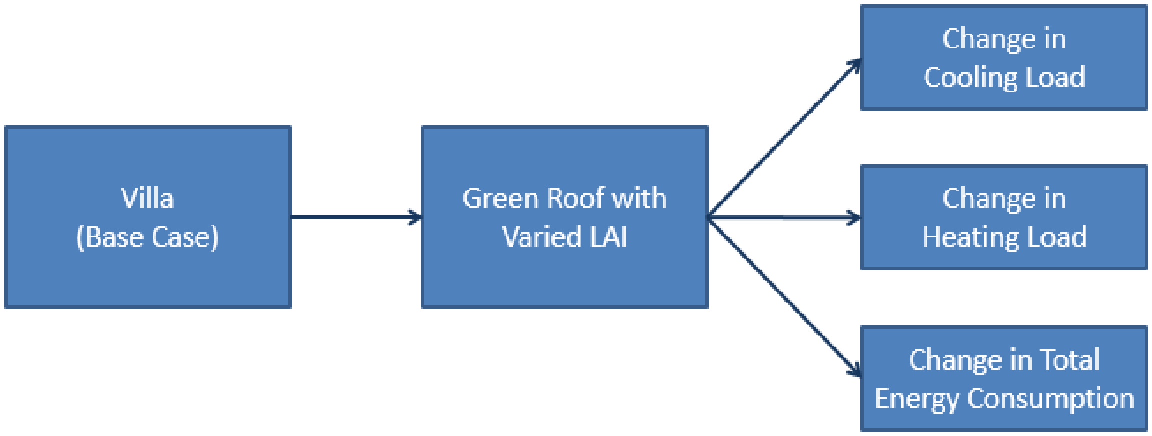


Figure 20 - Flow Diagram: Step-3

Another passive measure was applied to the roof of the residential villa. Green Roof with variable Leaf Area Index was imposed on the roof. Since DesignBuilder is not compatible with Vegetated walls, therefore only energy simulations with respect to the roof were carried out.

3.3.1 Application of Green Roof with variable LAI

A green roof is a roof that comprises of soil that acts as a growing medium and a vegetation layer as its outermost layer. It also contains a drainage layer, a roof barrier, and a waterproof membrane. A roof barrier creates a physical barrier between the roots of plants and the waterproofing membrane. [51]. Green roof differs from any conventional roof because it acts as a heat sink-an active energy device-which collects, processes and releases energy according to its immediate need. [52]. The evapotranspiration of plants helps to cool the roof by using the heat to evaporate water from the surface of the plant. Also, the shading of the plants helps in reducing the amount of sunlight striking the roof. This helps in reducing the indoor and outdoor temperatures in the buildings [53,54,55].

In this study, a 10.mm sheet of Ethylene propylene diene methylene (EPDM) was layered over the outer surface of the roof of the residential villa. This acted as a waterproofing membrane. This EPDM sheet was fully covered by 38.10 mm of gravel which acted as a drainage path for water. Over this drainage path, 9.50mm of PVC sheet was laid. This sheet acted as a roof barrier and it created a physical barrier between the plant roots and waterproofing membrane. This was followed by a layer of growing medium and the vegetation itself (both 100mm). (Figure 20)

The vegetation was varied through the Leaf Area Index (LAI) and this factor was considered as a variable causing different results for energy consumption. The Leaf Area Index is defined as the ratio of leaf's complete one-sided area per one unit of the surface area of ground soil. [56] However, LAI is ascertained by its vegetation canopy since it is a ratio & a non-dimensional quantity. The LAI is linked to the structure and behavior of any plant and is a very important parameter regarding green's roof energy performance when the rate of evaporation's influence is considered [57,58, 59]

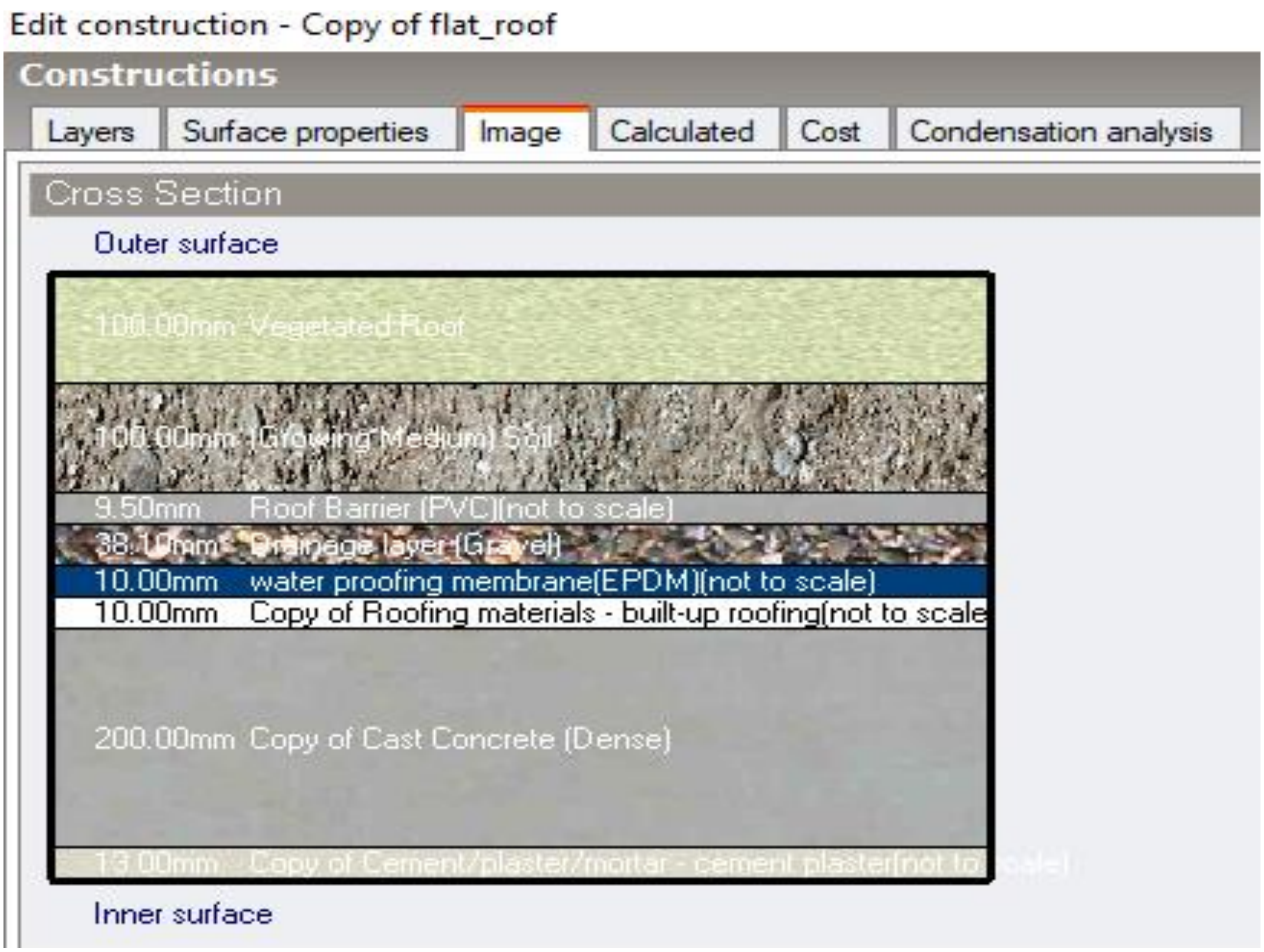


Figure 21 - Different Layers of Green Roof

The Leaf Area Index is varied from 1 to maximum of 5. Figure 21 shows LAI=3 as one of many simulation parameters to vary its value to find out change in energy consumption for the residential villa.

Figure 22 - Parameter for Green Roof Simulation- LAI

3.4 STEP-4

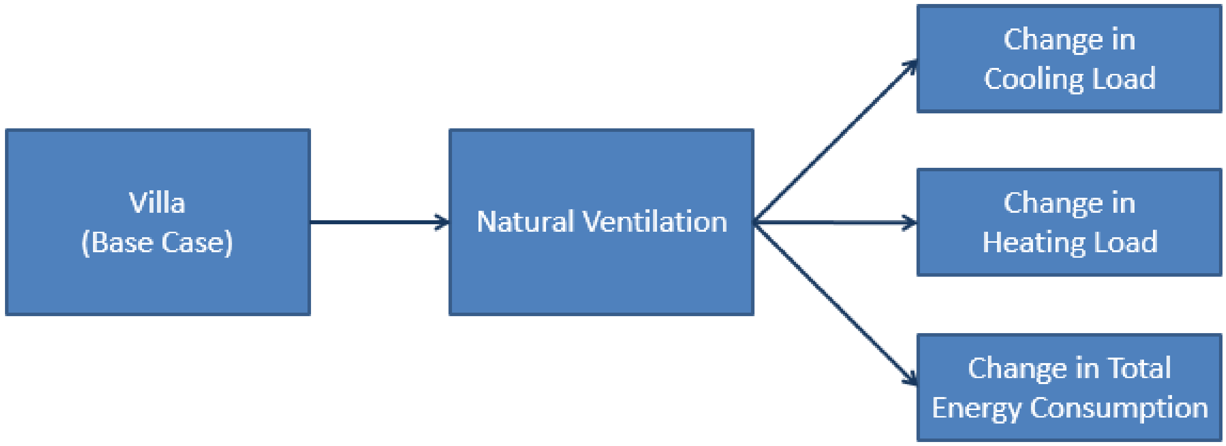


Figure 23 - Flow Diagram: Step 4

Another passive measure was applied to the residential villa. In this study mixed-mode ventilation strategies, which is the combination of both natural ventilation and HVAC schedules, were designed in such a way to ensure, improved air quality, thermal comfort and minimization of energy consumption for mechanical cooling. This was considered the most suitable strategy considering the climatic conditions of Riyadh where opening windows throughout the day weren't feasible and also opening it every day for some duration was also not conducive. Only when the conditions were suitable that the windows were opened and HVAC was turned off.

3.4.1 Application of Natural Ventilation

Natural ventilation is contemplated as a passive measure that can help in improving the indoor air quality and lowering the energy consumption of any type of building. This is due to the flushing out of the excessive heat from the building envelope by allowing natural airflow through the windows and openings of the envelope. [60]. This movement of excessive heat is due to pressure difference which is itself caused by the difference in temperature between the outside and inside of the building environment. [61]

In this study, natural ventilation parameters are set in such a way that it only operates when the environment is suitable for the natural phenomenon of improvement of the indoor temperature and subsequently minimizing the expending of energy load. Only at that moment, the HVAC system would be shut off. For the rest of the time, the HVAC system would be operating. The parameters of natural ventilation operation are shown in

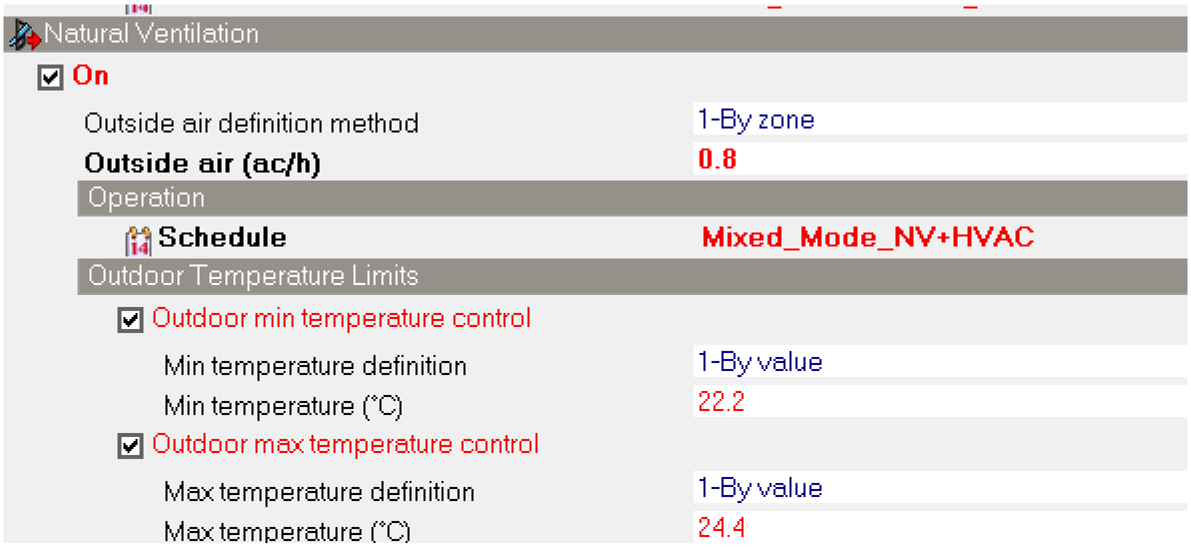


Figure 24 - Parameters of Natural Ventilation operation

3.5 STEP-5

In this step, short wave reflectivity or albedo effect was created by applying simple white paint to the building envelope. 3 different cases were analyzed. In the first case, only the roof of the residential villa was painted white. In the second case, all four walls were painted. For the final case, both the roof and the walls were painted white.

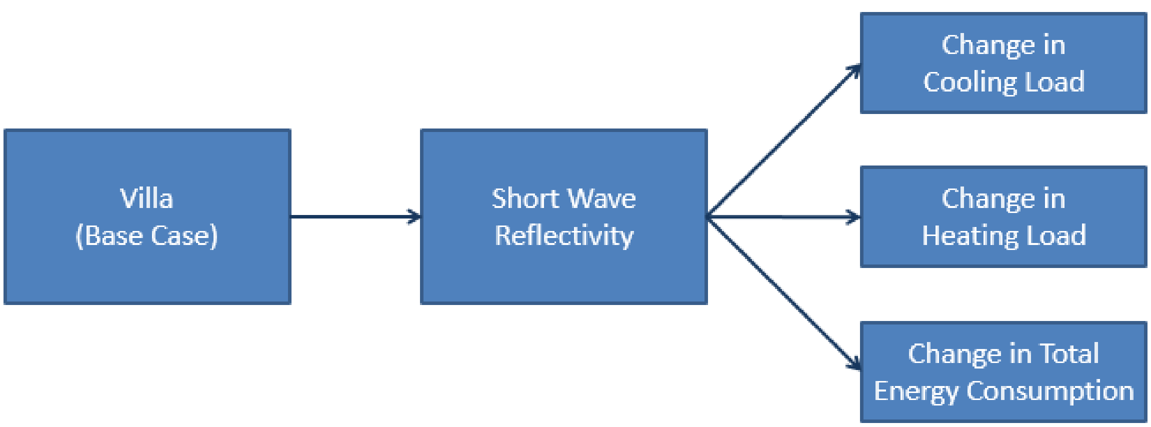


Figure 25 - Flow Diagram: Step-5

3.5.1 Application of White Paint (Albedo Effect/ SWR-Short Wave Reflectivity)

Short Wave Reflectivity (SWR) or albedo effect for the surface enables it to reflect the emitted radiations of the sun which is responsible for the disruption of internal thermal comfort. [62] A higher short-wave reflectivity is recommended which allows less heat flux entering the indoor space through exterior surfaces. [63]

In this research, the effect of white paint on the outer surface of the residential envelope is studied. For the base case (residential villa), the value of solar absorptance, for both walls and roof, is maintained at 0.6 as the default value. For passive measure, solar absorptance value is changed to 0.3 and emissivity to 0.9 which corresponds to the white paint

Three different scenarios are created in this research to study which one is responsible for optimum results. In the first case, only the roof's solar absorptance value is changed to 0.3 and emissivity to 0.9. In the second, these values are changed for all the walls. Then for the last scenario, the combined effect of white paint for both walls and roof is analyzed

Figure 26 - Parameter for SWR/ albedo effect

3.6 STEP-6

By using the same residential villa model as the base case, those passive measures which showed the optimum results for Riyadh city were now used for the city of Jeddah which is characterized by a hot and humid climate. Energy simulations were run using Design Builder to analyses energy consumption for this villa.

