Optimal Building Retrofits Assessment for Zero-Energy Building Implementation in Jordan

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Abstract

Energy has become an essential requirement for human activity and survival in the 21st century. Of all the key sectors around the world, the building construction and operation sector has been recognised as one of the largest energy consumers, globally. With the unprecedented fluctuations in fossil fuel prices on the global market, most energy-dependent countries are increasingly devising strategies and regulations to minimise their energy consumption, especially consumption involving buildings. One strategy that has been adopted and implemented globally in the last few decades is the Zero Energy Buildings (ZEB) approach. However, Jordan is a country that is yet to implement the ZEB strategy. The ZEB strategy could be particularly relevant for the case of Jordan, considering that residential and commercial buildings consume approximately half of the energy produced in the country. Yet, 96% of the country's energy generation is still dependent on fossil fuels that are imported. Therefore, this study aimed to study the possibly of developing a sustainable and comfortable ZEB reference retrofit that can be implemented on Jordan's existing buildings. Energy simulations using the Integrated Environmental Solutions Virtual Environment (IESVE) software tool were run to study and identify the optimal strategies and create a retrofit manual for existing buildings, for use as a guide for comfortable ZEB implementation in Jordan, by considering the various factors that affect energy consumption in buildings. The study found that changing the type of windows in existing buildings would lead to the highest energy reductions and also improve thermal comfortability. Utilising a green roof would also improve the thermal comfortability in the building space, while also achieving a slight reduction in the energy consumption. In terms of the building's systems and operations, Light Emitting Diode (LED) lighting utilisation could result in a 15% reduction in the building's annual energy consumption. The study established that while the set-point temperature controls the number of hours that achieve thermal comfort in the building, it is the occupancy behaviour that has the highest impact on energy consumption and human comfort inside the building space. In general, this study established that retrofitting an existing building in Jordan to run as a nZEB is achievable. In terms of energy consumption, the optimal result can be achieved by using 10 cm Polyurethane Boards (PUR) for additional insulation on the walls and roof, adopting LED lighting, and utilising a solar water heater and an air source heat pump to provide the building with domestic hot water. This would result in a reduction in annual energy consumption of about 48%, and photovoltaic cells could then be used to cover the rest of the energy demands of the building. Overall, the optimal case in terms of thermal comfort operation would implement the same measures described above, but with a set-point temperature of 21.1 ℃ for cooling and 20 ℃ for heating, along with a green roof for roof insulation. This would increase thermal comfortability by 11% in terms of the average number of hours that achieve the acceptable PMV range on ASHRAE 55.

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Chapter One: Introduction

1.1 Background

Energy has become an essential requirement for human activity and survival in the 21st century. Energy is one of the United Nations (UN) sustainable development goals (SDGs) and is specifically addressed in goal number seven (SDG #7). Currently, energy is an essential resource for industrial, economic, and residential sectors all over the world. It is anticipated that the world could have consumed around 160,000 TWh in 2019, with about 85% of this energy coming from fossil fuels [1]. Notably, the oil price rose to $71.31 per barrel in 2019, in comparison to $54.19/barrel in 2017 [2] and reached $75.55 recently in 2021[3].

Although energy consumption varies amongst countries and districts, based on the various sectors under consideration, overall, building construction and operation accounts for the highest share. Reports indicate that building construction and operation consumes about 36% of global final energy use [4]. According to the United Kingdom's (UK) energy statistics, commercial sector buildings consumed the largest amount of energy between 2017 and 2018 [5] and in their recent report in 2020 [3]industrial and domestic sectors contribute of 45% of the total energy consumption [6] . Several studies have shown that the majority of the building's energy consumption is attributed to Heating Ventilation and Air-Conditioning (HVAC) systems and lighting systems [7-11]. This fact has been repeatedly demonstrated in a variety of case studies [12]. In 2015, the United Nations suggested that the optimal solution for building construction and operation energy consumption should be the adoption of more efficient and sustainable strategies for managing natural resources [13].

Jordan's energy supply is mainly reliant on imports, with about 96% of all energy generated from imported fossil fuels [14]. Due to its energy dependence on the importation of fossil fuels, Jordan's energy costs are high and characterised by the annual increase in energy consumption as well as the minimal exploitation of other available energy resources such as solar energy [14]. According to the National Electric Power Company annual report of 2017, the domestic and government buildings sector in Jordan accounted for around 45.7% of the overall energy consumption [15]. Therefore, implementing high-performance building and construction techniques is essential in order to reduce the annual energy consumption which currently burdens Jordan's economy with excessive fuel importation costs. Zero Energy Building (ZEB) techniques are an ambitious approach to acquiring high-performance buildings with low annual energy consumption levels, but there is no single ZEB configuration that will be optimal for all climates and locations [16]. According to [17], despite the initial cost and the payback period, energy efficacy techniques might be able to achieve a 60% reduction in building energy consumption.

A Zero Energy Building (ZEB) is defined as a building with net zero energy consumption annually [18]. The U.S. Department of Energy defines a ZEB as one which consumes energy less or equal to the amount of the on-site energy generated annually [19]. The ZEB approach can involve several different concepts [20] such as passive design buildings, green buildings, nearly Zero Energy Building and zero carbon buildings [9]. According to Reeder [12], the ZEB approach is changing the typical design process by implementing the structure and procedures of the Leadership in Energy and Environmental Design (LEED) Platinum goal of a 50% reduction in energy consumption. However, there is, as yet no definite agreed definition for ZEB, globally. It is important to study this concept in different climates and circumstances and to identify the optimal solutions in different situations [7]. This research project considered the ZEB as a building that uses less energy than ordinary buildings, produces its own energy on-site, and achieves thermal comfort throughout the building life cycle. Finding solutions that take thermal comfort into consideration is a priority for occupancies [21, 22]. To achieve the required level of building energy performance, there are six main contributing factors to consider, as shown in **Figure 1** [19].

Figure 1: Factors affecting building energy performance

1.2 Project Problem Statement

Jordan has a very low level of utilization of locally available energy resources [23]. Approximately half of the annual energy consumption is attributed to building construction and operation [15]. Much research in Jordan is being carried out in order to identify the ZEB techniques that are most beneficial in improving building performance as well as reducing energy consumption. However, the zero-energy building concept has not yet been widely implemented in the Jordanian market, either in the government or in the private sector [24]. The absence of the ZEB adoption in the local market in Jordan might be due to different aspects such as the cost, policies, and the landlord's misunderstanding of the ZEB techniques' benefits [25]. It has been suggested that high cost estimates, the lack of strategic plans, and the customer's reluctance to implement high-performance solutions might be some of the causes of ZEB implementation delays in Jordan [24]. Therefore, this study seeks to present a sustainable retrofit solution for existing buildings in Jordan in order to help achieve the ZEB concept by considering the relevant factors that most affect building performance.

1.3 Project Aim

The key aim of this project was to develop a ZEB reference standard for a sustainable and comfortable retrofit that can be implemented on Jordan's existing buildings. The project also aimed to achieve comfortable human living conditions by taking into consideration the various factors that affect the performance of a building and ensure ZEB sustainability.

1.4 Project objective

To achieve the above-mentioned aim, the following project objectives were set:

i. To assess the performance of an existing contemporary building in Jordan in terms of energy consumption and human comfort, in addition to identify recent zero-energy building techniques.
ii. To identify the optimal retrofit scenario that can be adopted in Jordan's climate by studying different building scenarios.
iii. To evaluate the effect of energy consumption factors on the zero-energy building solutions adopted in this project in order to determine the robustness of those solutions.

1.5 Project Questions

i. What is the effect of various energy consumption factors on existing contemporary building performance in terms of energy consumption and human comfort (in Jordan)?
ii. What are the optimal zero-energy building techniques can be implemented in Jordan's climate (studying different scenarios)?
iii. What is the effect of various energy consumption factors on zero-energy building solutions in Jordan and what is the robustness of those solutions?

1.6 Project Scope

This study consisted of an energy simulation of existing contemporary buildings in Jordan by using the Integrated Environmental Solutions Virtual Environment (IES-VE) software. The investigation studied the most significant ZEB techniques currently used to reduce energy consumption in Jordan such as U- value evaluation, building materials, shading, lighting, and HVAC systems. In order to identify the optimal retrofit needed to create a comfortable ZEB, this process also involved studying different scenarios in the main climate zones of Jordan (Amman – the capital and the main city).

Chapter Two: Literature Review

2.1 Overview

The ZEB is a comprehensive definition that started to be discussed in the early 2000's to minimise the energy consumed in buildings and develop a high-performance building. According to [8], no single factor is significant in regulating building energy performance. Accordingly, a holistic process involving many different factors needs to be developed in order to create a successful high-performance building. Therefore, all the factors that affect energy consumption need to be studied in order to identify new methods and techniques for building behaviour enhancement.

Various past case-studies have worked on different assumptions and focused on different factors in order to investigate the ZEB or net-ZEB concept and create different strategies with which to adjust building performance accordingly. All the reviewed studies have examined at least one of the factors that affect building performance and then used the results to improve performance accordingly. Generally, however, the factors that affect building performance are often inter-dependent. **Table 1** categorises examples of these previous studies according to their main significant findings.

Table 1: ZEB case studies and the main factors studied

Reference	Weather (Climate change)	Building envelope	Building energy and services	Indoor design criteria	Building operation and maintenance	Occupants' behaviour
[18]		✓	✓	✓		
[26]		✓				
[27]		✓	✓			
[28]		✓	✓	✓		
[9]			✓	✓		
[7]		✓	✓	✓		✓
[19]	✓					✓
[29]		✓				
[30]		✓	✓	✓		
[31]		✓				

Table 1 lists six categories, the first category is the weather, it has been explained as the climate change effect that was discussed lately in different studies such as [19, 32]. The study of energy consumption in buildings usually requires the use of weather data for specific locations as prerequisite information for use in any energy simulation method or software. However, the effect of climate change on the building performance has not been comprehensively studied in different climate zones [19, 33].

The second category listed is the building envelope. This can be defined as the building materials used, along with related components such as windows, shading and insulation materials. It also includes building orientation effects [19, 26-29, 33, 34].

On the other hand, achieving comfortable indoor air quality also requires systems that consume energy in order to control indoor air characteristics. Therefore, the third and fourth categories, that is, building energy and services and the indoor design criteria, might be related to each other. This has been demonstrated in different studies such as [7, 9, 18, 28, 30]. The effect of operation and maintenance performance in buildings (the fifth category) is very important in achieving the concept of ZEB sustainability because developing a workable ZEB also requires a building life cycle study [12]. The building occupants' behaviours widely affect the energy consumption in the building. It was observed that it might have a crucial effect on the building energy consumption depending on other factors [19].

Tables 2 and **3** illustrate the most significant findings from several different studies that identified various retrofits to develop a ZEB in different climate zones. For instance, [18] involved 3-stage climate data collection, adjusting aspects the building envelope, such as the building orientation and facade design, to reduce the annual consumption, then simulating the results of these adjustments to investigate the effects of using different types of renewable energy systems which covered three main areas: HVAC, Domestic Hot Water (DHW), and lighting. In addition, two different renewable energy sources, that is, wind and solar energy, were considered to cover the annual energy consumption and it was concluded that over 90% of the energy required could be generated by wind energy [18]. However, this study, along with several others, such as [7], does not mention the financial impact on project costs and the thermal comfort status for ZEB adoption.

Table 2: Some global ZEB case studies with their significant findings

Reference	Country	Methodology	Key findings
[18]	UK	Simulation by Energy Plus and TRNSYS 16.0	Identified that the south-facing direction of a building in the UK is one of the passive solutions that can be used to create a high-performance home in terms of energy consumption.
[19]	California, USA	Simulation by Energy plus8.8	In mild weather, it was found that climate change does not have a significant impact. The occupant's performance has a higher impact on building performance.
[26]	China	Simulation using Energy plus	Shading, airtightness, and thermal bridges have a substantial impact in increasing the actual load
[33]	Italy	Design Builder	In cold conditions the case study could not achieve ZEB levels, however, in a warm climate, the concept of ZEB could have been accomplished
[9]	Malaysia	Adjustment based on thermal analysis	Controlling and adjusting the lighting system and the radiation effect leads to a reduction in the cooling load consumption.
[7]	MENA	Insights 360 to assess deferent scenarios of creating a nZEB	Energy consumption could be reduced by a third by applying ZEB techniques such as improving wall insulation, adjusting the lighting system, using highly efficient appliances, control occupant behaviour
[27]	Palestine	Mathematical analysis	The recommended shading coefficient was 0.5-0.6, otherwise the cooling load would decrease, and the annual heating load would increase

Table 3: Some Jordanian ZEB case studies with their significant findings

Reference	Country	Methodology	Key findings
[28]	Jordan	Engineering analysis to compare three hypothetical retrofits	The hypothetical models could reduce the annual energy consumption by 50% compared with existing projects. Similarly, water consumption could be reduced by nearly half.
[29]	Jordan	DEROB-LTH. Building Energy Software Tools Directory	The study found that the south-facing facade consumed almost 50% more of the energy consumed by the north-facing facade in the same building during the winter season.
[30]	Jordan	Engineering calculation	This study showed the importance of efficient insulation thickness (Rockwool at a sufficient insulation thickness), controlled lighting, and natural ventilation. The thermal chimney effect and wind pressure differences play a huge role in creating a ZEB.
[31]	Jordan	(DEROB-LTH. Building Energy Software Tools Director	The contemporary building cooling load was triple the vernacular building and the heating load per area was also higher compared with past buildings. This was related to the methods and materials of construction.

Concerning the investigation of the building envelope, various studies [18, 31] have agreed that a building's orientation is one of the most significant considerations in improving building performance. The importance of the building's orientation was deduced besides identifying the significance of the building's materials and insulation thickness on enhancing the building behaviour [7, 30, 31]. Although many authors such as [7, 9, 30] have highlighted the importance of the thermal insulation effect on a building's thermal behaviour, some other factors, such as thermal bridges, have not been assessed as widely because of their relatively minor impact on building performance, as stated by [35].

After studying several residential building case studies in Jordan, [29] clarified the importance of a building's orientation in minimising annual energy consumption. In addition, other studies also attest to the significance of developing a suitable building envelope [7, 30, 31]. However, regardless of these studies' findings, there have been no substantial adjustments made to Jordan's building regulations to minimise the energy consumption in existing buildings.

In addition to the building envelope, building energy systems and services are also a substantial factor in determining the overall energy consumption. Adopting the ZEB concept by adjusting existing buildings' systems performance has been investigated at length in studies such as [7, 9, 28, 33]. They have compared different energy generation resources (namely condensing boilers, gas boilers, and heat pumps), modified the lighting system and reduced solar radiation in order to examine the optimal solution to the problem of how to achieve maximum human comfort with the minimum use of resources [9].

Applying different optimisation techniques would improve the building's energy performance. Some studies have applied low-cost techniques in order to reduce energy consumption. For instance, study [9] found that a variety of methods could be used to improve building performance, such as adjusting the set-point temperature, improving the lighting efficiency, and using high-performance glassing to reduce the energy consumption by 0.10 kWh per square meter, annually. Other case studies have also asserted that adjusting the occupants' behaviours could have significant effects on building performance in certain circumstances [19].

Several case studies have emphasised the contribution of the climate on the building performance and have examined this from various perspectives. The importance of weather can be especially important in the reduction and control of the solar radiation effect on buildings. This can be addressed by implementing strategies such as shading. Shading impacts the building's energy consumption as well as airtightness and thermal bridges, which might also contribute to the actual building heating and cooling load. However, this effect has not been considered in many studies such as [26, 27].

In conclusion, numerous studies have agreed that building an efficient and affordable zero energy building is possible in both cold and hot climates [7, 9, 19, 33, 36]. However, one of the obstacles in implementing any green and sustainable project can be the capital cost and limited funds, as mentioned in several studies [9, 25]. Moreover, the optimal solution does not necessarily mean the best performance in terms of thermal comfort. It might just mean adequate performance and a compromise in terms of initial cost and running cost [33]. Therefore, this research project sought to implement the most significant findings in terms of a building energy analysis. This study identifies the most suitable retrofit that could be applied, in Jordan's case, to improve existing building performance and help realise the ZEB concept in order to enhance societal confidence in implementing further ZEB techniques in the future.

2.2 Weather characteristics

Jordan is located in the Middle East between the Arabian desert, the subtropical dry climate, and the Mediterranean region, the subtropical humid climate which leads to a dramatic variation in the weather between day and night, summer, and winter seasons and also the seasonal domination. For instance, the heating season is dominant in the highlands where Amman is located, while the cooling season is dominant in the Rift valley and the desert regions. In general, The Jordanian weather is hot, dry in summers, and the outside temperature can extend beyond 40°C, while winter is cold, humid, windy, and the temperature can exceed 5°C [37]. Thus, this distinct difference in climate characteristics advocates for various energy-efficient construction approaches.

Climate zoning differs in terms of both geographical and thermal perspectives. For instance, according to study [38], the Jordanian climate can be categorised into nine climatic zones. However, the country's Thermal Insulation Code [39] categorises the Jordanian climate into only three climate zones. Zone 1 includes the Western Rift Valley, which stretches along the entire western length of Jordan at an altitude of less than 600m, extending all the way to the southern end of Jordan (Aqaba). This zone constitutes of the Jordan valley, Wadi Araba, Aqaba and the Dead Sea; Zone 2: Eastern Highlands, which consists of the mountainous and hilly regions in the altitude range of 600 – 1,600 m [39]. This zone comprises of Ajloun in the Northern region and Almujib, Karak, and shoubak in the southern region that is the most populated area that includes Amman, the capital city of Jordan. Finally, Zone 3: Arid Desert, which covers the eastern part of the country, that is sparsely populated [39].

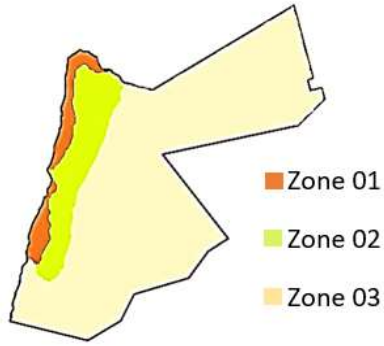


Figure 2: Jordan's climate zones

Consequently, the weather has a tangible impact on building performance. There are also different weather categories and classifications to consider, depending on the weather categoriser. In terms of simulation software, there are international databases for weather all over the world and one of these international databases is that of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). It was adopted for this study because it is one of the main references used in the Jordan international codes [40]. The ASHRAE categorises weather around the world into eight main climate zones: hot-humid, hot-dry, mixed-dry, mixed-humid, marine, cold, very cold, and subarctic. The map shown in **Figure 3** illustrates the climate zones categorised by ASHRAE 90.1-2004 edition. **Figure 3** shows that Amman, in Jordan, is classified as zone 3B - with warm and dry weather.

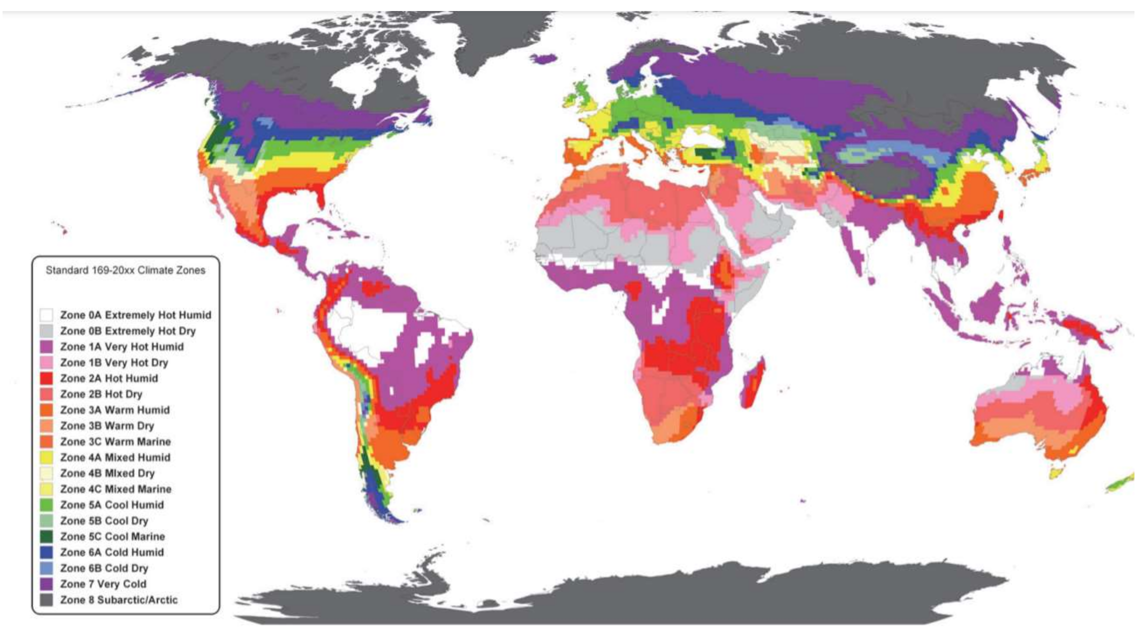


Figure 3: ASHRAE climate zone classification [41]

The ASHRAE classification is dependent on the number of cooling degree days (CCD), heating degree days (HDD), and the air pressure equation, thus the CDD10℃ value for Jordan is calculated as

2974 [41] and since a value between 2500 < CDD10ºC < 3500 is categorised as being within the 3B climate zone, Amman Jordan is also included in this zone.

2.3 Building envelopes

2.3.1 Overview

The building envelope concept relates to the exterior design and construction of a building. A desirable building envelope involves several different features, such as using exterior wall materials and designs compatible with the climatic proprieties of a particular location, which in turn leads to a structurally sound and aesthetically pleasing building. The building envelope of a dwelling consists of several components: ground-exposed floor, sub-floor, roof, exterior doors, windows, and the exterior walls.

2.3.2 Orientation

The orientation is one of the essential aspects that affects the building's energy consumption. It is related to the building's location and the position of the sun [42]. The effect of a building's orientation has been studied in many previous works by comparing the energy consumption of each façade in order to identify those with the highest and the lowest facades energy consumption in the conditioned place. Different studies have obtained different findings relating to the location of the building [43-46]. Study [43] found that a western façade consumes just over a quarter of the energy consumed by the southern facade of a building located in Tanta, Egypt. Thus, in order to reduce energy consumption by a building, it was preferable that the external walls and windows faced south. Other studies have confirmed these findings in different locations, such as [46]. Whereas studies [44, 45] have not identified a particular preferred direction for the exposed walls, these studies have found that buildings have different variables connected with energy consumption. Accordingly, the appropriate orientation of the building can result in the accomplishment of the minimum energy consumption. However, this can only be exploited in the early stages of the design process and cannot be adjusted in the retrofit and refurbishing of an existing building whose orientation has already been determined.

2.3.3 Thermal Insulation

Thermal insulation is the first defence line for heat rejection in the heating season and heat gain in the cooling season. Thus, utilising thermal insulation in the building envelop leads to a remarkable reduction in the energy consumed in a building. While study [47] found that thermal insulation in the wall and airtightness adjustments did not have a noticeable impact on building performance, while solar shading had the highest impact on the building's overall energy consumption, a change in the wall structure only could result in a 6% change in energy conversion [48]. External thermal insulation may contribute to a two-thirds reduction in the energy consumption of a building [49]. This finding is also compatible with the results shown in [50], whereby an increase in thermal insulation thickness was able to shift the peak load in the building and increase the energy savings. Similarly, roof insulation might also contribute to a reduction in the energy consumption in the building. Study [51] examined the impact of roof insulation location and thickness on building performance in the climate of Morocco. The study results indicated that the presence of roof insulation reduced the energy consumption of the building by 64% to 74%, compared with uninsulated roof buildings, with a thermal insulation thickness between 0.03 and 0.07, depending on the building's location, the [type of] insulation layer located on the roof, and its thickness [51]. This study also found that rockwool was an affordable and more environmental friendly solution in Morocco than extruded polystyrene, EPS, which was also considered in this study [52].

2.3.4 Window glassing

Residential buildings ought to contain a window to provide natural daylight. This is also the traditional way of building apartments in Jordan's climate as it also provides the basic ventilation method used in most building design. However, windows, like other building components, come in a variety of different types with different properties to be considered during their selection which is also mentioned in the building codes and standards. Relevant properties include the wall-to-window ratio, the shading factor, and the heat transfer coefficient U-value. The shading factor is the ratio between the solar radiation received from the sun to the radiation crossing the glass into the building [53]. The heat transfer coefficient or the thermal transmittance can also be defined as the heat transfer rate through a structure, or through the glass, divided by the temperature difference across that structure [54]. Past studies have examined the effect of changing the U-value and the shading coefficient of the glass on building energy consumption [27, 48, 53, 55-58]. Reducing the shading coefficient and the thermal transmittance of the glass can result in a reduction in energy consumption of almost 70%, depending on the wall-to-window ratio [55]. In a study conducted on a residential building in Gaza, different Solar Heat Gain Coefficient (SHGC) were studied which resulted in an optimal SHGC for glass of between 0.5 and 0.7 in order to achieve a suitable reduction in energy consumption in summer and still maintain adequate daylight and heat gain in winter [27]. Furthermore, study [56] investigated the glazing effect on the annual energy consumption of traditional apartments and houses and concluded that changing the glass type from single glassing to double glassing could lead to a reduction of about 2.9% and 6%, respectively.

2.3.5 Solar shading

Shading is one of the ZEB techniques that can help reduce the impact of direct radiation on a building's energy consumption. This is not just related to the type of glassing, although the use of glass may increase solar radiation as it is a transparent material that allows direct radiation access to the building. In order to restrict the amount of direct solar radiation entering the building in summer, and to help reduce the cooling load of the building, various shading devices have been implemented and studied in numerous publications [27, 53, 55-62]. These studies all agree that overhanging shading can have a significant impact on annual energy consumption. For instance, study [56] investigated the impact of adding overhanging shading to a building's facades on its energy consumption and reported that the addition of shading could result in a reduction in energy use of about 3.7%. Additionally, study [60] studied the impact of overhanging shading on daylighting and found that window diminution involved an optimal overhang length and height in order to deliver the highest amount of daylight during the winter while still restricting solar heat gains in the summer.

2.4 Building services systems and indoor criteria

The annual energy consumption of a building results from three main sources, that is, Heating, Ventilation, and Air Conditioning (HVAC) systems, domestic water heating, and lighting. To achieve nZEB, these systems must each be closely studied and customised in order to produce acceptable thermal comfort with a minimum of energy as these systems are all essential to the building's operation and cannot be excluded, especially in existing buildings that were not built to provide natural ventilation in the first place.

2.4.1 HVAC systems and set-point temperature

In most buildings, Heating, Ventilation, and Air conditioning (HVAC) systems are essential in order to adjust indoor air quality and achieve thermal comfort. These HVAC systems' requirements differ depending upon the weather and the building application. In the United States (U.S.), HVAC systems contribute about 40% of commercial buildings' energy consumption [63, 64]. In Jordan, these systems are normally responsible for about 57% of the energy consumption in residential apartments [59]. Previous studies that have examined annual energy consumption for existing buildings in Jordan have usually focused on Direct Expansion (DX) systems [55, 61, 65-67]. The DX system is the most common cooling system utilised in apartments, while various different systems are often used for space heating in buildings [59]. Because of the limited range of HVAC systems that are practical for use in residential buildings, modifying the HVAC energy consumption has generally been studied by adjusting system operation in terms of the set-point temperature in order to examine its potential for improving building performance.

The thermostat set-point range (dead band) in office buildings impacts both the occupants' thermal comfort and energy consumption. Increasing the cooling set-point from 22.2°C (72°F) to 25°C (77°F) can achieve an average saving of 29% in cooling energy and 27% in total HVAC energy consumption, without compromising occupant satisfaction levels [68].

2.4.2 Hot water systems

In the Jordanian national building code, each building has a set minimum requirement for the hot water supply. For instance, in residential apartments the minimum requirement for hot water is set at 45 litres per day per person. To provide this required amount of hot water, various different sources can be used, such as gas boilers, diesel boilers, and electrical heaters - in addition to solar water heaters. In a study that investigated the heating sources used for Domestic Hot Water (DHW), [59], it was found that 48% of Jordanian buildings obtain their hot water from electrical heaters in winter. Similarly, another study, [62] that utilised an electric water heater to provide hot water to apartments reported that 18% of the overall electricity consumption was used to heat water for domestic use.

2.4.3 Lighting

Lighting is an essential system in buildings to provide the required lighting for the operation and the utilisation of the building. Lighting influences building energy consumption since it directly affects the actual electricity consumption. Likewise, lighting has an indirect effect on building energy consumption through the heat produced, which can affect both the cooling and heating load. Study [62] found that lighting consumed 26% of the total electricity used by the particular building that was studied. Additionally, study [67] found that lighting contributed to 9% of the total energy consumption of the building. Study [59] found that about 52% of all the buildings in Jordan still do not use high-performance lighting. In order to improve overall building performance to reach nZEB levels, the lighting system ought to be considered and adjusted by adopting high-performance lighting systems that will emit less heat.

2.4.4 Renewable energy utilization

There are various different renewable energy resources that can be utilised to generate energy for use in buildings, such as hydropower, biomass, PV, and wind energy. In 2012, Jordan's renewable energy production comprised less than 1% of the country's overall energy consumption, and the government made plans to increase this contribution to 10% by 2020 [69]. The planned renewable energy sources' contribution would comprise 60.4% hydropower, 21.1% biomass, 9.7% PV and 8.8% wind, as shown in **Figure 4**.

	Wind	PV	Biomass	Hydro	Total RE	Total all Energy
MW	1.445	1.6	3.5	10	16.545	3100

	Wind	PV	CSP	Total	Target Date
MW	1200	300	300	1800	2020

a) b)

Figure 4: a) Renewable energy production and demand in Jordan in 2012, b) Planned renewable energy production by 2020 [69]

Hydropower resources are very limited in Jordan due to the limited water sources. There is only one hydropower plant in Jordan and that contributes about 0.4% of the annual national energy generation [70]. Similarly, biomass has a limited exploitation potential due to the weather and the limited amount of vegetation production in Jordan [70]. In contrast, Jordan has much potential for wind energy generation since several sites have adequate wind speed for electricity generation, both in the north and the south of the country. There are two main wind farms in Jordan that are already connected to the grid, and which generated about 3 GWh per year in 2012 [70]. However, wind turbines have space requirements that might not always be available in residential districts that are already congested with apartment buildings.

Solar energy has great potential in Jordan, with more than 300 sunny days per year [66]. Study [71] stated that solar power generation can be highly effective within certain weather and temperature ranges. Thus, studying the best means for its implementation could further improve its efficiency and impact. Solar energy could then be used for solar heaters to provide DWH to buildings. It could also be used to generate electricity by utilising Photovoltaic (PV) cells. PV panels are normally installed on a building's roof or façades. While installing PV systems vertically on walls is suitable for certain locations at low altitudes and where they would be highly efficient in winter [72], a roof location would be more likely for PV systems in Jordan.

Chapter Three: Methodology

3.1 Overview and validation

This section explores the methodology used in this study. Initially, the study investigated various building simulation tools currently used in the analysis of building performance and energy analysis. This involved three tools: EnergyPlus, eQuest, and IES-VE. Of these three tools, IES-VE was chosen for use in this study since it analyses a variety of the factors that affect energy consumption in buildings, such as the HVAC loads, occupant comfort, solar exposure, daylighting, wind loads, and carbon emissions, based on the model's building orientation, shading utilisation, construction materials and thermal performance data connected to the occupied spaces. In this research, IES Virtual Environment software version 2019 was utilized to implement the energy simulations. This software has been tested according to ASHRAE Standard 140 and it has been found to meet or exceed the requirements of this standard. IES VE was used to build the base model using the information for building properties obtained and analysed from previous studies [17, 61, 65, 73]. The simulation software used the site location for Queen Alia Airport in Amman. The hourly weather file used for the simulation was also for Amman and was based on a IWEC weather file compiled by the World Meteorological Organisation and published by the United States Department of Energy. The data used to create this weather file were supplied by the National Institute of Water and Atmospheric Research (NIWA) and it is a full hourly IWEC data file. Data features such as air temperature, humidity, solar radiation, cloud cover and wind speed were extracted from this file and used by the software in the subsequent analysis.

Building the base model that reflects a common residential building in Jordan has been done through a thoroughly literature review on the previous studies of building in Jordan to collect the row data which then has been used as a base scenario.

This data was also utilised to generate the model loads, internal gains, and the energy consumption values for the base model, which was then defined as the first scenario of the project. The base model loads were then verified by comparing them with the results of previous studies. The research also utilised IES-VE to implement different refurbishments to the base case in three separate scenarios in order to identify the optimal retrofit strategies which would enable an existing building in Jordan to conform with the concept of comfortable nZEB. This study aimed at assessing ZEB techniques in Jordan (Amman) in order to identify the optimal retrofits that may be the most suitable for the Jordanian case in terms of human comfort and energy consumption. The research explored four different scenarios where each scenario focused on two main aspects, as mentioned previously. These were energy consumption and thermal comfortability. The scenarios considered included photovoltaic cell implantation scenarios, building envelope adjustment scenarios, and a combination of the previous scenarios.

3.1.1 Scenario 1: Base model and validation

The base model was a general observation of a typical residential building in Jordan. This model was built up in accordance with an extensive investigation of previous studies carried out on existing buildings in Jordan. This scenario analysis was undertaken by utilizing IESVE as a simulation method to investigate comfortability and energy consumption. These results were then utilised to build up an understanding of the effect that the alterations described in the other scenarios would have on the parameters investigated in order to achieve the necessary ZEB requirements. Following the implementation of the IES-VE energy simulation tool, a validation process (as described in section 4.1) was carried out by modelling, simulating, and comparing the results of a previous study case with the results obtained from IES-VE by utilising the same building envelope and parameters.

3.1.2 Scenario 2: Refurbishments in the building envelope and the factors that affect building performance

We modified the building envelope by adjusting the U-values, shading and lighting, and by using efficient HVAC systems. The building envelope and the systems which are used to achieve human comfort play a crucial role in determining the energy consumption of a building. Previous studies have highlighted the impact of developing the building envelope and adopting strategies to reduce the energy consumption inside buildings in different climate zones [19, 26-29, 33, 34]. Therefore, this scenario studied the possible retrofits that could be implemented in order to adjust building performance in the Jordanian climate.

3.1.3 Scenario 3: Base model with utilisation of a renewable energy system (photovoltaic (PV) – cells) only

On average, Jordan experiences hot-mild weather with around 3,125 sunshine hours per year [71]. Thus, the use of solar power might be one of the best available resources for energy generation. In addition, PV-cell technology has reportedly been widely implemented in Jordan's residential sector over the past decade [74]. Therefore, this scenario studied the impact of utilising PV-cells on the base model.

3.1.4 Scenario 4: A combination of Scenarios 2 & 3

This scenario studied combining building retrofits with the utilisation of renewable energy solutions in terms of thermal comfortability and energy consumption.

Overall, this study analysed the findings in each scenario based on comfortability and energy consumption in order to identify the optimal solution that might be the most suitable for Jordan.

Therefore, this study built up a framework that can, hopefully, provide guidelines for the future implementation of zero-energy building practices in Jordan.

3.2 Thermal comfort

Thermal comfort is one of the most basic needs for human wellbeing. Human comfort is defined in ASHRAE-55 [75] as "a subjective concept characterised by a sum of sensations, which produce a person's physical and mental wellbeing, conditions for which a person would prefer". Thermal comfort is directly connected to the energy consumption in the dwelling. This study examined thermal comfort by utilising Integrated Environmental Solutions - Virtual Environment (IES-VE) software. IES-VE adopted ASHRAE-55 methodology which is based on studying the Predicted Mean Vote (PMV) value and the Predicted Percentage of human Dissatisfaction (PPD). This method was used to examine thermal comfort in each of the research scenarios in order to determine the human comfort solutions needed to convert an existing building into a comfortable nZEB.

The Predicted Mean Vote (PMV) and the associated Percentage of human Dissatisfaction PPD) are some of the earliest and most common methods used in examining human thermal comfort, and were introduced by Fanger [76] in the 1970s. This method was standardised in ASHRAE-55 [75] and the European EN ISO 7730 [77], which are the current standards for assessing thermal comfort in buildings. The PMV/PPD method is based on equations describing the thermal balance of the human body. However, it is also linked with human activities and clothing factors. Thus, thermal comfort standards may vary between individuals and it might be impossible to achieve an acceptable thermal comfort for all occupants in a given environment [75].

There are six main factors that affect thermal comfortability in a given environment. These are the metabolic rate, clothing, air temperature, radiant air temperature, air speed, and humidity. Due to the direct connection amongst the individuals' aspects, study [75] developed a thermal sensation scale that predicts the mean vote PMV score by quantifying and categorising thermal sensation into seven levels (+3 hot, +2 warm, +1 slightly warm, 0 normal, -1 slightly cool, -2 cool, -3 cold). The predicted percentage of human dissatisfaction (PPD) is an index that can be correlated with PMV. It assumes that scores of +3, +2, -2, or -3 on the thermal sensation scale all reflect dissatisfaction.

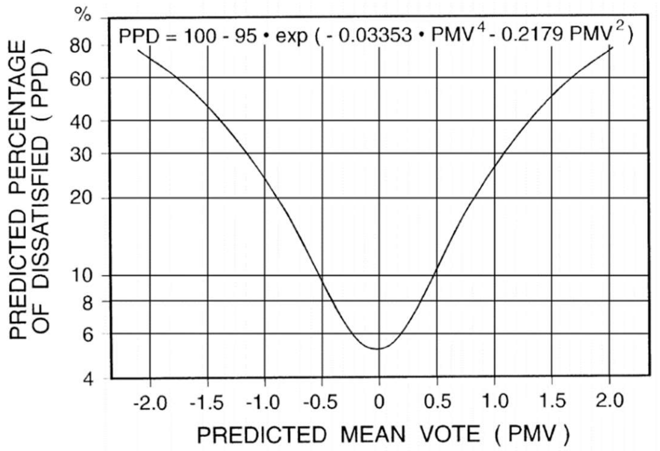


Figure 5: ASHRAE-55 Predicted Percentage Dissatisfied (PPD) values as a function of the Predicted Mean Vote (PMV) [75]

The PPD index indicates the percentage of an occupant's thermal discomfort sensation. According to ASHRAE-55, the standard thermal comfort of global comfort is 10% of the PPD index when PMV is in the interval between -0.5 and +0.5. Notably, even for PMV = 0, about 5% of occupants are in discomfort.

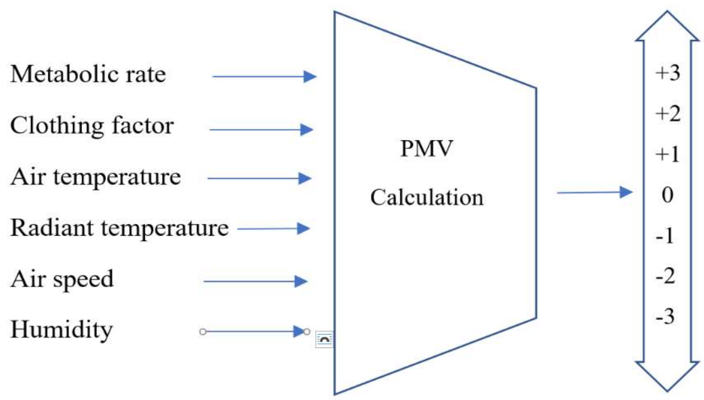


Figure 6: PMV calculation method

The relation used to evaluate the PMV index, as presented by [76] and applied by ASHRAE-55, is as follows:

$$PMV = (0.303e^{0.303} + 0.028) \cdot \Big((M - W) - 3.05 \cdot (5.73 - 0.007 \cdot (M - W) - p_a) - 0.42 \cdot \big((M - W) - 58.15\big) - 0.0173 \cdot M \cdot (5.87 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) - 3.96 \times 10^{-8} \cdot f_{cl} \cdot (t_{cl} + 273)^4 - (t_{mr} + 273)^4 - f_{cl} \cdot h_{cl} \cdot (t_{cl} - t_a)\Big) \quad (1)$$

Where:

$$t_{cl} = (35.7 - 0.0275 \cdot (M - W) - I_{cl} \cdot \Big((M - W) - 3.05 \cdot (5.73 - 0.007 \cdot (M - W) - p_a) - 0.42 \cdot \big((M - V) - 58.15\big) - 0.0173 \cdot M \cdot (5.87 - p_a) - 0.0014 \cdot M \cdot (34 - t_a)\Big) \quad (2)$$

The PPD index is expressed by the equation (3).

$$\text{PPD} = \Big(100 - 95\text{Exp}\big(-(0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2)\big)\Big) \quad (3)$$

where, M is metabolic heat rate [W/m2]; W is activity level [W/m2]; t_{cl} is temperature at clothes level [°C]; p_a is water vapour pressure [Pa]; t_a is air temperature [°C]; I_{cl} is thermal insulation of clothes [Clo]; f_{cl} is Clothing factor [-]; t_{mr} is Mean radiant temperature [°C]; and h_{cl} is Convective heat transfer [W/m²°C].

Metabolic rate is related to human activities and the place of application. It can be derived from ASHRAE-55 appendix A – activity levels and is depicted in **Table 4**. In the steady state case, the metabolic rate is usually between 1.0 and 1.3 [75].

The clothing insulation factor is related to the clothing layers worn and the type of clothing. It is assumed to be between 0.5 and 1.0 in the steady state case and can be derived from ASHRAE-55 appendix B, as depicted in **Table 5** [75].

Table 4: Activity levels and metabolic rates for typical tasks [75]

Activity	Met Units	Metabolic Rate W/m^2	$(Btu/h.ft^2)$
Resting			
Sleeping	0.7	40	(13)
Reclining	0.8	45	(15)
Seating, quiet	1.0	60	(18)
Standing, relaxed	1.2	79	(22)
Walking (on level surface)			
0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115	(37)
1.2 m/s, 4.3 km/h, 2.7 mph	2.6	150	(48)
1.8 m/s, 6.8 km/h, 4.2 mph	3.8	220	(70)
Office Activities			
Seated, reading, or writing	1.0	60	(18)
Typing	1.1	65	(20)
Filing, seated	1.2	70	(22)
Filing, standing	1.4	80	(26)
Walking about	1.7	100	(31)
Lifting/packing	2.1	120	(39)
Driving/flying			
Automobile	1.0–2.0	60-115	(18-37)
Aircraft, routine	1.2	70	(22)
Aircraft, instrument landing	1.8	105	(33)
Aircraft, combat	2.4	140	(44)
Heavy vehicle	3.2	185	(59)
Miscellaneous Occupational Activities			
Cooking	1.6-2.0	95-115	(29-37)
House cleaning	2.0-3.4	115-200	(37-63)
Seated, heavy limb movement	2.2	130	(41)
Machine work			
Sawing (table saw)	1.8	105	(33)
Light (electrical industry)	2.0-2.4	115-140	(37-44)
Heavy	4.0	235	(74)
Handling 50 kg (100 lb) bags	4.0	235	(74)
Pick and shovel work	4.0-4.8	235-280	(74-88)
Miscellaneous Leisure Activities			
Dancing, social	2.4-4.4	140-255	(44-81)
Calisthenics/exercise	3.0-4.0	175-235	(55-74)
Tennis, single	3.6-4.0	210-270	(66-74)
Basketball	5.0-7.6	290-440	(92-140)
Wrestling, competitive	7.0-8.7	410-505	(129-160)

Table 5: Clothing insulation values for typical ensembles [75]

Clothing Description	Garments Included	I_{cl} (clo)
Trousers	1) Trouser, short-sleeve shirt	0.57
	2) Trouser, long-sleeve shirt	0.61
	3) #2 plus suit jacket	0.96
	4) #2 plus suit jacket, vest, T-shirt	1.14
	5) #2 plus long-sleeve sweater, T-shirt	1.01
	6) #5 plus suit jacket, long underwear bottoms	1.30
Skirts/Dresses	7) Knee-length skirt, short-sleeve shirt (sandals)	0.54
	8) Knee-length skirt, long-sleeve shirt, full slip	0.67
	9) Knee-length skirt, long-sleeve shirt, half-slip, long-sleeve sweater	1.10
	10) Knee-length skirt, long-sleeve shirt, half-slip, suit jacket	1.04
	11) Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	12) Walking shorts, short-sleeve shirt	0.36
Overalls/Coveralls	13) Long-sleeve coveralls, T-shirt	0.72
	14) Overalls, long-sleeve shirt, T-shirt	0.89
	15) Insulated coveralls, long-sleeve thermal underwear tops and bottoms	1.37
Athletic	16) Sweat pant, long-sleeve sweatshirt	0.74
Sleepwear	17) Long-sleeve pajama tops, long pajama trousers, short ¾ length robe (slippers, no socks)	0.96

After applying the PMV-PPD index method by considering the air speed of 0.2 m/s or less, the humidity ratio was evaluated as below 0.012 with a water vapor pressure of 1.910 kPa. These values categorised as the steady state conditions. The comfort zone is observed in **Figure 7** for two levels of clothing 0.5 and 1.0 for the outdoor climate (warm and cool) [75]. The abilities of obtaining an acceptable level of hygiene in the indoor air of high efficient buildings through natural and mechanical ventilation has been discussed in [78]. The natural ventilation was studied relative to opening windows profile in [75] for the base model and the other scenarios studied the effect of the HVAC systems in the inside thermal comfort and also investigated in to identify

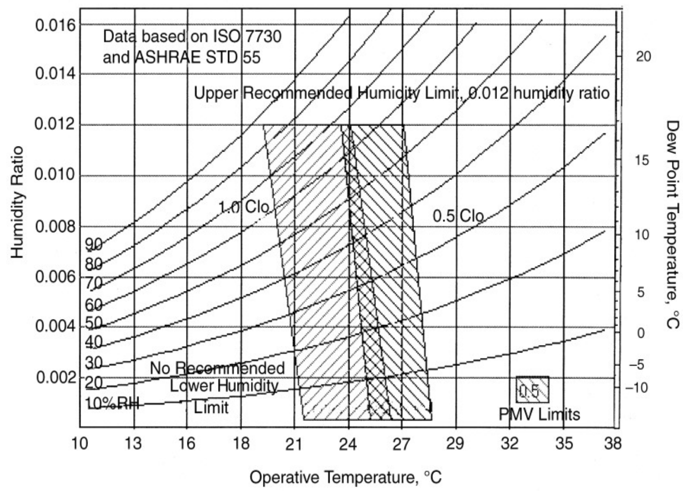


Figure 7: ASHRAE-55 acceptable range of operative temperature and humidity values for indoor spaces [75]

3.3 Energy consumption

The energy consumption in a building is distributed across various different sectors, namely, lighting, Heating Ventilation and Air Conditioning (HVAC), Domestic Hot Water (DHW), and other household appliances. Building energy consumption has always been affected by different variables - mainly the outside environment (weather), the building envelope, the system types used, and the operation profile. Therefore, the effect of each of these variables on building energy consumption was examined in detail. This was achieved by utilising IES-VE to create different scenarios and then compare them with the base model in order to study the effect of each variable on the amount of energy consumed annually. This analysis was also used to determine the optimal retrofit needed to realise the ZEB concept.

First, the base case was built up in ModetIT in IES-VE and assigned the building parameters, as described in section 4.1.2, before applying the building template - according to the type of accommodation provided by each room. Second, the heat gain of each zone was assigned, in accordance with ASHRAE and the operation profile of the system, and the type of zone operation was then used to calculate energy consumption for the base case scenario energy consumption. Lastly, applied the system that would be operating to accommodate the load in the dwelling. This cycle was repeated for each scenario to evaluate the amount of energy consumed in each model. The IES-VE algorithm calculated the heating and cooling load based on ASHRAE 90.1 calculations as well as the domestic hot water demand (as shown in the ASHRAE handbook for hot water, which is also the basic reference used for building load calculations in the Jordanian National Codes).

Chapter Four: Analysis

4.1 Scenario 1: Base model

4.1.1 Overview

A previous study on buildings in Jordan found that 46% of existing dwellings in 2019 were located in Amman [59]. In 2015, apartment buildings comprised 83.5 % of all housing in Jordan and 48% of them comprised 4 floors [59, 73]. In addition, over two-thirds of the buildings in Jordan are 10 years old, or more, which could be one reason why most of these buildings are uninsulated or might not be compliant with the Local Thermal Insulation Codes [39, 40]. According to the same study, just above a third of these buildings were uninsulated and almost a half of the participants surveyed were unsure if their buildings were insulated or not [59]. Another research study reported that only 15% of the existing dwellings in Jordan are insulated [79]. Thus, the base model used for this study was an apartment building in Amman, 10 years old, and not fully compliant with local thermal insulation building codes.

The Ministry of Public Work force] and Housing publishes Jordan's building code, which is designed to regulate the minimum requirements of the building construction process nationally. The thermal insulation code is one of the national codes that determines the minimum acceptable thermal heat transfer coefficient (U-value) for various building parameters. **Figure 8** illustrates the minimum acceptable U-values for each of these different parameters. This is explained further in **Table 6** [39, 40].

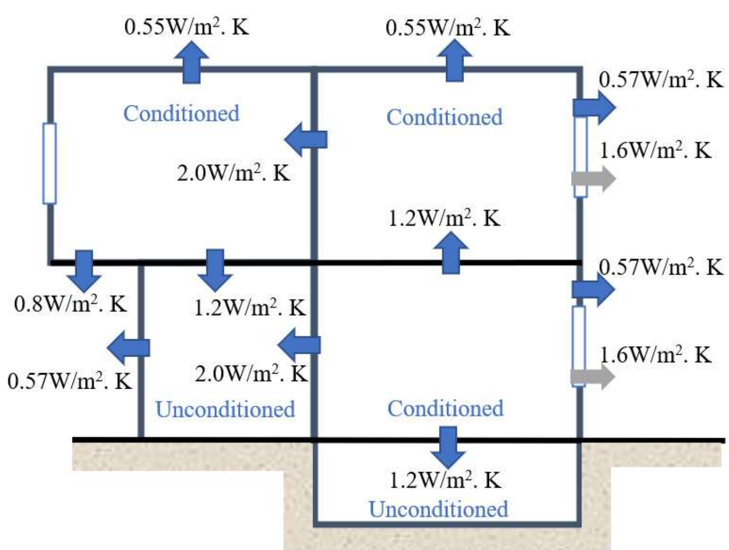


Figure 8: The minimum acceptable U-values for different building parameter

Table 6: The minimum acceptable U-values for different building parameters

Building parameters	**U-value $W/m^2.°C$**
Exposed walls	0.57
Exterior walls, including percentage of openings	1.6
Interior walls between 2 different energy sources or between air conditioned and non-air-conditioned places.	2.0
Exposed roof heat transfer towards bottom	0.8
Exposed roof heat transfer towards top	0.55
Interior roof/floor between 2 different energy sources or between air conditioned and non-air-conditioned places.	1.2

Based on past studies, it was established that the existing buildings are not compatible with the current codes and standards. Thus, this research adopted an average of past applied U-values to determine the optimal applicable retrofits needed to produce a ZEB in a building that has a level of insulation but not compliance with the national code requirements. The analysis carried out in this study was focused on two main areas, that is, comfortability and energy consumption.

4.1.2 Building Parameters

i. Wall structure – Thermal heat transfer coefficient (U-value)

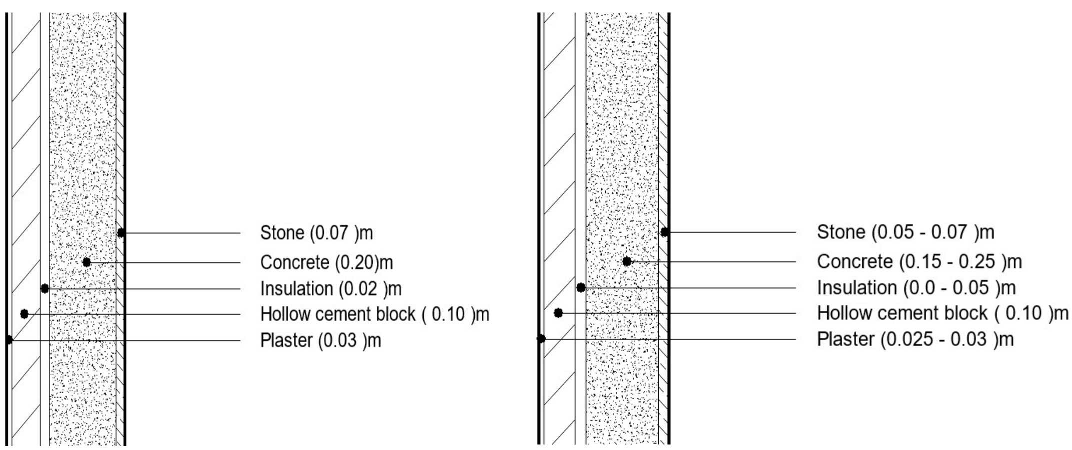
Previous studies have considered different case studies. These case studies used different U-values and found that most existing buildings are not compatible with current Jordanian codes and standards [61, 80, 81] [65, 67]. For instance, in one of the previous studies, 2.14 $W/m^2.K$ was the thermal heat transfer coefficient (U-value) calculated for the uninsulated external walls [81], while in other studies, the U-value was calculated as 1.323 $W/m^2.K$ [82] and 1.74 $W/m^2.K$ [67], as illustrated in **Table 7**. Normally, this depends on the wall thickness, the material used, and its structure.

Seven out of the eleven previous research case studies examined were broadly compatible in terms of the wall materials used and varied only in terms of their thicknesses. For instance, studies [61, 65, 66, 80-82] all found that their case study wall structure consisted of stone, concrete walls, hollow cement blocks and plaster - with variations in thicknesses and insulation. However, in studies [29, 31] the wall structure examined did not include a stone facade and in study [65] the inner layers were made of brick with different wall thicknesses, while studies [55, 67] did not mention the wall structure at all. The U-value calculated by taking the average of all these wall structure material thicknesses was about 0.79 $W/m^2.C$. Note that while the minimum overall heat transfer coefficient for external walls is specified in the national thermal insulation code [39], the code does not specify the thickness of each section of the wall needed to produce this minimum overall heat transfer coefficient.

Table 7: Heat transfer coefficients reported in previous case studies

Study	External Wall U-value $W/m^2.^{\circ}C$	Internal Wall U-value value $W/m^2.^{\circ}C$	Roof U- value $W/m^2.^{\circ}C$	Glassing $W/m^2.^{\circ}C$	Window details
[81]	2.14	-	-	-	-
[82]	1.323	-	1.163	6.121	Clear single glazing
[67]	1.74	-	1.372	5.52	SHGC 0.73 WWR 30%
[80]	3.34	-	2.44	-	-
[61]	2.55,1.99, 1.8 and 0.75	2.41, 2.15, and 1.94	1.7	-	-
[65]	0.49 (insulated)	-	0.78	5.7	SHGC 0.84 WWR (28%, 14%, 30%, 21%)
[66]	1.2 (insulation)	2.8	-	3.0	WWR 25%
[17]	2	-	1	5.8	-
[31]	2.9535	6.987	4.225		-
[29]	0.82	3.194	0.712	5.88	Single glazing
[55]	0.62.	-	0.52	-	-

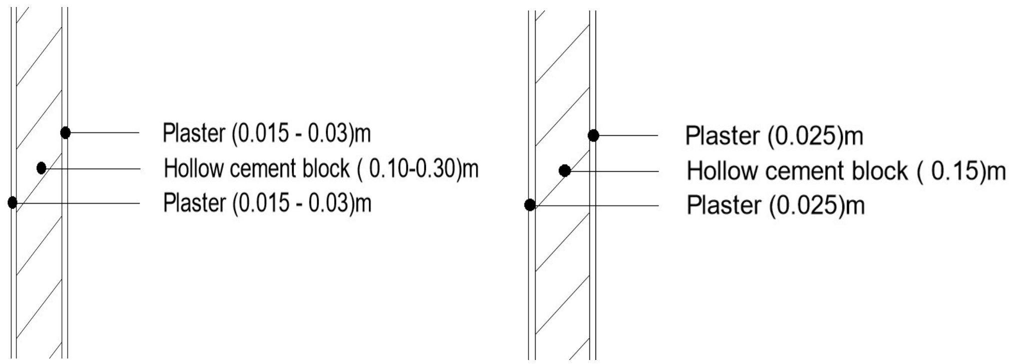
The external wall structure that shown in the **Figure 9 a)** illustrates the most common wall structure in Jordan's residential buildings which has been explored in [61, 65, 66, 80-82] to be employed in the basic model as shown on **Figure 9 b).**



a) b)

Figure 9: a) Common wall structure in Jordan, based on previous case studies (NTS); and b) base model external wall (NTS)

The internal walls' U-values are important when calculating the heat transfer inside the dwelling between the air conditioned and non-air-conditioned spaces. The absence of this value in past studies might lead to an assumption that all zones of the building are air conditioned. The studies that mentioned the internal wall structure all considered three main layers with different thicknesses: plaster, hollow concrete blocks, and then another plaster layer [29, 31, 61, 66], as shown in **Figure 10 a)**. The U-value calculated after employing the average of these wall structure material thicknesses was about 2.13 $W/m^2 \cdot$ °C, as illustrated in **Figure 10 b)**.



a) b)

ii. ***Figure 10:*** *a) Common wall structure in Jordan, based on previous case studies (NTS); and b) base model internal wall (NTS)**Roof and intermediate floor's structure – Thermal heat transfer coefficient (U-value)***

The thermal conductivity of roofs and floors have been discussed in past studies, and different values have been observed for existing buildings [17, 29, 31, 55, 61, 65, 67, 80, 82]. For instance, the floor U-value equals 2.44 $\mathrm{W/m^2 \cdot °C}$ for the case of uninsulated roof in [80] and 0.8 $\mathrm{W/m^2 \cdot °C}$ according to [61], while study [82] reported the U-value of 1.1601 W/m^2.k. The differences in reported U-values are related to the differences in construction materials and their thicknesses. Therefore, this study compared the construction components of roofs and floors studied in previous articles and used the results that are most compatible with current local codes in terms of materials and variations in thickness. However, some studies did not include roof and floor structure details when evaluating U-values [55, 82]. Furthermore, only three of the reviewed articles considered insulation in the roof or floor structure [29, 31, 55], while only two articles did not consider roof tiling [66, 67]. **Figure 11 a)** shows the type of roof/floor structure acquired from the previous studies. The base model utilised the average material thicknesses and the base structure from the national thermal insulation code in order to obtain the U-value. The U-value calculated after employing the average of wall structure material thicknesses was about 0.67 $W/m^2 \cdot °C$ for the roof and 0.64 $W/m^2 \cdot °C$ for the floor, as illustrated in **Figure 11 b)**.

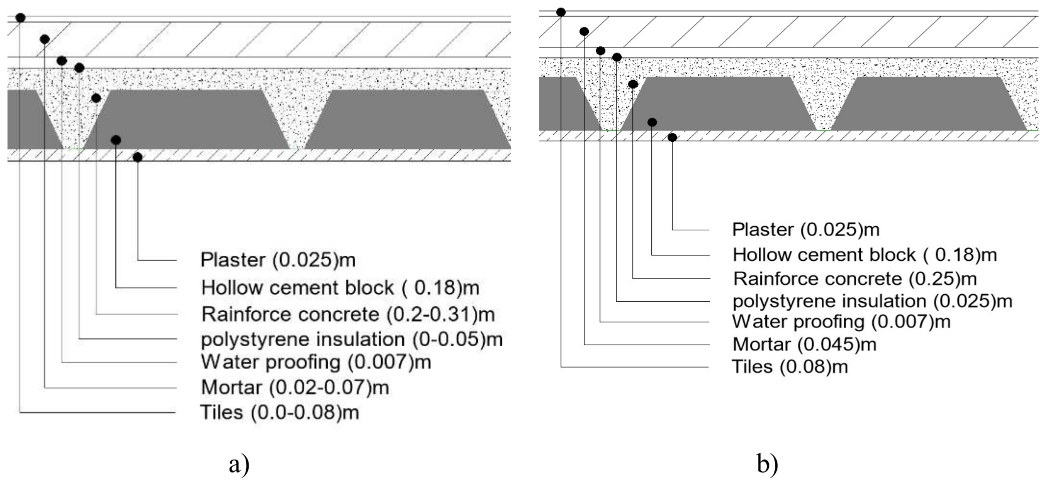


Figure 11: a) Common wall structure in Jordan, based on previous case studies (NTS**)**; and b) Base model internal wall (NTS)

iii. Window type - Thermal heat transfer coefficient (U-value)

In Jordan, apartment windows are most likely to be sliding windows. According to [59], over 90% of the buildings in Jordan utilise sliding windows. In addition, 80% of window glassing involves single-glazed or double-glazed windows. Previous studies reportedly used single-glazed windows with U-values between 5.2 and 6.12 $W/m^2 \cdot °C$ [17, 65, 67, 82]. In these studies, the wall-to-window percentage varied between 14% and 30%. However, it is usually about 30%. Thus, in this study, windows were assumed to be single-glassed, sliding windows with a U-value of 5.2 $W/m^2 \cdot °C$ - reflecting the predominant style of buildings in Jordan at present. In this study, the base model was assumed to represent an apartment building on the third floor with an exposed roof. The typical characteristics of an apartment building over 10-years old are shown in **Table 8** and the layout of such an apartment building is shown in **Figures 12** and **13**.

Table 8: Base model characteristics

Characteristic	**Dimensions**
Outside construction	Stone
Window area	(2.0 x 1.1) m^2
Number of bedrooms	Three
Number of guest rooms	One
Number of living rooms	One
Number of bathrooms	Three
Number of kitchens	One
Average area of apartments	149 m^2

External wall (U-value)	0.78 $W/m^2 \cdot ℃$
Internal wall and partitions (U-value)	2.13 $W/m^2 \cdot ℃$
Typical floors (U-value)	0.64 $W/m^2 \cdot ℃$
Roof (U-value)	0.67 $W/m^2 \cdot ℃$
Window type (U-value)	Single glazed and 5.2 $W/m^2 \cdot ℃$
Door / balcony door (U-value)	1.4 $W/m^2 \cdot ℃$/ 3.0 $W/m^2 \cdot ℃$ [66]

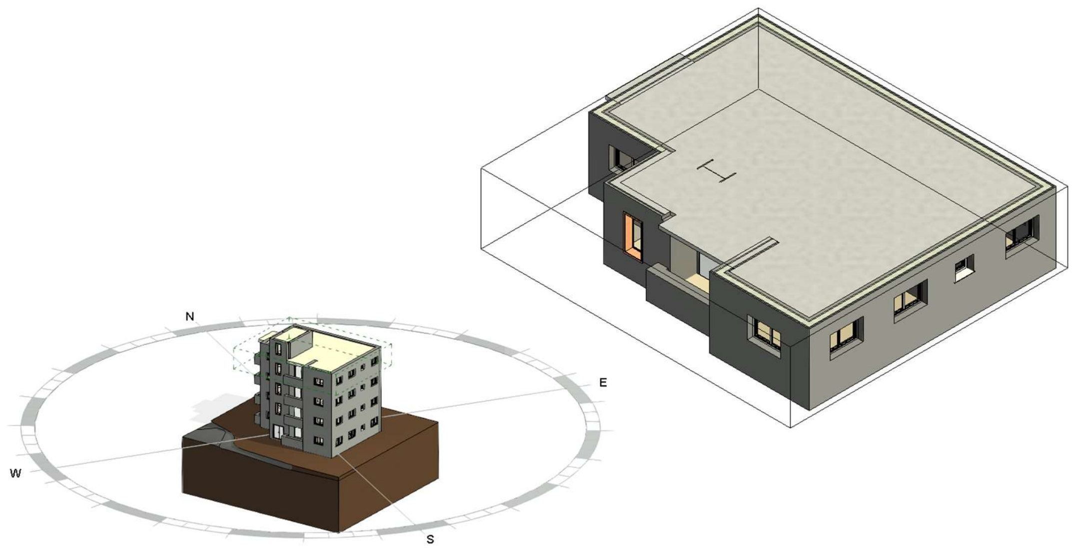


Figure 12: The base model – modelled in Revit 2021

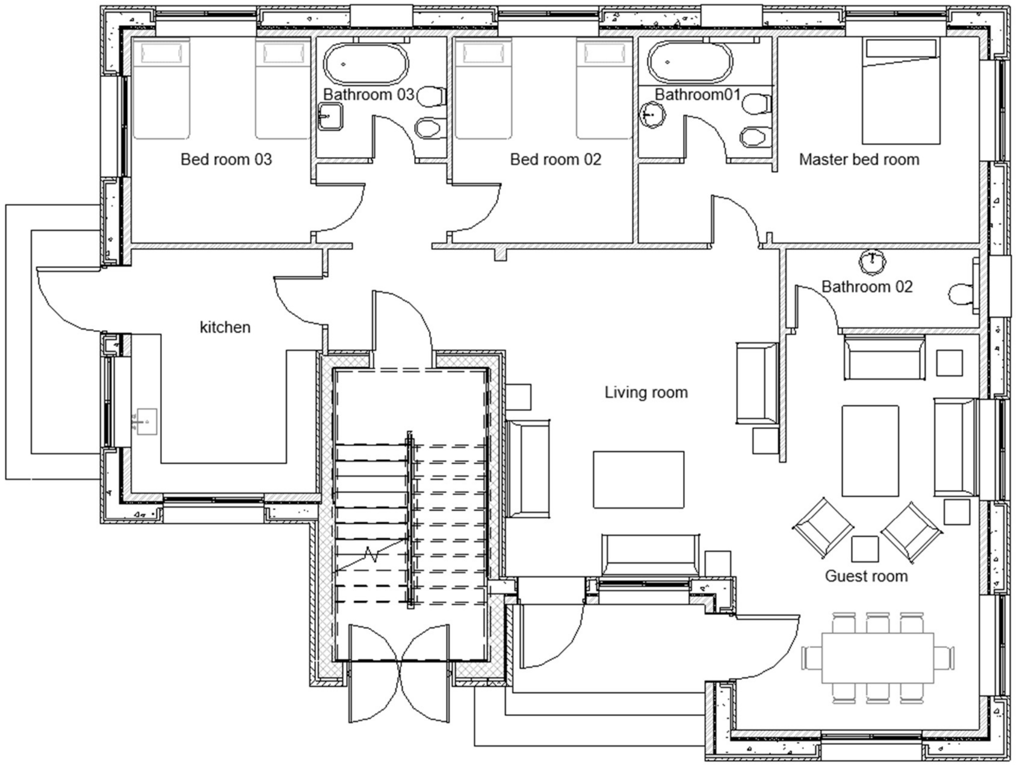


Figure 13: Base model layout

4.1.3 Indoor air conditions

The indoor air temperature was appointed as shown in **Table 9**. These values have been obtained according to the Jordanian national codes for heating and cooling as well as the ASHRAE standard that is reported in **Appendix 1** since the local code has not detailed the indoor conditions and obligate a general rule for residential building.

Table 9: Indoor design conditions

Space application	**Winter design conditions**	**Summer design conditions**
Rooms	20 °C and 30% RH	21 °C and 30% RH
Kitchen	21.1 °C (Not air conditioned)	28.9 °C (Not air conditioned)
Bathroom	22.2 °C (Not air conditioned)	28.9 °C (Not air conditioned)
Corridors	18 °C (Not air conditioned)	26 °C (Not air conditioned)
Staircase	18 °C (Not air conditioned)	26°C (Not air conditioned)

4.1.4 Thermal templates (heat gains)

Heat gains are part of the thermal profile inside the building. The causes of heat gains can be grouped into three main segments, namely, lighting, occupancy, and appliances. In the base case model, four thermal templates were assigned to the air-conditioned zones, according to their type of application. These templates were labelled "dormitory" for the bedrooms, "food dining" for the kitchen, "living room" and "guest room". The non-air-conditioned spaces, namely, the staircase, the corridors and the bathrooms, were assigned their own separate templates. For each template, the heat gains produced by each segment were assigned according to ASHRAE standard 90.1 [54].

i. Lighting heat gains

Lighting heat gains are the amounts of heat transferred into a place due to the operation of lighting applications. In past studies, this was sometimes implemented differently. For instance, the overall lighting intensity was assumed to be 25 W/m^2 in study [55] but 10 W/m^2 in study [61]. In other studies such as [67] the heat gains reported were 8, 6, 12 and 10 W/m^2 for the living room, bedroom, kitchen and toilet, respectively [17]. Although heat gains have been mentioned in past studies, they have not always been investigated explicitly for each zone separately. Also, none of the past case studies reviewed ever mentioned experimental data acquired for existing building operation. Therefore, the heat gain data used in this study are based on ASHRAE standard 90.1 [54], since this was the primary source for the lighting heat gain values used for each space] in the energy model. Accordingly, these data were applied to IES-VE, as shown in **Table 10,** based on the lighting heat gain values for various different building zones in ASHRAE standard 90.1, as shown in **Appendix 2** [54].