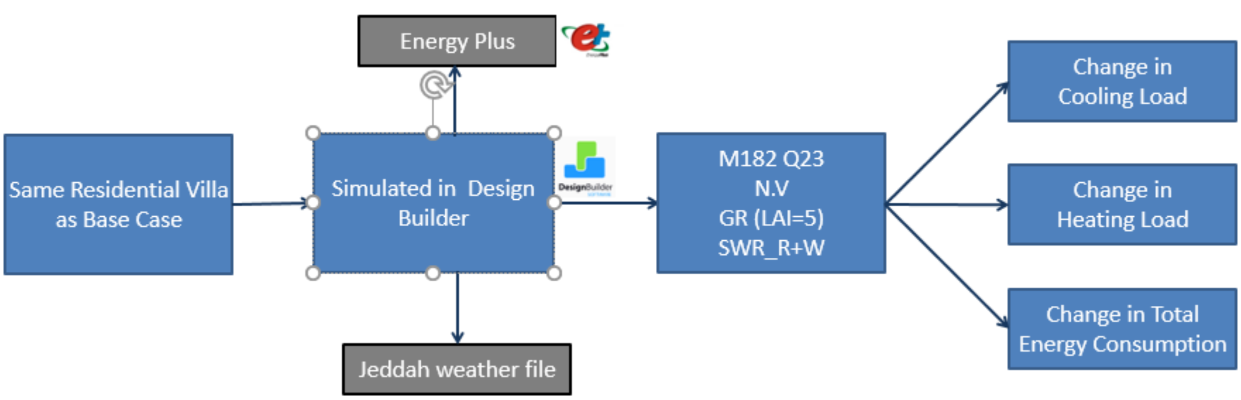


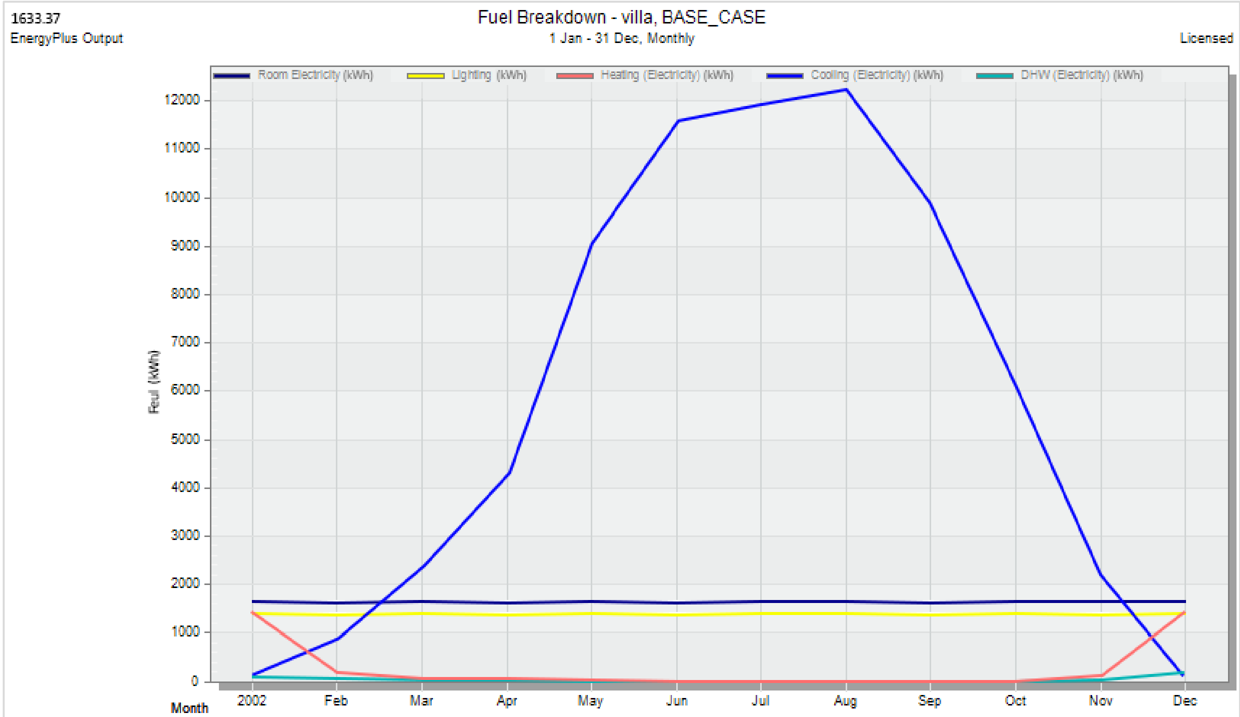
Figure 27 - Flow Diagram: Step 6

CHAPTER 4: RESULTS

4.1 VALIDATION OF SOFTWARE RESULTS

Initially, the results of the comparison between the actual energy consumption of the under-study residential building in Riyadh (KSA) with the energy output of the simulation software showed that there was a difference of less than 8 % between these two results. Therefore, the software result was validated since a similar result was reproduced. Figure 26 shows the actual results reproduced from software DesignBuilder. The results present that the residential villa consumes the most energy for its cooling requirements. The cooling demand for the villa is extremely high from July- August when the temperatures are extremely high. Since the duration of winters is only for a few months, the heating demand is high from December to January only. Besides, demand for Domestic Hot Water is also maximum in these respective months. The energy consumption due to lighting and room electricity (which includes room appliances) remains constant throughout the year as the values of Lighting Power Density and Equipment Power Density doesn't vary. Also, both follow a fixed operation schedule for all weeks of the year. The operational schedule is given in Table-2

The result of Figure 26, which is the monthly energy simulation of the residential villa (base case), is summarized in Figure 27. It can be deduced that cooling demand for the villa is responsible for most of the energy consumption. Indeed, as evidently shown in Figure 28, cooling demand consumes (65%) of total annual energy consumption, followed by Room Electricity (including appliances,18%), Lighting (14%), Heating (3%) and Domestic Heat Water (DHW, 0.003%).



Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Room Electricity (kWh)	1633.37	1629.64	1632.15	1630.27	1632.15	1629.64	1638.37	1632.15	1629.64	1632.15	1629.64	1633.37
Lighting (kWh)	1333.08	1323.72	1332.08	1323.40	1333.08	1322.52	1332.08	1332.08	1320.35	1332.99	1333.08	1333.08
Heating (Electricity) (kWh)	1380.48	221.25	32.22	13.25	7.22	0.87	0.87	0.87	0.86	0.86	121.77	1370.12
Cooling (Electricity)(kWh)	112.22	824.19	2360.85	4297.25	9061.41	11651.84	11972.48	12320.71	9961.35	6140.77	2188.36	101.22
DHW (Electricity) (kWh)	106.25	38.36	12.18	3.22	1.89	0.62	0.62	0.62	0.62	0.64	27.25	108.25

Figure 28 - Actual Simulation Results- DesignBuilder

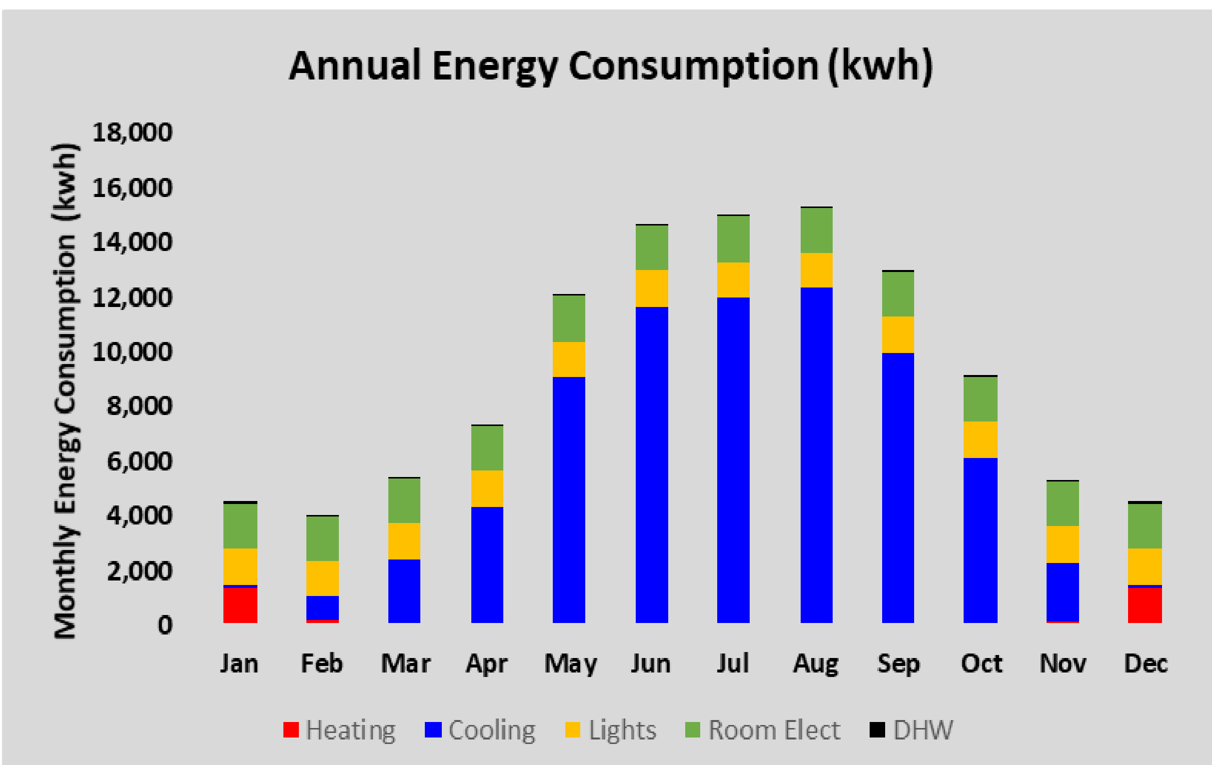


Figure 29 - Monthly Energy Consumption (kWh)

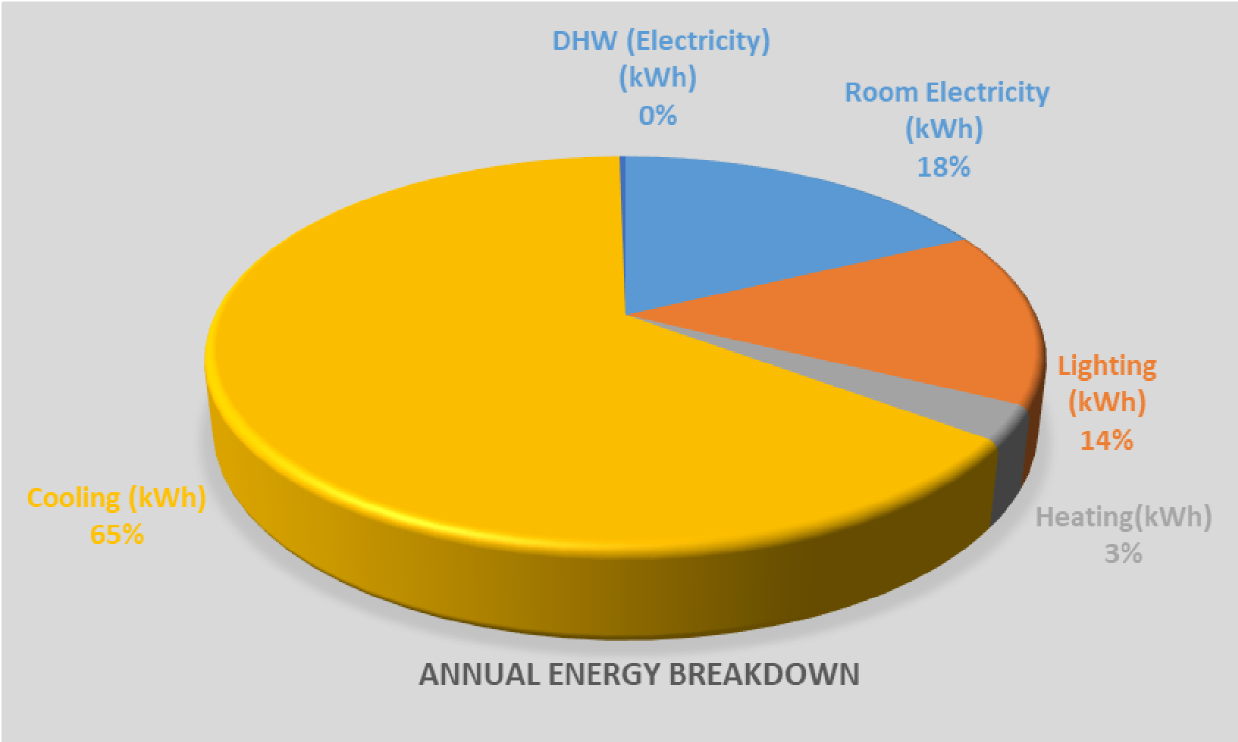


Figure 30 - Total Energy Consumption Breakdown

Figure 29 shows the same comparative results produced by Krarti et al. in this respective research paper. [64] The energy consumption in the green bar graph (Model Prediction) is the very same result, the author simulated from his previous research work [10] (Figure 30). The energy consumption in the blue bar graph is the actual billed consumption of the residential villa. The purpose of putting this comparison (Fig 29) was for the understanding of the readers as the research paper under study [10] showed only the simulated results.

Hence, the validation of software through these comparative results are shown in Fig 31 and Figure 32. The grey bar chart of Base Case Total represents the Billed consumption (blue bar chart) of Figure 29. The yellow bar chart represents the results of the simulation in this study using DesignBuilder Software.

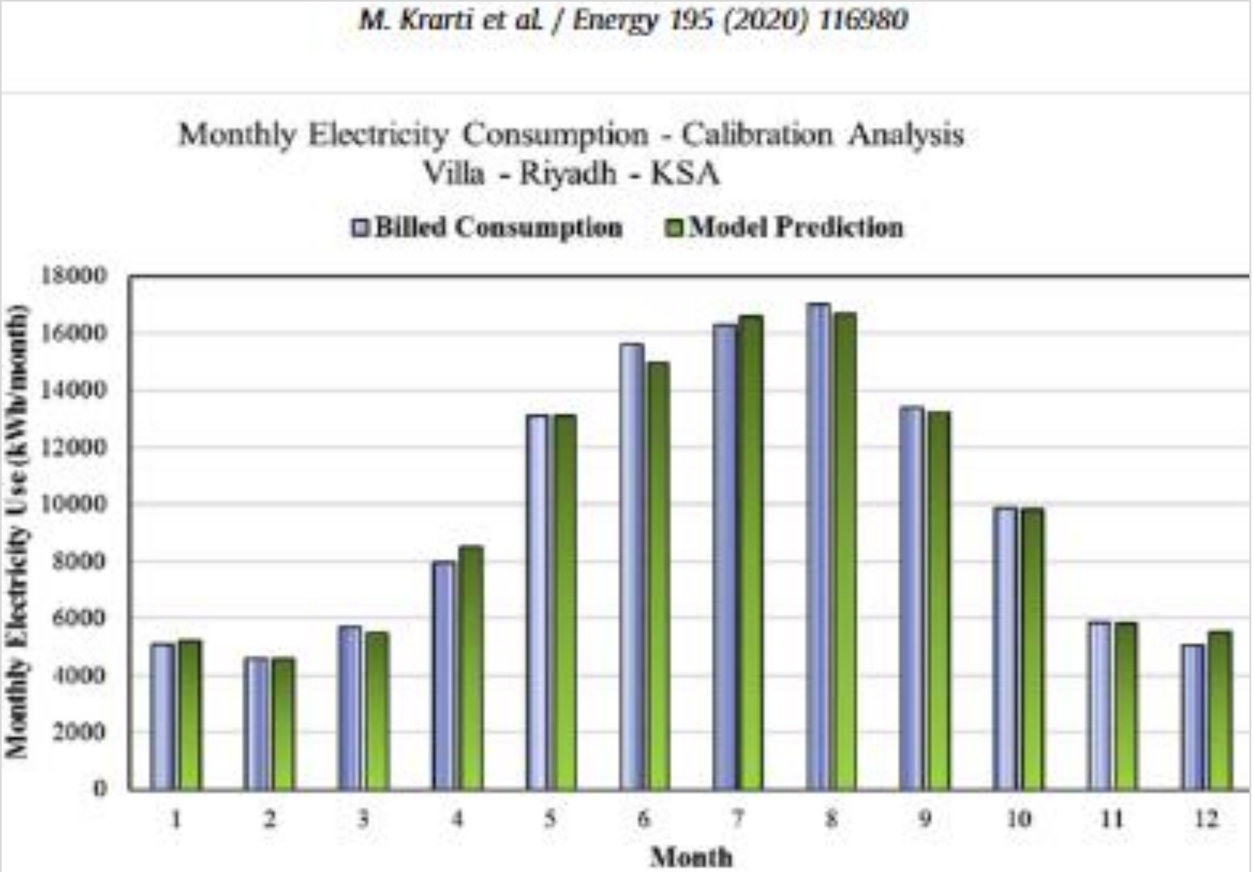


Figure 31 - Comparison b/w Actual Result and Simulated Result (Krarti et al.)

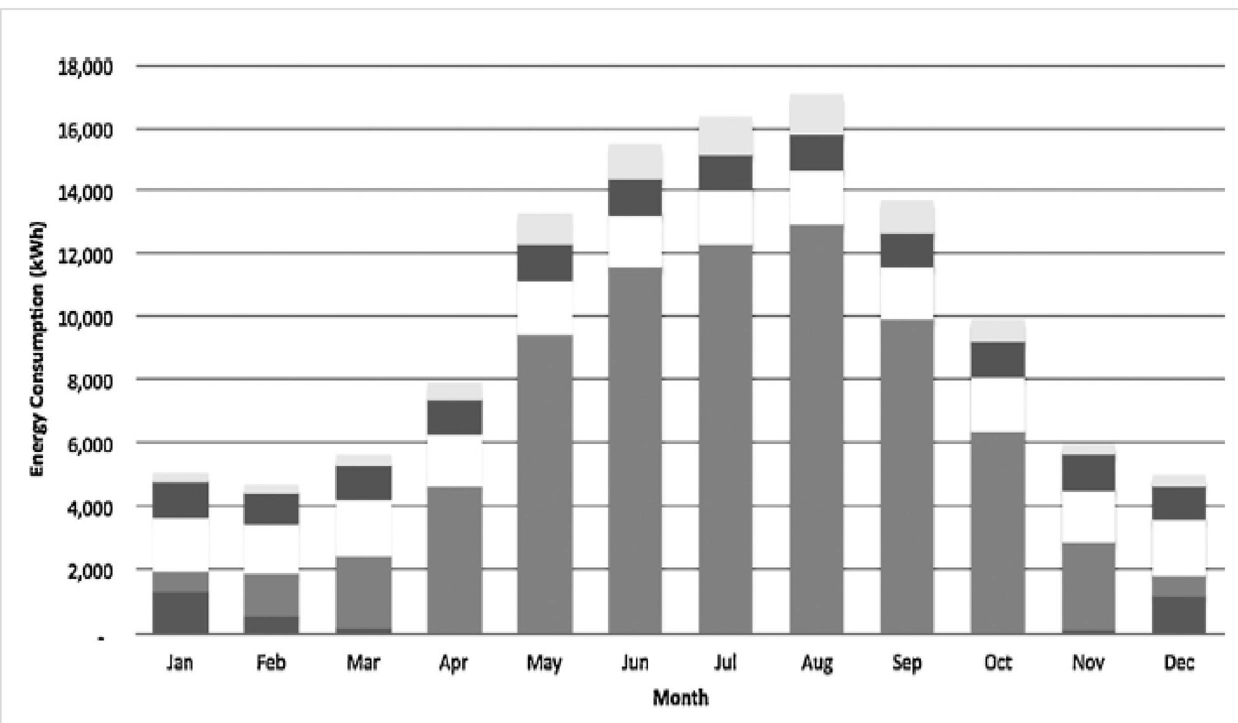


Figure 32 - Source [10]