Table 10 : Lighting heat gains

Space application	ASHRAE standard – common space type	Lighting heating heat gain (W/m^2)
Bedrooms	Sleeping quarters	3
Living rooms	Dormitory – living room	12
Guest room	Motel Guest room	12
Kitchen	Dining area for family	23
Bathroom	Bathroom	10
Corridors	Corridor	5
Staircase	Staircase	6

ii. Occupancy and equipment's heat gains

The heat gain from occupants and equipment was not mentioned in any of the reviewed articles, except for study [61] which assumed it to be 50 W/m^2 per person (for occupant heat gain). In this model, the occupancy rate was derived from the 2017 ASHRAE Handbook—Fundamentals (SI) [54], as it is an approved source for the national building code of Jordan. Other internal gain values were derived from the heat rejections produced by the electrical equipment used in each particular space. These values were also obtained from 2017 ASHRAE Handbook—Fundamentals (SI) [54], as shown in **Appendix 3**. The specific occupancy and heat gains used for the model in this study are shown in **Table 11**. In addition to the purely numerical values assigned to the different types of heat gain, an operation profile was also assigned to each template in IES-VE in order to calculate the most accurate energy consumption.

Table 11: Occupancy and equipment's heat gains

Space application	ASHRAE standard –common space type	Occupancy heat gains	Occupancy heat gains	Equipment heat gains (W/m^2)
		Latent (W/P)	Sensible (W/P)	
Bedrooms	Sleeping quarters	55	75 (2 people)	3.2
Living rooms	Dormitory – living room	55	75 (5 people)	5.4
Guest room	Motel Guest room	55	75 (7 people)	5.4
Kitchen	Dining area for family	55	75 (4 people)	264 W 147 W cooking
Bathroom	Bathroom	55	75 (1 person)	
Corridors	Corridor	55	75 (1 person)	
Staircase	Staircase	-	-	6.0

4.1.5 Building's systems

The energy consumption in buildings is mainly affected by building construction and operation. Building operation is related to the systems utilised in the building. These can be grouped into five main categories, namely, heating ventilation and air conditioning systems (HVAC), lighting, domestic water heating, cooking, and appliances.

i. Heating ventilation and air conditioning systems (HVAC)

In general, buildings require heating in winter and cooling in summer in order to attain thermal comfortability. A previous study observed that around 34% of the buildings in Jordan employ central heating with diesel boilers for space heating, while around 30% of the apartments use gas heating units and only 11% use AC split units for heating [59]. In the summer season, 67% of the respondents in the past study reported using cooling methods to adjust the indoor temperature and just over a half of those participants used cooling for less than five hours a day [59]. Thus, in the base model, heating and cooling applied to the system was assumed to involve split units. These split units have been selected from the range of brands commonly available on the Jordanian market and details regarding this model were implemented in Apache HVAC in IES-VE in order to calculate the energy consumption (see also **Appendix 4)**. These split units were assigned to the bedrooms, while the kitchen was equipped with an exhaust fan **-** as this is the common practice in residential buildings in Jordan. The bathrooms were also equipped with exhaust fans to facilitate air exchange inside that space. Details of the systems built in Apache HVAC in IES-VE are shown in **Figure 14**.

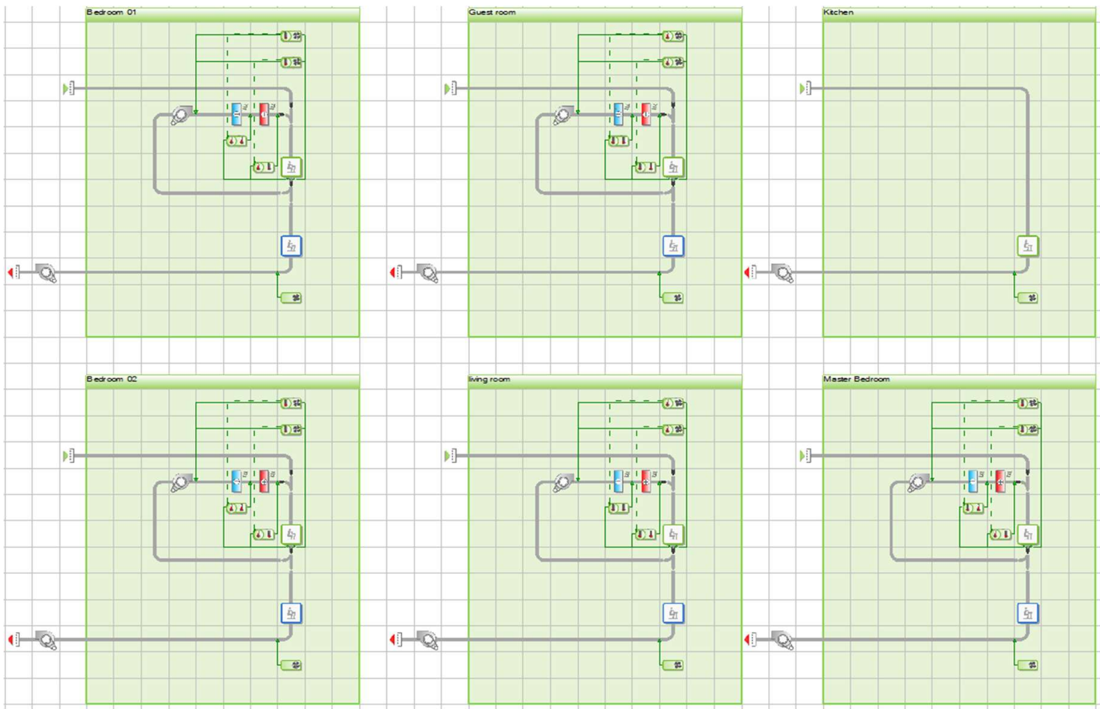


Figure 14: Systems implemented in IESVE for the base model

After applying the base model characteristics and calculating the heating and cooling loads, as per ASHRAE, as well as assigning the systems used to accommodate the building's heating and cooling load, the simulation calculated the heating and cooling loads for all the zones in the building, in addition to the building's energy consumption. To do this, the simulation required the building profile for each of the assigned systems. These profiles differed, based on their zone of application, as explained in the following section.

i. Building operation profile

The energy consumption has a direct relationship with the duration of a system's operation in the building. Operation profiles are the expression of the time and the duration of the system's operation and were used in this study to reflect the usual situation found in residential apartments. With reference to past studies, the typical heating and cooling system operation profile for residential buildings in Jordan is shown in **Figure 15,** as presented in study [59]. It represents the main heating and cooling seasons in Jordan, with respect to the operation of heating and cooling systems. As shown in **Figure**

15, during December, January, and February there is 100% operation of the heating system, while even in the peak of the summer season the operation of the cooling systems only reaches about 64%. These data were collated by a quantitative research study that was conducted on residential buildings in Jordan. Whilst there is a certain amount of variation in the operating hours reported between different studies, Nazer [59] found that over half of the residential buildings studied operated their heating/cooling systems for five hours or less, which is in general agreement with previous studies [31, 67].

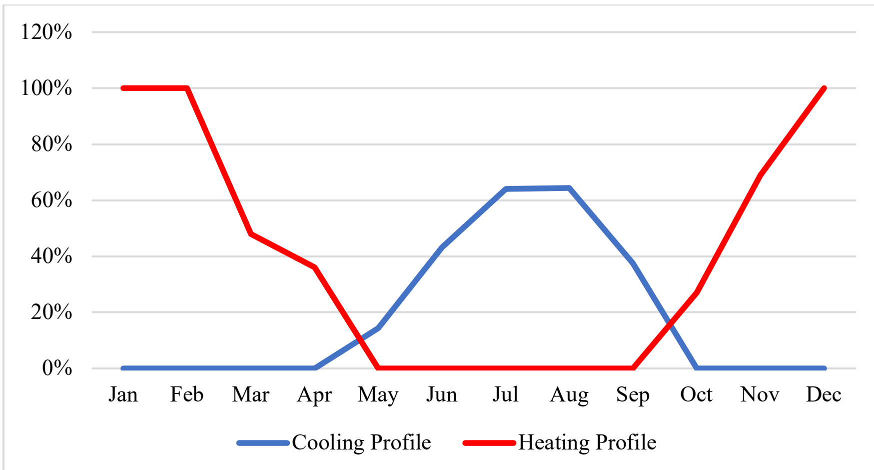


Figure 15: Heating and cooling profile [59]

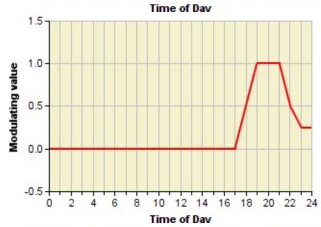
In this study, operation hours were assigned separately for each system and collated in order to reflect the approximate daily use of each zone. **Table 12** illustrates the way in which these operation profiles were assigned to each zone in the model. Each zone was assumed to be operating during certain hours. For instance, the living room and guest room are not occupied continuously, and the bedrooms are mainly occupied only at night. The kitchen is only used at lunch time and, partially, in the morning.

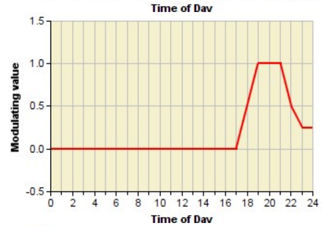
Table 12: Base model profiles

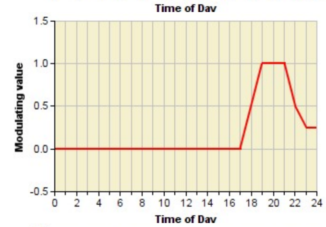
Space application	Lighting profile	Occupancy profile	Equipment Profile
Bedrooms			

Living rooms

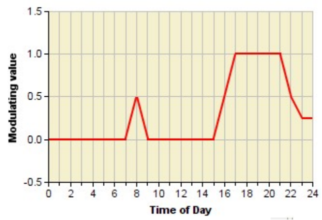
Guest room

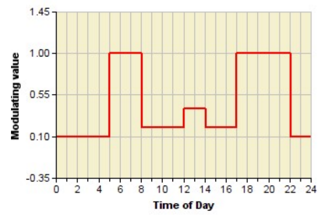


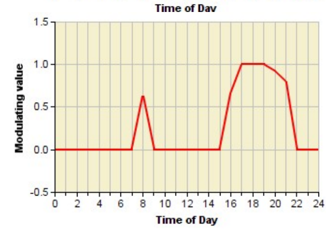




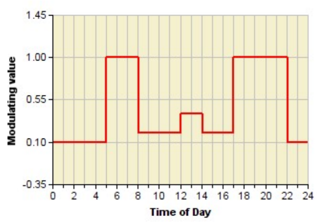
Kitchen

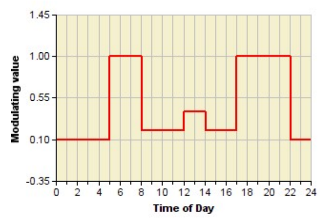




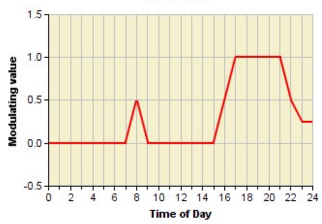


Bathroom

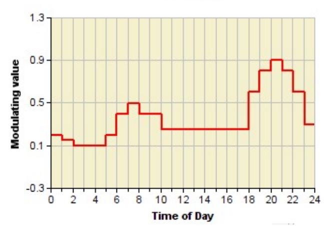




Corridors



Staircase



ii. Domestic hot water:

The domestic hot water consumption is the amount of hot water assigned according to the national water supply code in Jordan. The model was designed to accommodate hot water usage of 45 L per person a day. The consumption of this hot water was assumed to follow the same profile as that of the bathroom's operation. This load was accommodated in the base model by utilising a regular gas boiler with a water heating capacity of 225 L/day, which was calculated as enough to supply the daily domestic hot water load for a family.

4.1.6 Simulation and analysis

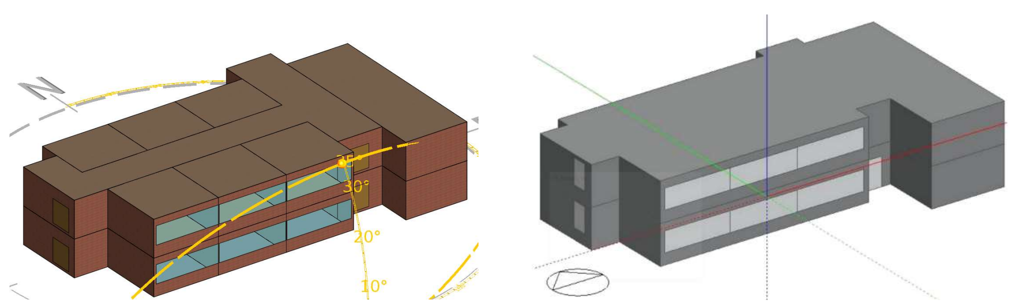
i. Validation

The current research utilised IES-VE for the simulations and results generation. Hence, a validation process for the results was also undertaken - investigating the IES-VE software accuracy by modelling and simulating a published paper's model, previously presented in study [82]. The examined building is a public school located in the capital city of Jordan, Amman. It was a three-storeys building with an overall area of 1,224 m^2 and each floor is 409 m^2. The building characteristics were obtained from the previous study and implemented in IES-VE, as shown in **Table 13.**

Table 13: Validation parameter

Reference Parameter	Building elements
Wall U-value	1.323 $W/m^2.^oC$
Roof U-value	1.163 $W/m^2.^oC$
Window U-value	6.121 $W/m^2.^oC$
Operation Profile	For lighting, occupancy and equipment was assigned to operate 8 hours a day, five days a week, from 7:00 to 15:00, and from Sunday to Thursday.
Occupancy rate	1.67 m^2/ person
Ventilation	Obtained from 20% window opening and 5 L/s/person from forced ventilation
Set-point temperature	18^0C in heating and 24^0C in cooling

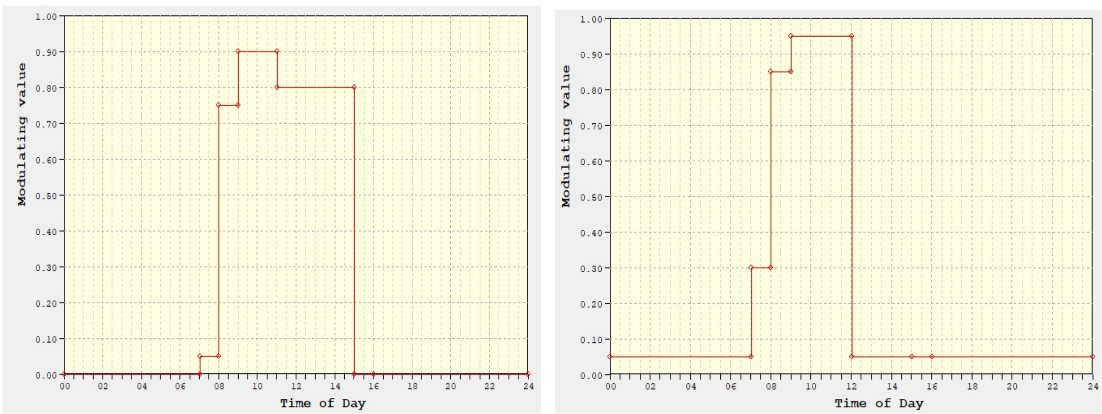
In study [82], DesignBuilder energy simulation software was utilised to obtain the results. The same model was reproduced built by implementing its characteristics using the ModelIT tool in IES-VE. **Figure 16** shows the resulting layout built using IES-VE and that obtained from the past study.



a) b)

Figure 16 : Validation model: a) The model acquired from IES VE; and b) A model picture acquired from the past study [82]

The validation process was conducted by comparing the heating and cooling energy consumption indicated in the original study with the results obtained from IES-VE for the same model. This required implementing the heating, cooling and ventilation systems that were utilised in the original study. The mechanical systems were assigned to be only a partial mechanical ventilation of 5 L/s and a natural ventilation obtained from 20% of opening areas of the windows. The operation profiles for lighting, occupancy and electrical equipment heat gains are a noticeable factor that affects the energy consumption in a building. Thus, the operation profiles were assigned to follow the original building's profiles shown in **Table 13. Figure 17** shows the operation profiles obtained from IES-VE.



a) b)

Figure 17: The profiles utilised in IES-VE for model validation: a) Operation profile for occupancy and electrical equipment; and b) Lighting operation profile

The weather data used in the previous study were acquired from the metrological department of the University of Jordan in 2003, while the weather data applied in IES-VE was the same weather data that was utilised in this research thesis.

All the previous characteristics were implemented in order to run the Apache system load simulation in IES-VE. The results obtained were then compared with the results of the original study, as shown in **Figure 18**. Notably, **Figure 18** shows that the results of both energy simulation methods were generally compatible. While there was a small variation present that could have resulted from reading the weather profile differently and from programming variations, overall, the results acquired from IES-VE were validated - showing close compatibility with the results obtained using other validated simulation tools.

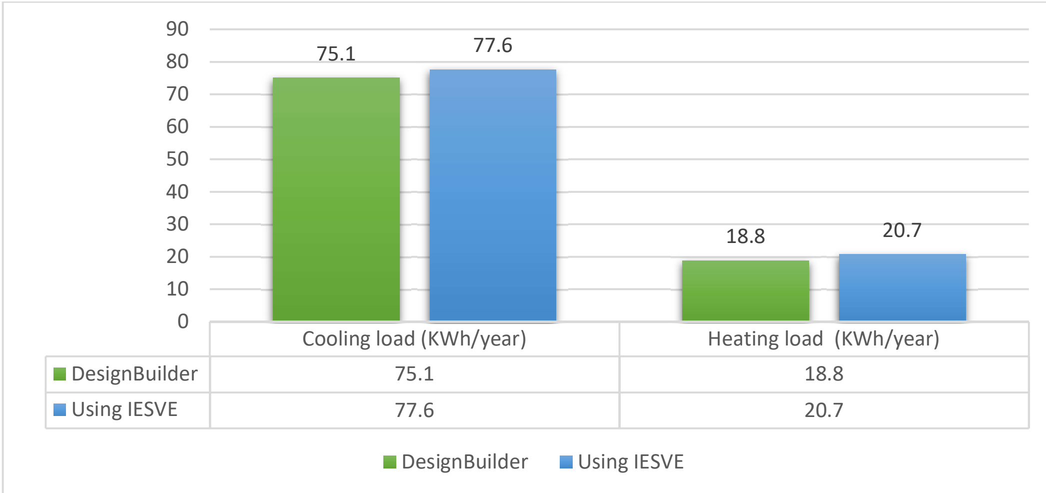


Figure 18 : Validation results

ii. Base model energy consumption

The base model was implemented in IES-VE 2019 software to study the heat gains obtained from the sun with reference to the weather and the location of Amman, Jordan. The weather data were classified as zone (3b) - hot and dry by ASHRAE. **Figure 19** illustrates the number of sun-exposed hours for the building facades and roof. **Figure 19** shows that the roof was exposed to the maximum number of sun-exposed hours annually, with almost 4,352 hours, followed by the south-east façade with approximately 3,050 hours/year. The north-west façade had the least number of sun-exposed hours (around 870 hours/year).

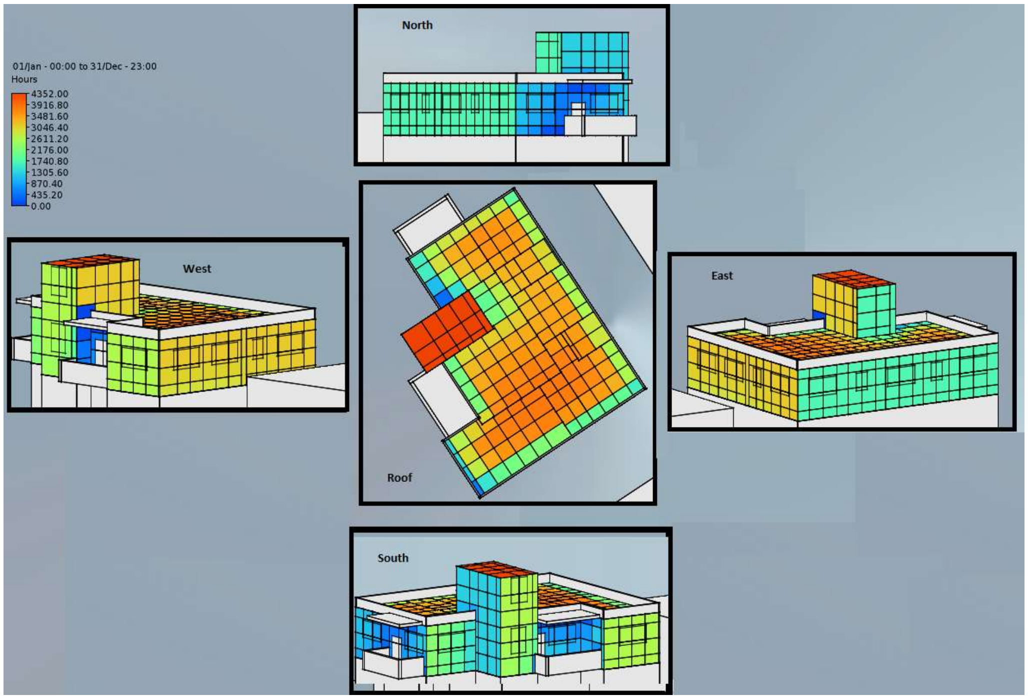


Figure 19: Sun cast simulation (hours)

The Sun cast tool in IES virtual environment was used to study and visualise the solar radiation heat gains in the base model. **Figure 19** shows the amount of energy obtained, annually, from solar radiation on the building's facades from the 1st of January to the 31st of December. This shows that solar gains reached about 1,972 $\mathrm{kWh/m^2}$ annually, in some parts. It also shows that the roof recorded the highest number of solar gains, followed by the south-east façade, with maximum gains of 1,972.5 $\mathrm{kWh/m^2}$ and 1,110.7 $\mathrm{kWh/m^2}$, respectively, while the north-west façade received the least amount of solar radiation energy (around 766.4 $\mathrm{kWh/m^2}$ maximum).

Figure 20 shows that the building experienced the highest average solar radiation heat gain in June, while the average daily heat gain was 8.25 $\mathrm{kWh/m^2}$, which is close to the figure reported in a previous study for another residential building in Jordan [66]. The study [66] reported that the maximum daily solar gain was 7.98 $\mathrm{kWh/m^2}$ in June, since June has the highest daily amount of solar radiation, annually. This heat gain is close to this study's simulation results obtained from IES-VE (8.25 $\mathrm{kWh/m^2}$) although there is some variation in the amounts reported. This difference in value could be attributed to the inclusion of the rooftop in the apartment envelope and the variation in the construction materials and thicknesses considered in this study as well as the surrounding building's shading .

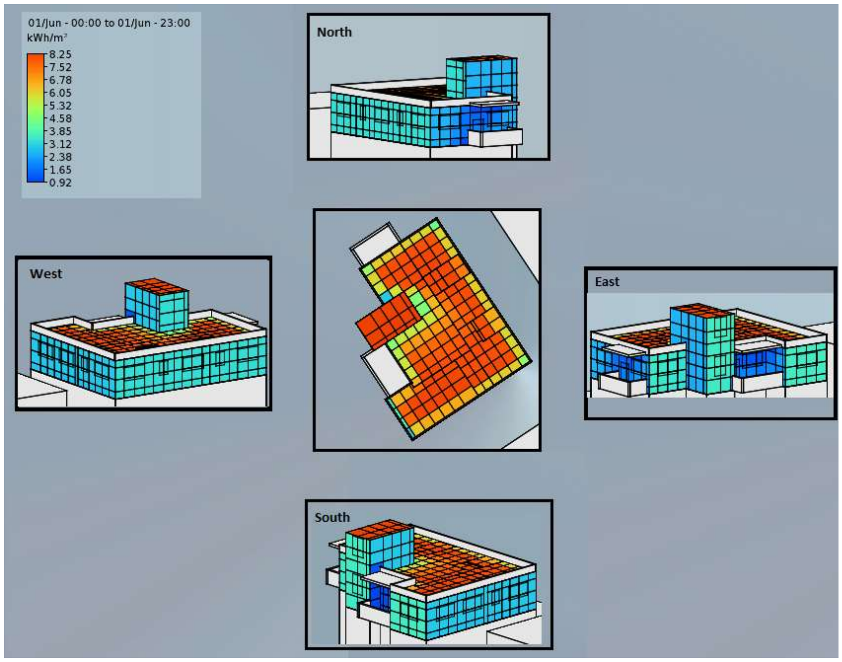


Figure 20: Sun cast simulation (kWh/m^2) in June

Consequently, as shown the previous investigations into solar heat gains, the roof tends to be the most vulnerable parameter in determining building heat accumulation and so this has to be adjusted in order to reduce the overall energy consumption. Looking at the conduction gains in the base model, there is another factor that also makes a significant contribution to the heat gains in a dwelling, the exposed windows. **Figure 21** shows the flow of the heat gains from the main building's components on a monthly basis throughout the year. The heat gains from windows seem to be the highest contributor to the building's loads, followed by the wall's conduction heat gains. This suggests that both the walls and the windows have to be adjusted in order to reduce the energy consumption of the base model to realise the ZEB concept.

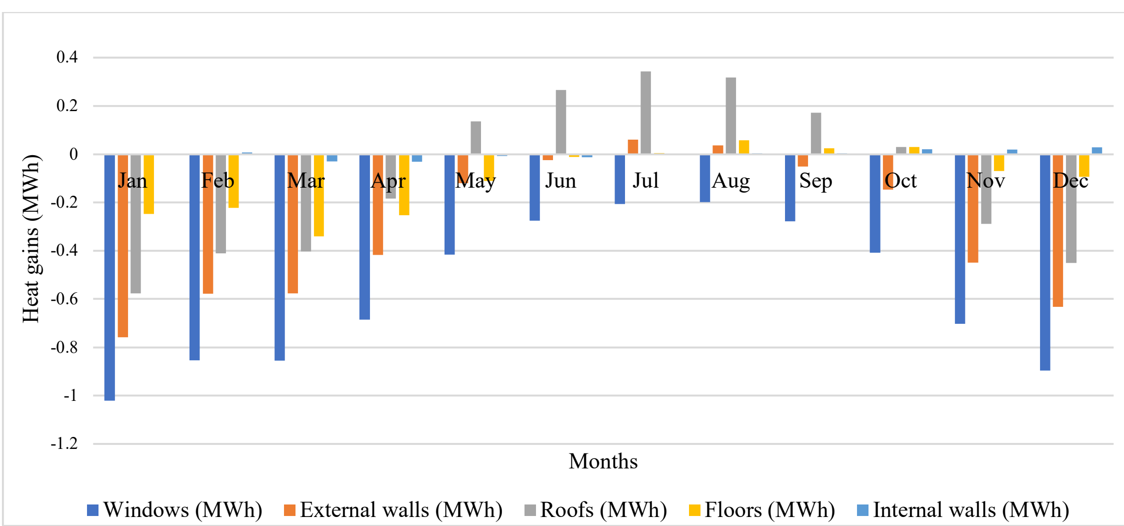
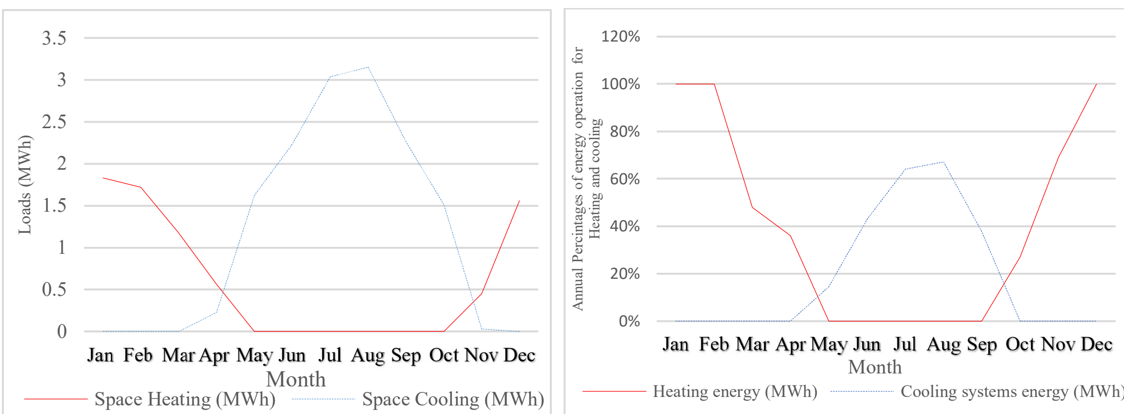


Figure 21: Annual conduction heat gains

iii. Energy loads and energy consumption

The first scenario was designed to reflect an existing middle-class apartment in Amman. It was built using ModelIT in IES visual environment and simulated using Apache sys in order to determine the building's loads. These loads are shown in **Figure 22 a)**, while **Figure 22 b)** shows the energy operation percentages reported in [59]**. Figure 22 a)** shows the amount of heating and cooling energy required inside the base model. It shows that the main period for heating consumption is between November and March, and that the maximum heating energy consumption occurs in January, at around 2.0 MWh. The main period for cooling energy consumption is from June to September, with a peak in August of around 3.0 MWh. The months of April, May, October and November are intermediate seasonal months. This profile has been validated against previous studies, as shown in **Figure 22 b),** which illustrates the trends in general heating and cooling systems operation in residential buildings in Jordan – based on questionnaire results regarding heating and cooling building operation [59] which showed that the cooling load was not fulfilled in the actual operation which show prospective hours of discomfort.



a) b)

Figure 22: a) Heating and cooling loads of the base model; and b) Annual percentages of energy operation for heating and cooling [59]

The energy consumption in a building can be divided up into several different categories. **Figure 23** shows these main categories and the amount of the energy consumed by each category per month. Heating, cooling and domestic hot water account for most of the building's energy consumption. Lighting, occupancy and electrical heat gains also contribute to the energy consumption of a dwelling, but they are only responsible for about a quarter of the total energy consumption, overall.

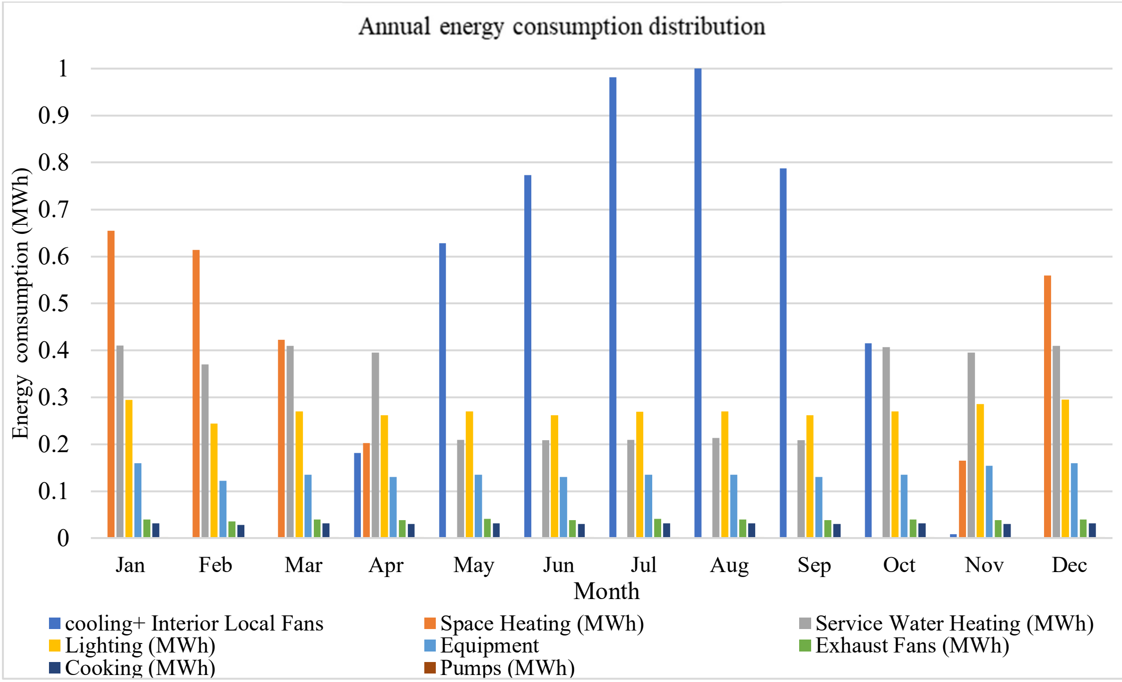


Figure 23: Annual energy consumption distribution- Base model

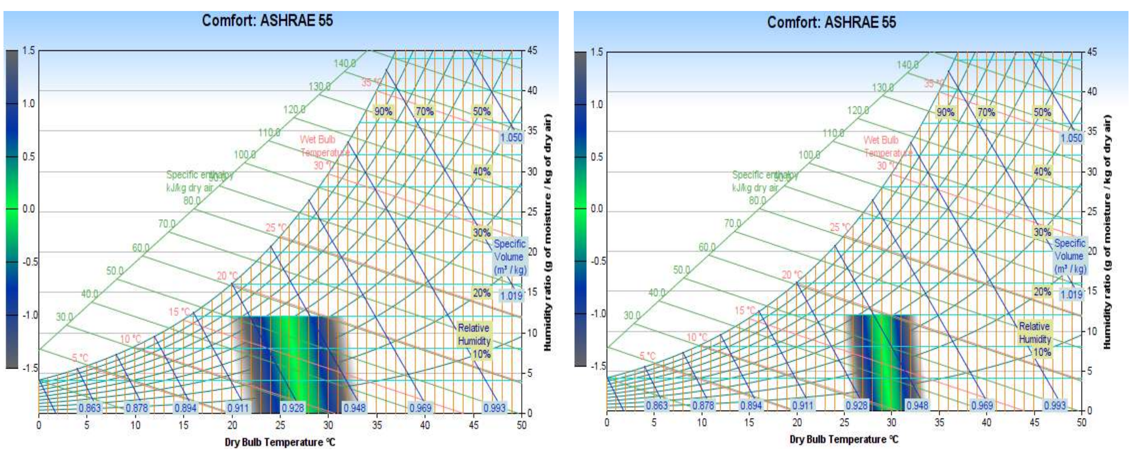
In our analysis of the base model, the heating and cooling, HVAC systems, and Domestic Hot Water (DHW) were the main contributors to the annual energy consumption of the building which is compatible with pervious publications such as [59, 62]. A 46% of the annual consumption used for HVAC systems operation. This is slightly less that some previous investigated case in [59] which calculated the HVAC system consumption to be 57% of the annual consumption. This variation might be justified by the differences between the building envelop characteristics (for both cases) especially because the base case, in this study, comprises of a level on insulation. The base model simulation also found that 21% for the annual consumption used for DHW. this is similarly, close to the finding from the instigation done by [62] which found that the average annual DHW consumption was 18% of the apartment energy consumption per year. This is followed by 18% of the annual consumption for lighting while other studies show variations on the energy consumed for lighting. In the following scenarios, various retrofits were studied and compared to quantify their effectiveness in improving the energy performance in order to reach nZEB.

iv. Thermal comfort

Thermal comfort in a building can be defined as attaining a comfortable environment for humans, inside a dwelling. This may be the main reason for applying any type of heating, ventilation and air conditioning systems to a dwelling. Thermal comfort depends on two main variables - the weather and human activities. These variables are described in more detail in subsection 3.2. According to

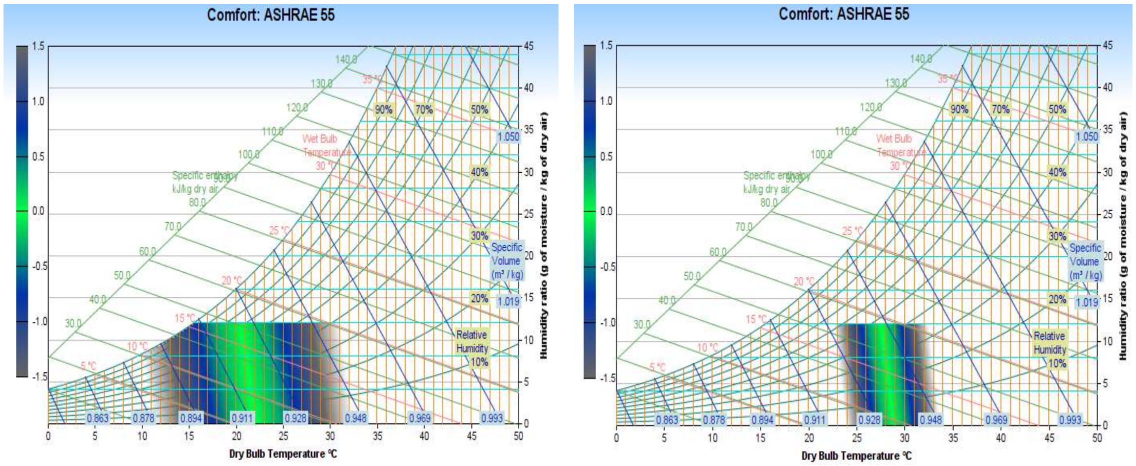
ASHRAE-55, thermal comfort can be defined by two main terms, Predicted mean vote (PMV) and the Predicted Percentage of human Dissatisfaction (PPD) as a function of PMV. This method was first proposed by Fanger and later standardised by ASHRAE and utilised by IES visual environment. Using this method, the base model was examined in terms of thermal comfort by implementing VisaPro in IES-VE. The base model selected was an apartment designed to reflect the type of apartments commonly found in Amman. The HVAC system in this apartment was built to reflect the type of system most commonly utilised in existing dwellings in Jordan – based on a questionnaire investigation conducted by study [59]. In the base model, a boiler was utilised to cover the domestic hot water load, while an air conditioning split units were utilised to meet the cooling and heating load. The hours of operation were assumed to be 5 hours on weekdays and 6 hours on weekends – as found in previous studies on Jordanian dwellings [59, 67].

After applying the mechanical systems to the base model in IES-VE, the relevant weather-related features were extracted from the weather file for Amman. The relevant human-related factors were the activity level and clothing level, since any variations in these parameters could affect the range of thermal comfort in each room of the base model. These variations are shown in **Figures 24** and **25** and depict the effect of clothing levels and activity levels, respectively, on the overall human thermal comfort levels in the model. The thermal comfort factors used in this study are shown in **Table 14**. These factors were assigned to the model in accordance with ASHRAE-55, along with an assumed air speed of 0.2 m/s, as recommended by the same standard.



a) b)

Figure 24: The impact of clothing level on the thermal comfort range: a) Clothing level 0.96 - Activity level 60; and b) Clothing level 0.96 - Activity level 60



a) b)

Figure 25: The impact of activity level on the thermal comfort range: a) Clothing level 0.61 - Activity level 50; and b) Clothing 0.61 - Activity level 100

Table 14: Thermal comfort factors

Space application	Activity level	Clothing level
Bedrooms	50	0.36
Kitchen	100	0.61
Living Room	70	0.61
Guest Room	70	0.61

Regarding the implementation of the thermal factor values in each room in the model in IES-VE, **Figure 26** shows the predicted mean vote values for each room, at their stated hours of occupancy. **Figure 26** was based on a one-year operation of the HVAC system assigned to the apartment and the operation hours were obtained from the occupation schedules assigned to the model, as described earlier. As shown in **Figure 26**, the living room and guest room operated between 0.5 and -0.5, which is an acceptable mean vote value (with a tolerance of 10%) for the Predicted Percentage of Dissatisfied (PPD), followed by bedrooms 1 & 2, while the master bedroom remained outside the acceptable comfort zone for almost 56.2% of its operation hours. Furthermore, the kitchen operated outside the acceptable thermal comfort zone values for nearly 83.4% of its occupied hours.

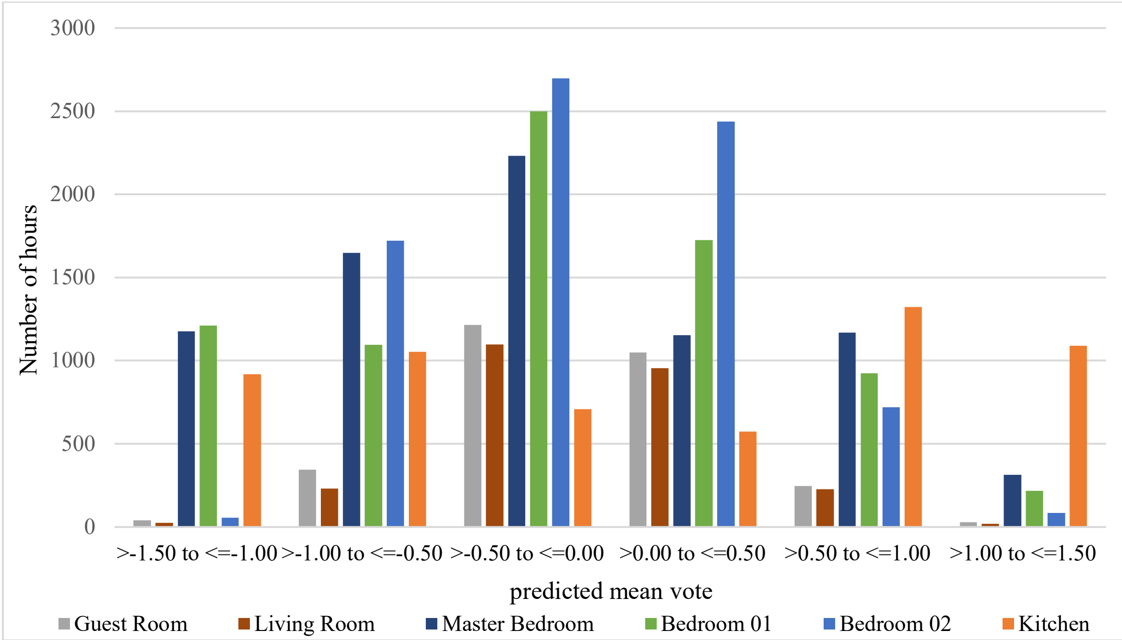


Figure 26: Hourly predicted mean vote values for the Base model

In summary, the investigation of thermal comfort in this section was based on the number of occupation hours assigned for each room throughout the year. The results showed that the implementation of the Apache system that was described earlier succeeded in achieving acceptable levels of thermal comfort for the living room and the guest room for 77.5% and 80% of their operation hours, respectively, and was also able to achieve thermal comfortability for bedrooms 1 & 2 for 54.7% and 66.5% of their operation hours, respectively, while the master bedroom achieved thermal comfortability for 43.8% of its operation hours. In contrast, the kitchen was only able to achieve 16.6% thermal comfort during the hours of its operation. In the following scenarios, thermal comfort was investigated further by studying the effect of each retrofit on the number of thermal comfort hours.

4.2 Scenario 2: Adjusting the factors that affect energy consumption in buildings

This scenario studied three main retrofit strategies, namely, thermal insulation, shading and occupant behaviour in relation to their impact on the building's energy consumption and thermal comfort.

4.2.1 Building envelope adjustment

i. Thermal insulation (roof and wall)

Thermal insulation improvement requires incremental increase in the building components' thermal insulation thickness. This leads to a reduction in the heat gains and rejections to/from the building and is one of the most obvious solutions for improving a building's energy efficiency in order to accomplish the ZEB target. Additional thermal insulation can be added in two ways, either as interior insulation or as exterior insulation. One example of this is the use of stone facades, which was part of the base case scenario. The effect of adding interior wall insulation on building performance was also studied as a potential retrofit to reduce annual energy consumption. In this study, the simulation was run for three insulation materials combined with an additional cladding material - 15 mm gypsum board. It should be noted that the cladding material, itself, does not have any significant impact as additional wall insulation, as shown in **Figure 27** where the impact of changing the cladding material on the annual energy consumption can be seen to be negligible. However, gypsum board is a common building material utilised for insulation in Jordan.

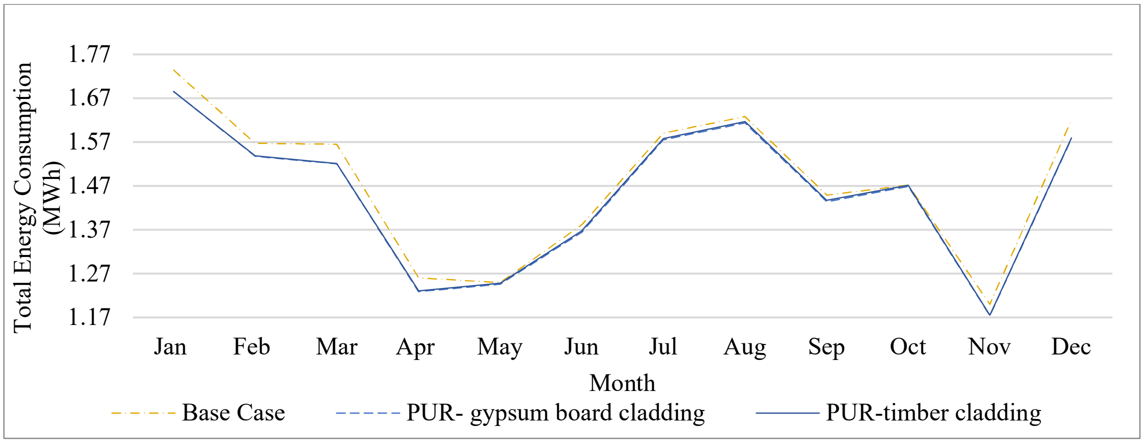


Figure 27: Effect of cladding on total energy consumption

This study investigated the effect of thermal insulation by considering three materials, namely, Extruded Polystyrene (EPS), Polyurethane Boards (PUR), and Rockwool (RW). These materials were compared in four different thicknesses (that is, 2.0cm, 3.0cm, 5.0cm, and 10.0cm) to establish their potential application as an additional wall insulation material for ZEB in Jordan. **Figure 28** shows the effect of these thermal insulation thickness and materials on the heat gain from the walls. In **Figure 28**, all the materials follow the same general base model curve throughout the year, despite a notable reduction in the wall heat gain with increasing thickness. However, each material had a different impact on heat gain, overall. As shown in **Figure 28,** Rockwool has the least efficiency with respect to the other materials. An additional 10cm of RW and 5 cm of PUR had almost the same impact on the annual wall heat gain, that is, 1.4 MWh for RW10 and 1.6 MWh for PUR05. Thus, PUR had the largest impact on the reduction in heat gained from the walls at all thicknesses, that is, 33.9%, 43.1%, 55.5%, and 71.12% for PUR02, PUR03, PUR05, and PUR10, respectively.

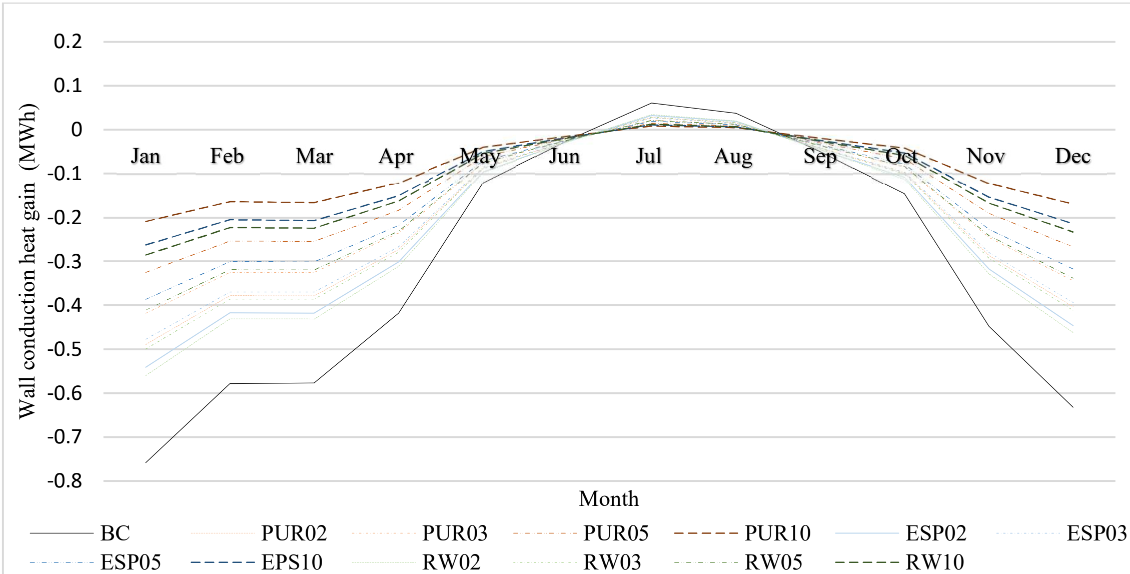


Figure 28: Annual wall heat gains for different thermal insulation materials

It was also noted that the additional wall insulation had the highest impact during the winter season, regardless of the material used and the thickness of the additional insulation. **Figure 29** shows the effect of the additional insulation on annual energy consumption, with all simulation runs producing the same general pattern but with a slight difference in the annual energy consumption, especially in the first-third of the year. Overall, additional thermal insulation implementation resulted in a reduction in heating energy consumption ranging from 4.9% to 12%, depending on the material and the thermal thickness used, as shown in **Table 15.** However, the additional insulation had no significant impact on cooling energy consumption.

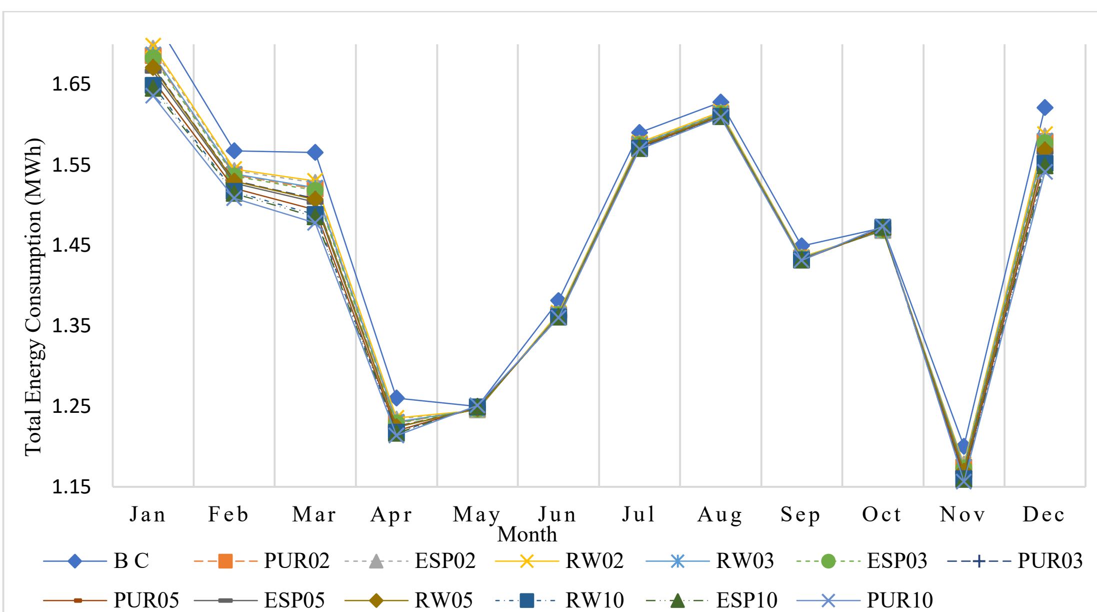


Figure 29: Annual energy consumption for different thermal insulation materials

Table 15: The effect of thermal insulation on heating and cooling energy reduction

Insulation material	Thickness (cm)	Heating energy reduction (%)	Cooling energy reduction (%)
PUR	2	6.4	1.4
	3	7.8	1.4
	5	9.7	1.4
	10	12.0	1.3
ESP	2	5.3	1.3
	3	6.6	1.4
	5	8.4	1.4
	10	10.9	1.3
RW	2	4.9	1.3
	3	6.1	1.4
	5	8.0	1.4
	10	10.5	1.4

Overall, PUR has the highest impact on the energy consumption of the building, followed by EPS and lastly RW. From **Figures 28** and **29**, the effect of the additional insulation is slightly small, that is, a reduction in the total annual energy consumption of 2.76% is recorded for 10 cm PUR and 1.65% is recorded for 2 cm as shown in **Figure 30**, which depicts the effect of the additional thermal insulation layers on the annual energy consumption. **Figure 30** also shows that the increment in the thermal insulation of the building that has been insulated has significant effect on the amount of energy reduction recorded, even though the thermal insulation thickness might have different values.

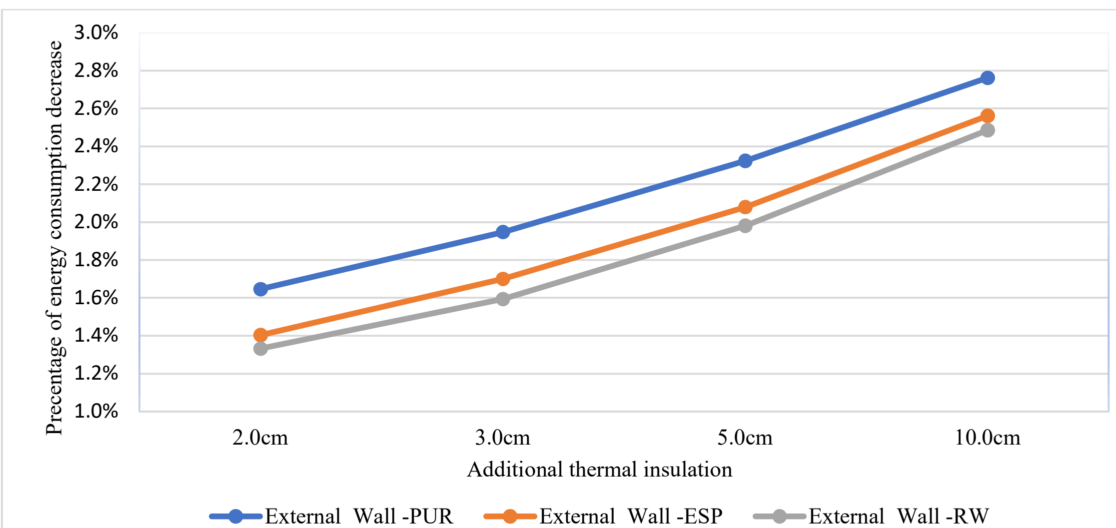


Figure 30: Percentage reduction in energy consumption with additional insulation thickness

Similarly, the effect of adding extra insulation to the roof was also studied in several different scenarios. **Figure 31** shows the effect of additional thermal insulation thickness and materials on the amount of heat gained from the roof. It should be noted from **Figure 31** that all the materials follow the same general base model curve, despite the somewhat different behaviour of the green roof which shows a slight shift in the heat gain over the first half of the year. Overall, any incremental increase in the insulation thickness led to a reduction in the heat gain from the roof, although it can be seen that each material had a slightly different impact. Overall, the green roof was the least efficient compared to the other materials, with only a 4.3% heat gain reduction. Rockwool reduced the heat gain by 25%, 33%, 45%, and 62% for RW02, RW03, RW05, and RW10, respectively, and Extruded Polystyrene (EPS) reduced the heat gain by 27%, 36%, 48%, and 65% for EPS 02, EPS 03, EPS 05, and EPS 10, respectively, while Polyurethane Boards (PUR) reduced the heat gain by 35%, 44%, 56%, and 72% for PUR02, PUR 03, PUR 05, and PUR10, respectively.

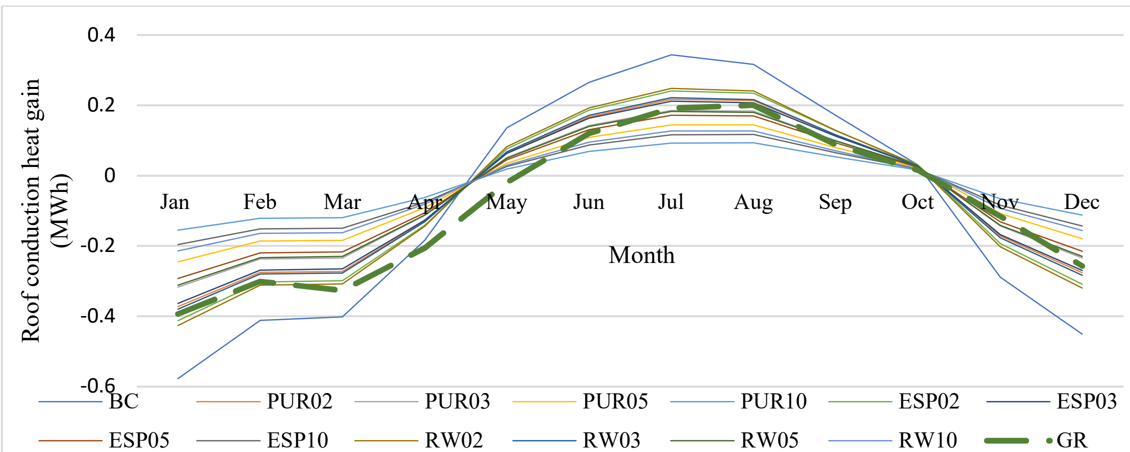


Figure 31: Annual roof heat gains for different thermal insulation materials

The heat gain reduction reflects the energy consumption as shown in **Figure 32** which depicts the differences in the energy consumption of the model resulting from an additional roof insulation.

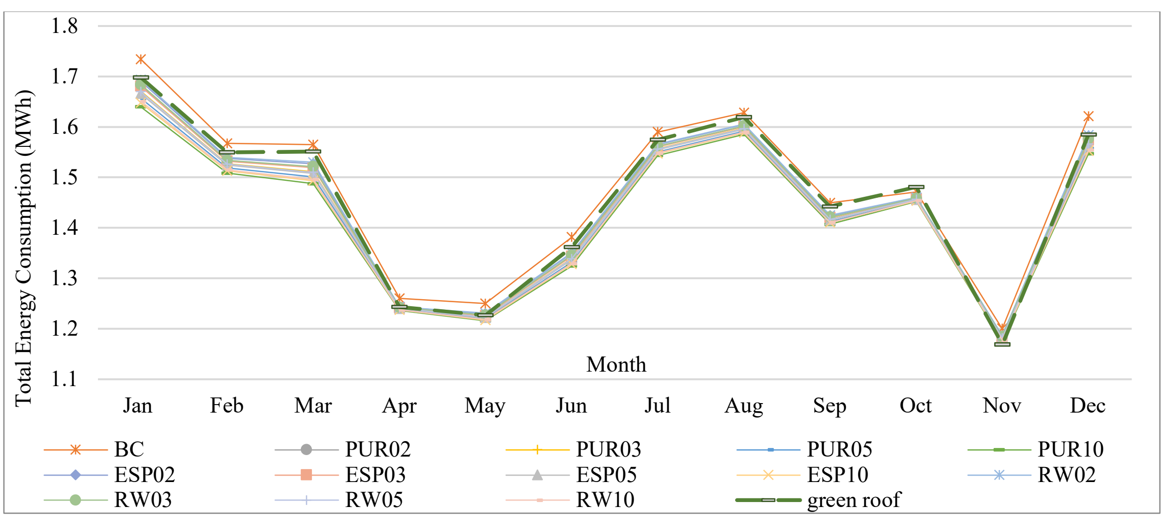


Figure 32: Annual energy consumption for different thermal insulation materials

Figure 32 shows building energy consumption in relation to the type of additional roof insulation used. It can be seen that there was a consistent pattern in energy consumption performance throughout all the simulation runs but with no significant effect on the annual energy consumption. Likewise, the thickness of the thermal insulation in the building did not always seem to have a notable effect on energy reduction, even though each type of thermal insulation produced slightly different results. Nevertheless, some reductions in the total annual energy consumption were recorded: 3.4% for 10 cm PUR and 2.1% for 2 cm PUR and 1.8%, 3.12%, 1.7%, and 3.03% for EPS 02, EPS 10, RW02, and RW10, respectively. An annual energy reduction of 1.23% was achieved by the adoption of the green roof. These energy consumption reductions are summarised in **Figure 33**.

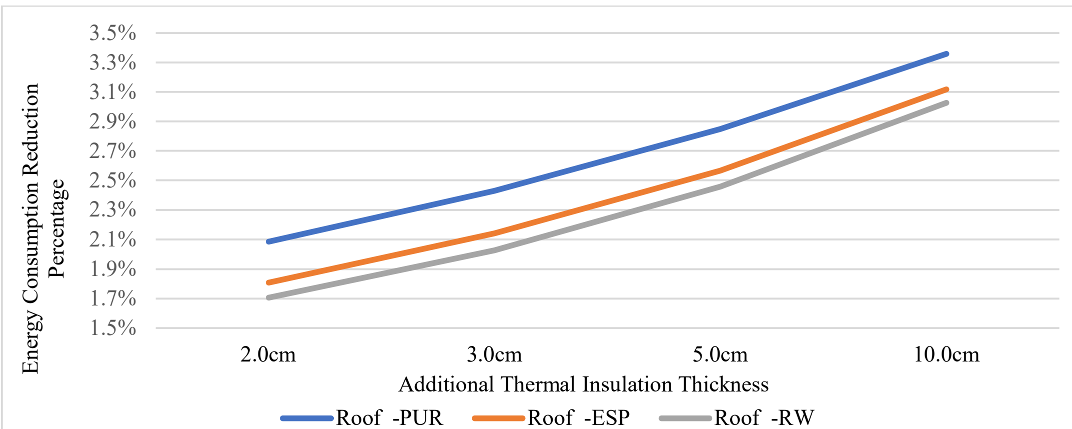


Figure 33: Percentage energy consumption reductions achieved with additional insulation thickness

Figure 33 shows the effect of the additional thermal insulation on the annual energy consumption. Overall, the additional roof thermal insulation resulted in a reduction in heating and cooling energy consumption ranging from 4.1% to 10.5% for heating and between 1.8% and 4.86% for cooling, depending on the material and the thermal thicknesses used, as shown in **Table 16.** The implementation of a 70% green roof did not have a significant impact on the cooling and heating energy consumption and recorded the least effect on heating and cooling energy consumption reduction at only 4.1% and 1.8%, respectively.

Table 16: Percentage heating and cooling energy reductions with roof thermal insulation

Insulation material	Thickness (cm)	Heating energy reduction (%)	Cooling energy reduction (%)
PUR	2	6.21	3.26
	3	7.37	3.69
	5	8.78	4.23
	10	10.50	4.86
ESP	2	5.31	2.89
	3	6.40	3.33
	5	7.85	3.86
	10	9.70	4.55
RW	2	5.00	2.73
	3	6.03	3.18
	5	7.49	3.72
	10	9.39	4.44
Green roof	70%	4.10	1.58

Despite the fact that the base model was not compliant with the local regulatory requirements for insulation, the addition of extra thermal insulation on a pre-insulated model did not have a significant effect on the building's energy consumption. However, it did result in a reduction in the total heat gain of the building.

ii. Glassing

The benchmark model shows that windows have the highest contribution to heat gains. In this section, the simulation targeted the effect of changing the window type on the building's energy consumption. Five different window types were examined in two scenarios. The first one involved changing the U-value by comparing the impact of group 01 (W01 and W02) and group 02 (W03, W04, W05) on the annual energy consumption and the benchmarked model. The second scenario involved changing the Solar Heat Gain Coefficient (SHGC) in each window type to investigate its impact - as in the case of the first scenario. The various window types and specifications are shown in **Table 17** and their effects on the base model are shown in **Figure 34**.

Table 17: Window types and specifications

Groups	Windows	U-value $W/m^2 \cdot ℃$	Solar heating gain coefficient
Base model	W 00	5.878	0.73
Group 01	W 01	2.16	0.54
	W 02	2.16	0.63
Group 02	W 03	1.36	0.40
	W 04	1.36	0.50
	W 05	1.36	0.54

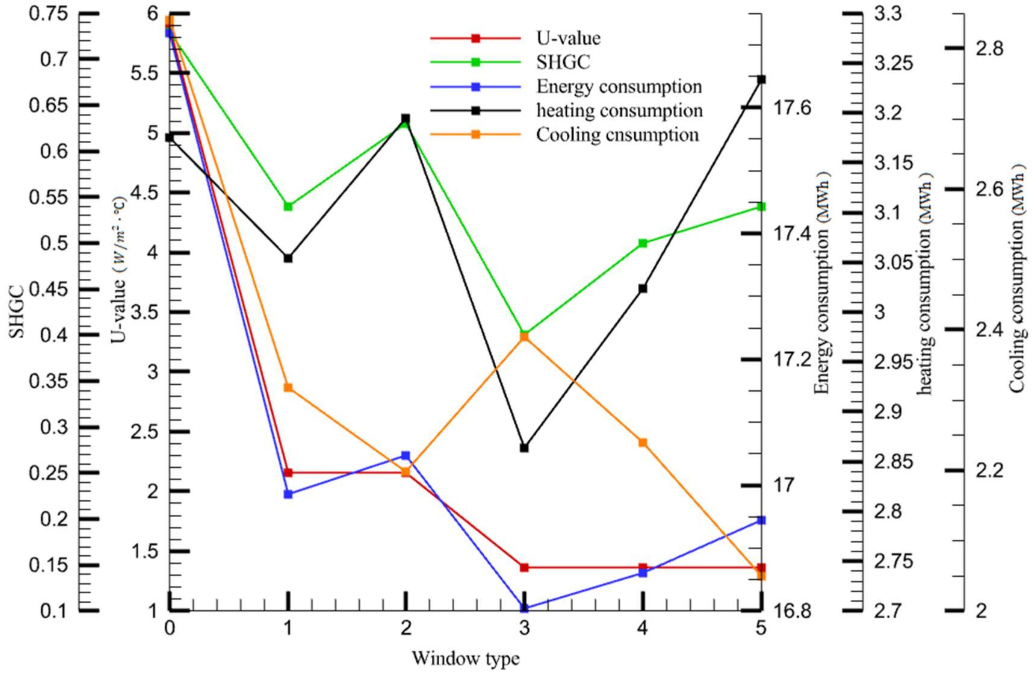


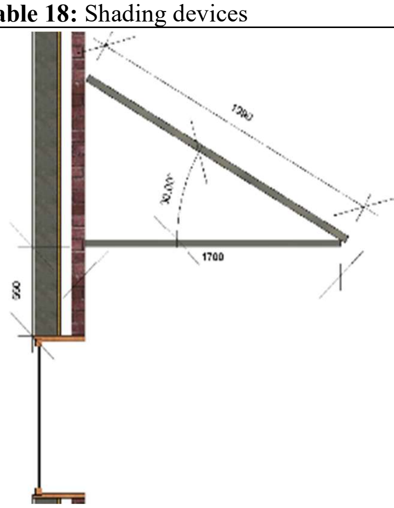
Figure 34: The effect of window type on heating, cooling, and the annual energy consumption of the model

Figure 34 shows the building behaviour when different window types were applied to the base model. **Figure 34** shows that, for all window types, the annual energy consumption was reduced compared to the energy consumption of the benchmark model. While W01 and W02 were double-glassed windows that had the same U-value (2.3 $W/m^2 \cdot °C$), each had a different effect on energy consumption. W01 reduced the heating and cooling energy consumption and resulted in a reduction in the overall annual energy consumption from 3.18 MWh, 2.84 MWh, and 17.7 MWh (for the base model) to 3.05 MWh, 2.31 MWh, and 16.8 MWh, respectively. W02 recorded a reduction in cooling and total annual consumption but produced a small increase in the heating energy consumption with values of 2.19 MWh, 3.2 MWh, and 17.04 MWh for cooling, heating, and total energy consumption, respectively. In group 02, the energy consumption increased with the increase in SHGC. For instance, window W05 resulted in the highest consumption of the group despite its cooling annual consumption which was the least of all. The lowest energy consumption was achieved by applying W03, with 0.4 SHGC and 1.36 $W/m^2 \cdot °C$.

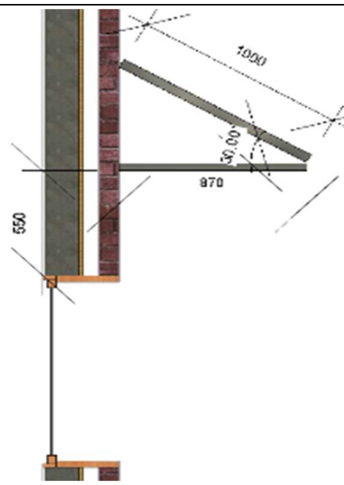
iii. Solar shading

The effect of solar radiation on a building's facades results in decreased heat gains for building components. Shading strategies are, therefore, one of the passive building techniques that can lead to both a heating and cooling load reduction by reducing the amount of direct radiation transferred to the facades. This section investigated the effect of adding overhanging shading around the building facades on its annual energy consumption. This was achieved by studying three lengths of overhang shading, that is, 0.65 m, 0.87 m, and 1.7 m. These lengths were selected based on the findings of study [60] that examined the shading efficiency of different window types by changing the height of a shading device with a length of 0.65 m. In study [60], shading with a height of 0.55 m was found to be the optimal solution that allowed for the highest amount of daylight in winter and the least solar radiation in summer. This result was for window dimensions of 1.96 m x 1.04 m, which is close to the base case. However, study [60] did not compare different shading lengths at that height. Study [62] found that any increase in the shading device's length would affect the building's energy consumption. The selection of 0.87 m and 1.7 m lengths was based on determination of the sine and cosine of the angle of 30° used for the solar panels which also provided a shading device for the building facades, as shown in **Table 18**.