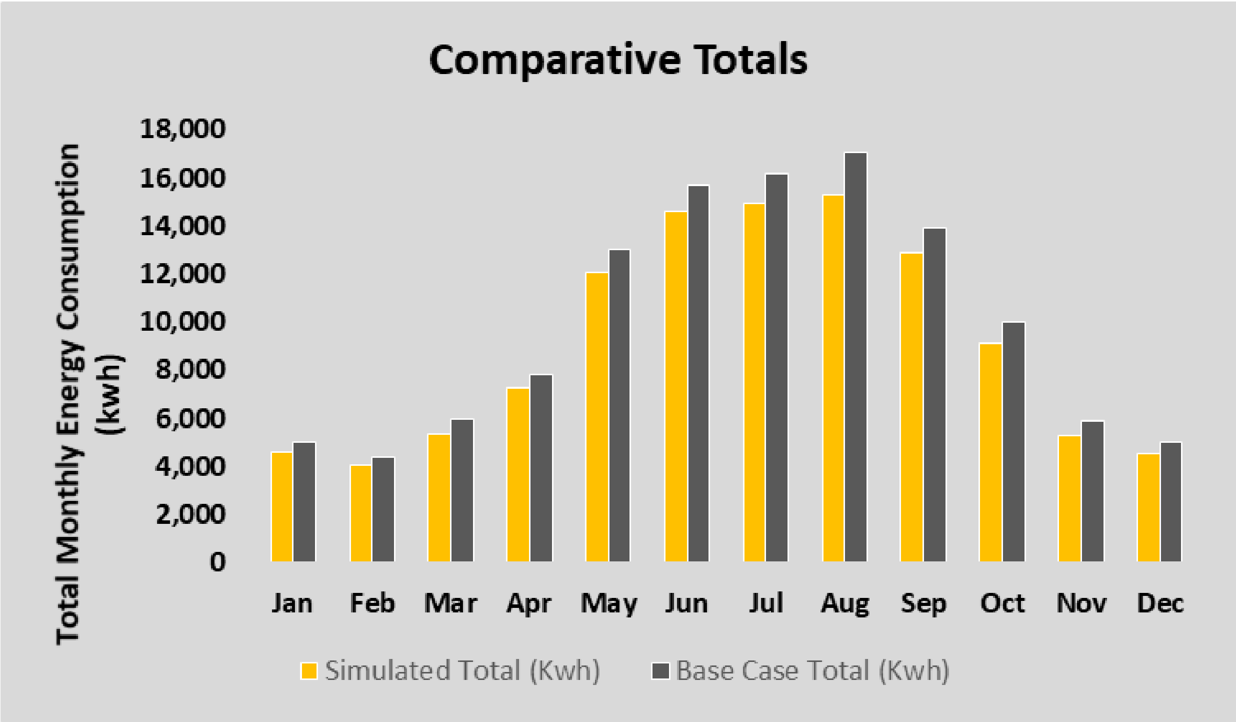


Figure 33 - Results Comparison-I (Simulated vs Actual)

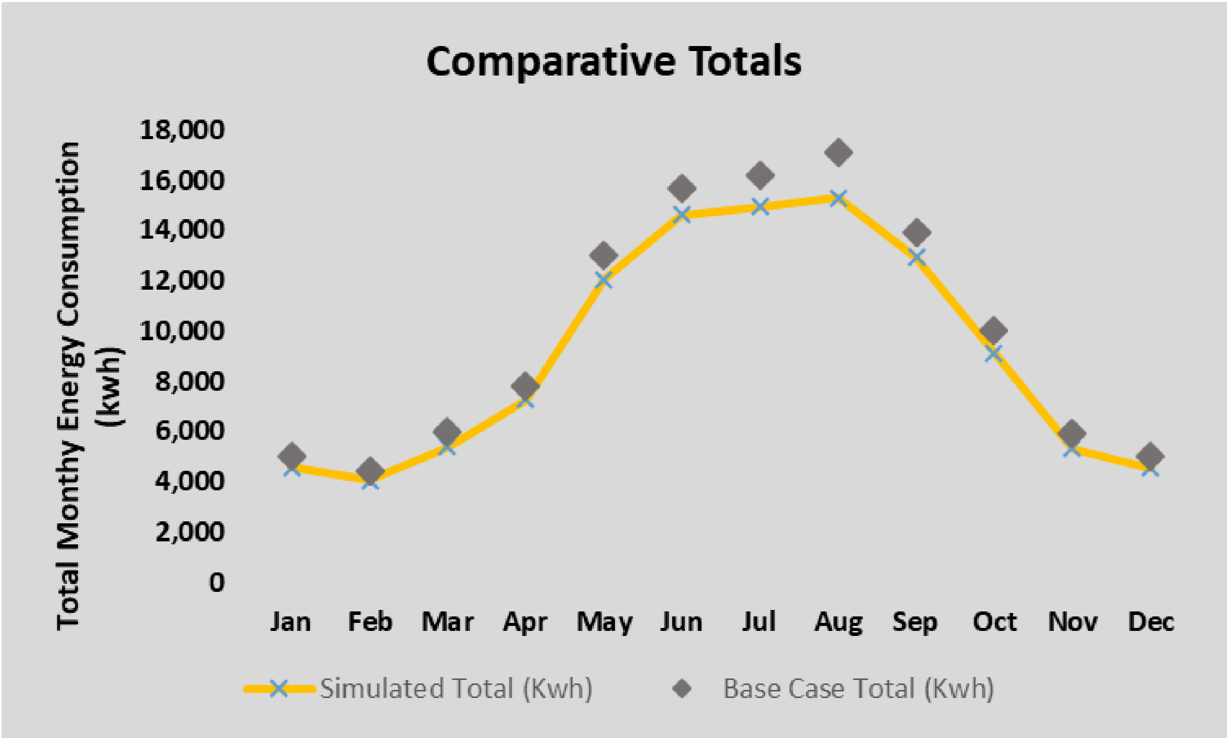


Figure 34 - Results Comparison-II (Simulated vs Actual)

4.2 APPLICATION OF PASSIVE MEASURES

Figure 28 illustrates that the total annual cooling demand is responsible for 65% of total energy consumption. So it was imperative to reduce this cooling demand through the application of PCAMs. Even though heating accounted for 3 %, its reduction was also important considering its relation to the climate. The values of Room Electricity and Lighting were fixed throughout the year and had a very negligible effect due to the application of PCAMs. Similar was the case with the Domestic Hot Water.

Hence, results for change in total energy consumption, annual cooling demand, and annual heating demand in kWh are presented

4.2.1 Change in Energy Consumption due to application of Phase Change Materials

Improvement in the energy efficiency of the building took place through the adaptation of passive measures. Figure 33 compares the annual total energy consumption in (kWh) of base case with various incorporated Phase Change Materials (PCM).M182_Q23 reduced the total energy consumption from 109,978 kWh to 86,626. Hence the best results are shown by PCM M182_Q23 which was able to reduce total energy consumption by 21.2%. Likewise, all types of PCMs showed positive results. The range of percentage of energy reduction varied from 4.9% ~21.2%. (Figure 34).

Figure 35 clearly shows that there is little or no change in energy consumption due to Room electricity, Lighting, and DHW, therefore these parameters would be ignored in the other results. Figure 36 shows the monthly trend of energy consumption of the Base Case villa with different type of macro-encapsulated PCMs.

In terms of annual cooling demand, PCM M182_Q23 showed the most desirable result. It reduced the annual cooling demand by 31.2%. Through the application of different Phase Change Material, the annual cooling load was reduced from 7.1 % to31.2%. This illustration is represented in Figure 37 and Figure 38