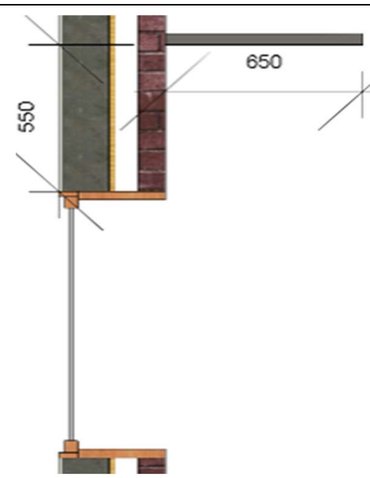
Table 18: Shading devices



1.7 m shading device



0.87 m shading device



0.65 m shading device

The additional shading restricted the amount of heat radiation reaching the building facades. **Figure 35** shows the effect of shading on the solar gains in the building. In general, all the shading scenarios resulted in a reduction in solar gains. However, the results differed with regard to the amount of reduction achieved. **Figure 35** shows that the solar gains were reduced as the length of the shading device was increased. For instance, 0.65 m shading produced the least reduction in solar gain whereas 1.7 m shading produced the maximum solar gain reduction. The annual solar gain for the base case was 15.54 MWh, while the solar gains for the three shading scenarios were 13.57 MWh, 12.5 MWh, and 10.18 MWh for 0.65 m, 0.87 m, and 1.7 m shading devices, respectively.

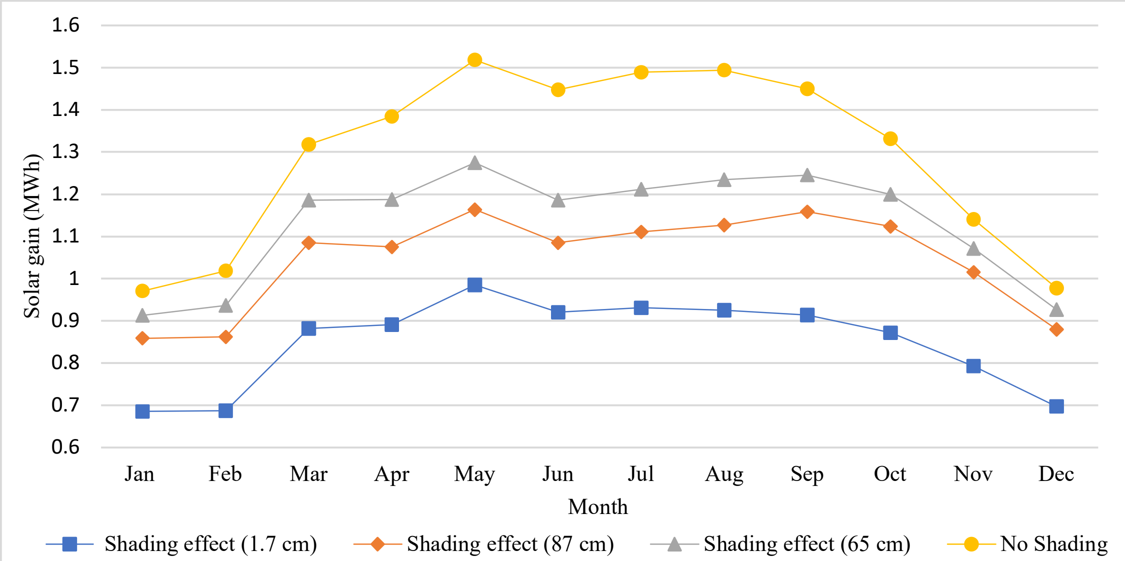


Figure 35: The effect of different shading scenarios on the solar gains in the model

The effects of shading devices on the apartment facade have similar implications for window heat gains. **Figure 36** shows the impact of shading on the heat gained by windows in the model. It shows that, in all scenarios, the heat gains were reduced as the length of the shading device was increased. With 0.65 m shading, the highest reduction was recorded in comparison to the base model for the months of September and October, and the lowest heat gain reduction was recorded for the first seven months of the year, particularly in July when an overall annual reduction in heat gain of 3.23% was achieved. With 0.87 m shading, there was even more reduction in the heat gain with an annual heat gain decrease of 6.5%. In this case, the lowest heat gain was achieved in the winter months from December to March, while the highest heat gain reduction was in the summer months, particularly July. Likewise, 1.7 m shading produced the highest heat gain reduction of 70.6% in summer and the lowest heat gain reduction of 8.2 % in January. Accordingly, 1.7 m shading resulted in the highest overall reduction in the heat gain at 15.4% annually, as shown in **Figure 36**. However, while shading could effectively reduce the amount of radiant heat transferred to the building, it also affected the amount of daylight entering the model, as shown in **Table 19**.

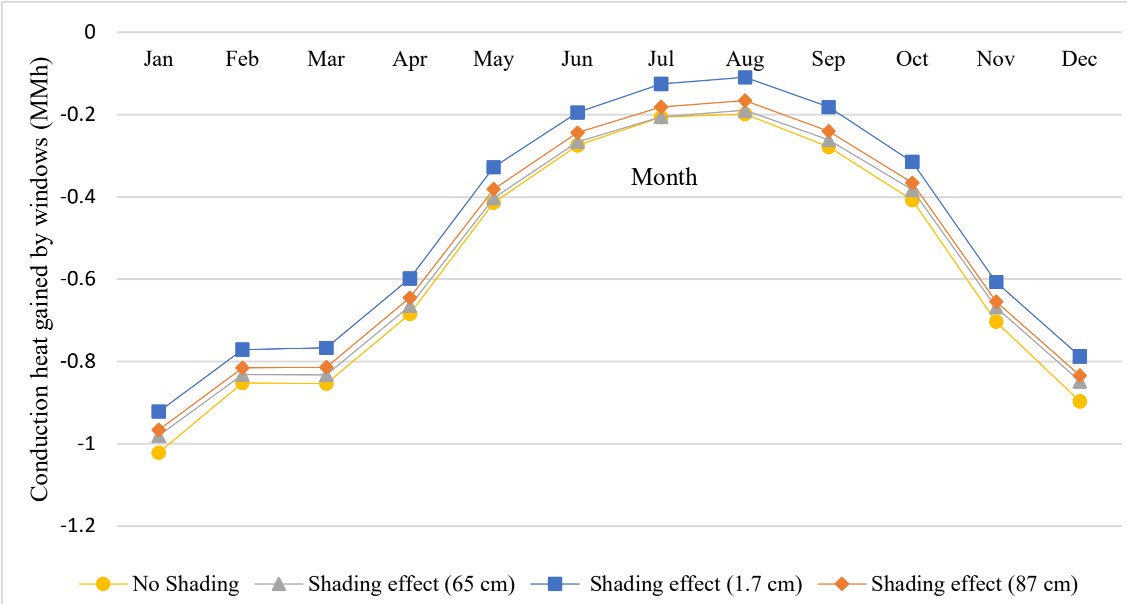


Figure 36: The effect of shading on window conduction heat gains

Table 19: Daylight factors used for the additional shading scenarios

<table>
<tr><th>Cases</th><th>Daylight factor (%)</th></tr>
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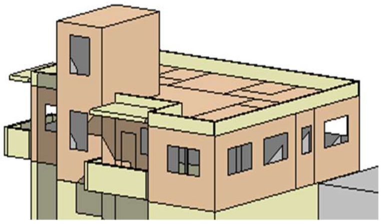
The benchmark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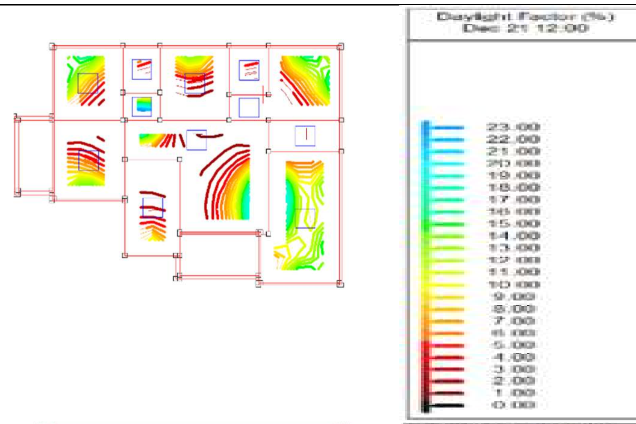

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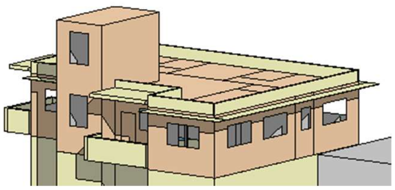
Overhang shading with a length of 0.65 m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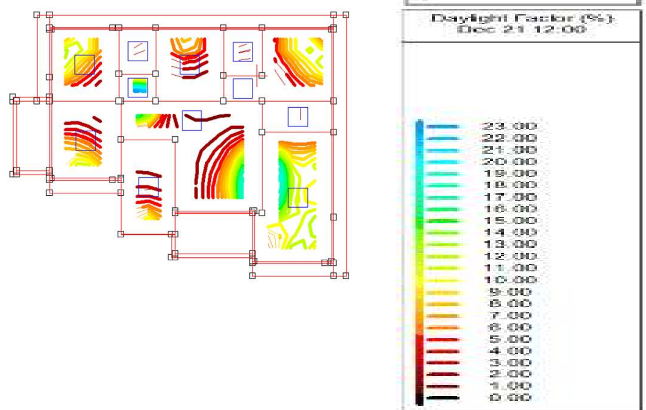

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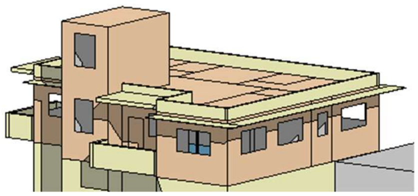
Overhang shading with a length of 0.87 m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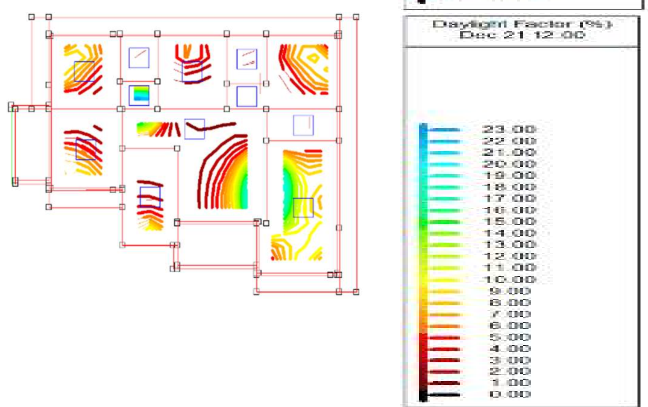

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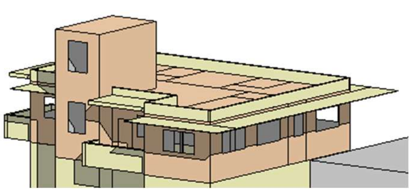
Overhang shading with a length of 1.7 m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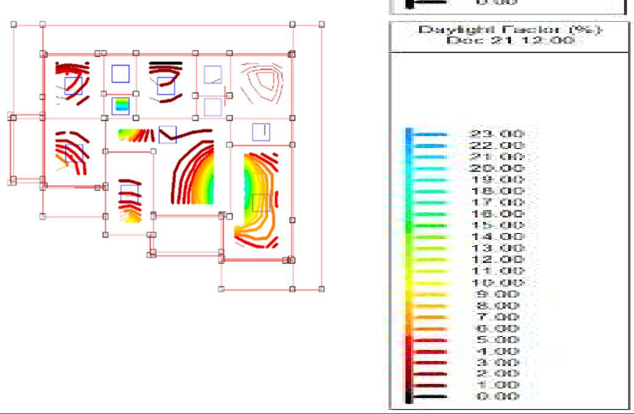

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The daylight factor is the ratio of the inside light level compared to the outside light level, expressed as a percentage [83]. In **Table 19**, the simulation results illustrate the effect of the shading devices used on the daylight factor inside the model. The daylight factor can be seen to diminish as the shading extensions increase.

In the shading studies, all the factors examined, namely, heat gain reduction, solar radiation gains, and daylight factors, resulted in a change in the energy consumption - the key factor in reaching the ZEB. In **Figure 37**, it can be seen that in all the shading scenarios, the energy consumption increased slightly in the first-third of the year before it began to flip and consume less energy than the base model, while in October the energy consumption started to increase again compared to the benchmark. **Figure 37** also shows that all the shading strategies examined resulted in a reduction in overall annual energy consumption in the model. The three shading options followed almost the same trajectory. It can be seen that the highest impact on annual energy consumption was in the mid-season months, with annual energy reductions of 0.57%, 0.69% and 0.89% for 0.65 m, 0.87 m, and 1.7 m shading devices, respectively.

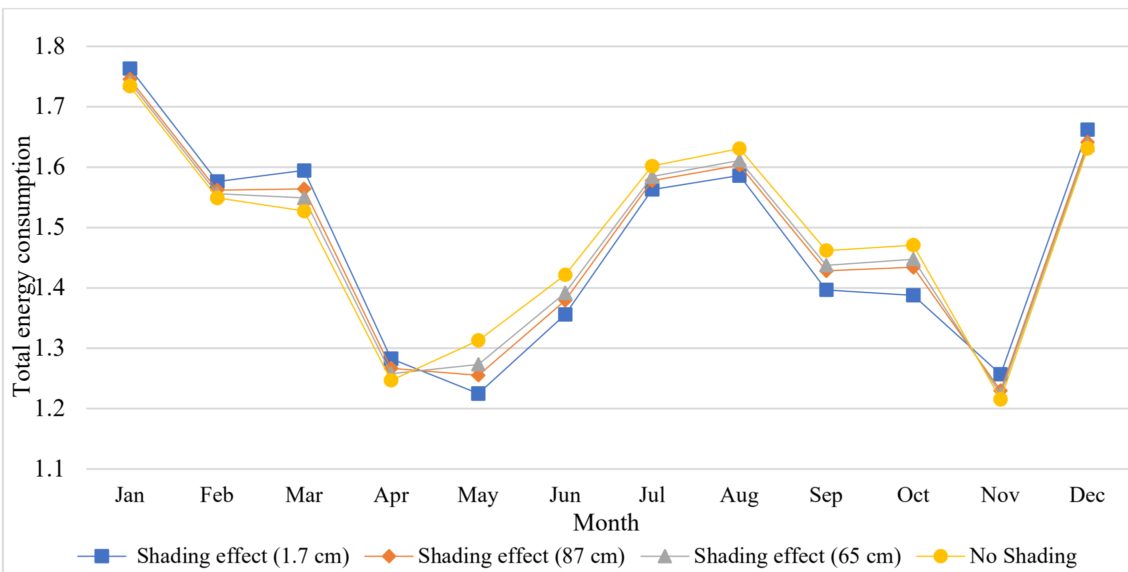


Figure 37: The effect of shading on the building's energy consumption

4.2.2 Building services system operation and maintenance

In residential buildings, different systems are utilised to achieve thermal comfort as well as to supply domestic hot water in the hot and cold seasons. These systems are an important part of the annual energy consumption in the building because they supply the heating load, cooling load, and domestic hot water. There are many different systems that can be used in the residential sector to meet these requirements. However, the most commonly used system involves split units, especially for cooling the building in the warm seasons, while in colder seasons there might be different types of heating facilities in use, such as boilers, electrical heaters and infrared heaters. However, in this study, the main system used was assumed to be a split unit system. This section studied the operation criteria of these split units – examining the effects of set-point temperature inside the house in order to find the best way of adjusting this system to achieve a comfortable nZEB.

i. HVAC systems: Operation temperatures

The temperature difference between the system's coil temperature and the required temperature in the occupied zones (set-point) is directly related to the heating and cooling load calculations and the total amount of annual load consumption. The set-point temperature is controlled by the system controller, although another factor to consider is the dead band that is defined as the range around the set-point at which the system is not required to respond. Thus, an investigation on the adjustment of the set-point temperature and the dead band (DB) was undertaken to determine their effect on annual energy consumption. Two set-points (SP) were examined (22.5 $°C$ for the whole year as well as 24.5 $°C$ for cooling and 19 $°C$ for heating) in order to study their effect on the heating and cooling load, in addition to the base case set-point temperature of 20 $°C$ in winter and 21$°C$ in summer with dead band (1). These set-points were selected in accordance with a study conducted on office buildings in different climate zones [84]. It was found that there is a significant relationship between the outdoor temperature and the set-point temperature, namely, the hotter the weather, the higher the acceptable set-point temperature. Study [84] found that 24.5 $°C$ was the optimal indoor set-point temperature for the climate zone of Amman (zone 3b). However, the reference set-point temperature used in that research study was 22.5 $°C$. Study [84] also used a constant set-point temperature throughout the yearand recommended that further study of the effect of implementing seasonal set-point temperatures should be undertaken. Therefore, in this section, the set-point selected was 19.0 $°C$ in the heating season and 24.5 $°C$ in the cooling season. **Figure 38** shows the impact of implementing different set-point temperatures on the heating and cooling loads. **Figure 38** shows that the implementation of 19.0 $°C$ in the heating season and 24.5 $°C$ in the cooling season could result in a reduction in heating energy consumption from 7.6 MWh to 6.6 MWh per year, as well as a decrease in the annual cooling energy consumption from 13.2 MWh to 8.14 MWh and an overall reduction of 1.6 MWh in the apartment's annual energy consumption. Similarly, study [85] adopted design conditions of 24.4 $°C$ in summer and 21.1$°C$ in winter.

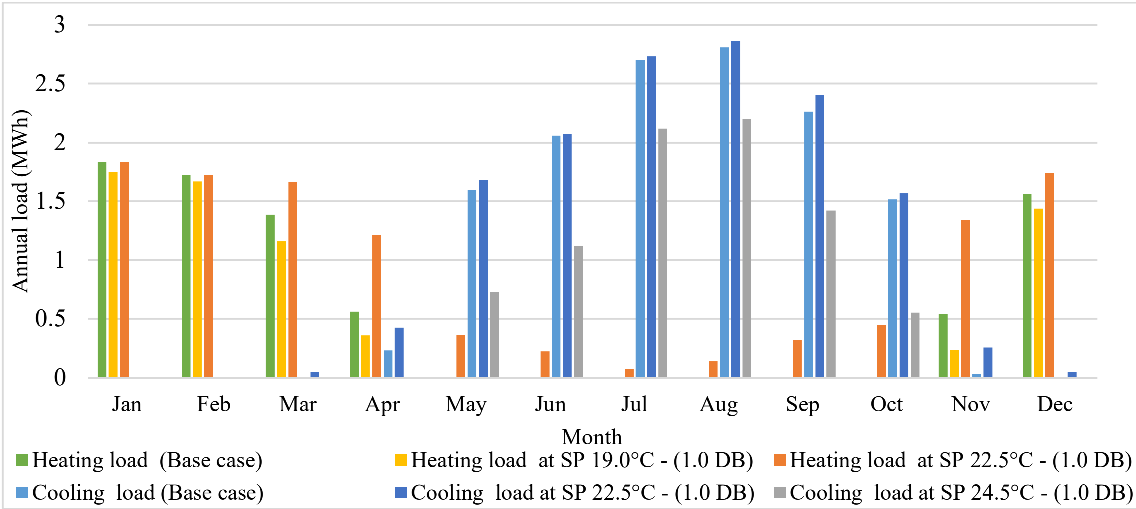


Figure 38: The Set-point temperature effect on the heating and cooling load

The effect of implementing different dead band ranges (DB) was studied by comparing 3 different values (2, 4, 6) in addition to the main case which was 1 (+0.5, -0.5) for a constant set-point temperature. **Figure 39** shows the impact of setting the controller at different dead band ranges. There was a direct relationship between the heating and cooling energy consumption and variation in the dead band range. Thus, 6.0 [DB] (+3$°C$, -3$°C$) resulted in the highest energy reduction annually with 1.90 MWh cooling energy reduction and 1.6 MWh heating energy reduction, as well as a reduction in the annual energy consumption from 17.7 MWh to 16.8 MWh.

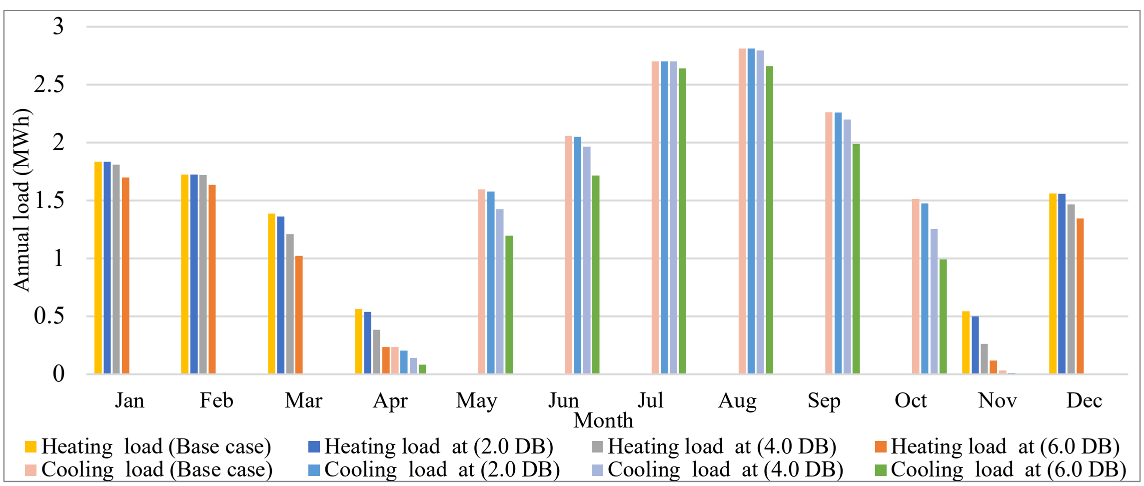


Figure 39: The dead band effect on the heating and cooling load

Therefore, one of the potential procedures that can be used to reduce energy consumption that leads to the nZEB is to increase the set-point temperatures in summer and reduce them in winter. Without any additional expenses, adjusting the set-point temperatures in summer and winter led to a reduction of 5.3% in the annual energy consumption.

ii. Lighting

Lighting is one of the fundamental systems required to operate on a daily basis. Unlike the commercial buildings, lighting is required at night times in the residential buildings since it is the highest occupation time in the dwelling. Thus, the energy consumption due to lighting cannot be totally eliminated, it can be reduced by utilising highly efficient lighting sources such as Light Emitting Diodes (LED). LED lighting uses a solid-state semiconductor device that transforms electrical energy into light. As well as being easily dimmable, LED lighting has a variety of other advantages over conventional incandescent lamps, including, among other things, a longer lifespan, reduced energy consumption, a wide range of colours, durability, design versatility, the ability to use a low-voltage power supply, and environmental compatibility [86]. In order to help reduce the internal load in buildings, this sub-section investigated the effect of replacing conventional lighting with LED lighting on the annual energy consumption.

LED lighting was implemented in the base model in IES-VE to study its effects on the annual energy consumption in the building. **Figure 40** shows that LED lighting had a significant impact on the annual energy consumption. Utilisation of LED lighting resulted in a 15% reduction in annual energy consumption in the base model, as shown in **Figure 40**.

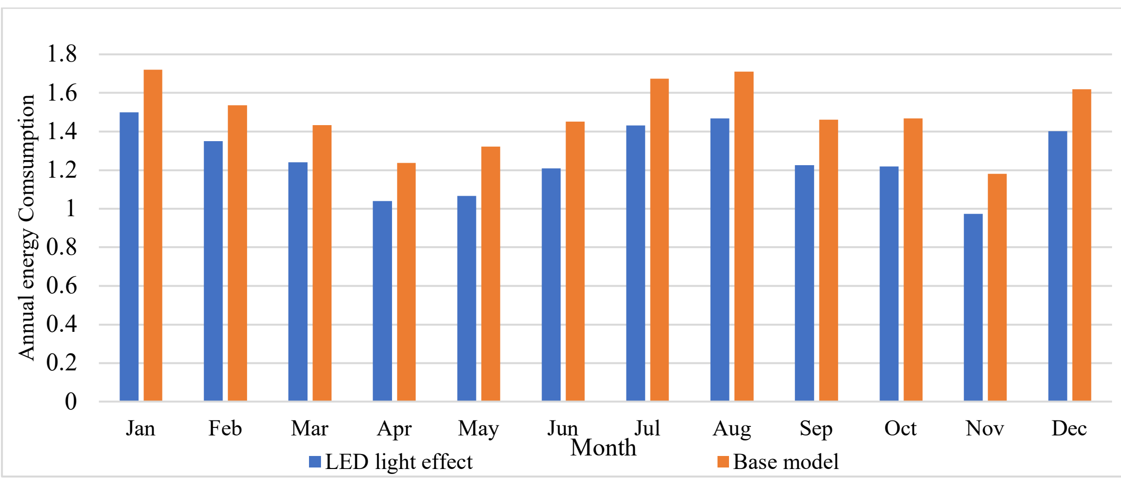


Figure 40: The effect of LED lighting implementation

The implementation of LED lighting in a conventional building led to a reduction of 77% in the annual amount of energy consumed by lighting. Furthermore, the annual energy consumption was reduced from 17.8 MWh to 15.3 MWh. Some previous studies have highlighted the effect of LED lighting utilisation on the annual energy consumption of a building. Study [62] stated that the annual energy consumption could be reduced by 4.5%. In study [62], the lighting intensity was assumed to be constant throughout the building at 6.0 W/m^2. However, in the current study the lighting intensity settings were based on ASHRAE standards. Therefore, these variations could explain the difference between the results of the current study compared to those reported in study [62]. Overall, both studies show a notable effect of LED lighting on the annual energy consumption.

4.2.3 Occupancy effect

Occupancy behaviour is one of the factors that contribute to the energy consumption in buildings by controlling the system's operation in the building [19, 87, 88]. Unlike commercial buildings, residential homes do not have any consistent operation schedules. Thus, this sub-section studied the impact of the occupants' varying behaviour on house operation by implementing three main scenarios: "base case", "austerity", and "wasteful". These cases were derived from previous studies conducted by Hong et al on three office building operations [85, 89, 90]. In addition, these same categories, that is, austerity, base case, and wasteful, were also developed by study [19] specifically for use with residential buildings. Thus, with some adjustments, these categories were also implemented in the current study. These categories were used to represent different energy operation conditions in order to identify the effect of occupancy behaviour and help determine the necessary conditions for achieving nZEB status in the climate of Jordan.

The austerity scenario was designed to represent a proactive approach to energy saving in buildings. In this category, the clothing level was assumed to be adequate for the weather conditions and the set-point temperature for cooling was increased while the heating set-point temperature was reduced. Similarly, austerity operation represents the minimization of all electrical application operation such as lighting, appliances and HVAC. The minimization of electrical application operation was achieved by reducing the hours of operation to 4 hours daily and adding dimming sensors to control the lighting operation in rooms. The domestic hot water usage level was reduced to half the recommended water usage rate for buildings in Jordan.

The base case represented a common type of scheduled occupancy operation with average levels of energy consumption. In contrast, the wasteful occupancy category represented a high level of energy consumption without any attempts at energy saving. In this category, the set-point temperature was assumed to be constant at $23°C$ throughout both the cooling and the heating season. The hot water consumption was doubled, and all lighting and electrical appliances were assumed to be always operating whenever the building was occupied.

Those three categories were adopted from previous studies conducted on office buildings. Thus, the HVAC operating conditions were assumed to be the same, due to the similarity between human activities in offices and residential buildings, while lighting levels and the operation of appliances were adjusted to fit the properties and characteristics of residential building operation. **Table 20** describes each of these categories in detail.

Table 20: Assumptions regarding occupant behavior

Reference	Baseline Model operation	Austerity operation	Wasteful operation
Cooling set-point temperature	Table 10	26°C	23°C
Heating set-point temperature	Table 10	18°C	23°C
Appliances	Table 13	4 hours operation from 6 to 10	Always on
Lighting	Table 13	Applying a dimming system during operation	Always on
Domestic Hot water	Section 4.1e	Consumption reduction by half	Consumption doubled

The standard heating and cooling temperatures, as well as hot water consumption, were implemented according to the Jordanian national codes. However, the implementation of hot water consumption alterations was based on the Residential Energy Consumption Survey (RECS) [91], due to the lack of data for actual hot water consumption in residential buildings in Jordan. A survey carried out by study [91] found that 15% of all users only consume half of the average recommended hot water amount, while 5% consume double the recommended amount, which was also the level adopted for residential buildings in study [19]. Thus, these values were also adopted in this study's simulation as the upper and lower limits for hot water consumption.

Lighting and appliances were assumed to operate for only 4 hours in the austerity scenario, reflecting the assumed occupancy time in the house, while in the wasteful scenario it was assumed that all lighting and appliances were always operational, since there was no consideration for energy saving.

The three scenarios of operation were implemented in the base model in IES-VE to assess the effect of each approach on the building's annual energy consumption. The results of these simulations are shown in **Figure 41**. There was a notable increase in the annual energy consumption during the wasteful scenario, while the austerity scenario recorded a reduction in energy consumption across all sectors. In this study, the building operation simulations all highlighted the importance of occupancy behaviour in residential building operation and illustrate how they might be the dominant factor affecting building performance. For instance, the results show that austerity operation could result in a 26% reduction in the annual energy consumption of the building. In contrast, the results also show that wasteful operation could lead to an increase in annual energy consumption of 44%.

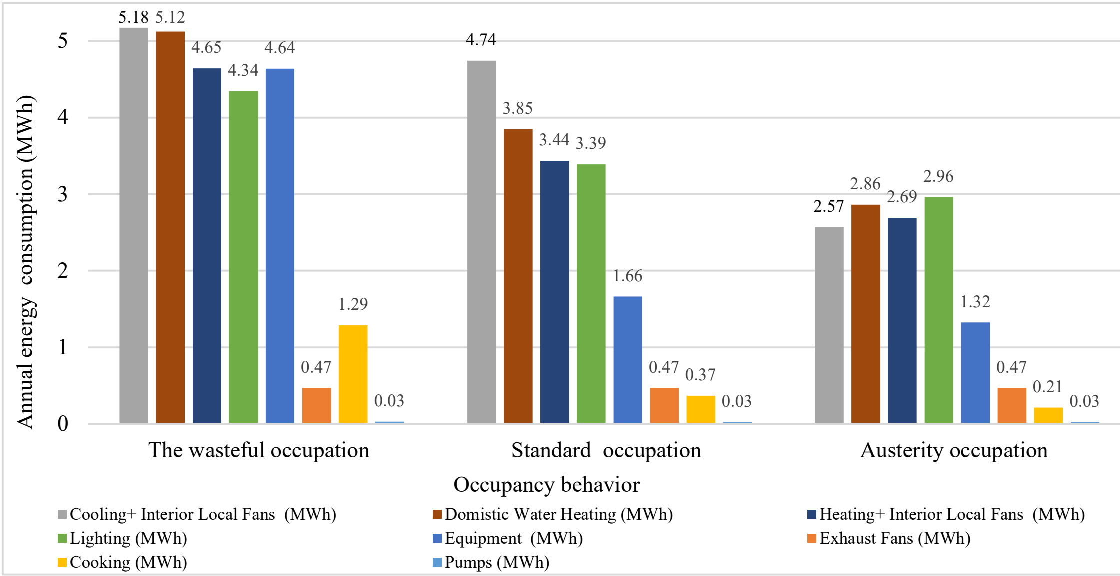


Figure 41: Occupancy effect on the building energy consumption

Notably, the effect of occupancy behaviour has been investigated in several previous studies such as [19, 85, 87, 88, 90], which all found that occupancy behaviour has a significant impact on the buiding's annual energy consumption. These studies, as well as the current study, suggest that controlling the occupancy behaviour could result in a notable reduction in the annual energy consumption of the buildings which ought to be implemented by house owners as one of the first steps in realising the ZEB concept. On the other hand, the sort of wasteful category operation described is not common in Jordanian domestic buildings. However, it does demonstrate how occupancy behaviour can have a huge impact on the annual building energy consumption.

4.2.4 Simulation and analysis

i. Energy consumption (annual consumption)

This scenario consisted of three main parts: building envelope adjustments, building system operation, and occupancy effects. The building envelope adjustment part considered three variables: thermal insulation for roof and windows, glassing, and solar shading were investigated. Building operation temperature, lighting, and occupation effects were also studied in the section on building services systems operation.

After analysing the effect of these variables on building energy consumption individually, different combinations of these variables were compared to find the highest possible energy conversion benefits for use as retrofits to reach nZEB standard. As explained earlier, incremental increases in the insulation thickness increased the energy reduction percentage. PUR was found to be the best-performing insulation material, as also reported in study [80]. Accordingly, adding 10 cm of insulation to the roof and the wall would be expected to lead to an 8.0% reduction in the annual energy consumption. Combining additional insulation with changes made to the wall type and adding improved shading could lead to even more reductions in energy consumption, as shown in **Table 21. Table 21** illustrates the effect of changing the window type and the shading length on annual energy reduction, after adding 10 cm PUR insulation to the walls and the roof of the building. This combination shows that a reduction in annual energy consumption of around 15% could be achieved by changing the type of window to W03 and adding 1.7 m of shading. However, this additional shading had the least impact on the annual energy consumption and could be excluded if the priority was simply to reduce annual energy consumption. Although the building would still be exposed to the same amount of solar radiation, it would also be affected by other buildings' shade. Despite its relatively low impact on overall energy consumption, shading is still significant in controlling the amount of daylight, however, which could also increase the natural lighting in a given space [57].

Table 21: The effect of building envelope variables on energy consumption

		Wall insulation					
		PUR10 - 3.40%					
Roof insulation	PUR10 – 4.70%	14.96%	14.76%	14.64%	5.57%	W01	Window Type
		14.61%	14.41%	14.28%	5.22%	W02	
		15.98%	15.77%	15.65%	6.59%	W03	
		15.66%	15.46%	15.34%	6.27%	W04	
		15.20%	14.99%	14.87%	5.80%	W05	
		14.96%	14.76%	14.64%			
		Shading (1.7 m)	Shading (87 cm)	Shading (65 cm)			
		Shading Type					

Another significant aspect in operating a building as nZEB is the building system's operation. In this subsection, the energy consumption was evaluated by changing the operation temperatures and the lighting fixtures.