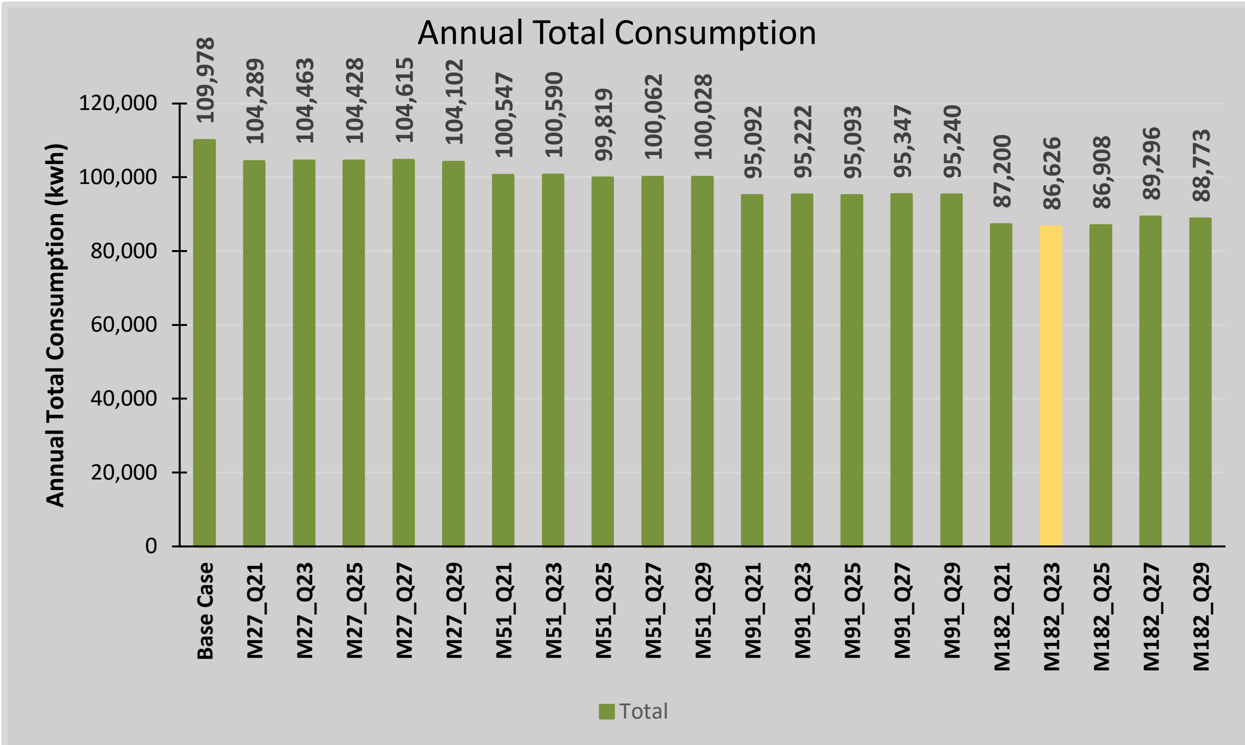


Figure 35 - Annual Total Consumption of Base Case with PCM

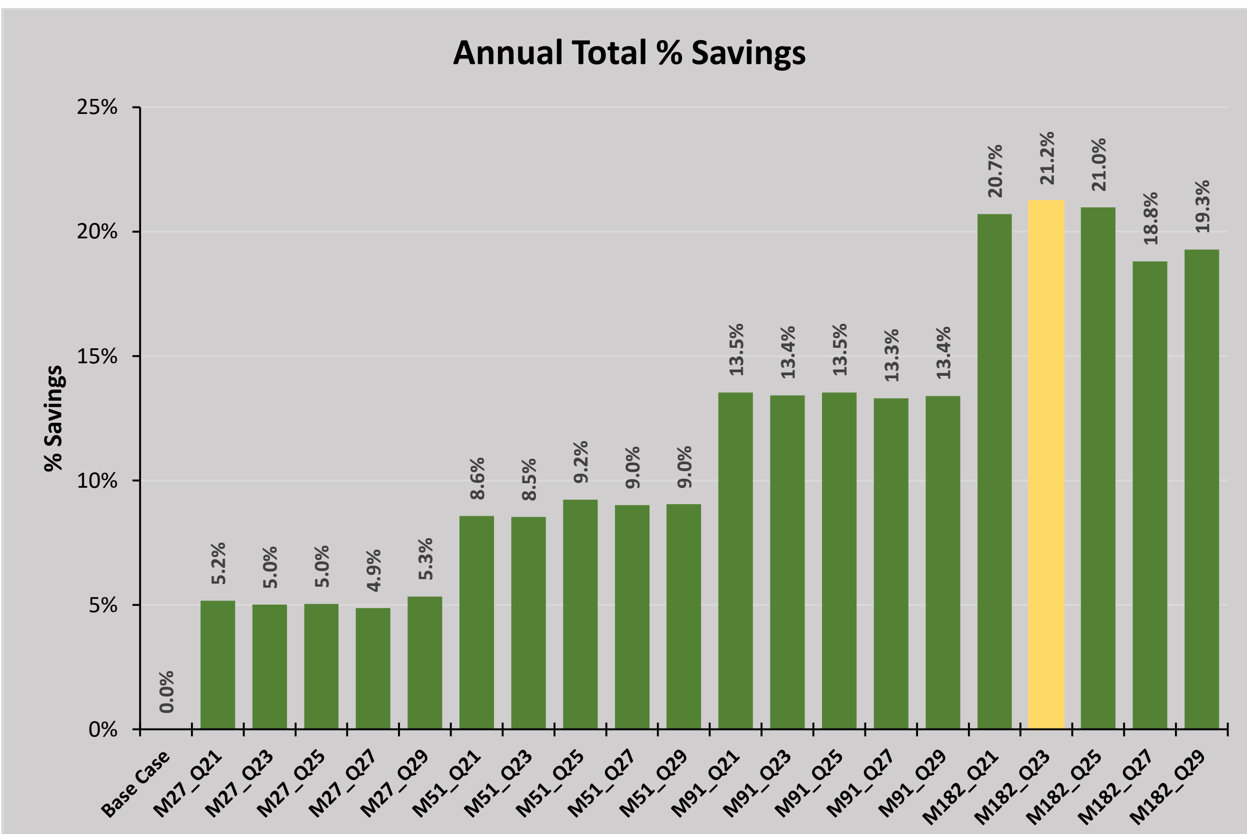


Figure 36 - Annual Total % savings of PCMs

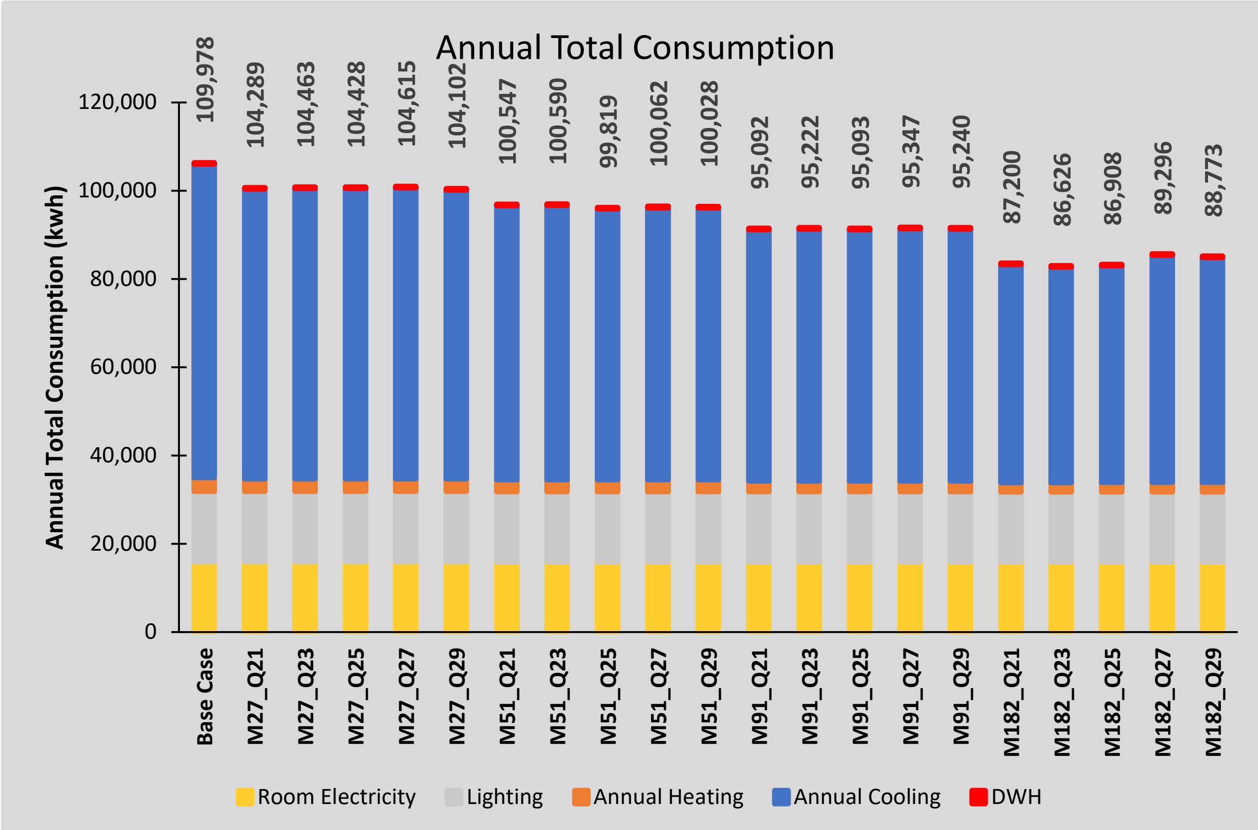


Figure 37 - Annual Total Consumption –All parameters

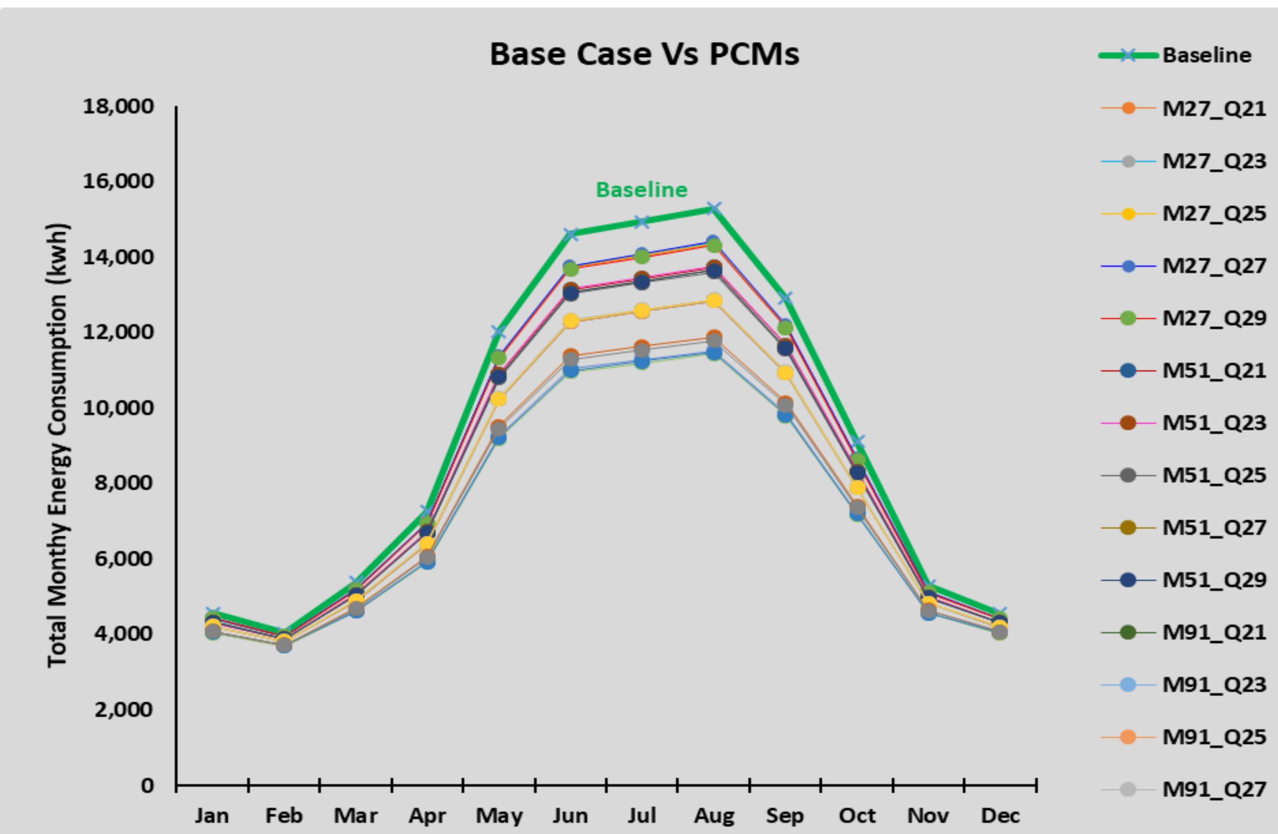


Figure 38 - Monthly Energy Consumption Comparison

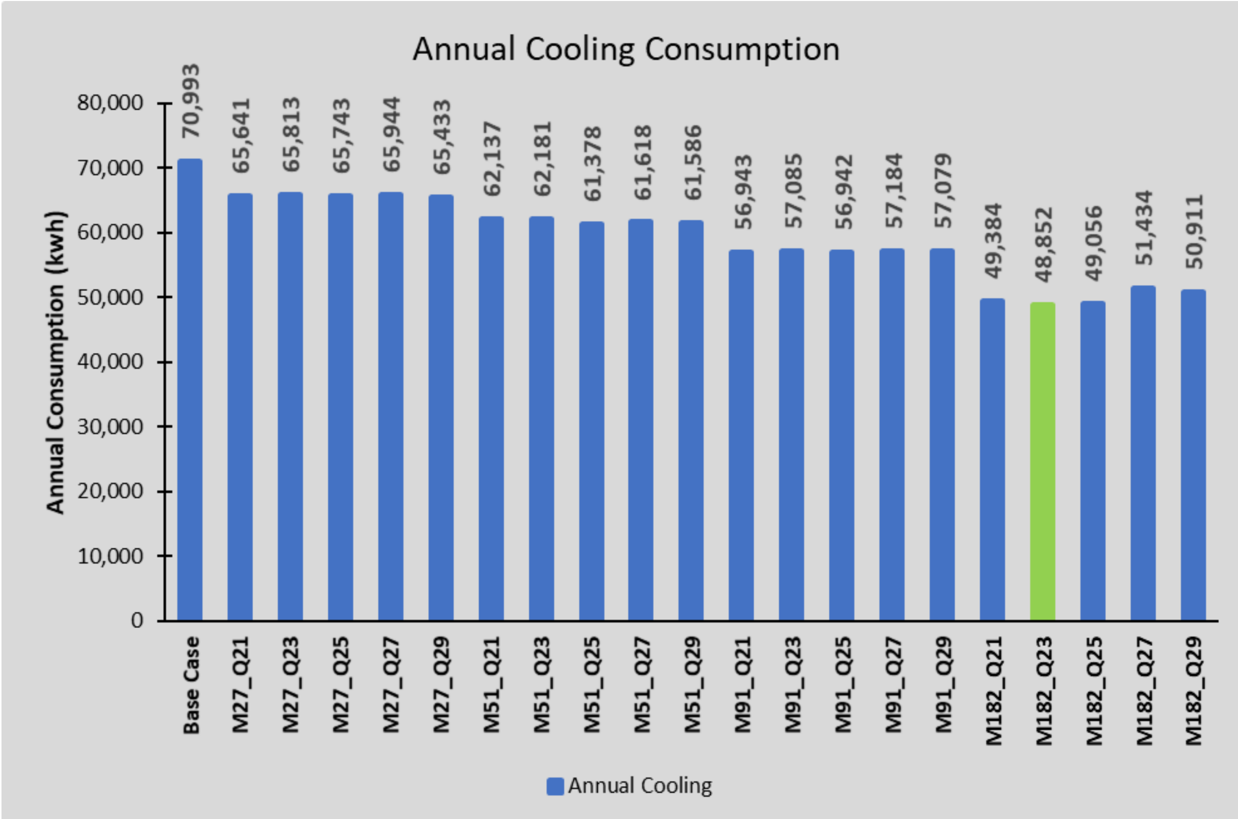


Figure 39 - Comparison of Annual Cooling Consumption b/w base case and PCMs

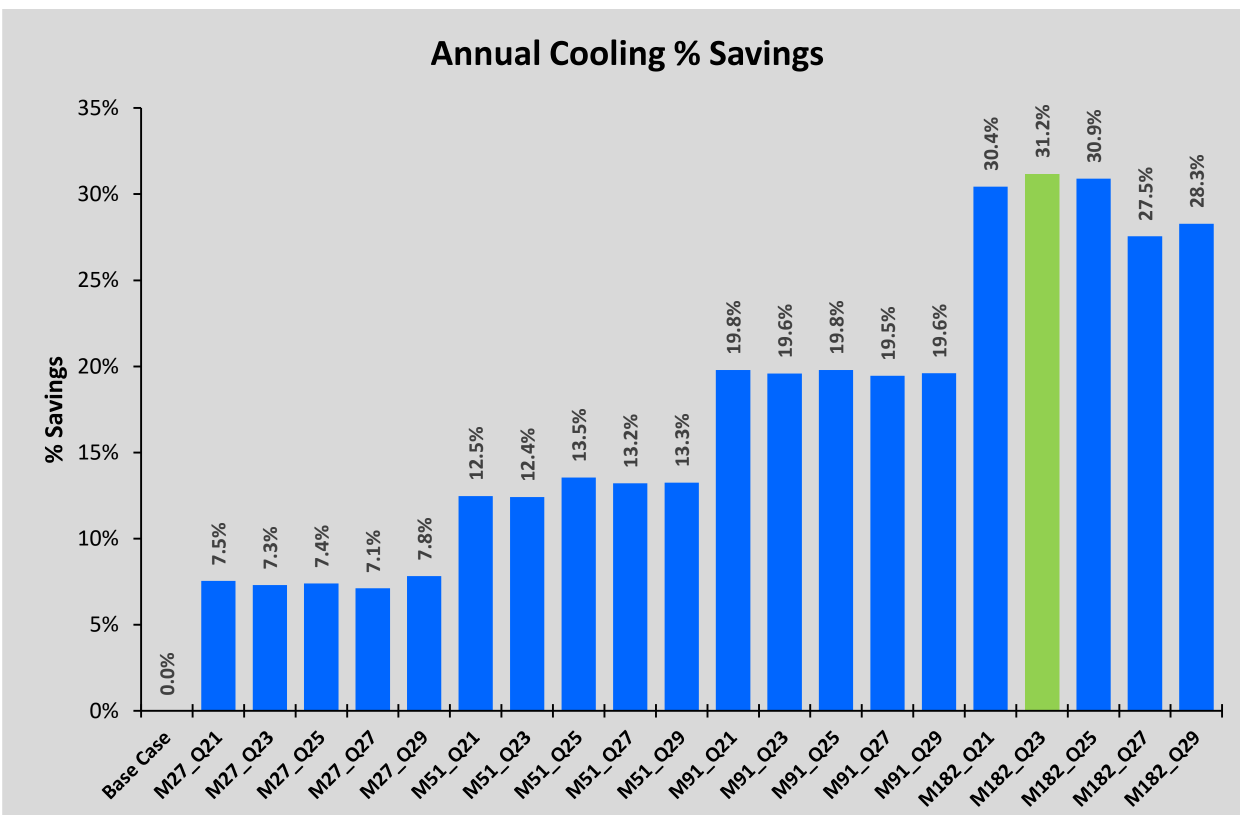


Figure 40 - Annual % Cooling Reduction

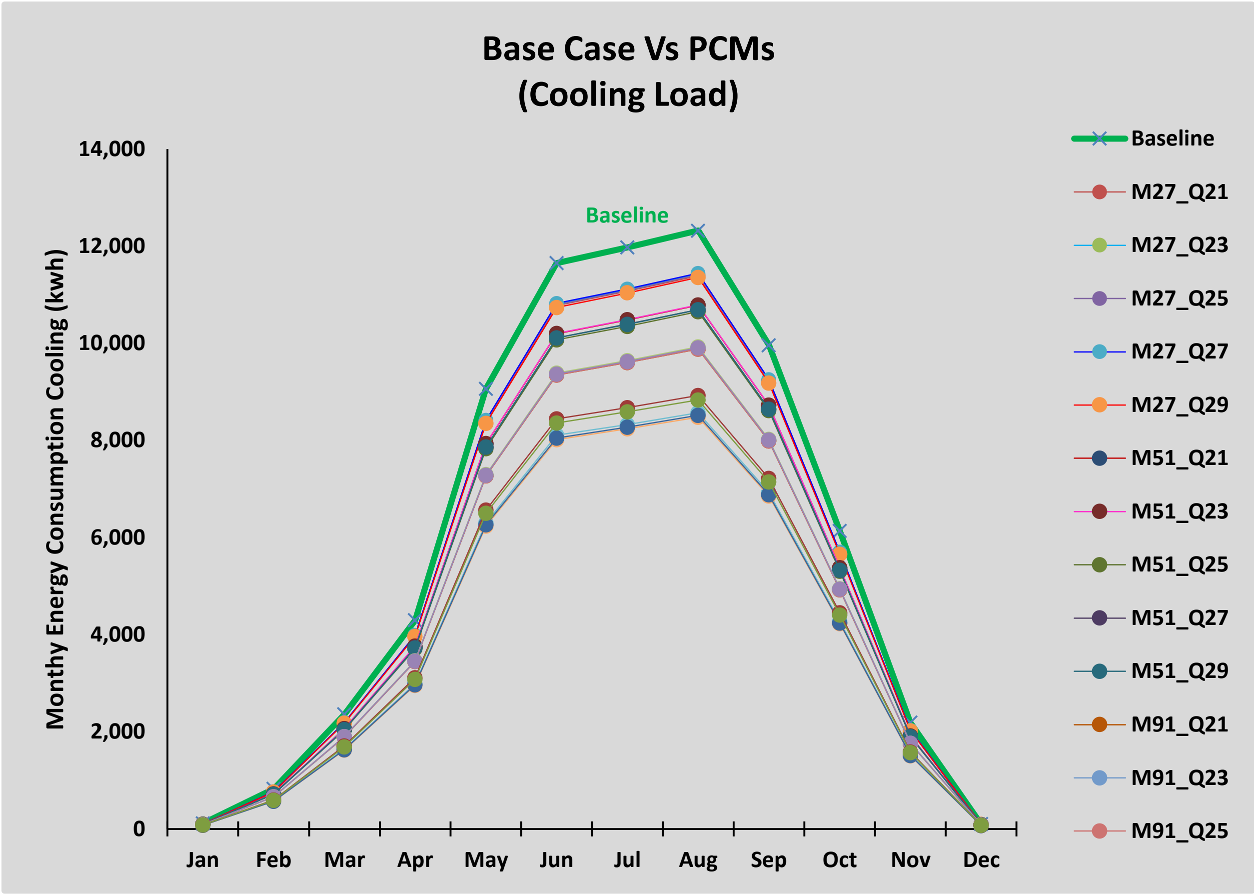


Figure 41 - Monthly Cooling Load Comparison

In terms of annual heating demand, PCM M182_Q23 again showed the most desirable result. It reduced the annual heating demand from 3151 kWh to 2058 kWh. (Figure 40) This same type of PCM with a melting point of 23^{0}C reduced the heating load by 34.7% (Figure 41) Through the application of different Phase Change Material, the annual heating load was reduced in the range from 8.5% to 34.7 %.

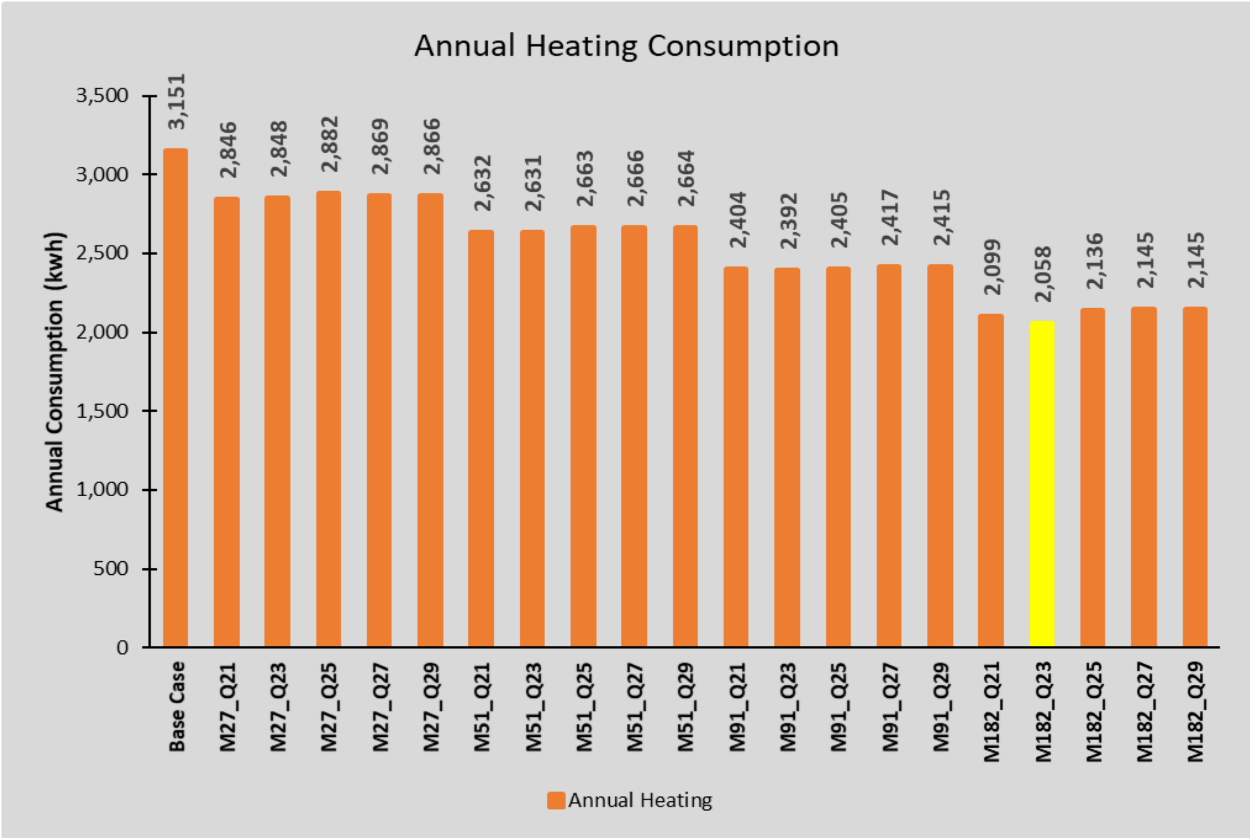


Figure 42 - Comparison of Annual Heating Consumption b/w base case and PCM

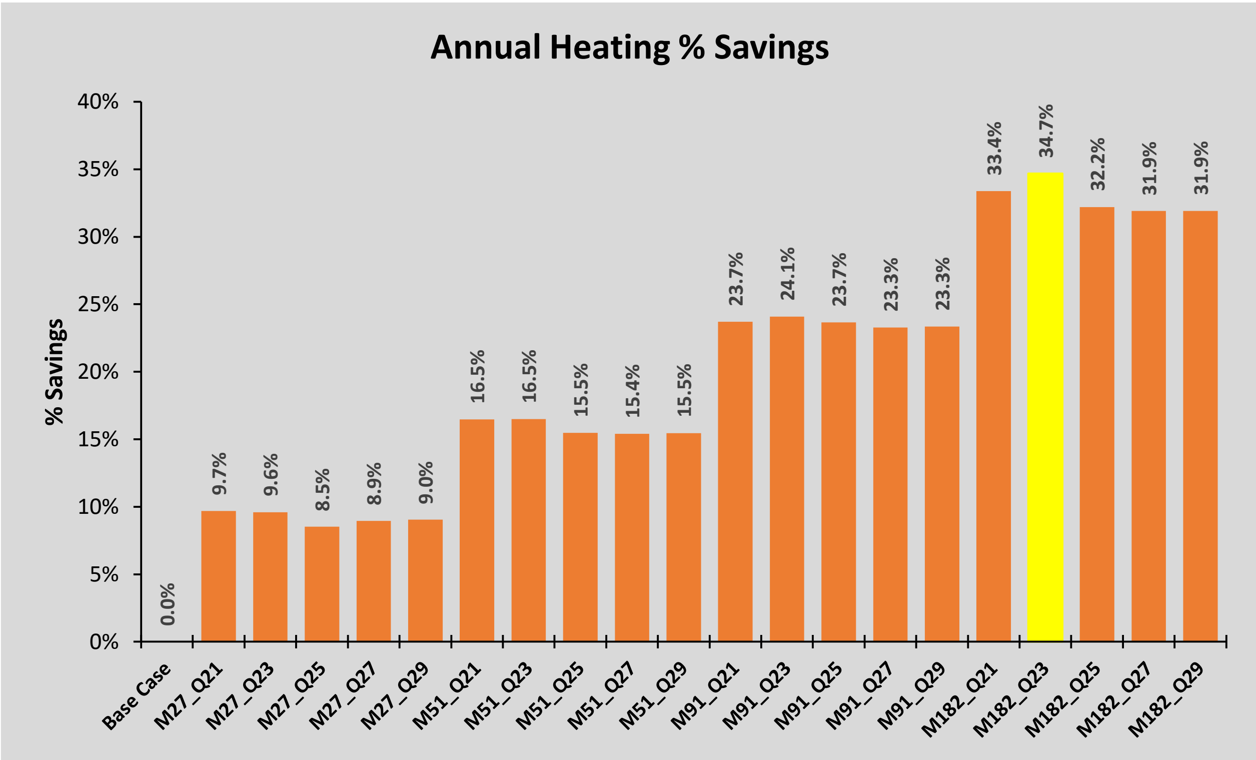


Figure 43 - Annual % Heating Reduction

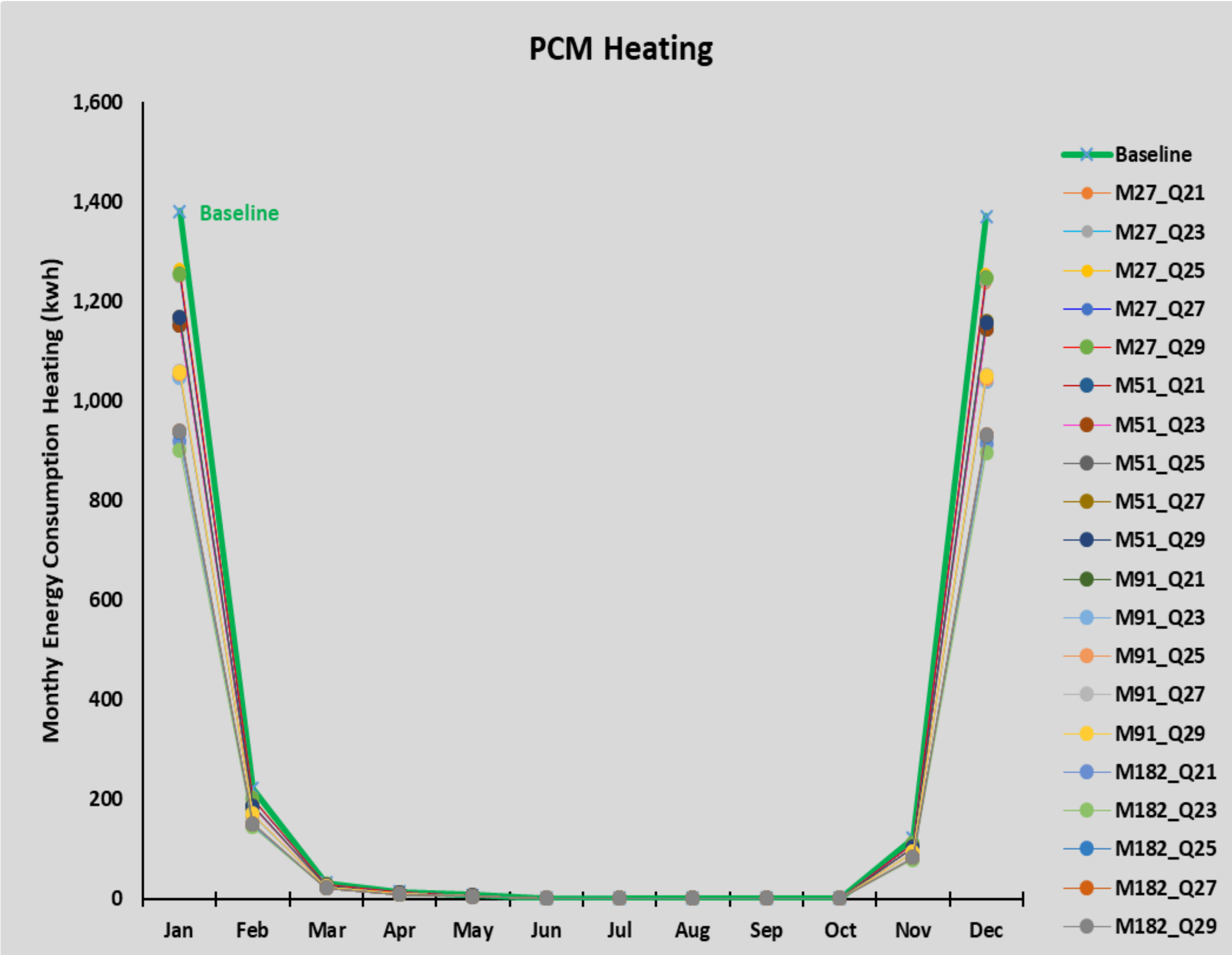


Figure 44 - Monthly Heating Load Comparison

4.2.2 Change in Energy Consumption due to Green Roof with varied LAIc

The green roof with a Leaf Area Index of 5 showed the best result in terms of total annual energy reduction. Figure 43 shows that annual total energy consumption was reduced from 109,978 kWh to 102,905 kWh (6.5 % energy saving, Figure 44). However, the % difference between the green roof with LAI 1 and LAI 5 is very less (0.5%). Infact the difference in % reduction between LAI 4 and LAI 5 is just 0.1%

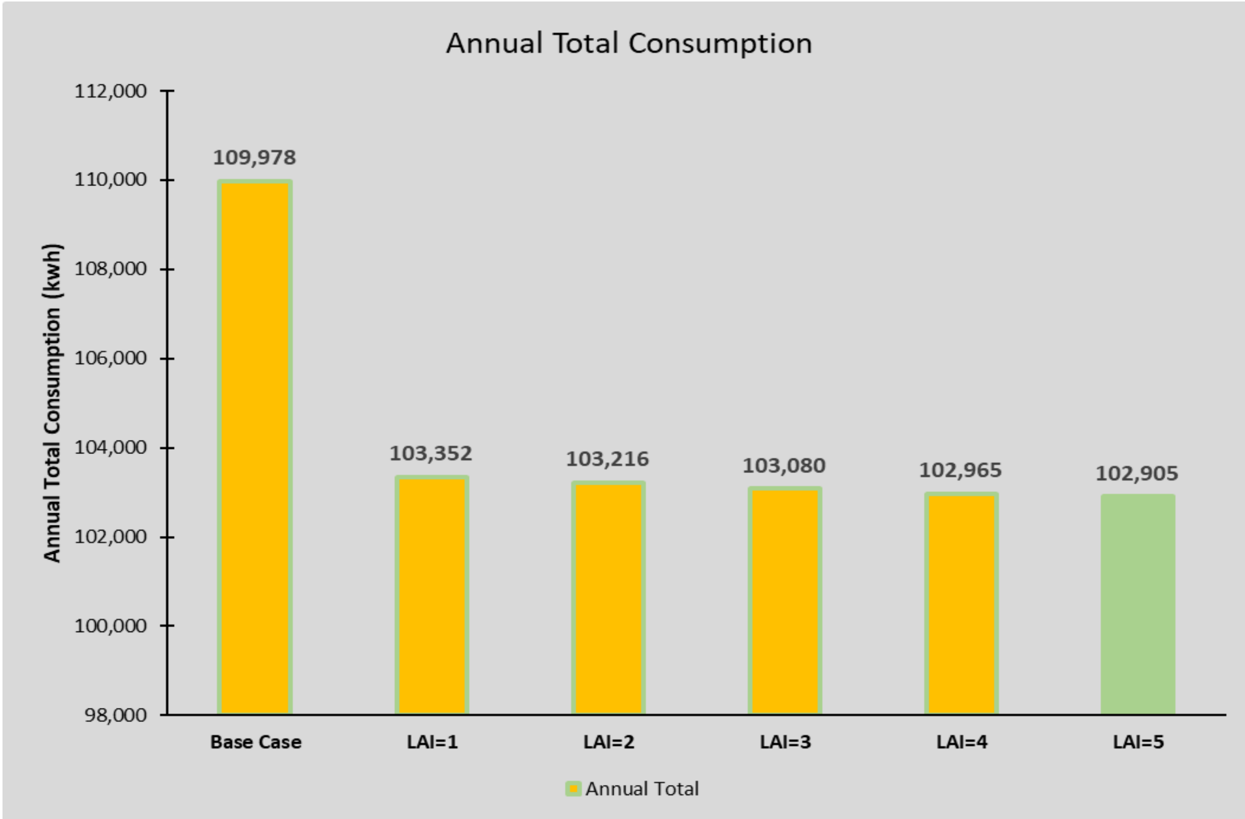


Figure 45 - ATC- Green Roof with varied LAI

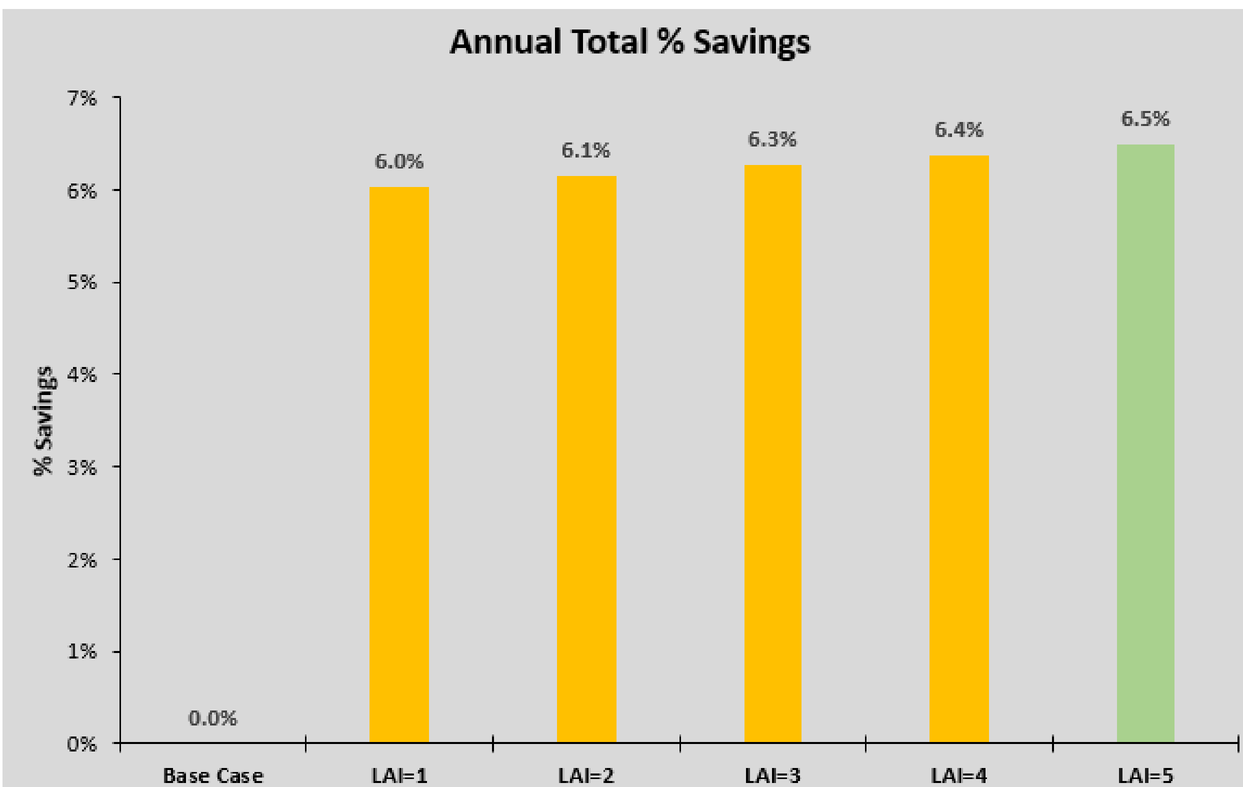


Figure 46 - Annual Total % Savings-Green Roof with varied LAI

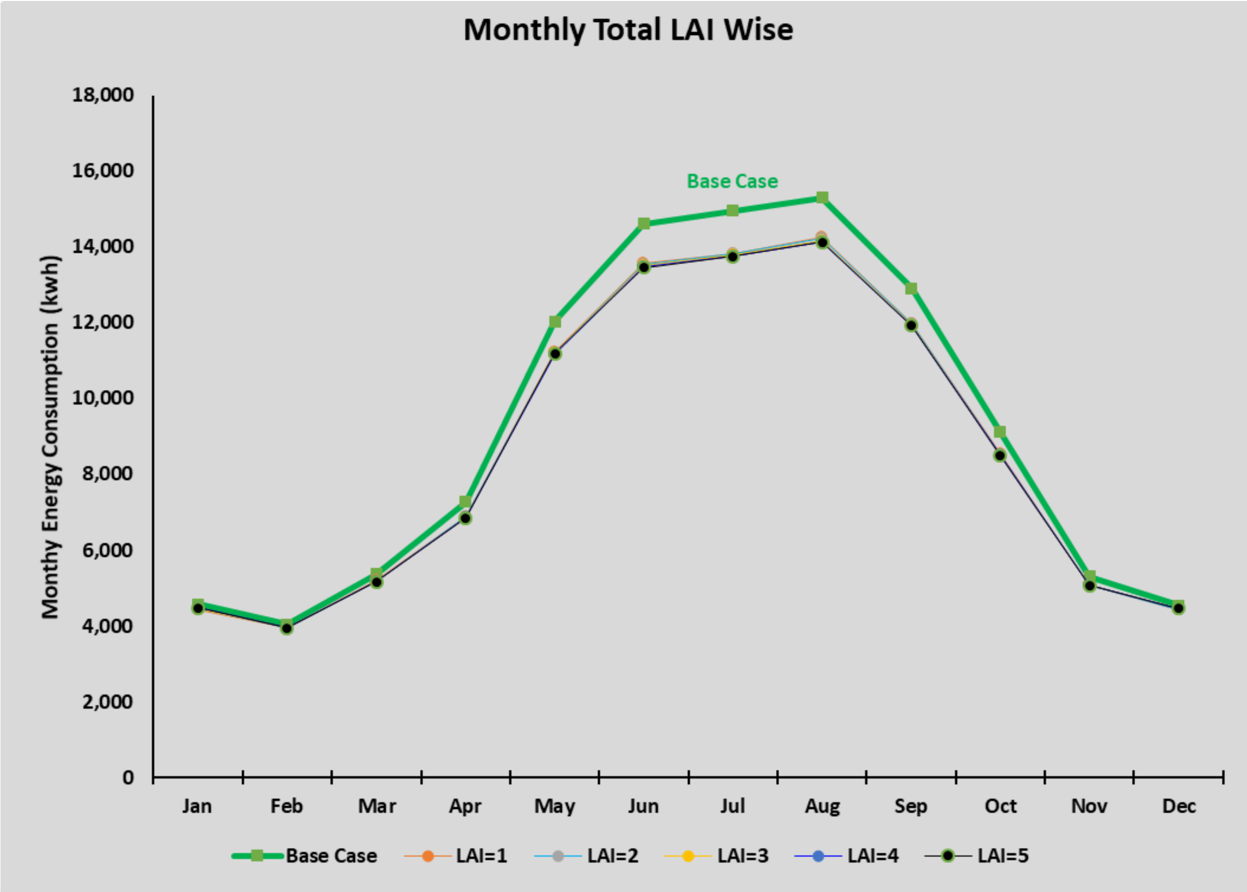


Figure 47 - Monthly Total- Green Roof with varied LAI

The annual cooling demand was reduced to 9.7% (Figure 46) when a green roof with LAI= 5 was applied to the roof of the base case. All Green roofs with varied LAI showed positive results with the reduction of annual cooling demand however percentage difference in cooling reduction was less than 1% as the value of LAI was increased from 1 to 5. The % difference between a green roof with LAI 1 and LAI 5 is very less (0.8%). The difference in % cooling reduction between LAI 4 and LAI 5 is just 0.1%