As it was pointed out previously, the energy consumed for lighting operation was investigated and it was found that replacing the ordinary fluorescent lighting fixture with LED lights leads to 2.7 MWh energy reduction annually, as shown in **Figure 42**. Changing the existing lights to high-efficiency lighting would reduce the building energy consumption by 15% of the annual consumption, which agrees with the finding of study [66] regarding the amount of energy reduction. Surprisingly, this is the amount of energy reduced by implementing the building envelop retrofits strategies. The effect of lighting replacement has been also pointed out in previous studies about the building energy consumption and included this strategy of using high-performance lighting as one of the processes to cut on the lighting energy consumption [62, 66, 85, 92, 93].

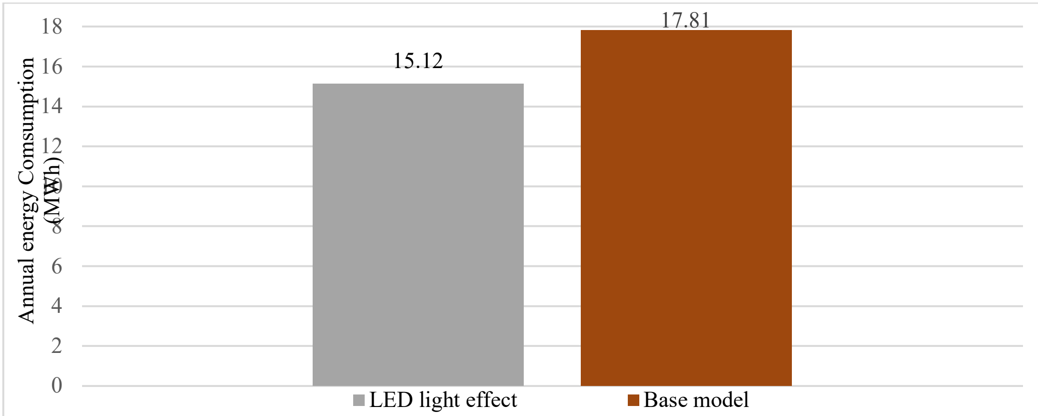


Figure 42: The effect of LED lighting implementation

Considering the set-point temperature and the Deadband effect on building energy consumption, **Figure 43** shows that simply changing the set-point temperature would impact the annual energy consumption. For instance, setting a constant set-point temperature for both seasons would increase the annual energy consumption of the building. In contrast, setting two set-point temperatures, one for heating and the other for cooling, leads to a reduction in the annual energy consumption of the space.

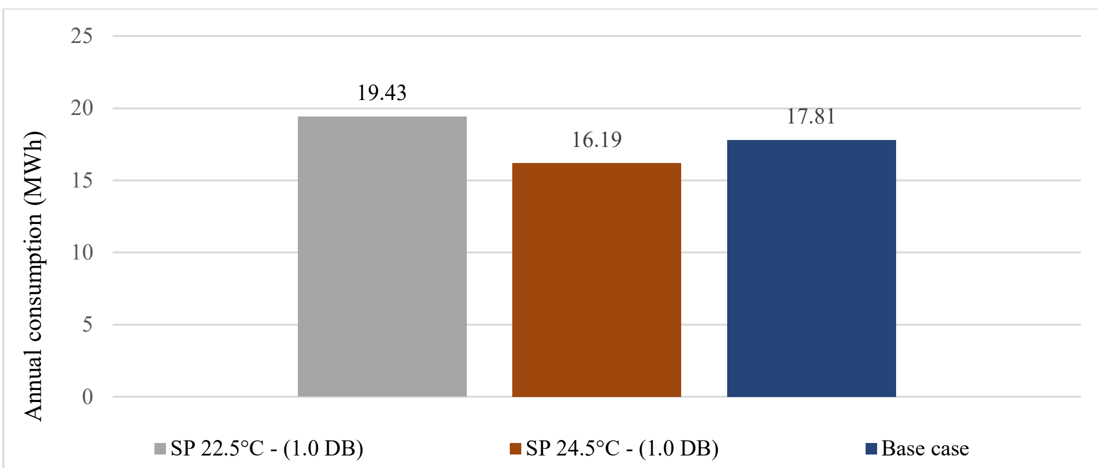


Figure 43: Set-point temperature effect on the annual energy consumption

As illustrated in **Figure 43**, operating the heating and the cooling system at 22.2 ºC would increase the energy consumption of the building by 1.61 MWh per year, while operating the HVAC system at 24.5 ºC in summer and 19.0 ºC in winter would reduce the annual consumption by 1.61 MWh. Consequently, operating the system at 24.5 ºC in summer and 19.0 ºC in winter tends to be the most efficient solution in terms of energy saving. This finding agrees with study [84] that investigated the relationship between set-point temperature and annual energy consumption in different climate zones and found that 24.5 ºC/19.0 ºC was the optimal operating temperature combination for the 3B climate zone.

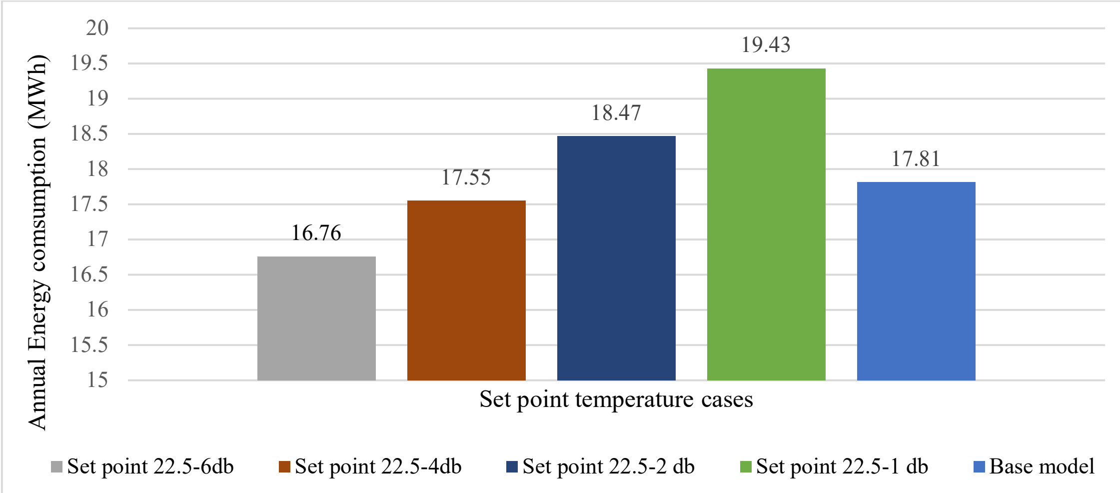


Figure 44: Deadband effect on the annual energy consumption

The Deadband effect was also studied to determine its ability to maintain a certain set-point temperature. **Figure 44** illustrates the variations in annual energy consumption achieved by changing the Deadband effect and found that setting the temperature at 22.5±3 ºC reduced the energy consumption by almost 1 MWh annually, whereas having the set-point temperature at 22.5±1 ºC increased the annual consumption by 1.63 MWh, which results from increasing the set-point temperature in winter by 2 ºC and 1.5 ºC in summer.

Considering the occupancy behavior investigation on the building's annual energy consumption, **Figure 45** presents the effect of the occupancy behavior on the energy consumed annually in relation to the assessed three behaviors. **Figure 45** reveals that under the wasteful behavior, the energy consumption almost doubled, while under the austerity behavior, the energy consumption reduced by 25% of the base model annual consumption.

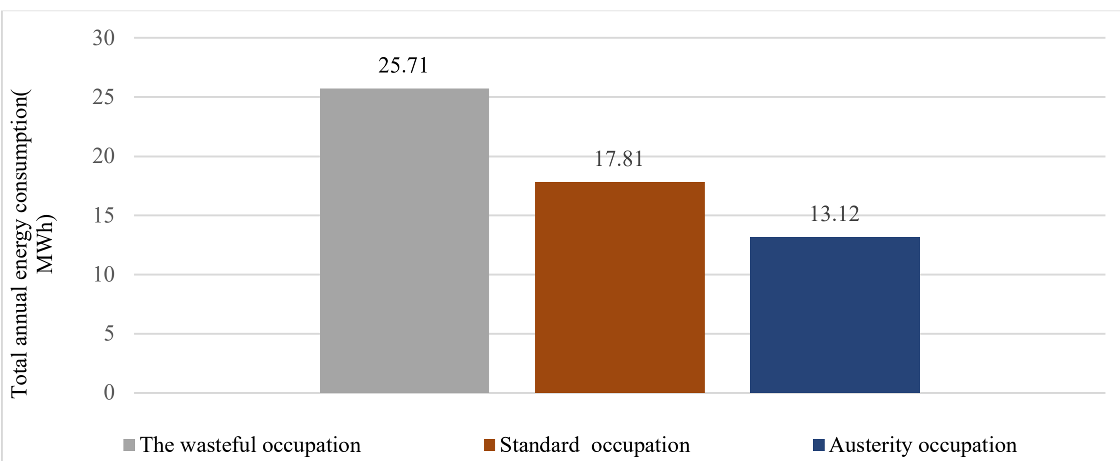


Figure 45: Deadband effect on the annual energy consumption

ii. ***Thermal comfort***

In the process of developing the building performance, several simulations were run to study the impact of different variables on the building's energy consumption in order to identify possible retrofits that would be most likely to reduce the energy consumption and lead to nZEB operation. In this section, these variables were compared in terms of their impact on thermal comfort in the building.

Figure 46 illustrates the percentage of the occupied hours that achieved acceptable PMV values (0.5 to -0.5) in relation to different wall insulation materials and thicknesses. There was a slight increase in the number of thermal comfort hours achieved with the increase in the insulation thickness for each material. However, **Figure 46** also shows that for all thicknesses and insulation materials this effect was barely noticeable. This means that for buildings that already have a certain level of insulation, increasing the insulation thickness further will not have a significant impact on the thermal comfort inside that space. However, the results also show that each room exhibits a different level of performance in relation to its orientation and its exposed wall percentage.

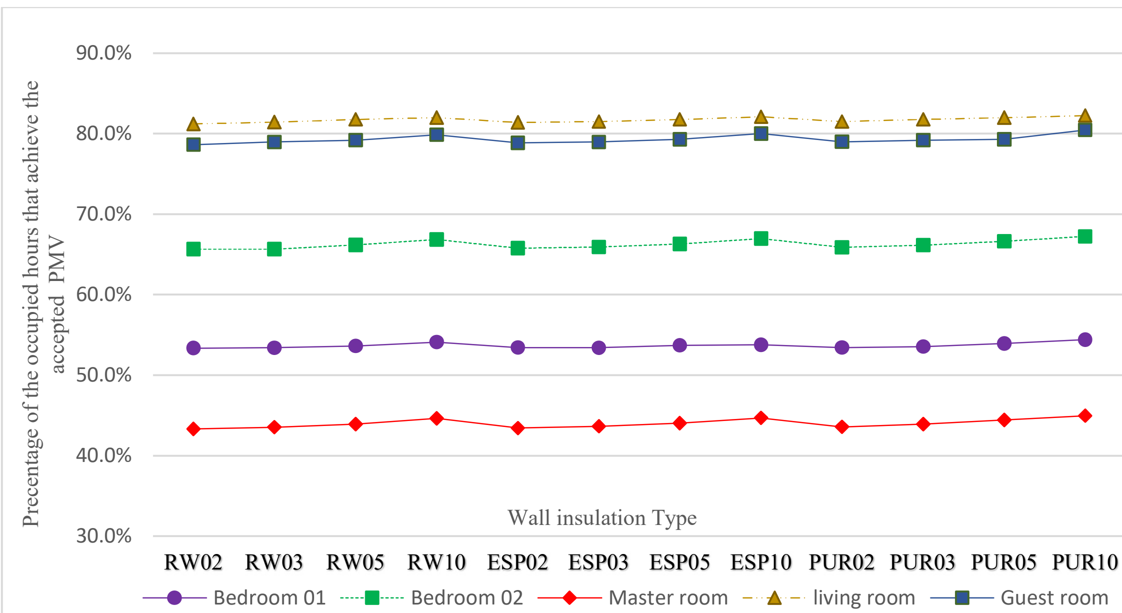


Figure 46: Wall insulation effect on the thermal comfort of different rooms

Figure 47 shows the percentage of the occupied hours that achieved acceptable PMV values (0.5 to -0.5) in relation to different roof insulation materials and thicknesses. As with the wall insulation results, there was a slight increase in the number of thermal comfort hours achieved with the increase in insulation thickness for each material. However, while the green roof had a slightly better effect than all the other roof types for the bedrooms (Bedroom01, Bedroom02, Master bedroom), the achieved thermal comfort hour increment was not major. Nevertheless, in the other rooms, the living room and the guest room, there was no noticeable recorded effect of green roof implementation since it was not applied on the top of their roofs. Thus, for buildings that have a certain level of insulation, the increase in the roof insulation thickness would not improve the thermal comfort except in the case of implementing a green roof where the thermal comfort would be improved in all spaces in the building performance in relation to thermal comfort.

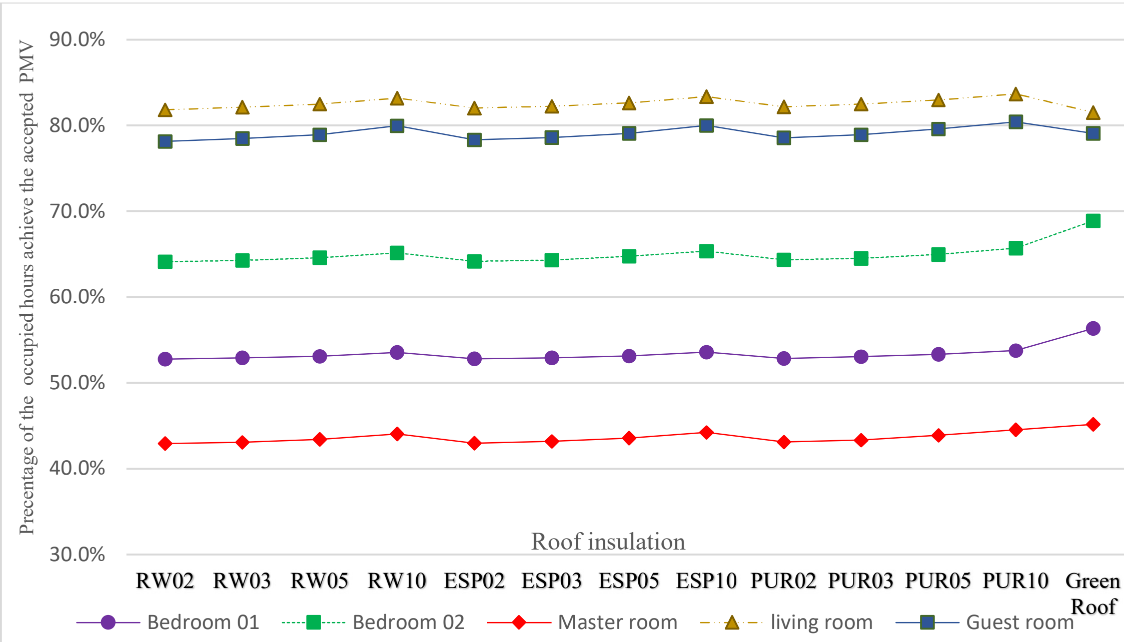


Figure 47: The effect of wall insulation on the thermal comfort in different rooms

Figure 48 shows the variation in thermal comfort in each of the spaces inside the building in relation to the type of window and plots the percentage of occupied hours that achieved acceptable PMV values (0.5 to -0.5). As shown in **Figure 48**, each room displayed a different response towards window alterations. In all spaces examined, window W02 was the worst-performing option in terms of thermal comfort hours. In contrast, all the rooms achieved the highest percentage of thermal comfort hours when window type W03 was utilised.

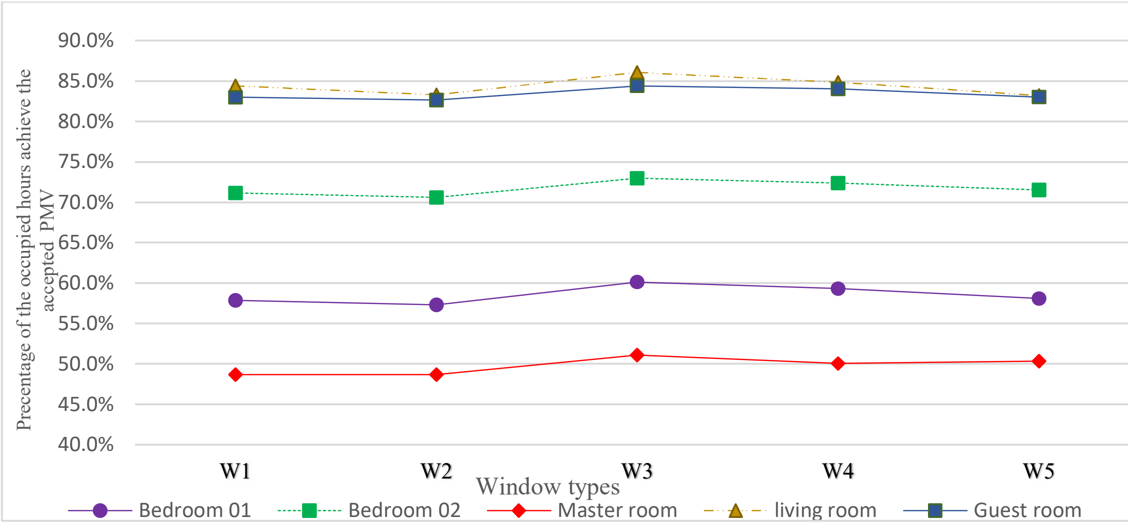


Figure 48: The effect of window type on thermal comfort in different rooms

Figure 49 shows the percentage of the occupied hours that achieved acceptable PMV values (0.5 to -0.5) for the three different shading lengths examined. As shown, there was no significant difference in thermal comfort in any of the spaces compared, regardless of the shading addition.

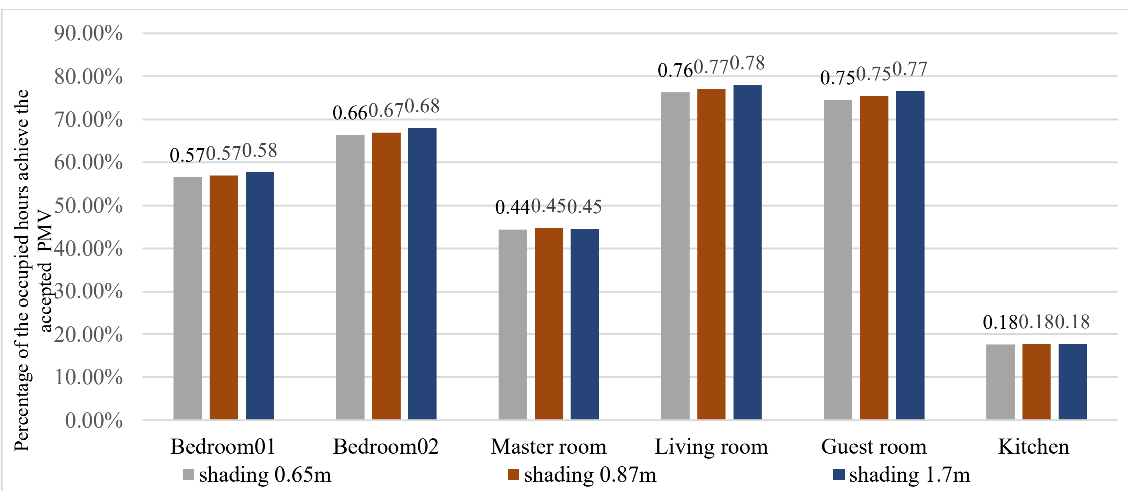


Figure 49: The effect of shading on thermal comfort in different rooms

The other significant aspect that was investigated in relation to building operation was the effect of set-point temperature and Deadband implementation on the annual energy consumption in each space. **Figure 50** shows different operation settings and the corresponding percentage of occupied hours that achieved acceptable PMV levels. A setting of 22.5±0.5 ºC achieved the highest level of thermal comfort among all the alternatives tested – a result which agrees with study [84] - while the Deadband had a negative impact on the number of thermal comfort hours. **Figure 50** shows that 22.5±3 °C was the set-point temperature that produced the least thermal comfort hours. Similarly, operating the HVAC system at temperatures of 24.5 °C in summer and 19.0 °C in winter failed to achieve a high percentage of occupied hours at acceptable PMV levels.

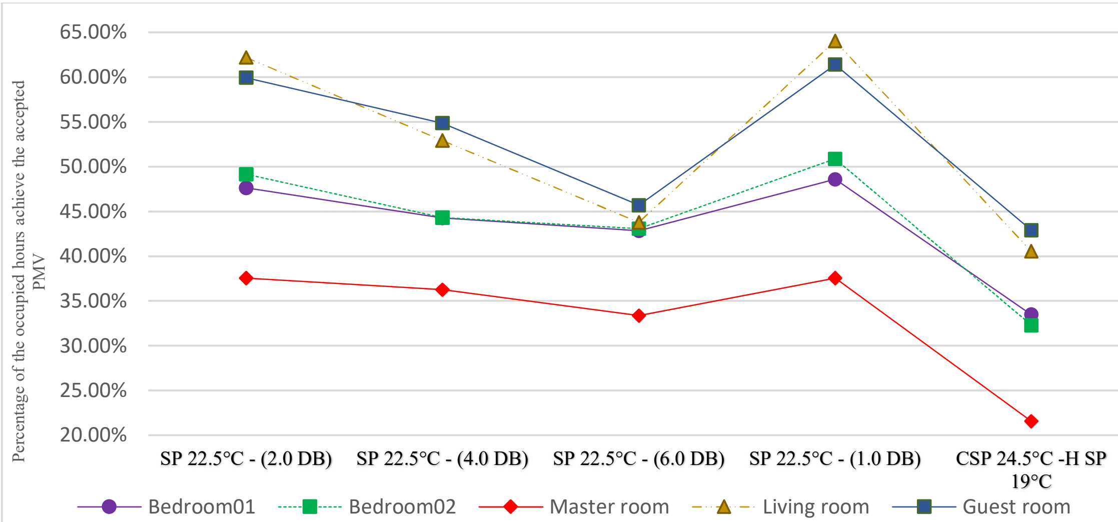


Figure 50: The effect of operation conditions on the thermal comfort in different rooms

Considering the impact of lighting fixture replacement on thermal comfort, **Figure 51** shows the percentage of occupied hours that achieved acceptable PMV values (0.5 to -0.5) after replacing ordinary fluorescent lamps with LED lighting. **Figure 51** shows that there was no significant difference in thermal comfort in any of the spaces examined, regardless of whether the lights were replaced with LEDs or not. Similarly, none of the previously published papers reviewed showed any direct relationship between lighting adjustments and thermal comfort improvement.

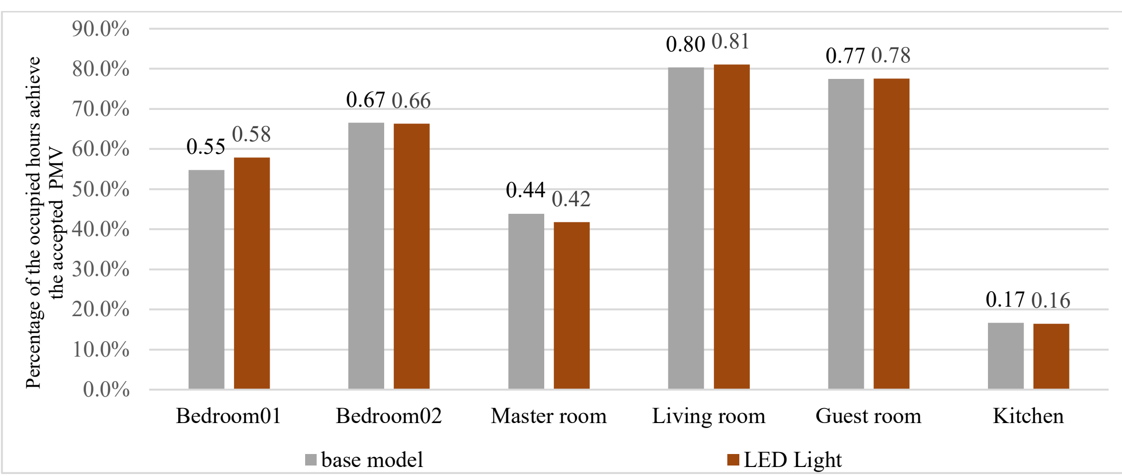


Figure 51: The effect of lighting replacement on thermal comfort in different rooms

Figure 52 shows the occupancy behaviour effect on the spaces' thermal comfort. **Figure 52** shows that both occupancy behaviours, wasteful and austerity behaviours failed to increase the hours that achieved the accepted PMV interval (-0.5 to 0.5). In the two different occupancy behaviours, all the space show less adherence to the thermal comfortability hours according to ASHRAE 55, compared with the base case behaviour.

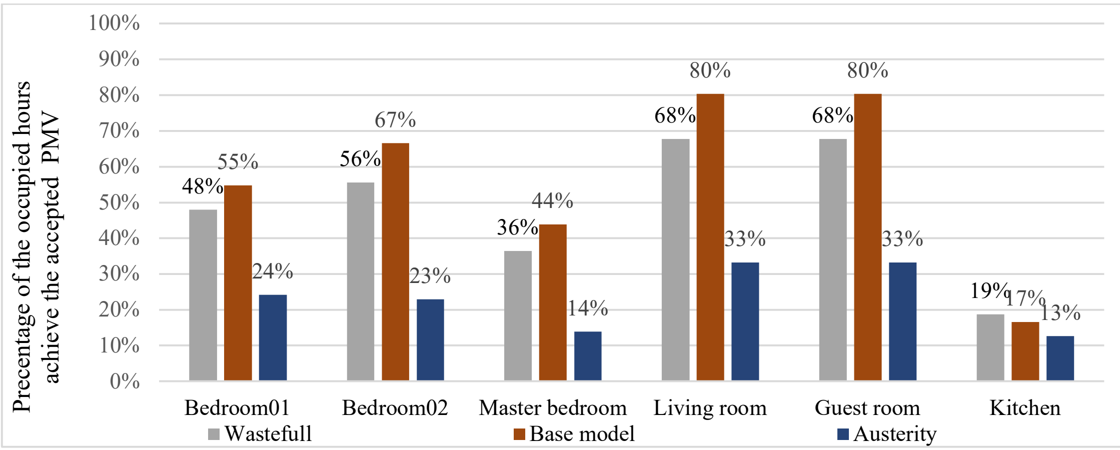


Figure 52: The effect of occupancy behaviour effect on thermal comfort in different rooms

4.3 Scenario 3: Renewable energy utilization

The building's operation relies on different energy resources. Currently, the existing residential buildings in Jordan cannot operate as ZEB without a supplementary energy system to supply on site energy. In the process of retrofitting a building to operate as a ZEB, generating energy on-site by utilising a renewable energy resource is one of the most valid solutions to minimise the annual energy dependence and annual energy consumption cost of the building.

A range of differentDifferent renewable resources were introduced in **sub-section 2.4.4** in addition to an investigation on Photovoltaic (PV) cells utilisation that was explained in terms of benefits and validity. Due to the fact that the sun is one of the most effective sources for the weather and the location properties. In this scenario, solar energy was utilised to contribute by supplying some of the annual energy consumption in the model. This was executed by implementing a solar water heater and PV cells to supply the apartment's energy consumption. This scenario studied the effect of implementing photovoltaic cells in the base model by taking into consideration the Jordanian local regulations and requirements.

Several heating sources were examined in a variety of scenarios to determine the impact of solar energy integration on the building. **Figure 53** shows the solar energy implementation layout used. There are various types of domestic hot water heating system available, including direct electric heaters, gas boilers, diesel boilers and even heat pump water heaters. In this section, the energy consumption of three typical examples of water heating systems, namely, an electric water heater, a gas boiler and a diesel boiler, were compared since they are the most common types of water heating system utilised in Jordanian apartments. Their energy consumption was then compared with that of a heat pump water heater. A solar water heater reheating process was also utilised to supply the energy to each DHW system. In the next section, the implementation of photovoltaic cells in the base case to help realise a nZEB is discussed further.

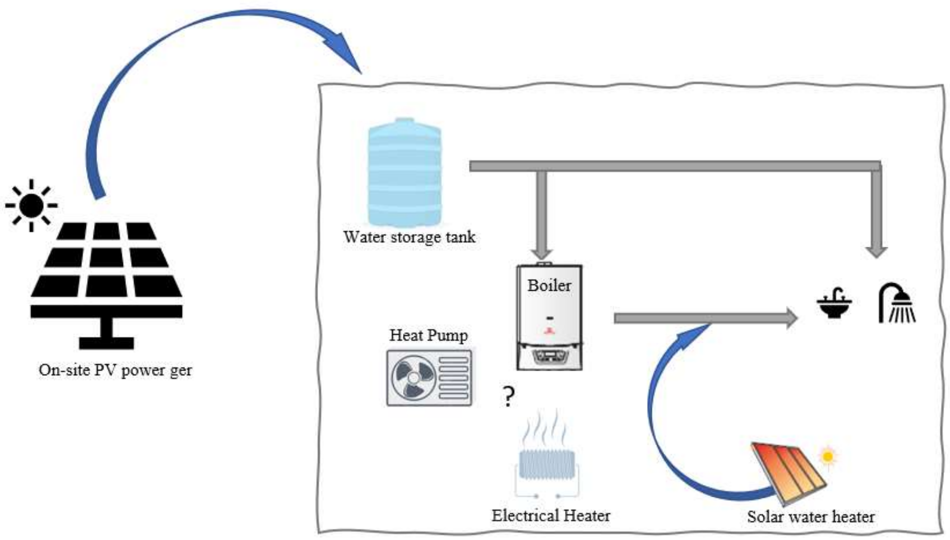


Figure 53: Solar energy implementation diagram

4.3.1 Hot water system adjustment (solar power)

The domestic hot water energy supply is one of the largest contributors to energy consumption in buildings since, according to some reports, it can account for about 18% of the annual electricity consumption in some buildings [62] or a tenth of the annual energy consumption in others [59]. In this study's model it was assumed to account for about 20% of the energy consumed annually in the base case scenario. The variation reported elsewhere could be related to the alterations made to the heating systems in each building. Different residential buildings can rely on various different heating systems to provide hot water. This can include traditional gas boilers, gas condensing boilers, electrical heaters, diesel boilers, and solar heaters. Solar heaters have been widely used in recent years, reportedly providing almost half of the hot water used in summer, while electric heating systems are mainly responsible for providing hot water in winter [59, 62]. Notably, local regulations mandating the use of solar water heaters and their installation in apartments above 150 m^2 are not applicable for existing buildings [59].

$$E_{WH} = \frac{Q_s\, C_P\, \Delta T_s}{\eta_{WH}}\, SD + \frac{Q_s\, C_P\, \Delta T_W}{\eta_{WH}}\, WD$$

Where Q_s, Q_w are the hot water daily consumption in summer and winter, respectively, C_p is the specific heat of water $4.19\ \mathrm{KJ/kg}\ °\mathrm{C}$, ΔT_s , ΔT_w are the increase in water temperature for summer and winter, η_{WH} is the energy efficiency of the water heating unit, and SD, WD are the number of opperating days in summer and winter, respectively.

Solar water heaters comprise three main components, namely, the absorber plate, the storage tank and the piping network. A solar water heater operates by exposing the water to the sun via the absorber. The water then absorbs the heat from the solar radiation that falls naturally on its surface [94]. A solar water heater is a free-energy heating system; however, it does not operate during wintertime. On the other hand, the heat pump employs a refrigerant cycle that heats the water by means of energy transfer between it and the refrigerant. This system has a high coefficient of performance and could be a useful energy reduction tool for producing in-house hot water.

In this section, different scenarios involving solar water heaters and heat pumps were examined in order to compare the amount of energy consumed by water heating, especially in summertime and wintertime.