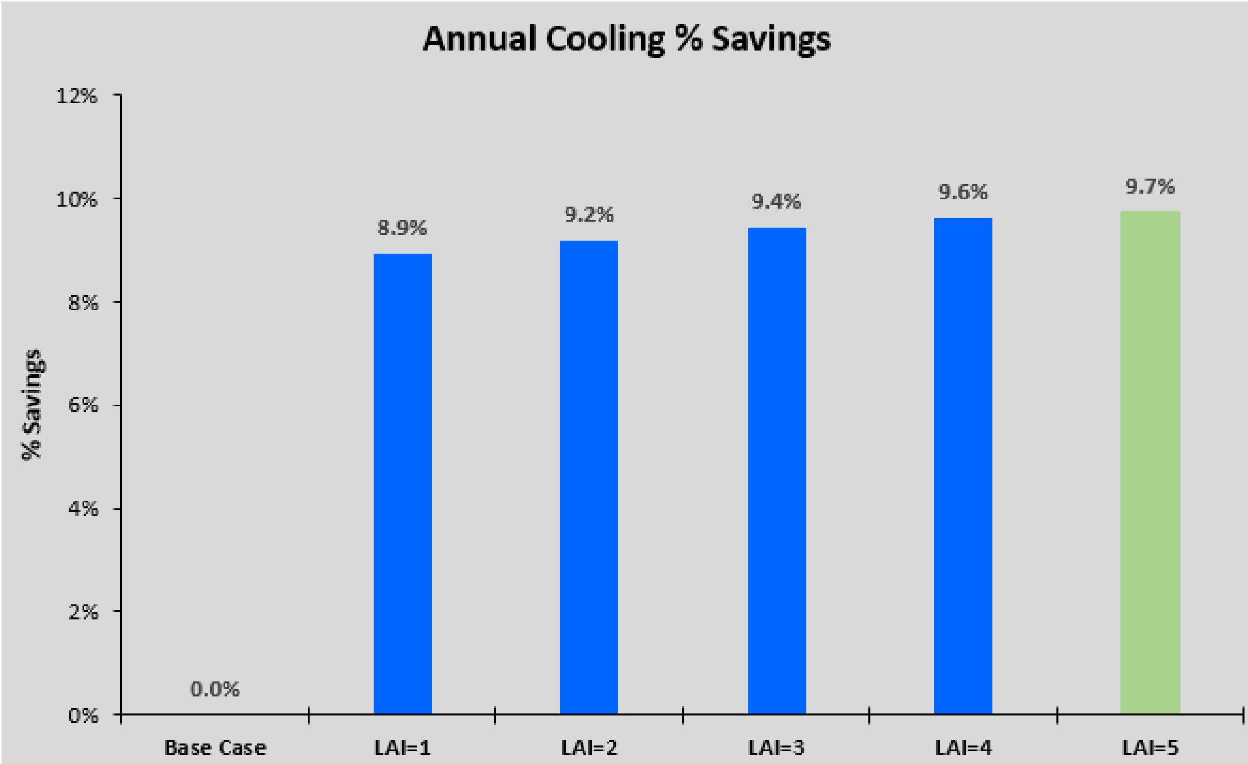


Figure 48 - Annual % Cooling Saving of Green Roof with varied LAI

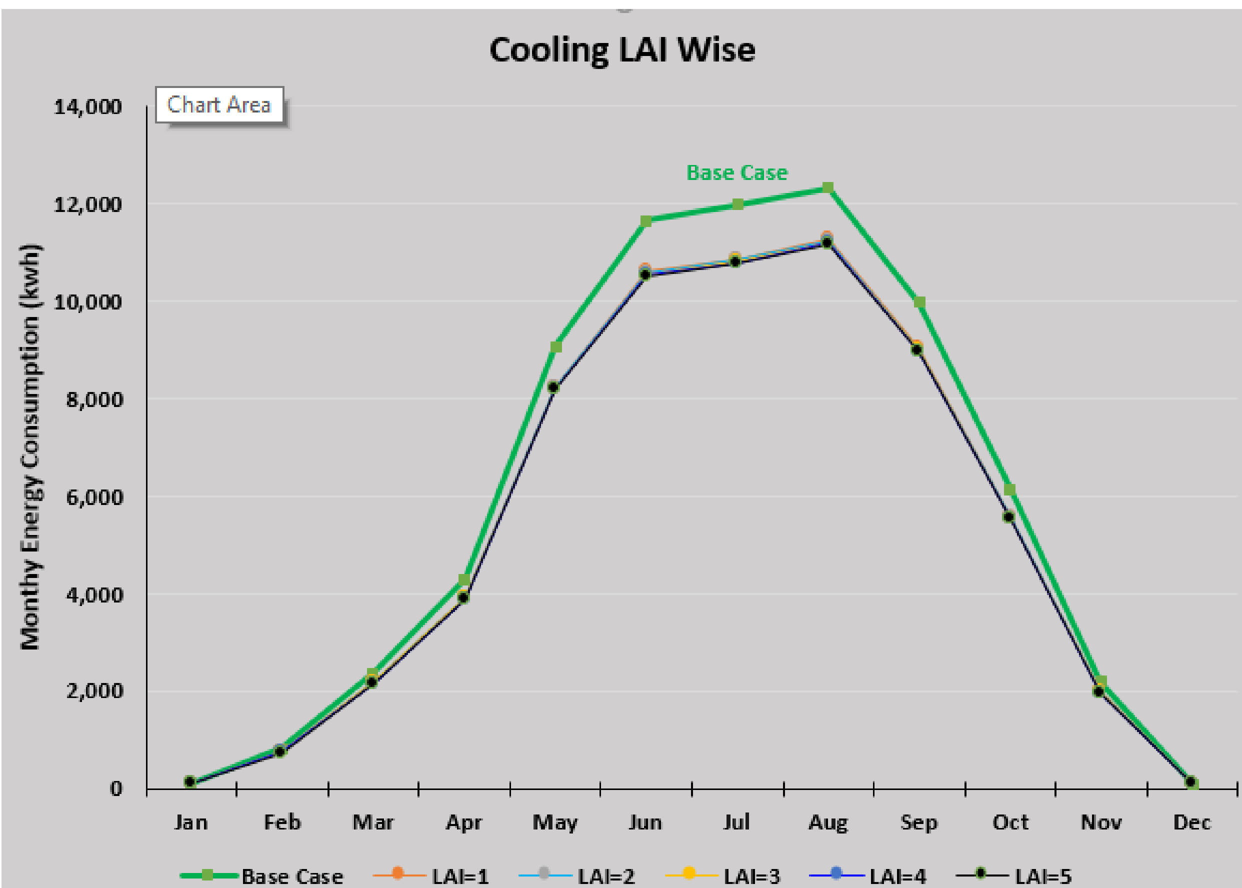


Figure 49 - Monthly Cooling Consumption- Green Roof with varied LAI

The annual heating savings for the Green roof with LAI=1 was the highest with 9.0% (Figure 48). This trend was opposite to the one in Figure 4.21. Even though annual heating savings took place with the application of green roof, however, its percentage got reduced with an increase in LAI. The possible explanation would be given in the next chapter of Discussion and Conclusion

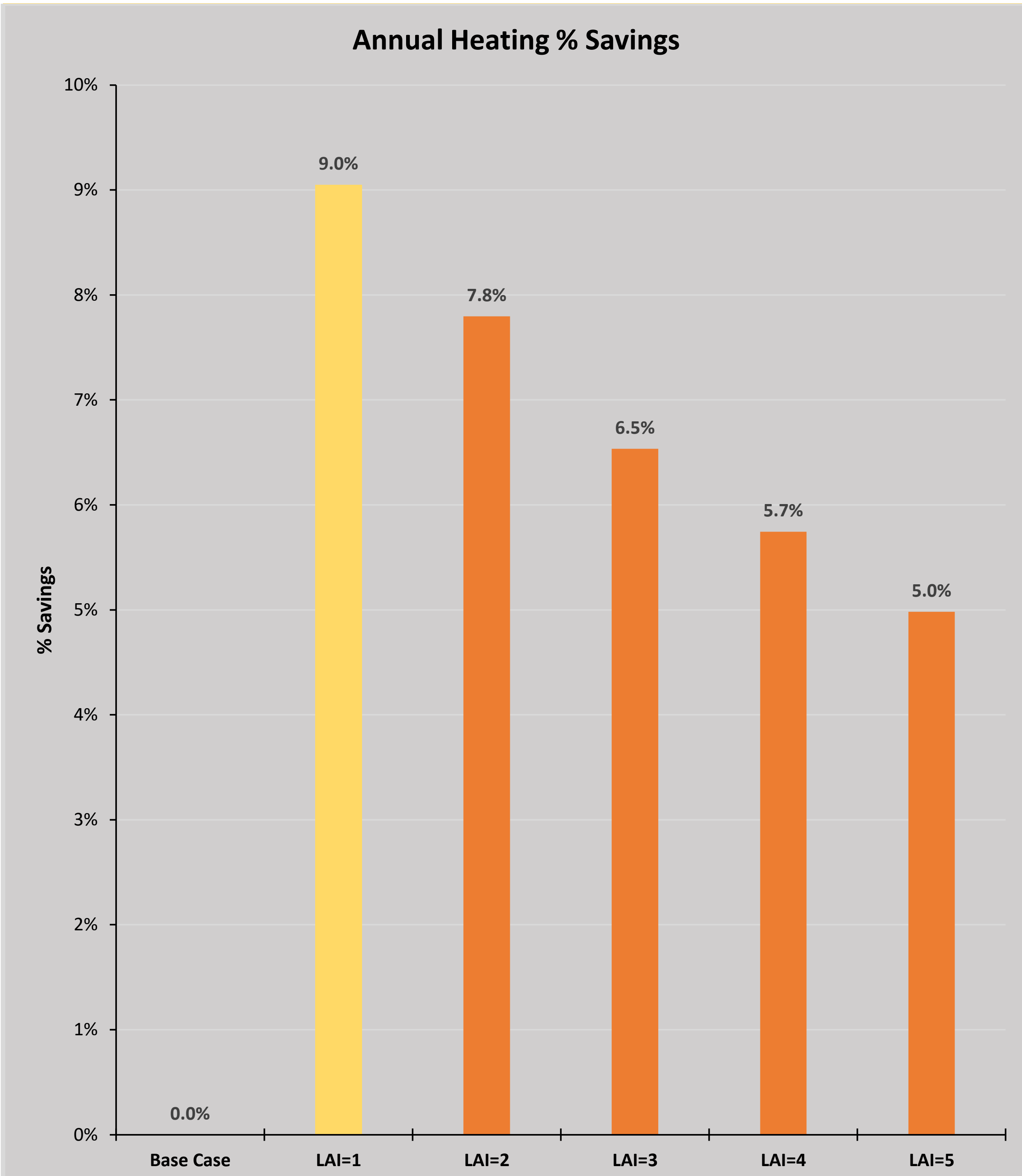


Figure 50 - Annual Heating % Savings of Green Roof with varied LAI

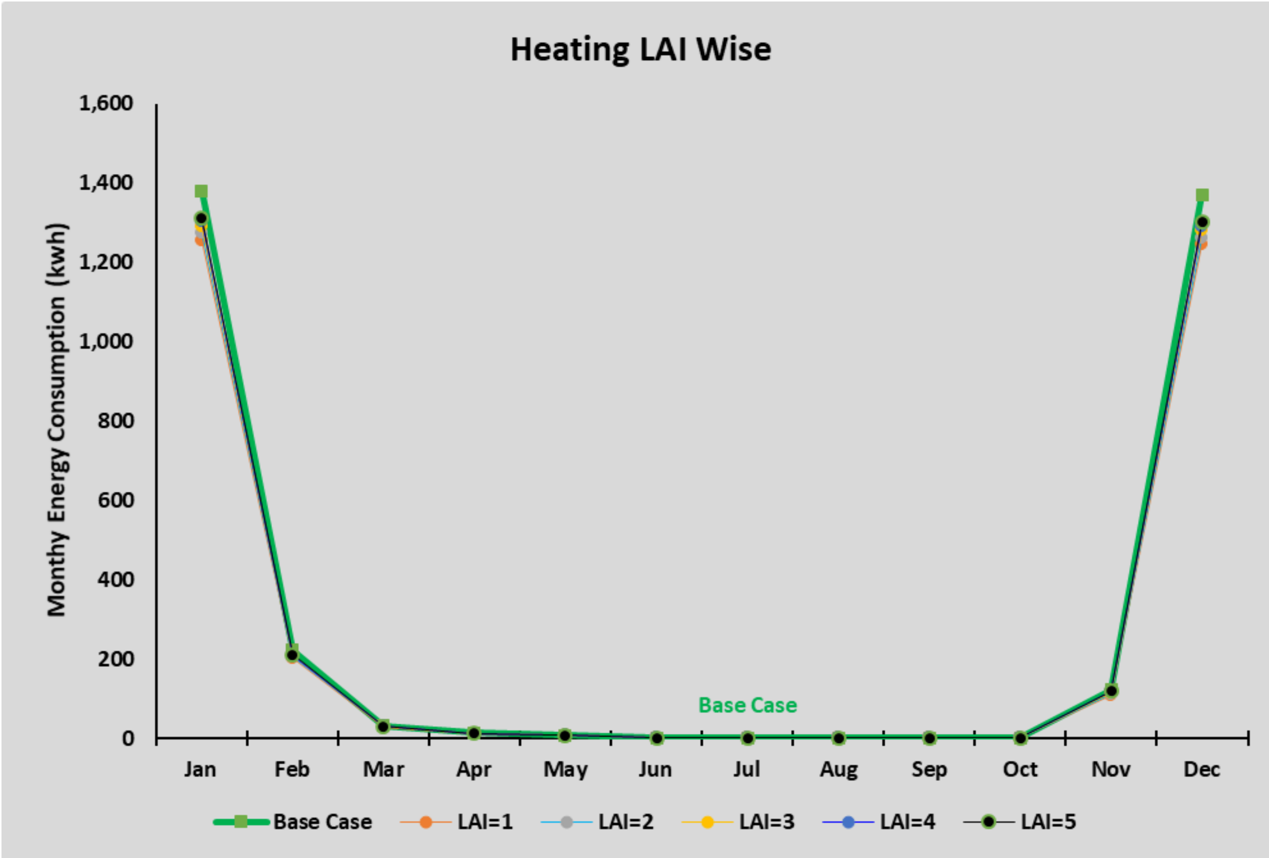


Figure 51 - Monthly Heating Savings- Green Roof with varied LAI

4.2.3 Natural Ventilation

The effect of natural ventilation is only effective for a few months when the climatic conditions are favorable. The change in annual energy consumption is also negligible. However, when this phenomenon is effective for a few months, it can reduce the cooling demand by up to 18%. This trend can be seen in Fig 53 and Fig 54 where the positive effect of Natural Ventilation can be observed from Feb-Apr and Oct-Dec. For the rest of the months, the temperature was either too high due to extreme summers or too low due to winters for natural ventilation to be effective. In this figure, it can also be observed that there is no change in energy consumption of room electricity, lighting, and DHW as discussed earlier.

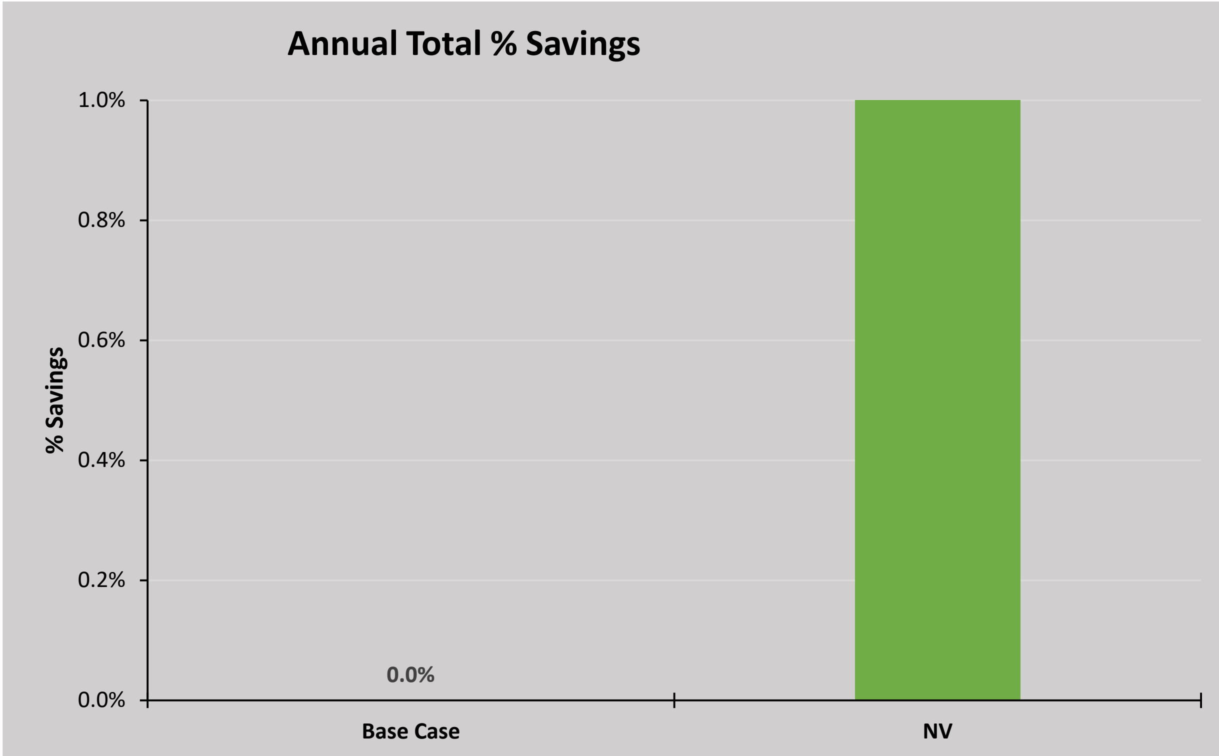


Figure 52 - Annual Total % Savings-NV

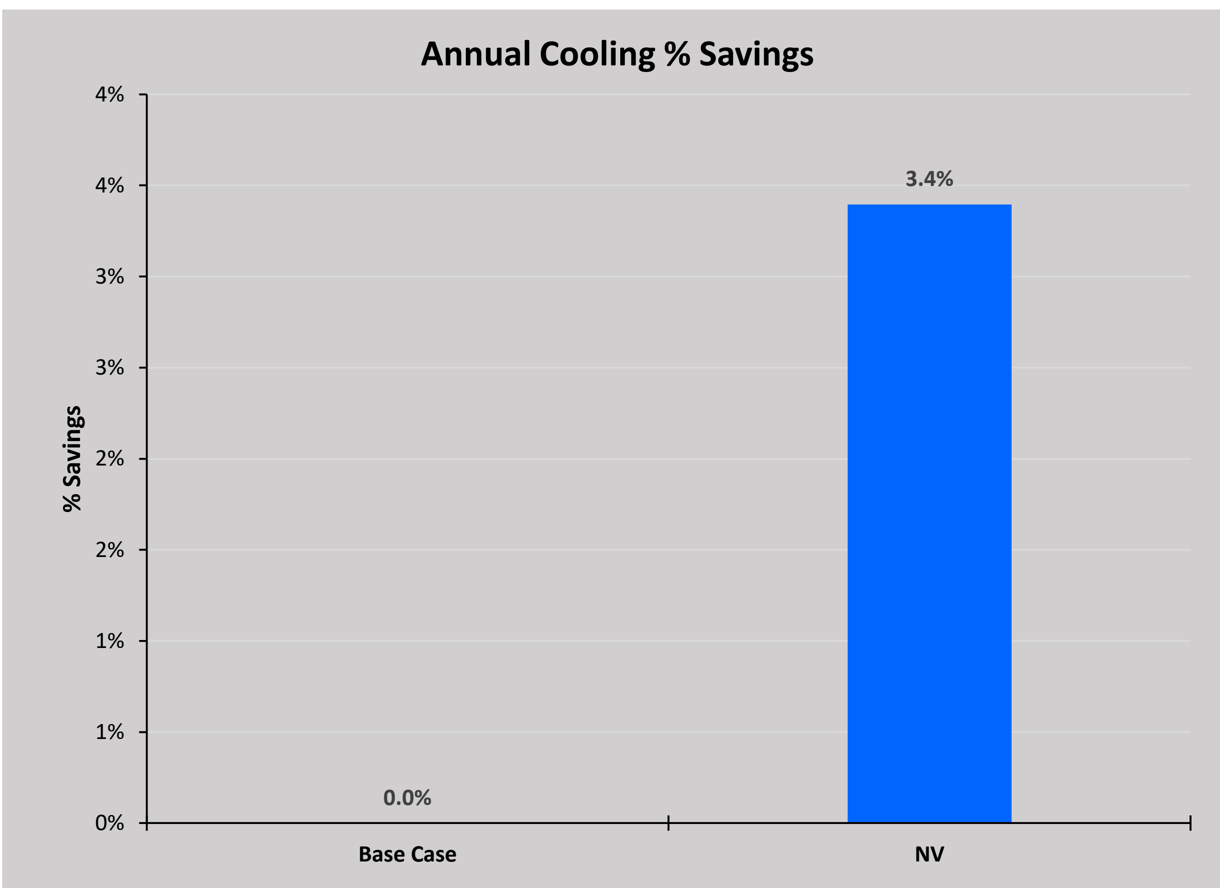


Figure 53 - Annual Cooling % Savings-NV

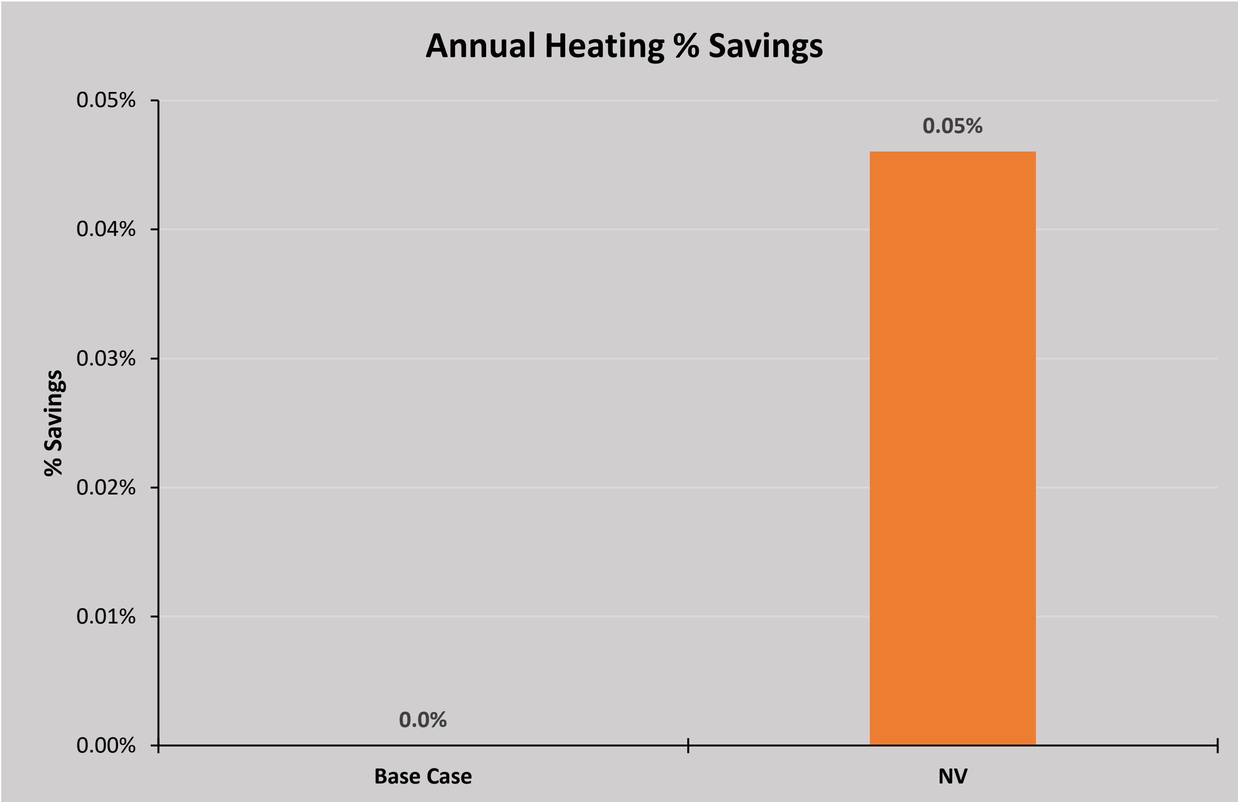


Figure 54 - Annual Heating % Savings-NV

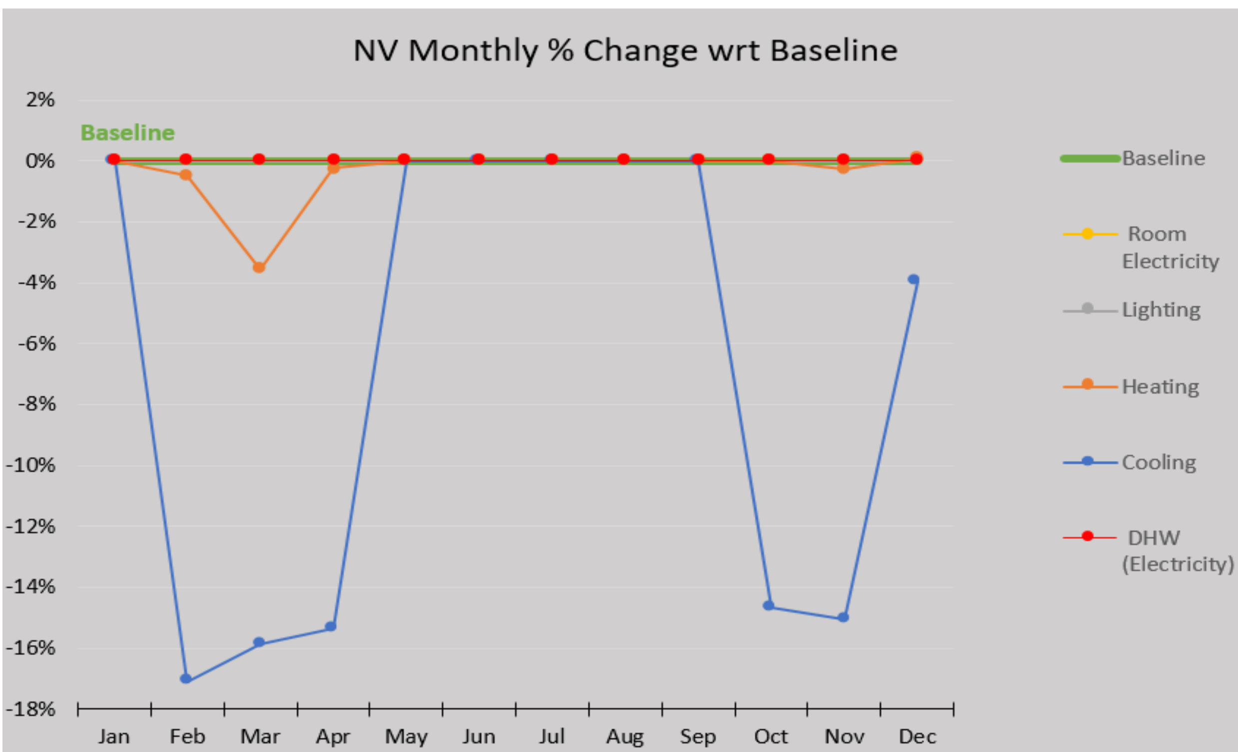


Figure 55 - Monthly % Change wrt Base Case- Natural Ventilation

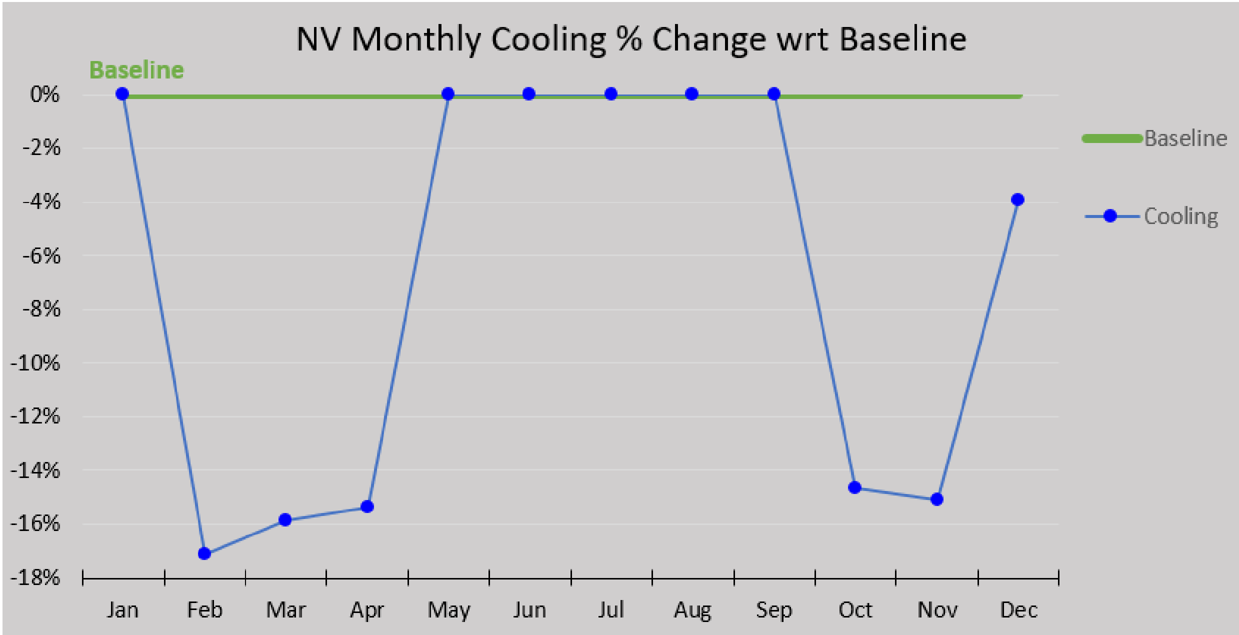


Figure 56 - Monthly % Cooling Change wrt Base Case- Natural Ventilation

Figure 55 also shows that the positive effect of Natural Ventilation is not throughout the year rather it is for a few months. That is why the two plots on the graph overlap each other for the most part of the year

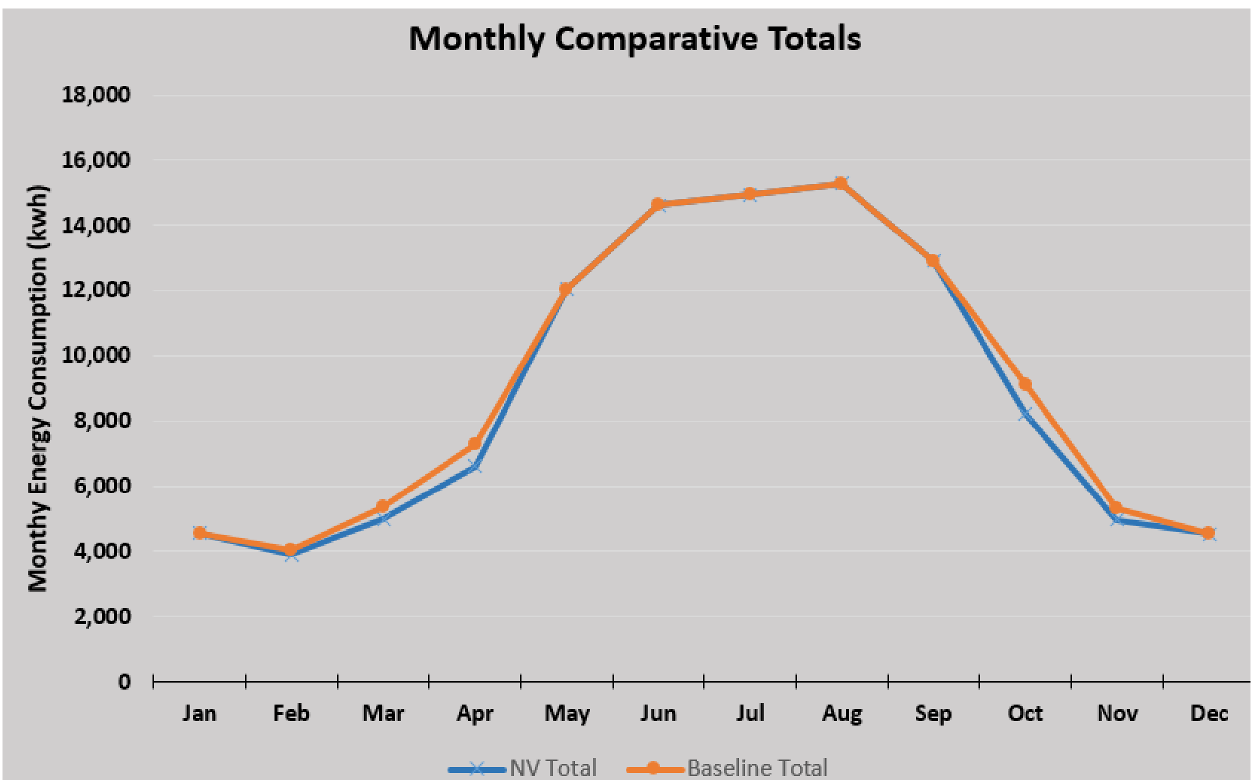


Figure 57 - Monthly Energy Comparison b/w Base Case & NV

4.2.4 Short Wave Reflectivity

When both roof and walls of the base case were painted white, it showed the best result in the reduction of annual cooling demand. Around 1.4 % of annual cooling demand was reduced. Besides annual cooling demand got reduced for all three cases. However, the difference between the three cases (only walls, only roof, roof + walls) in terms of % savings was very less.

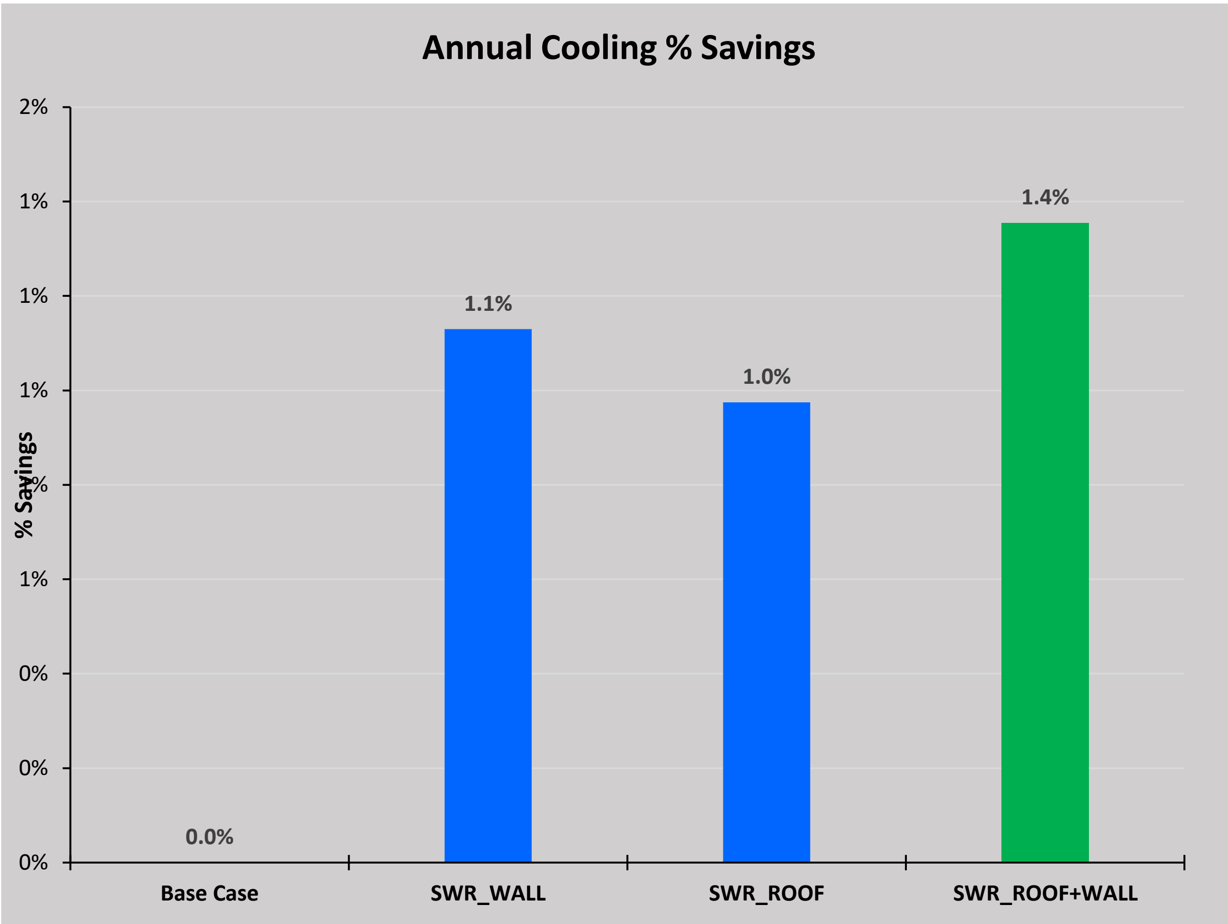


Figure 58 - Annual Cooling % Savings-SWR

Meanwhile, a negative trend is observed for all the three cases i-e heating load gets increased. It can be seen in Figure 57 that the heating load gets increased up to 5.7 % when both roof and walls are painted white. The increase in heating load is comparatively less for the white painted roof only. The possible reasons for this trend would be discussed in the next chapter. Overall, the highest reduction in total energy consumption took place for the combined effect of roof and wall.