Figure 54 shows the annual energy consumption for DHW using different heating systems. The results in **Figure 54** obtained by developing the Apache system in IES-VE and implementing a solar heater with the size of 4.06 m^2 absorber plate and a water storage tank of 200 litres that was selected for implementation and its specifications have been attached in **Appendix 6**. After utilising that solar heater, the energy required for DWH in the base case reduced by almost two-third of the annual domestic consumption for water heating. Since the solar water heater accounts for an annual consumption of 2.32 MWh. In the case of heating by direct electrical heaters, the annual DHW consumption contribution reduced by almost 90% of the electricity consumed for heating the water. Besides achieving a zero-energy heating consumption for DHW by implementing a heat pump and a solar water heater for providing the hot water to the base case apartment, solar energy is producing more energy than the energy required to cover the water heating load by about 0.74MW annually. Investigating the energy consumption for different water heating sources, the gas boiler consumes slightly more energy than the direct electrical heater. This is mainly because the efficiency of the gas boiler was assumed as 80%, while the electrical heater efficiency is 90%. In addition, the gas boiler ought to operate for almost half an hour before starting to provide hot water to the water demands. However, the heat pump implementation resulted in the most efficient system of heating water with an annual energy consumption of 1.58 MWh. The solar water heater was implemented to supply the rest of the DHW consumption which results in overheating the water. Thus, a smaller solar water heater was adequate to supply the overall energy load without overheating the water. Noting that this investigation does not consider the additional annual consumption added from the pump operation

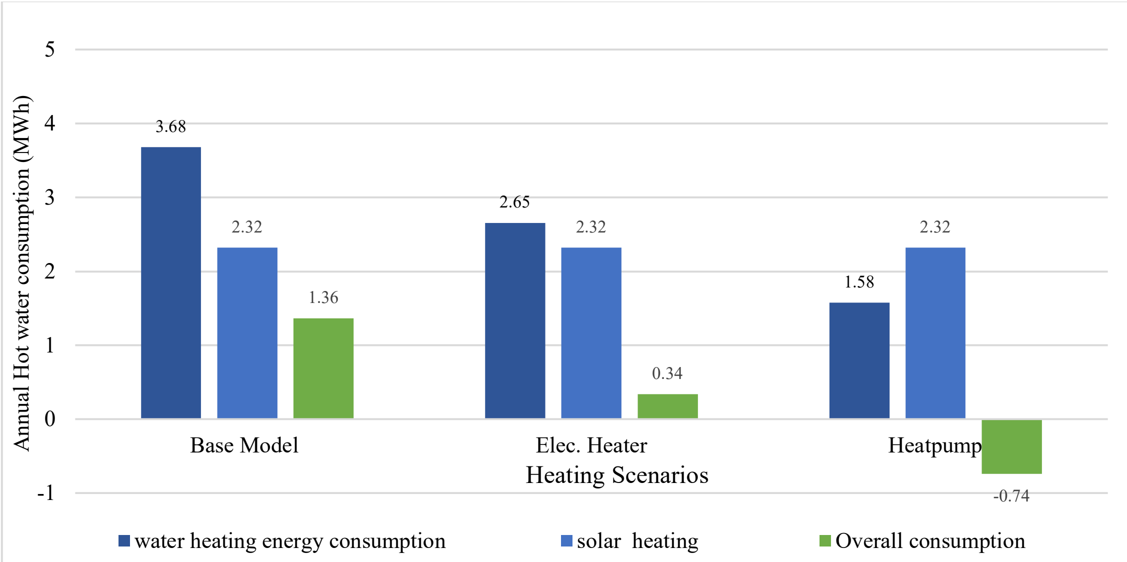


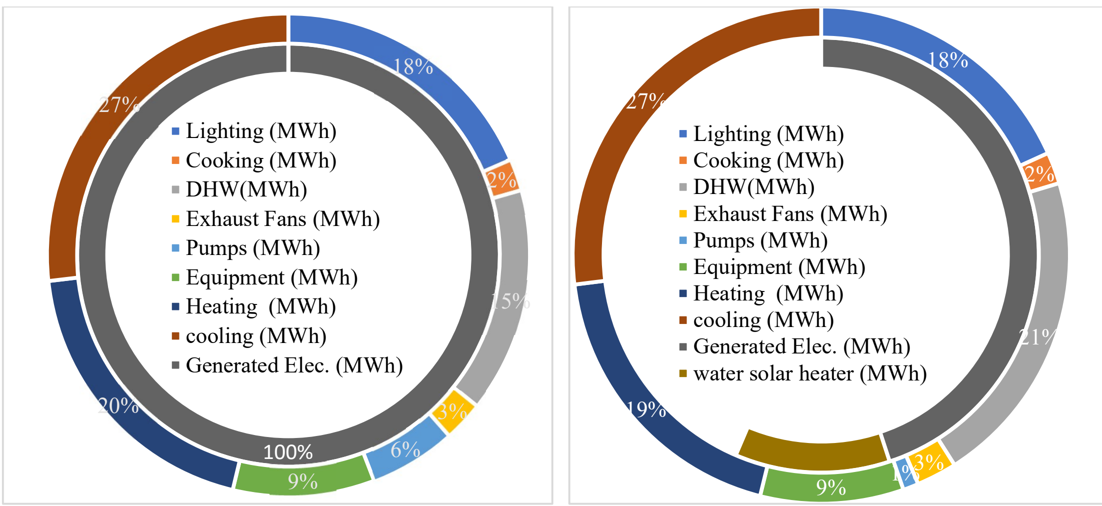
Figure 54: Annual hot water energy consumption scenarios

4.3.2 Photovoltaic cells implantation

Photovoltaic panels are an on-site expectable source of energy to be integrated in a residential existing building. IES-VE was utilised to conduct a solar analysis to identify the building energy gain. The solar energy gain was quantified by the energy yield as a result of implementing PV panels. This amount of solar energy was quantified using IES-VE simulation of PV panels' modelling as described by study [95] that IES-VE calculation methodology for PV is based on study [96].

Photovoltaic cells generate electricity from the solar power with an environmentally clean process with zero emissions. PV energy system implementation is divided into four categories, namely, off-grid domestic system, off-grid non-domestic system, on-grid system that are applicable to buildings, and on-grid centralised system [97]. PV panels efficiency normally lies between 10 – 20% [98, 99]. PV panels are mainly produced in three types, namely, monocrystalline, polycrystalline, and amorphous silicon [99]. The PV module performance is dependent on different factors, namely the location, irradiative properties, and the latitude [100]. The common approved instructions for attaining high energy performance of the PV system are to avoid PV panels' shading (rising from the panel above the roof levels and well as nearby trees and building) and facing panels toward the sun. The solar panel characteristics were obtained from the datasheet in **Appendix 5**. The PV panel array was considered to be installed on the roof at an azimuth angle of 0° and a tilt angle is 20° which is recommended by the suppliers for Jordan as shown in **Appendix 5**.

Developing the base model to achieve the nZEB may occur by implementing a solar PV system that supplies the overall annual energy consumption and use electricity only in moments of PV energy generation insufficiency. **Figure 55 a)** shows the performance of a 10.45 kW solar PV system that produces 17.13 MWh (using an annual solar PV energy yield of 1,639.15 kWh/kW [98]) supplies the total annual energy requirements for the base case model. To supply a considerable amount of energy to an apartment in Jordan, the electrical apartment meter has to be 3-Phase meter. However, the ordinary apartments in Amman use 1-Phase electric connection only. The maximum amount of solar PV power generating system eligible for on-grid integration under 1-phase is one with 9.04 MWh annual energy generation, an equivalent of 5.52 kW solar PV system. **Figure 55 b)** shows the performance of 5.52 kW PV system on the conventional building case in Jordan.



a) b)

Figure 55: PV system performance**:** a) 100% PV system implementation; and b) PV panel implementation for a conventional building in Jordan

Notably, implementing the maximum possible PV panels to the base model and adding a solar heater to supply the DHW demand reduces the annual energy consumption of the building by 44%, for the conventional building. To understand the nature of the energy consumption in the base case, the energy sources ought to be known and likewise, the alternation of their utilisation could lead to a promising efficient development.

Figure 49 shows the energy source of the base model in three cases: the first case is the base model case which shows no on-site energy generation, and the majority of the energy consumption has been electricity whereas a portion of energy acquired from LPG for cooking and DHW supply. There is small implementation of oil for disposable heaters; the next case is adding a water solar heater to the building system which resulted in reducing the DHW annual consumption and in contrast increase the electrical consumption energy due to the additional system operation in terms of pump. The last case is generating on-site energy by utilising 10 PV panels, with the maximum allowed for 1-phase electricity grid connection besides covering the DHW partially by a water solar heater utilisation.

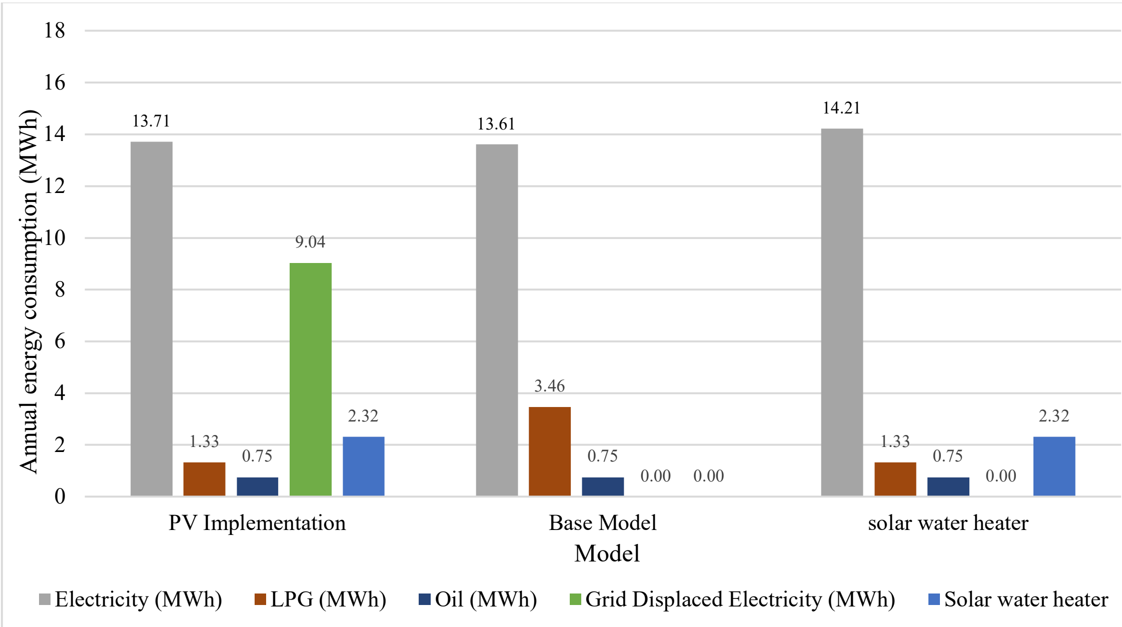


Figure 56: Base model energy source analysis

After investigating the source of energy in the base model, the DHW scenarios were compared to examine their implementation with PV panels operation. **Figure 57** shows that the implementation of the heat pump has the highest energy conservation and reduces the annual consumption to 6,570 kWh, followed by implementing solar heater and the direct water heater at 7,260 kWh and 8,070 kWh, respectively. Noting that also in **Figure 57** the addition pump energy consumption carried out from the solar water heater system was not considered.

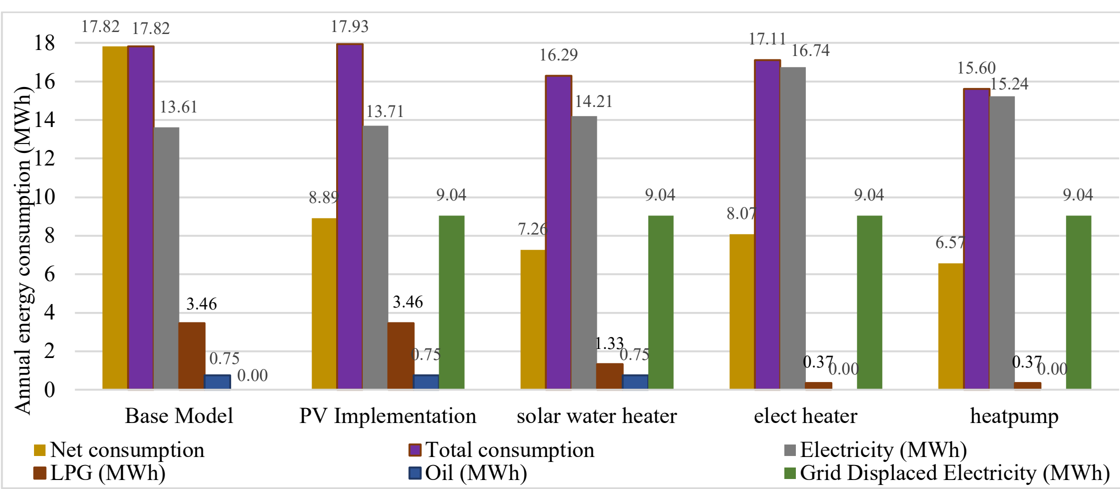


Figure 57: Base model energy source analysis

In the previous scenario, different building's performance strategies retrofits were studied to estimate the percentage of the energy consumption reduction to each nZEB. In this scenario, the annual energy consumption of the Base case 17.8MWh was considered in the investigation about the possibility of producing this energy onsite by changing the energy source of some of the systems such as the domestic hot water heating source. This was done by investigating the potential of using higher performance system such as a heat pump for water heating which reduced the water heating annual consumption to almost the half. Other than the change in the energy source, there are not any other changes on this scenario in terms of thermal comfort variables, thus, the thermal comfort performance follows the base case results as well.

4.4 Scenario 4: a combination of scenario 2 & 3

This scenario combined the best results obtained in scenarios 2 & 3 in order to identify optimal solutions for implementation.

4.4.1 Scenario 2 optimal implementation

Based on the results for various building envelope retrofit options discussed earlier in subsection 4.2.1, glass replacement was determined to have the highest influence on energy consumption and thermal comfort. Also, setting the operational temperature and replacing the lighting improved the building performance in terms of energy consumption, but had only variable success in achieving thermal comfort. Similarly, occupant behaviour had a significant effect in reducing the energy consumption of the building in the austerity scenario, which almost doubled the annual energy consumption of the wasteful scenario, although neither had much positive impact on thermal comfort. **Table 22** shows the impact of each variable on the base case energy consumption.

Table 22: The impact of different variables on the building operation

Category	Variables	Reduction in energy consumption	The percentage changes in the number of hours that achieve acceptable PMV comfort zone values			Variables	Reduction in energy consumption	The percentage changes in the number of hours that achieve acceptable PMV comfort zone values	
wall insulation	RW02	2.78%	↑	-0.02%	Roof insulation	PUR03	3.36%	↑	0.10%
	RW03	3.04%	↑	0.13%		PUR05	3.79%	↑	0.55%
	RW05	3.43%	↑	0.44%		PUR10	4.30%	↑↑	1.17%
	RW10	3.93%	↑	0.94%		green roof	2.16%	↑↑	1.48%
	ESP02	2.85%	↑	0.10%	Glassing	W01	5.57%	↑	3.97%
	ESP03	3.15%	↑	0.22%		W02	5.22%	↑	3.54%
	ESP05	3.52%	↑	0.52%		W03	6.59%	↑↑	5.65%
	ESP10	4.00%	↑	0.97%		W04	6.27%	↑	4.94%
	PUR02	3.09%	↑	0.21%		W05	5.80%	↑	4.19%
	PUR03	3.39%	↑	0.42%	Shading	Shading effect (0.65 m)	0.57%	↔	-0.61%
	PUR05	3.77%	↑	0.73%		Shading effect (0.83 m)	0.69%	↔	-0.10%
	PUR10	4.20%	↑↑	1.28%		Shading effect (1.70 m)	0.89%	↔	0.52%
Roo	RW02	2.64%	↑	-0.40%	Ope	SP 22.5°C - (1.0 DB)	-9.09%	↓	-9.73%

	RW03	2.96%	↑	-0.19%		SP 24.5°C - (1.0 DB)	9.12%	↓↓	-25.60%
	RW05	3.39%	↑	0.13%		Set point 22.5-2 [DB]	-3.69%	↓↓	-10.71%
	RW10	3.96%	↑	0.76%		Set point 22.5-4 [DB]	1.46%	↓↓	-14.83%
	ESP02	2.74%	↑	-0.31%		Set point 22.5-6 [DB]	5.92%	↓↓	-19.00%
	ESP03	3.08%	↑	-0.12%	Lighting	LED light	15.10%	↔	0.24%
	ESP05	3.50%	↑	0.25%	Occupancy	wasteful	-44.36%	↓↓	-7.57%
	ESP10	4.05%	↑	0.88%		austerity	26.33%	↓↓	-33.23%
	PUR02	3.02%	↑	-0.15%					

Table 22 lists each variable's impact on the building operation and its thermal comfort. As shown, additional PUR10 insulation had the highest impact on the annual energy consumption – as found in other studies [80]. Other than that, implementation of the green roof improved thermal comfort the most but it was not the most effective in reducing energy consumption. Shading with an overhang length of 1.7 m was the best of the shading options studied. Additionally, lighting replacement with LED had a positive impact on the annual energy consumption. However, it should be noted that, in the literature reviewed, there was no direct connection between lighting replacement and thermal comfort in any of the buildings studied. These variable adjustments were combined together in a single model and then a simulation was run in the IES was to determine which combinations came closest to meeting the thermal comfort and energy consumption requirements for a comfortable nZEB. **Table 23** lists the details of the different cases that were studied to investigate the combined effect of these variables on the building model in order to identify the best means of achieving both thermal comfort and energy conservation. After comparing the cases shown in **Table 23,** an energy analysis was then carried out on one of these cases, as shown in **Figure 58**.

Table 23: Scenario 04 combined case details

CASE-00	**Base case sittings**
CASE-01	PUR 10 cm additional insulation for walls and roof, LED lighting, 1.70 m shading, set-point temperature 21.1°C for cooling and 20.0°C in winter
CASE-02	PUR 10 cm additional insulation for walls and roof, LED lighting, 1.70 m shading, set-point temperature 24.5°C for cooling and 19.0C°C in winter
CASE-03	PUR 10 cm additional insulation for walls, green roof, LED lighting, 1.70 m shading, set-point temperature 21.1°C for cooling and 20.0°C in winter
CASE-04	PUR 10 cm additional insulation for walls, green roof, LED lighting, 1.70 m shading, set-point temperature 23.0°C for cooling and 20.0°C in winter
CASE-05	PUR 10 cm additional insulation for walls and roof, LED lighting, 1.70 m shading, set-point temperature 23.0°C for cooling and 20.0°C in winter
CASE-06	PUR 10 cm additional insulation for walls, green roof, LED lighting, 1.70 m shading, set-point temperature 24.50°C for cooling and 19.0°C in winter

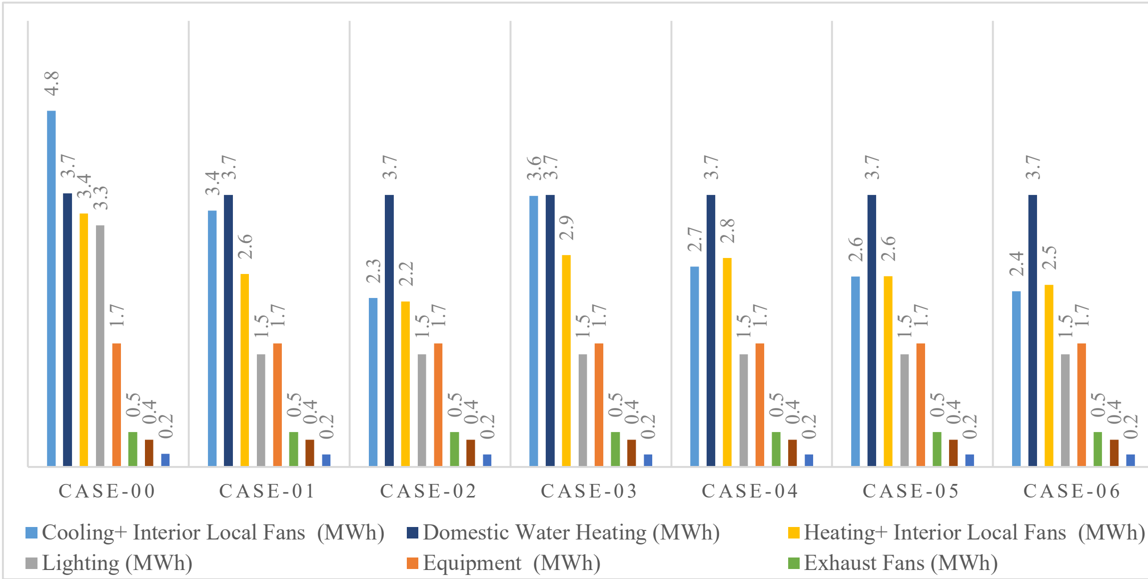


Figure 58: Annual energy analysis for scenario 04 CASEs

In the previous cases discussed earlier, energy consumption reductions of between 19% and 30% were achieved, compared to the base case. **Figure 58** shows that CASE-02 conserved most energy, with 12.4 MWh annual energy consumption, while CASE-03 performed worst with 14.3 MWh annual energy consumption. (It was also the combination with the highest number of thermal comfort hours achieved. This will be examined in further detail later in this subsection). Note that, in this investigation, hot water consumption remained constant in each case and the main alterations involved lighting (replacing existing lighting with LED lights), and heating and cooling load reductions (which were related to set-point temperature changes). The thermal comfort analysis results for these same cases are summarized in **Figure 59**.

Figure 59 shows the percentage of occupied hours that achieved an acceptable PMV level. CASE-03 achieved the highest thermal comfort rating. This is in agreement with the results reported in study [84]. CASE-01 was next in terms of thermal comfort but consumed less energy – making it a possible compromise between thermal comfort and energy conservation that could yet lead to the creation of a comfortable nZEB.

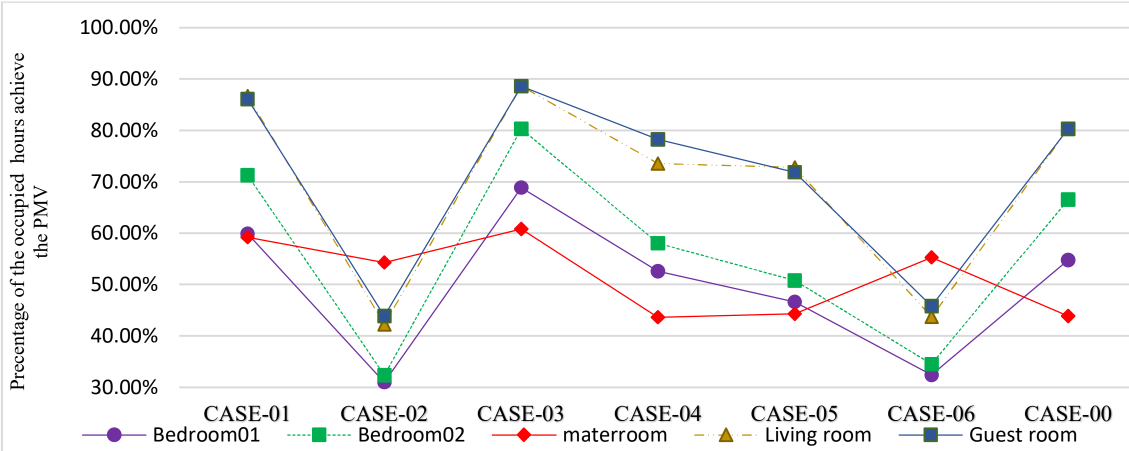
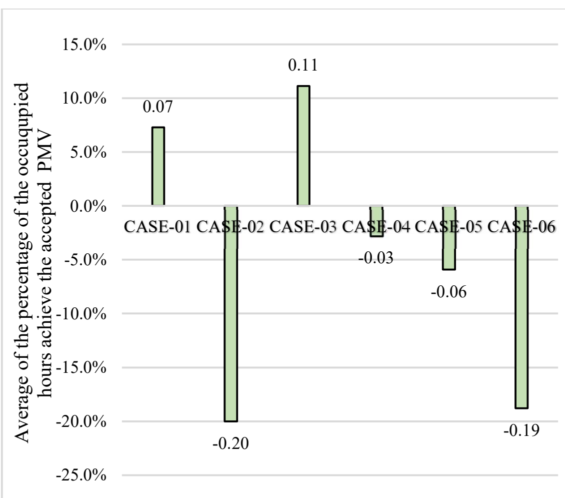
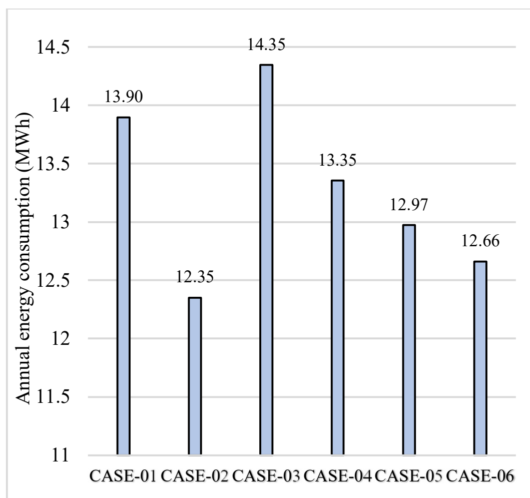


Figure 59: Thermal comfort analysis for scenario 04 CASEs

With regard to the building envelope cases, the main differences were the roof insulation type and the set-point temperature. In all cases, those that utilised a green roof (CASE-03, CASE-04, CASE-06) performed better in terms of thermal comfortability at the same set-point temperatures, as shown in **Figure 60 a)** while cases that assigned a set-point temperature of 24.5 ℃ in summer and 19.0 ℃ in winter (CASE-02, CASE-06) achieved the lowest energy consumption but also had the least thermal comfortability (CASE-02, CASE-06), as shown in **Figure 60 b).**



a)



b)

Figure 60: Analysis of scenario 04 CASEs: a) average thermal comfort percentage for each CASE; and b) annual energy consumption for the combined CASEs

In conclusion, although all the variables examined had a noticeable effect on thermal comfort inside the building space and the amount of energy consumed, set-point temperatures had the most impact on the total annual energy consumption - since the set-point both increased in summer and decreased in winter, ensuring that it had the widest possible impact. However, this set-point temperature adjustment also reduced the total number of occupied hours that achieved acceptable thermal comfort. Therefore, different ways of adjusting the set-point temperature on the space model so that it would have less impact on thermal comfort were also investigated. It is worth mentioning here that although the PMV-PPD thermal comfort investigations followed an approved and tested method, thermal comfort is a personal preference that can vary between different people even in the same family (group). So, if achieving nZEB status is the main priority of the landlord, it might be worth testing different set-point temperatures on-site and then adopting the most agreed-upon conditions.

4.4.2 Scenario 3 optimal implementation

After implementing the highest efficiency variables on the base model to obtain the fourth scenario, different renewable energy systems were then added in to evaluate the implementation of each of these systems on the building. The cases selected were CASE-01, CASE-02, CASE-03, and CASE-06. They were the best performers in terms of energy consumption (CASE-02 and CASE-06) and thermal comfort (CASE-03 and CASE-01). This subsection examined how these 4 cases performed with the addition of highly efficient water heating applications, as investigated earlier in subsection 4.3.1, along with on-site PV systems to help meet the annual energy demand. This subsection also discusses the results obtained in order to identify which combined cases might achieve both thermal comfortability and nZEB operation. In this subsection, two water heating systems were assigned to the four cases. The first was a solar water heater with an electric heater coil, for operation on overcast or cloudy days with no sun. The second system was a solar water heater but with an Air Source Heat Pump (ASHP) added to facilitate hot water consumption even on winter days with little or no sun. **Figure 61** summarizes the energy consumption breakdown for CASE-01, CASE-02, CASE-03, and CASE-06 and shows the relative cooling, heating, DHW, pump and the exhaust fan energy consumption levels (at constant cooking, lighting, and equipment loads in all cases), presenting more details to help understand the building's behaviours in each case**. Figure 61** shows that in CASE-02 and 06, the cooling load dropped significantly, and that this led to a change in the relationship between heating and cooling as the heating load switched to become higher than the cooling load. This variation can also be related to the change in the set-point temperature in both cases. An increase in the cooling set-point temperature of 3.5 ℃ and a heating set-point temperature reduction of 1 ℃ caused a difference in the heating and cooling loads because of the direct relationship between the set-point temperature and heating/cooling loads.

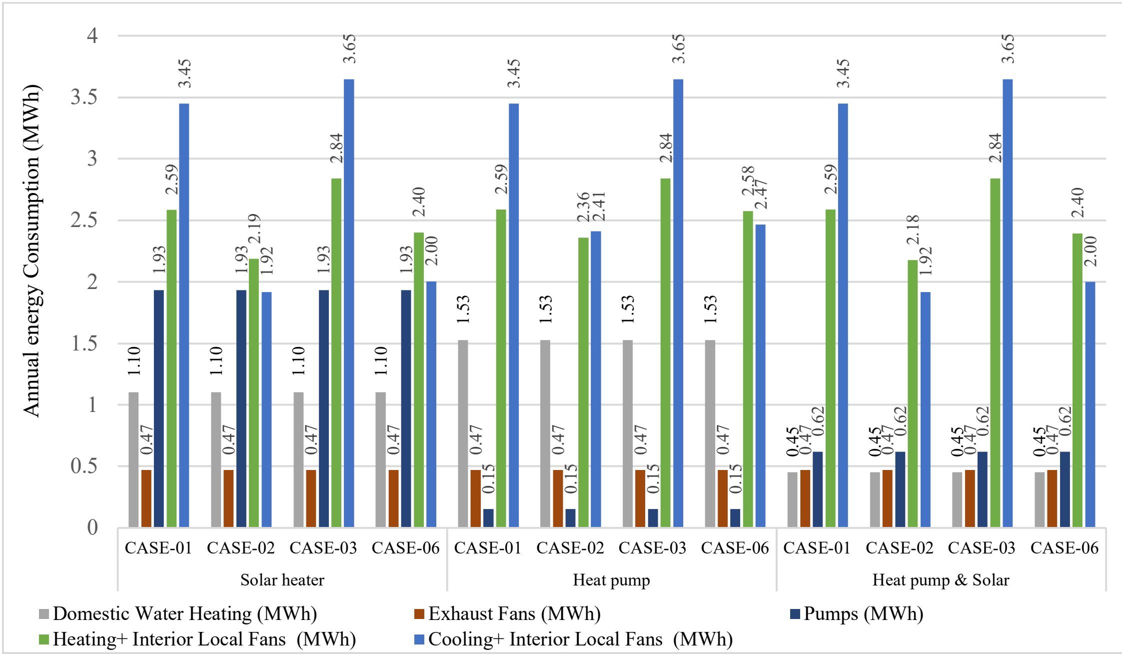


Figure 61: Energy consumption breakdown for CASE 01,02,03, and 06

Another significant difference between the two-water heating systems is the pump and the DHW consumption. When operating solar water heater systems, the need for a return hot water pump results in added pump load, as shown in **Figure 61** where the DHW consumption was reduced by 2.3 MWh annually but, in contrast, the pump load was increased by 1.75 MWh. On the other hand, when a heat pump was added to accommodate the DHW load, the load was reduced by 75% of the base case DHW load. Combining a solar water heating system with an air source heat pump for ASHP implementation resulted in a high-performance system with a total DHW load of only 450 kWh annually, representing a reduction of 3.2 MWh in the annual energy consumption.

In general, the annual energy consumption of the building was reduced by implementing the two water heating systems. **Figure 62** shows that the use of the solar water heating system reduced the annual consumption by 5.8%, 9.7%, 5.6% and 9.5% in CASE-01, 02, 03, and 06, respectively. Similarly, the utilisation of ASHP generally resulted in a 15% reduction compared to the original case load. Noting that the implementation of a combination of SWH and ASHP led to a reduction of 20%, 25.7%, 19.3% and 25.1% for CASE-01, 02, 03, and 06, respectively, the utilisation of the ASHP and SWH can be seen to have produced the best performance in all cases.

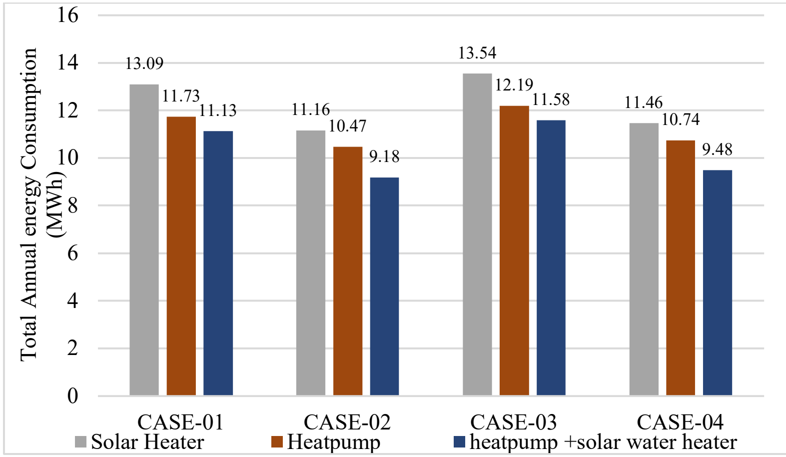


Figure 62: Total annual energy consumption for CASEs 01,02,03, and 06

Figure 62 shows that CASE-02 had the highest performance and that the utilisation of the combination of a water heating system incorporating both SHW and ASHP resulted in an annual energy consumption reduction of 8.6 MWh compared with the base case loads.

4.4.3 Simulation and analysis

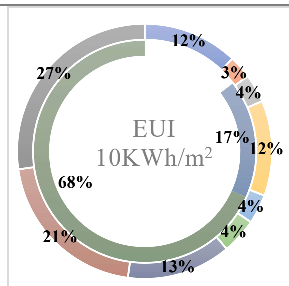
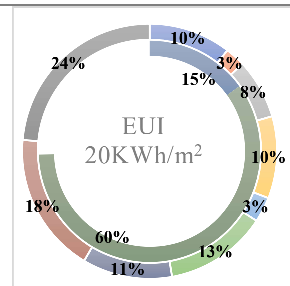
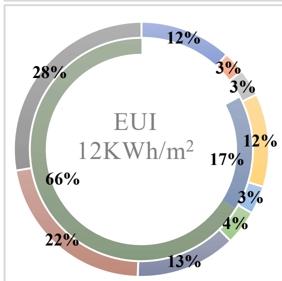
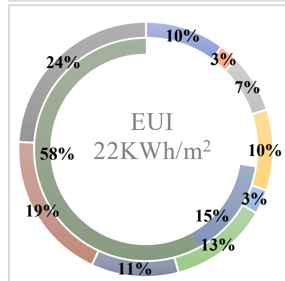
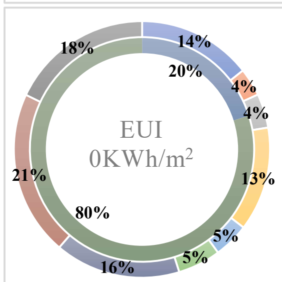
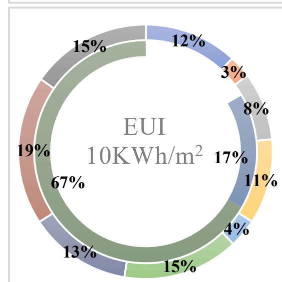
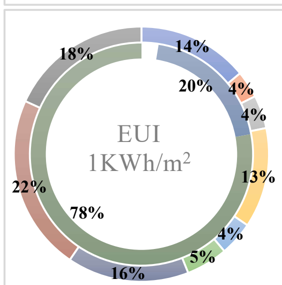
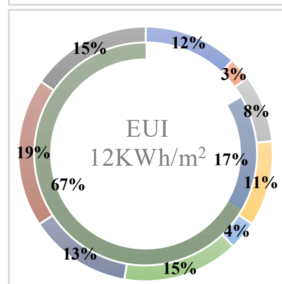
In this sub-section, the optimal solutions from both scenarios 2 and 3 were implemented in order to assess their impact on energy consumption and thermal comfort in the model used for scenario 1. In scenario 2, the variables that had the highest performance in terms of energy consumption and thermal comfort were combined to create 6 cases describing possible retrofits, with three of them achieving improved thermal comfort and the other three achieving improved energy performance.