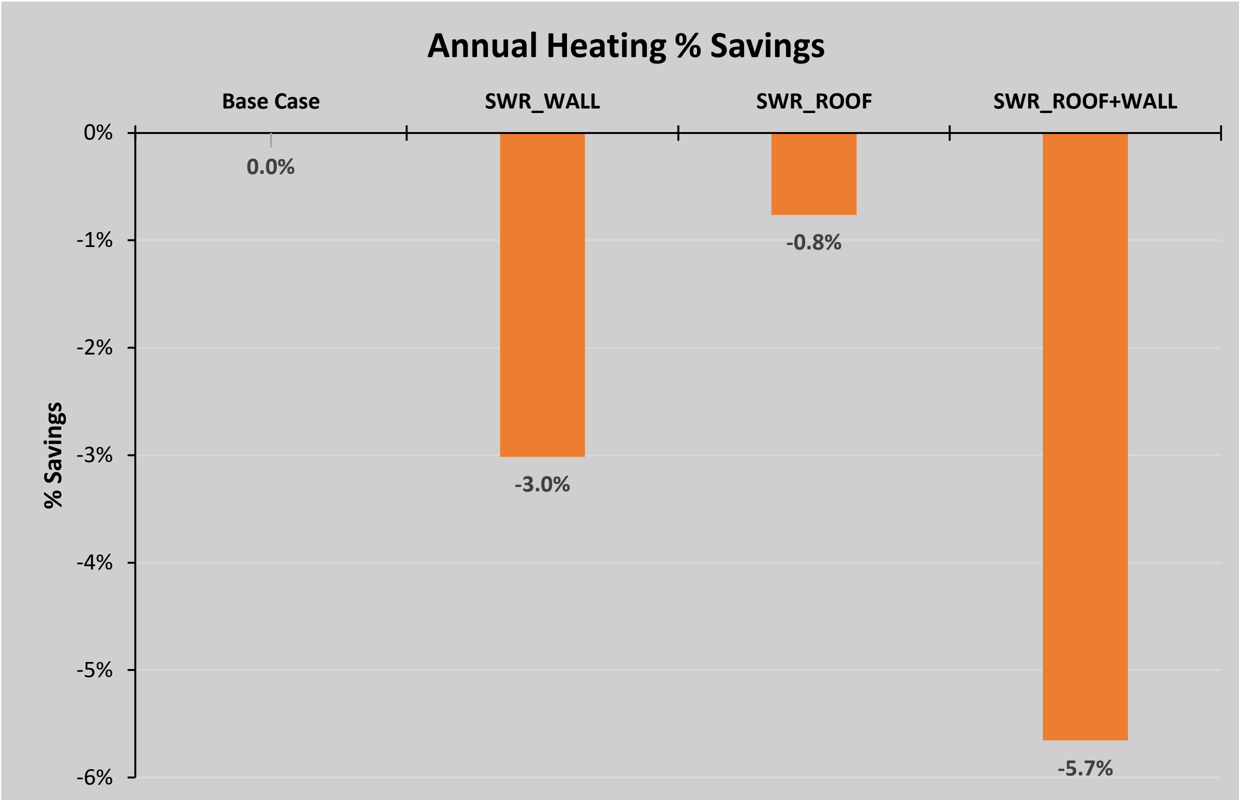


Figure 59 - Annual Heating % Savings-SWR

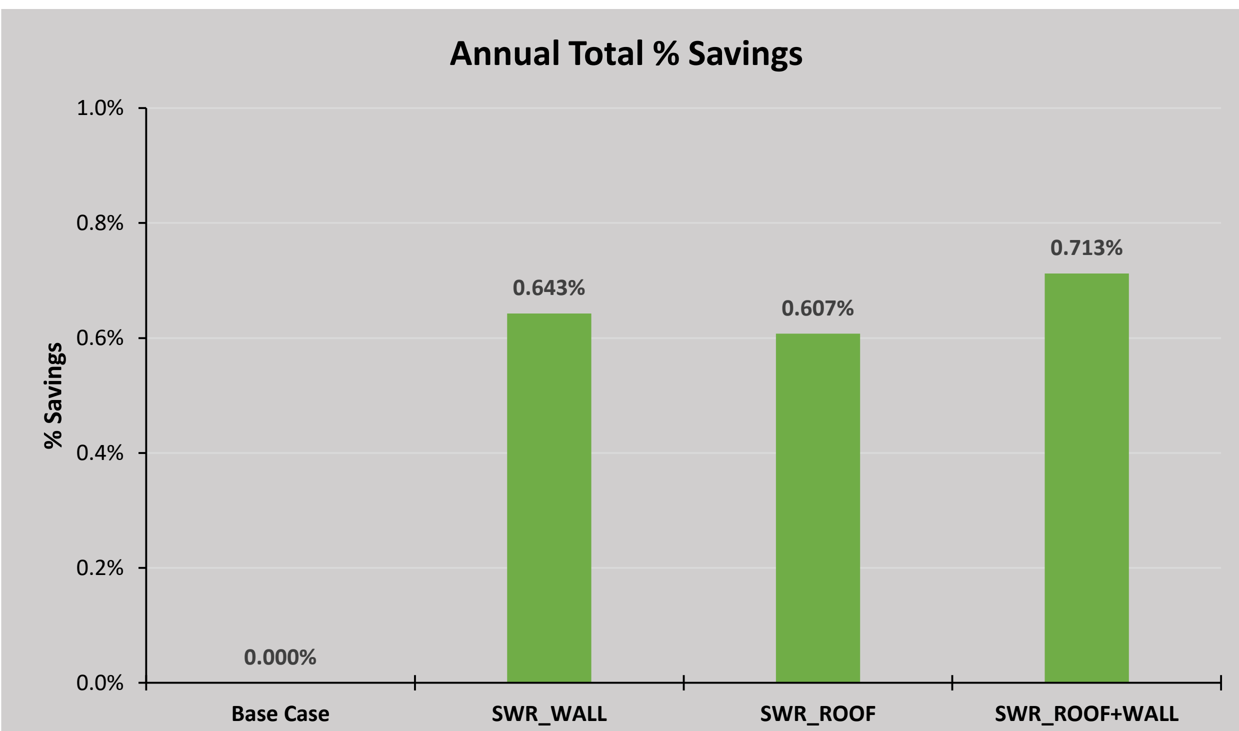


Figure 60 - Annual Total % Savings-SWR

4.3 Energy Consumption for Jeddah

By using the same residential villa as the base case, these passive measures which showed the best results for Riyadh city were now used for the city of Jeddah which is characterized by a hot and humid climate. Energy simulations were run using DesignBuilder to analyze energy consumption for this villa. Results showed that Jeddah has negligible annual heating consumption therefore only total energy savings and cooling savings were calculated. Figure 59 shows the screenshot of DesignBuidler software presenting a Heating load almost negligible, but cooling demand is extremely high due to hot and humid conditions. The annual Cooling load is 70 % as shown in Fig 4-35.

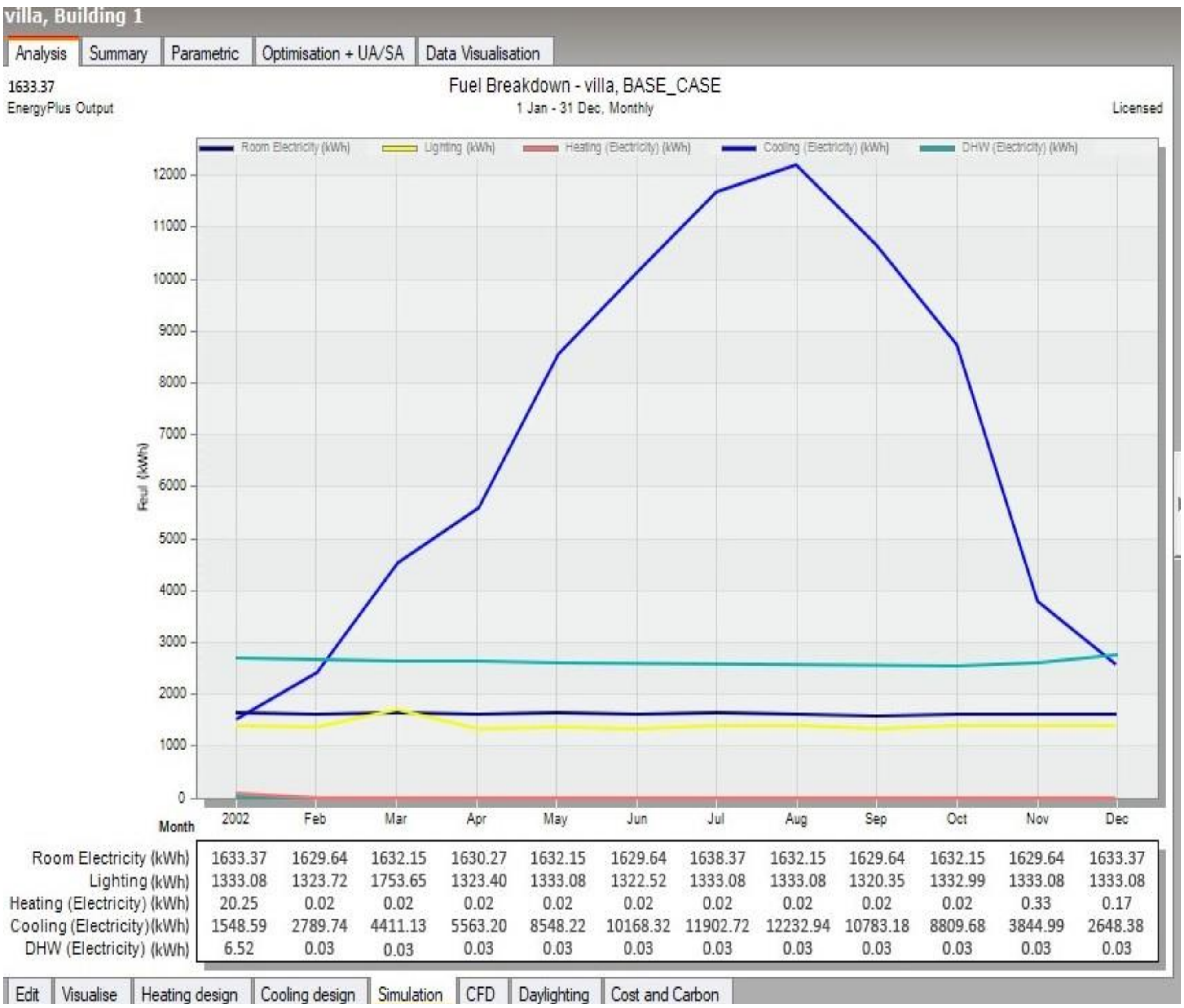


Figure 61 – Fuel Breakdown-Jeddah

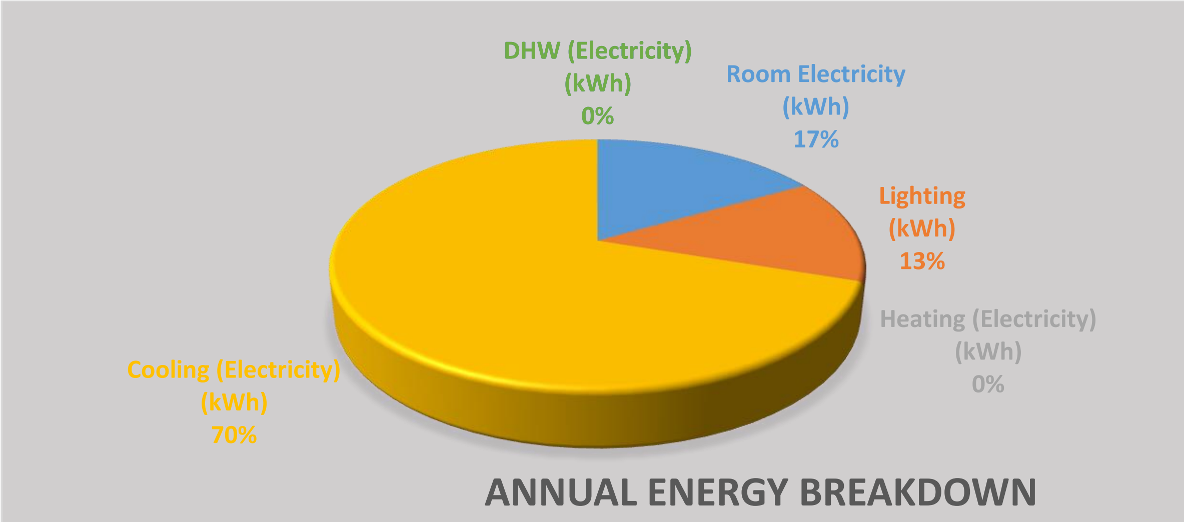


Figure 62 - Annual Energy Breakdown-Jeddah

When PCM M182_Q23 was incorporated in the walls and roof of the villa in Jeddah, annual cooling savings of 27.1 % was achieved. Besides, Green Roof with LAI=5 achieved annual cooling savings of 8.7%. About 2.7 % of the cooling load was reduced due to Natural Ventilation. However, results don't show in which month NV was effective. Just like for the previous case, NV cannot be conducive for the whole year. The effect of white paint (albedo effect, SWR) produced 1.3% of annual cooling savings.

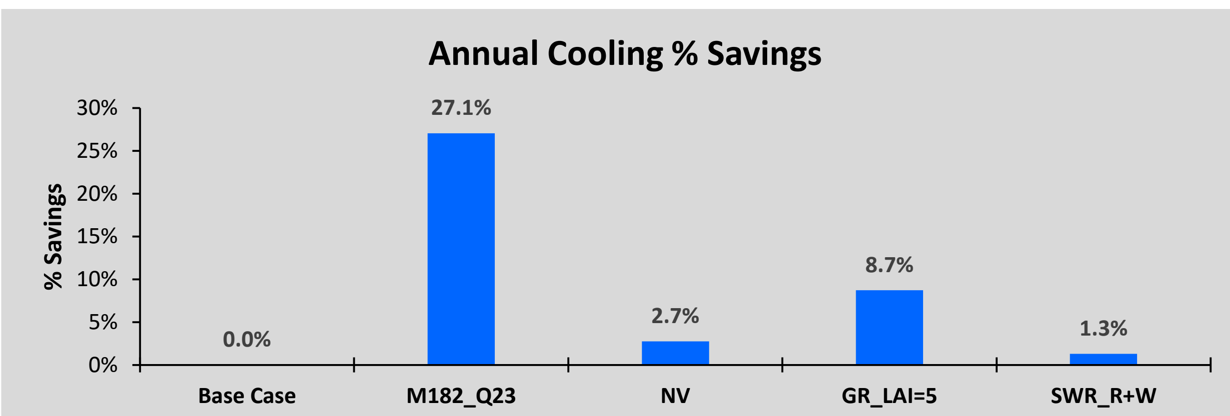


Figure 63 – Annual Cooling % Savings

CHAPTER 5: CONCLUSION AND DISCUSSION

In this study, the application of passive measures has resulted in a change in total energy consumption for the understudy villa. In most cases, these measures were successful in reducing the total energy load especially the annual cooling load. However, some measures like SWR showed negative results by increasing the annual heating load of the villa. The Macro-encapsulation of PCMs presented the best results in terms of energy savings. Their efficiency emerged from the release of energy during short winters and the absorption of excess heat during long and hot summers.

In the category of PCMs, the most optimum results in terms of total energy, cooling and heating savings were shown by PCM M182_Q23. It was also visible that as the value of M increased (i-e thickness and Energy Storage Capacity increased), the energy-saving for all PCM also increased. This may be due to more energy capacity for PCMs to store energy. Also, the optimum result was shown by PCM with Q23(Melting Point of 23^0C) which is closer to the thermostat settings for the villa (22.2~24.4^{o}C). These results are totally in line with the study of Mishra et al.[65] . Table 4 shows the energy savings due to the application of PCMM182_Q23

Annual Cooling Load Reduction	Annual Heating Load Reduction	Annual Total energy Reduction
31.2%	32.2%	21.2%

Table 4 - Energy Savings-PCM M182_Q23

For Green Roof, the maximum cooling was reduced when LAI=5. But the maximum heating reduction took place when LAI=1. However annual total savings were highest for LAI=5.

The cooling load decreased when the value of LAI increased as compared to the base case. This was due to the united effect of evapotranspiration and shading effect. As more energy is released to the environment, the villa used less energy to maintain indoor temperature. As a result cooling load decreased at a higher constant LAI.

For heating, the graph in Figure 48 showed that a green vegetated roof can reduce the heating load of the villa because its soil has a good insulating effect. Secondly, it also showed as LAI increased; the heating load decreased. This is also due to evapotranspiration: A higher-valued LAI would need a higher latent heat flux to release heat energy to the outside environment.

Hence more energy would be required to maintain the indoor temperature especially during winters Table 5 shows the optimum results shown by Green roofs with respective LAIs

Maximum Cooling Load Reduction	Maximum Heating Load Reduction	Annual Total energy Reduction
LAI=5 (9.7%)	LAI=01 (9.0%)	LAI=05 (6.5%)

Table 5 - Optimum Energy Savings-Green Roof

Natural Ventilation was only effective from March to April and Oct to Dec since for other months, the outside ambient temperatures were either too high or too low for these natural phenomena to be effective. Table 6 shows the amount of energy saved during these months.

Month	Total % Energy Savings
Feb	17%
March	16%
Apr	14.8%
Oct	15%
Nov	15.5%
Dec	4%

Table 6 - Total % Energy Savings –NV

For Short Wave Reflectivity, maximum energy savings took place when both walls and roofs were painted white, but it showed a negative trend (heating load was increased) for all three cases. White paint causes more reflectance of solar rays so little thermal energy is stored in the building envelope. Therefore the villa requires more energy to maintain the indoor temperature, especially during the winter.

Maximum Annual Cooling Load Reduction	Maximum Heating Load Reduction	Annual total energy reduction
ROOF+WALL (0.713%)	ROOf (-0.8%)	ROOF+WALL (0.713)

Table 7 - Total % Energy Savings-SWR

Finally, Riyadh with its hot and desert climate and Jeddah with its hot and humid climate were used in this study. Even though the maximum reduction in cooling load in this study was 31.2 %, it can still be very useful in reducing and mitigating climate change’s negative effect.

CHAPTER 6: FUTURE WORK

- In this study a single sheet of a single type of PCM was macro-encapsulated. Future studies can involve multiple layers of different types of PCMs with the same Melting Point or thickness or even both. (for example: combined effect of M182_Q23 & M182_Q25 or M182_Q23 & 91_Q23).

- Also, a combination of PCMs with both varied values of M and Q can also be used for future study (for example combined effect of M182_Q23 & M91_Q27)

- In this study, the layer was incorporated near the inner walls and roofs. Further study can also take place for layers incorporated near to the outer surface (exposed to outside conditions) of the walls or roof. Also when studying for combined effect, these 2 layers can be placed both in outer and inner surfaces respectively.

- All those passive measures, which were not simulated for Jeddah, can be the reference for future work. In this way, a better comparison can be made with different cities in the same country. Infact more these measures can be applied in all major cities of the same country for a comprehensive comparison

- The effect of PCMs with other mentioned passive measures can also be studied for future study.

- Cost Analysis should also be included to ascertain whether these measures are economically viable to take place,

APPENDIX

ABBREVIATIONS

PCAM	Passive Climate Change Adaptation Measures
PCM	Phase Change Material
EPW	EnergyPlus Weather
TMY	Typical Meteorological Year
NV	Natural Ventilation
SWR	Short Wave Reflectivity
KSA	Kingdom of Saudi Arabia
ATC	Annual Total Consumption
LPD	Light Power Density
EPD	Equipment Power Density
EPDM	Ethylene Propylene Diene Methylene
ESC	Energy Storage Capacity

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