In scenario 3, high-performance water systems were utilised to determine the optimal implementation strategy for those systems. The cases with the highest performance in subsection 4.4.1 were then taken into consideration in order to further study the final energy consumption and thermal comfortability. CASE-01, 02, 03 and 06 were selected from that subsection for further study since CASE-02 and 06 had the best performance in terms of energy consumption, whereas CASE-01 and 03 had the best performance in terms of thermal comfort. In this subsection, optimal results from both subsections were combined, in addition to on-site energy utilisation, to determine the overall Energy Utilisation Index (EUI) of each case. The Energy Utilisation Index (EUI) can be defined as the ratio between the overall energy consumed annually by the building and the building floor area [101]. In the discussion of this scenario, CASE-01, 02, 03, and 06 will be compared in terms of their EUI, after assigning on-site energy values to each case.

i. Energy consumption (annual consumption)

As discussed earlier in subsection 4.3.2, the maximum amount of on-site power generation eligible for ordinary apartment is 9.04 MWh, which is equivalent to a 5.52 kW solar power system. This PV system was utilised, in addition to solar power, to substitute for the water heating system. CASE-01, 02, 03, and 06 all utilised solar power and could be grouped into two main categories. The first category utilised ASHP as the main system, in addition to SWH, and the second category utilised a SWH with electrical coil substitution for use on cloudy or overcast days with little or no sun. A breakdown of energy consumption for each of these cases is shown in **Table 24.** This shows that the utilisation of a 5.52 kW PV system produced 0 kWh/m^2 EUI in CASE-02 when water heating was accomplished by ASHP and SWH. In comparison, CASE-02 (the case with least energy consumption) achieved 10 kWh/m^2 EUI, followed by CASE-06 with an EUI of 1 kWh/m^2 and 12 kWh/m^2 for the utilisation of SWH +PV and ASHP+SWH+ PV, respectively.

Table 24: The implementation of the PV system on the building CASEs

	- SWH & ASHP & PV	SWH & PV
CASE-01		
CASE-03		
CASE-02		
CASE-06		

Interior Lighting (MWh) | Cooking (MWh) | Service Water Heating (MWh) | Interior Local Fans (MWh)
Exhaust Fans (MWh) | Pumps (MWh) | Equipment | heating+ Interior Local Fans
cooling+ Interior Local Fans | water solar heater (MWh) | Generated Elec. (MWh)

As previously mentioned, CASE-02 and 06 were the cases that yielded the most efficient solutions in terms of energy consumption. On the other hand, CASE-01 and 03 yielded the highest thermal comfort levels. CASE-01 and 03 yielded a $10\ kWh/m^2$ EUI, which was more than their counterparts that achieved the lowest levels of energy consumption (CASE-02 and 06). The only difference between these cases was the set-point temperature, which is reflected in the number of cooling load differences in CASE-01 and 03 on the one hand and CASE-02 and 06 on the other, as the CASE-02 and 06 set-point temperature was 24.5 ℃, which resulted in a 9% reduction in the cooling load between CASE-01 and 02, for instance. It is also important to consider that adding a solar system also increases the pump's annual load consumption.

The EUI is a universal tool used to investigate the energy performance of buildings [59]. The energy use intensity differs between buildings, depending on many variables such as building type, weather, the building operations systems, and hours - in addition to the number of people in the building. ASHRAE 90.1 estimated the EUI of buildings in Jordan to be 131 kWh/m^2, while study [7] stated that the primary energy consumption for a residential building in Jordan was around 229 kWh/m^2. However, another study has estimated the EUI of Jordanian residential buildings to be around 91.4 kWh/m^2[59]. The same study considered that nZEB also means 0 kWh/m^2 EUI [59], whereas another study regarded nZEB as having 50 kWh/m^2 EUI [65]. In this study, an apartment model was constructed based on a review of the case studies that had been published on other Jordanian buildings. The base case simulated was found to consume 131 kW/m^2EUI. After implementing the best cases for both building envelope adjustments and solar energy implementation, the model used in this study produced a value of 0 kWh/m^2 for Case 02, only. On the other hand, the model used for this research was assumed to be an existing building, which may restrict the number of possible adjustments that could be made, and which might justify a value greater than 0 kWh/m^2. This line of reasoning is backed by study [65] which accepted an annual energy use of 50 kWh/m^2 for an existing nZEB. If this is valid, all the four cases in this study can be regarding as achieving nZEB status. Otherwise, only CASE-02, which utilised ASHP in addition to SWH, can be regarded as meeting all zero energy building requirements.

ii. Thermal comfort

In the combined cases described earlier, the annual total of hours that achieved acceptable levels of thermal comfort in each space were analysed to determine the effect of adding all retrofits together, in addition to PV utilisation. **Figure 63** shows the average thermal comfort percentage achievements for each case. CASE-01 and 03 still achieved the highest number of thermal comfort hours, according to the range specified by ASHRAE 55 (-0.5 >PMV<0.5). In contrast, CASE-01 and 06 scored lowest but were still the best in terms of energy consumption. This shows that PV utilisation will not adversely impact the thermal comfort of a building in those cases where an improvement in thermal comfort has already been achieved, whereas in those cases that have already failed to achieve thermal comfort, it will only increase the gap between them and better-performing buildings.

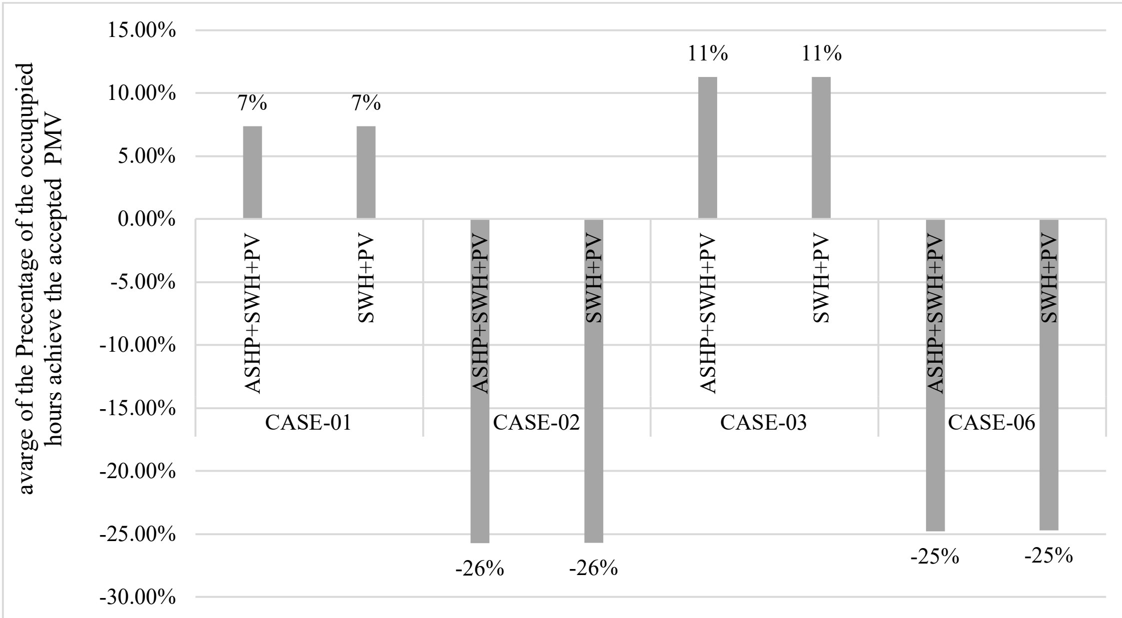


Figure 63: Average thermal comfort percentage achievement scores for each CASE.

Chapter Five: Conclusion and Future work

5.1 Study Conclusions

This research work was focused on identifying the optimal retrofits that could be implemented on an existing residential building in Jordan. In this research, the factors that affect the building's energy consumption, such as the weather, the building envelope, building operation, and occupancy behaviour, were all taken into consideration. These factors were investigated based on 7 categories with 41 variables in order to identify the impact of each variable on the Base model. The effects of these variables were then compared to establish the best case for each category. Comparisons focused on two main categories, namely, annual energy consumption and thermal comfort.

The variables that resulted in the best performance in those two categories were identified and combined into six (6) Cases that constituted the best building envelope retrofit and later, the highly efficient building systems were implemented in the best 4 Cases out of the 6 in addition to the utilisation of a solar PV system. Those 4 Cases were also compared to identify the best retrofit for upgrading the building to a nZEB with the highest thermal comfort conditions. The analysis findings revealed that Case 02 that included the implementation of 10cm extra insulation on walls and roof, utilising windows with U-value 1.36 $W/m^2 \cdot ℃$ and 0.4 SHGC, a set-point temperature of 24.5 ℃ in cooling and 19 ℃ in heating seasons in addition to the implementation of ASHP+SWH+PV on the model. This combination resulted in a possible retrofit that reaches a $0kWh/m^2$, that moves CASE-02 to a nZEB. This finding indicates that a transition to a nZEB is a possible undertaking on the existing residential buildings in Jordan. Additionally, if buildings that consume less than $50kWh/m^2$ are classified as a nZEB, then all the 4 Cases, that is, CASE-01, 02, 03, and 06 considered in this analysis could be referred to as a nZEB in Jordan.

In the thermal comfort category, the cases that implemented the same building envelop retrofits (10 cm extra insulation on walls, windows with a U-value of 1.36 $W/m^2 \cdot ℃$ and 0.4 SHGC) but with two main alterations - a green roof instead of 10 cm PUR insulation and a set-point temperature of 21.1 ℃ in cooling and 20 ℃ in heating operation seasons resulted in the highest number of hours that achieve the accepted PMV intervals. This was implemented in CASE-01 and 03, which consumed 10 – 22 kWh/m^2 annually and resulted in a tremendous reduction in the annual energy consumption of the building in comparison with the base case.

The significant result of this research work is that although the green roof installation would not result in high thermal insulation, it is the best insulation to accomplish thermal comfort in the space. Overall, the main factor that resulted in better thermal comfortability was the set-point temperature.

This is because the cases that set the operating temperature at 21.1 ℃ in cooling and 20 ℃ in heating seasons were also the cases that achieved more hours of thermal comfortability, that is, CASE-01 and 03. CASE-03 achieved more thermal comfort hours that met acceptable ASHRAE 55 PMV thermal comfort intervals. This was also the case that implemented a green roof in addition to the operating temperature of 21.1 ℃ in cooling and 20 ℃ in heating seasons. This shows that increasing the set-point temperature in summer and decreasing it in winter would improve the overall energy consumption but could have a negative effect on the thermal comfort. Therefore, according to the investigation method used for this research work, the Jordanian thermal insulation code's set-point temperatures are currently the best options for thermal comfortability but the worst options in terms of energy consumption.

Another aspect that was examined in this study was the effect of occupancy behaviour on the building's operation and annual energy consumption. The study established that wasteful occupancy behaviour would result in an increase of 44% compared to] the base case annual energy consumption, whereas austerity occupancy behaviour would reduce the annual energy consumption by 26%. This highlights the importance of occupancy behaviour in determining the annual building operation conditions. Notably, the examination of the occupancy behaviour against the thermal comfortability test was not a success in this investigation, mainly due to the variations in the set-point temperature that were subject to the occupants' requirements at any given moment.

5.2 Future Work

This research has only investigated the possibility of operating an existing residential apartment as a nZEB theoretically, as on-site data collection for different existing buildings in Jordan was impossible due to travel restrictions caused by the Coronavirus (COVID-19) global pandemic. This made it impossible to obtain real-time data, so that published literature and simulation data had to be used for all the analyses carried out in this study. Thus, in the future, this work should be undertaken by using real-time data from Jordan to validate the reported findings concerning the optimal retrofits that could be implemented on existing residential buildings.

Furthermore, the energy consumption calculation process used by IES VE has certain limitations. The IES Virtual Environment 2019 modelling software is normally able to simulate only specific mechanical systems in operational scenarios which may not always reflect the expected operation of all aspects of the building's services. Thus, in this study, the assigned systems were built and adjusted to reflect the original system operation properties. In addition, some assumptions were made for certain systems to reflect the actual system operation conditions in the building. Thus, some of the systems that were limited by the use of the IES VE, that is, implementation of the infrared plate heater, should be examined further using alternative software tools and real-time data to ascertain the validity of this study's methodology.

Notably, human thermal comfortability is directly related to building occupancy, and it can differ from person to person in the same place even if they all share the same activity level and clothing factor. Therefore, given the importance of the set-point temperature to both energy consumption and thermal comfortability, further on-site investigation of the actual occupancy response should be undertaken for different cases and different buildings in Jordan in order to establish the most comfortable and acceptable set-point range for all buildings and thus to update the local building codes accordingly.

This research work studied the possibility of refurbishing a building to operate as a thermal comfort nZEB. However, no economic analysis was carried out concerning the optimal retrofits that could realistically be implemented on an existing residential building in Jordan. Establishing that the proposed optimal retrofits are affordable and economically feasible, in comparison with the existing systems already used in residential buildings, it is very important because it would inspire building owners to adopt the nZEB approach. Thus, in the future, an affordability analysis of the optimal retrofits proposed in this study will need to be carried out to ascertain whether they are equally economically feasible and suitable for adoption in residential buildings in Jordan.

Appendix

Appendix 1: Indoor air temperature ASHRAE Handbook—HVAC Applications (SI) (2011) [102]

Table 2 Typical Recommended Indoor Temperature and Humidity in Office Buildings

	Indoor Design Conditions		
	Temperature, °C/ Relative Humidity, %		
Area	**Winter**	**Summer**	**Comments**
Offices, conference rooms, common areas	20.3 to 24.2 20 to 30%	23.3 to 26.7 50 to 60%	
Cafeteria	21.1 to 23.3 20 to 30%	25.8 50%	
Kitchen	21.1 to 23.3	28.9 to 31.1	No humidity control
Toilets	22.2		Usually not conditioned
Storage	17.8		No humidity control
Mechanical rooms	16.1		Usually not conditioned

Appendix 2: Thermal template – lighting – ASHRAE standard 90.1 (2010) [54]

TABLE 9.6.1 Lighting Power Densities Using the Space-by-Space Method

Common Space Types[a]	LPD, W/m^2	Building-Specific Space Types	LPD, W/m^2
Office—Enclosed	12	Gymnasium/Exercise Center	
Office—Open Plan	12	Playing Area	15
Conference/Meeting/Multipurpose	14	Exercise Area	10
Classroom/Lecture/Training	15	Courthouse/Police Station/Penitentiary	
For Penitentiary	14	Courtroom	20
Lobby	14	Confinement Cells	10
For Hotel	12	Judges' Chambers	14
For Performing Arts Theater	36	Fire Stations	
For Motion Picture Theater	12	Engine Room	9
Audience/Seating Area	10	Sleeping Quarters	3
For Gymnasium	4	Post Office—Sorting Area	13
For Exercise Center	3	Convention Center—Exhibit Space	14
For Convention Center	8	Library	
For Penitentiary	8	Card File and Cataloging	12
For Religious Buildings	18	Stacks	18
For Sports Arena	4	Reading Area	13
For Performing Arts Theater	28	Hospital	
For Motion Picture Theater	13	Emergency	29
For Transportation	5	Recovery	9
Atrium—First Three Floors	6	Nurses' Station	11
Atrium—Each Additional Floor	2	Exam/Treatment	16
Lounge/Recreation	13	Pharmacy	13
For Hospital	9	Patient Room	8
Dining Area	10	Operating Room	24
For Penitentiary	14	Nursery	6
For Hotel	14	Medical Supply	15
For Motel	13	Physical Therapy	10
For Bar Lounge/Leisure Dining	15	Radiology	4
For Family Dining	23	Laundry—Washing	6
Food Preparation	13	Automotive—Service/Repair	8
Laboratory	15	Manufacturing	
Restrooms	10	Low Bay (<25 ft Floor to Ceiling Height)	13
Dressing/Locker/Fitting Room	6	High Bay (≥25 ft Floor to Ceiling Height)	18
Corridor/Transition	5	Detailed Manufacturing	23
For Hospital	11	Equipment Room	13
For Manufacturing Facility	5	Control Room	5
Stairs—Active	6	Hotel/Motel Guest Rooms	12
Active Storage	9	Dormitory—Living Quarters	12
For Hospital	10	Museum	
Inactive Storage	3	General Exhibition	11
For Museum	9	Restoration	18
Electrical/Mechanical	16	Bank/Office—Banking Activity Area	16

Appendix 3: Occupancy heat gains- ASHRAE Handbook—Fundamentals (SI) [54]

Table 1 Representative Rates at Which Heat and Moisture Are Given Off by Human Beings in Different States of Activity

Degree of Activity	Location	Total Heat, W Adult Male	Total Heat, W Adjusted, M/F[a]	Sensible Heat, W	Latent Heat, W	% Sensible Heat that is Radiant[b] Low V	% Sensible Heat that is Radiant[b] High V
Seated at theater	Theater, matinee	115	95	65	30		
Seated at theater, night	Theater, night	115	105	70	35	60	27
Seated, very light work	Offices, hotels, apartments	130	115	70	45		
Moderately active office work	Offices, hotels, apartments	140	130	75	55		
Standing, light work; walking	Department store; retail store	160	130	75	55	58	38
Walking, standing	Drug store, bank	160	145	75	70		
Sedentary work	Restaurant[c]	145	160	80	80		
Light bench work	Factory	235	220	80	140		
Moderate dancing	Dance hall	265	250	90	160	49	35
Walking 4.8 km/h; light machine work	Factory	295	295	110	185		
Bowling[d]	Bowling alley	440	425	170	255		
Heavy work	Factory	440	425	170	255	54	19
Heavy machine work; lifting	Factory	470	470	185	285		
Athletics	Gymnasium	585	525	210	315		

Appendix 4: Split unit selection

WALL MOUNTED SPECIFICATION

ARTCOOL (R410A)

* ARTCOOL models may contain preliminary data

LG participates in the ECP programme for EUROVENT AC program. Check ongoing validity of certification: www.eurovent-certification.com

• Single Combination

UNIT				9K	12K	18K
INDOOR				AM09BP.NSJ	AM12BP.NSJ	AM18BP.NSK
Capacity	Cooling	Min/Rated/Max	W	890/2500/3700	890/3500/4040	900/5000/5525
	Heating +7°C	Min/Rated/Max	W	890/3200/4100	890/3800/5100	900/5800/6438
	Heating -7°C	Rated	W	3000	3600	3800
Power Input	Cooling	Rated	W	670	1080	1587
	Heating +7°C	Rated	W	840	1000	1611
EER			W/W	3.73	3.24	3.15
S.E.E.R.				6.5	6.4	6.5
P design C			kW	2.5	3.5	5.0
COP			W/W	3.81	3.80	3.60
S.C.O.P.				4.0	4.0	4.0
P design H			kW	2.4	2.5	3.9
Energy Label	Cooling (A++ to E Scale)			A++	A++	A++
	Heating (A++ to E Scale)			A+	A+	A+
Annual Energy Consumption	Cooling		kWh	134	191	269
	Heating		kWh	840	875	1365
Sound Pressure	Cooling	Sleep	dBA	19	19	31
		Low	dBA	27	27	34
		Medium	dBA	35	35	39
		High	dBA	41	41	44
	Heating	Low	dBA	27	27	34
		Medium	dBA	35	35	39
		High	dBA	41	41	44
Sound Power	Cooling	High	dBA	59	59	60
Air Flow Rate	Cooling	Sleep	m³/min	3.0	3.0	8.0
		Low	m³/min	4.2	4.2	10.5
		Medium	m³/min	7.5	7.5	13.0
		High	m³/min	10.0	10.0	14.5
		Max (Power)	m³/min	11.5	12.5	15.5
	Heating	Low	m³/min	5.6	5.6	11.0
		Medium	m³/min	7.2	7.2	13.5
		High	m³/min	10.0	10.0	16.0
Dehumidification Rate			l/h	1.1	1.3	1.8
Running Current	Cooling	Rated	A	3.0	4.7	5.9
		Max	A	6.0	6.0	9.0
	Heating	Rated	A	3.7	4.5	7.1
		Max	A	7.0	7.0	9.5
Starting Current	Cooling	Rated	A	3.0	4.7	5.9
	Heating	Rated	A	3.7	4.5	7.1
Power Supply			Ø / V / Hz	1 / 220-240 / 50	1 / 220-240 / 50	1 / 220-240 / 50
Circuit Breaker			A	15	15	20
Power Supply Cable			N.x mm²	3*1.0	3*1.0	3 x 1.5
Power & Transmission Cable			N.x mm²	4*1.0 (Including Earth)	4*1.0 (Including Earth)	4 x 1.0 (Including Earth)
Dimension			mm	837*308*192	837*308*192	998*345*212
Net Weight			kg	9.9	9.9	13.2
Fan Motor Output			W	30	30	30
OUTDOOR				AM09BP.UA3	AM12BP.UA3	AM18BP.UL2
Operation Range	Cooling	Min~Max	°CDB	-10~48	-10~48	-15~48
	Heating	Min~Max	°CDB	-10~24	-10~24	-10~24
Sound Pressure	Cooling	High	dBA	49	49	53
	Heating	High	dBA	50	50	55
Sound Power	Cooling	High	dBA	65	65	65
Air Flow Rate	Cooling	High	m³/min	27	27	35
Piping	Length (Odu/Idu)	Min	m	3	3	3
		Max	m	15	15	20
	Elevation (Odu/Idu)	Max	m	7	7	10
Piping Connection	Liquid	OD(Outside)	mm	6.35	6.35	6.35
		OD(Outside)	inch	(1/4)	(1/4)	(1/4)
	Gas	OD(Outside)	mm	9.52	9.52	12.7
		OD(Outside)	inch	(3/8)	(3/8)	(1/2)
	Drain	OD(Outside)	mm	21.5	21.5	21.5
		OD(Outside)	inch	0.85	0.85	0.85
Refrigerant	Type			R410A	R410A	R410A
	Charge at 7.5 m		g	950	950	1200
			t-CO₂ eq.	1.98	1.98	2.51
	Additional charge		g/m	20	20	20
	GWP			2087.5	2087.5	2087.5
Fan Motor Output			W	43	43	43
Compressor Type				1P Rotary	1P Rotary	Twin Rotary
Net Weight			kg	29	29	36.7
Dimension			mm	717*483*230	717*483*230	770*545*288

Appendix 5: PV specifications

www.jinkosolar.com

Tiger Pro 72HC

530-550 Watt

MONO-FACIAL MODULE

P-Type

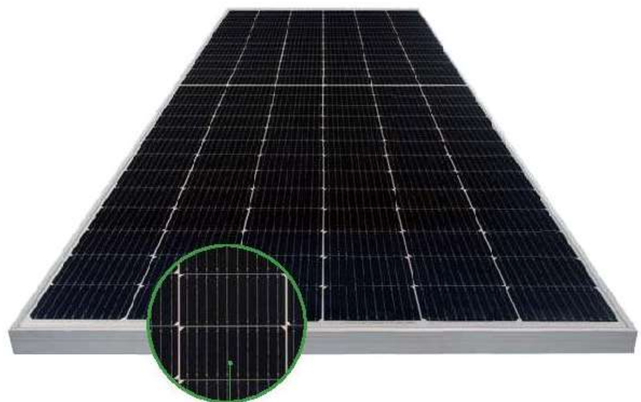
Positive power tolerance of 0~+3%

IEC61215(2016), IEC61730(2016)

ISO9001:2015: Quality Management System

ISO14001:2015: Environment Management System

ISO45001:2018
Occupational health and safety management systems



Key Features

Multi Busbar Technology
Better light trapping and current collection to improve module power output and reliability.

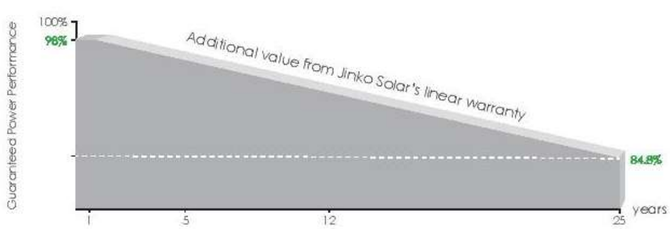
Durability Against Extreme Environmental Conditions
High salt mist and ammonia resistance.

Reduced Hot Spot Loss
Optimized electrical design and lower operating current for reduced hot spot loss and better temperature coefficient.

Enhanced Mechanical Load
Certified to withstand: wind load (2400 Pascal) and snow load (5400 Pascal).

Longer Life-time Power Yield
0.55% annual power degradation and 25 year linear power warranty.

LINEAR PERFORMANCE WARRANTY

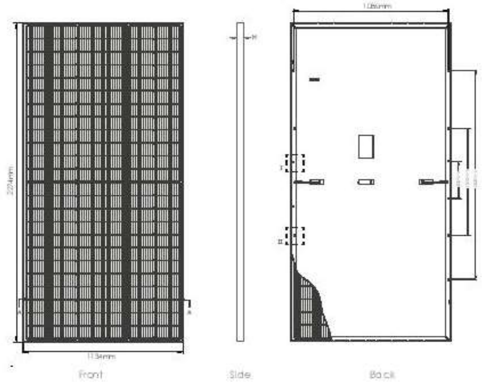


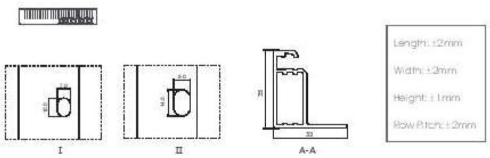
12 Year Product Warranty

25 Year Linear Power Warranty

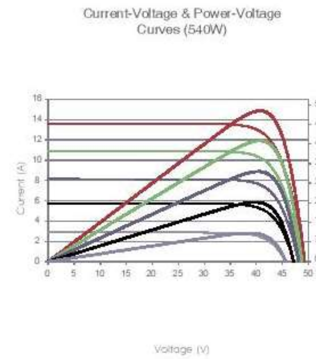
0.55% Annual Degradation Over 25 years

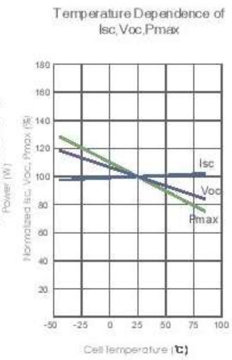
Engineering Drawings





Electrical Performance & Temperature Dependence





Packaging Configuration

(Two pallets = One stack)

31pcs/pallets, 62pcs/stack, 620pcs/ 40'HQ Container

Mechanical Characteristics

Cell Type	P type Mono-crystalline
No. of cells	144 (6×24)
Dimensions	2274×1134×35mm (89.53×44.65×1.38 inch)
Weight	28.9 kg (63.7 lbs)
Front Glass	3.2mm,Anti-Reflection Coating, High Transmission, Low Iron, Tempered Glass
Frame	Anodized Aluminium Alloy
Junction Box	IP68 Rated
Output Cables	TUV 1×4.0mm (+): 400mm , (-): 200mm or Customized Length

SPECIFICATIONS

Module Type	JKM530M-72HL4 JKM530M-72HL4-V		JKM535M-72HL4 JKM535M-72HL4-V		JKM540M-72HL4 JKM540M-72HL4-V		JKM545M-72HL4 JKM545M-72HL4-V		JKM550M-72HL4 JKM550M-72HL4-V	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	530Wp	394Wp	535Wp	398Wp	540Wp	402Wp	545Wp	405Wp	550Wp	409Wp
Maximum Power Voltage (Vmp)	40.56V	37.84V	40.63V	37.91V	40.70V	38.08V	40.80V	38.25V	40.90V	38.42V
Maximum Power Current (Imp)	13.07A	10.42A	13.17A	10.50A	13.27A	10.55A	13.36A	10.60A	13.45A	10.65A
Open-circuit Voltage (Voc)	49.26V	46.50V	49.34V	46.57V	49.42V	46.65V	49.52V	46.74V	49.62V	46.84V
Short-circuit Current (Isc)	13.71A	11.07A	13.79A	11.14A	13.85A	11.19A	13.94A	11.26A	14.03A	11.33A
Module Efficiency STC (%)	20.55%		20.75%		20.94%		21.13%		21.33%	
Operating Temperature(℃)	-40℃~+85℃									
Maximum system voltage	1000/1500VDC (IEC)									
Maximum series fuse rating	25A									
Power tolerance	0~+3%									
Temperature coefficients of Pmax	-0.35%/℃									
Temperature coefficients of Voc	-0.28%/℃									
Temperature coefficients of Isc	0.048%/℃									
Nominal operating cell temperature (NOCT)	45±2℃									

*STC: Irradiance 1000W/m² Cell Temperature 25℃ AM=1.5

NOCT: Irradiance 800W/m² Ambient Temperature 20℃ AM=1.5 Wind Speed 1m/s

JKM530-550M-72HL4-(V)-F1-EN

Geographical Site	**Amman**		Country	**Jordan**
Situation	Latitude	31.96° N	Longitude	35.93° E
Time defined as	Legal Time	Time zone UT+2	Altitude	950 m
	Albedo	0.20		
Meteo data:	**Amman**	NASA-SSE - Synthetic		

Simulation variant : New simulation variant

Simulation date 27/04/21 14h44

Simulation parameters	System type	**No 3D scene defined, no shadings**		
Collector Plane Orientation	Tilt	25°	Azimuth	0°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			
User's needs :	Unlimited load (grid)			

PV Array Characteristics

PV module	Si-mono	Model	**JKM535M-72HL4-V**		
Custom parameters definition		Manufacturer	Jinkosolar		
Number of PV modules		In series	10 modules	In parallel	1 strings
Total number of PV modules		Nb. modules	10	Unit Nom. Power	535 Wp
Array global power		Nominal (STC)	**5.35 kWp**	At operating cond.	4888 Wp (50°C)
Array operating characteristics (50°C)		U mpp	371 V	I mpp	13 A
Total area		Module area	**25.8 m²**	Cell area	23.8 m²

Inverter	Model	**SUN2000MA-4KTL-M0**		
Custom parameters definition	Manufacturer	Huawei Technologies		
Characteristics	Operating Voltage	160-980 V	Unit Nom. Power	4.00 kWac
Inverter pack	Nb. of inverters	1 units	Total Power	4.0 kWac
			Pnom ratio	1.34

PV Array loss factors

Array Soiling Losses			Loss Fraction	3.0 %
Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	464 mOhm	Loss Fraction	1.5 % at STC
Serie Diode Loss	Voltage Drop	0.7 V	Loss Fraction	0.2 % at STC
LID - Light Induced Degradation			Loss Fraction	2.0 %
Module Quality Loss			Loss Fraction	-0.8 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %

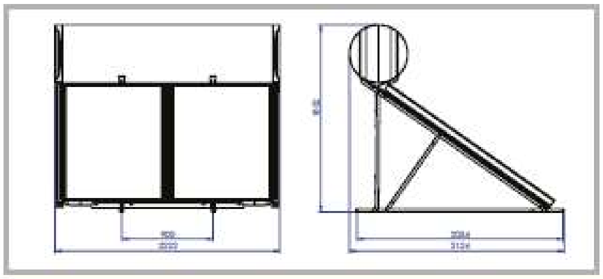
Incidence effect (IAM): User defined profile

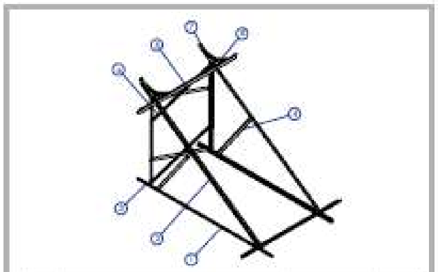
0°	30°	50°	60°	70°	75°	80°	85°	90°
1.000	1.000	1.000	0.999	0.988	0.965	0.925	0.743	0.000

Unavailability of the system 7.3 days, 3 periods Time fraction 2.0 %

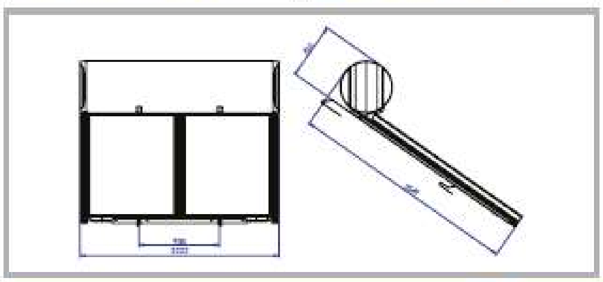
Appendix 6: Solar water heater

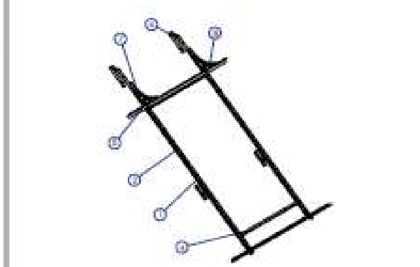
APOLLON 320lt/4m² LAYOUT





Nr.	PART NAME	DIMENSIONS	QTY.
1	Beam L (Laminate section 60 x 2.5mm)	2060 x 60mm	2
2	Beam L (Laminate section 60 x 2.5mm)	2250 x 60mm	2
3	Beam L (Laminate section 60 x 2.5mm)	1190 x 60mm	2
4	Beam L (Laminate section 60 x 2.5mm)	925 x 60mm	2
5	Collector Support	1500mm	2
6	Beam (Laminate section 33 x 2mm)	980mm	4
7	Boiler Support		2
8	Plastic Cover for Supporting Strips (Slab)		2
9	Hexagon Head Bolt M8	M8x16	40
10	Hex Nut M8		32
11	Washer	Ø8	8
12	Bolt M8 x 60		4
13	Upat D10		4
14	Hexagon Head Screw with Washer		4





Nr.	PART NAME	DIMENSIONS	QTY.
1	Beam L (Laminate section 60 x 2.5mm)	2060 x 60mm	2
2	Beam L (Laminate section 60 x 2.5mm)	2250 x 60mm	2
4	Beam L (Laminate section 60 x 2.5mm)	925 x 60mm	2
5	Collector Support	1500mm	2
6	Beam (Laminate section 33 x 2mm)	980mm	4
7	Boiler Support		2
8	Plastic Cover for Supporting Strips (Slab)		2
9	Hexagon Head Bolt M8	M8x16	32
10	Hex Nut M8		24
11	Washer	Ø8	8
12	Hexagon Head Screw with Washer		4

TOTAL SYSTEM	APOLLON 320lt/4m²
NUMBER OF COLLECTORS	2
SYSTEM WEIGHT EMPTY / FULL (kg)	231 / 581
MAX WATER TANK OPERATING PRESSURE (bar)	8
CLOSED CIRCUIT MAX OPERATING PRESSURE (bar)	3,5

WATER STORAGE TANK	320lt
DIMENSIONS (mm)	580x2210
WEIGHT EMPTY (kg)	118
JACKET CAPACITY (lt)	26
JACKET SURFACE (m²)	2.14
MAX TEST PRESSURE (bar)	12
MAX OPERATING PRESSURE (bar)	8

COLLECTOR	APOLLON AL 2000
TOTAL AREA (m²)	2.03
NUMBER OF MANIFOLDS	10
HEAT TRANSFER MEDIUM	PROPYLENE GLYCOL SOLUTION
CAPACITY (lt)	1.75
ABSORBER SURFACE (m²)	1.81
TOTAL DIMENSIONS (mm)	2010x1010x110
COLLECTOR TOTAL WEIGHT (without liquid) (kg)	38
ABSORBER	SELECTIVE ALUMINIUM
ABSORBENCY / RADIATION COEFFICIENT	95% ±2% / 5% ±2%

Note: All dimensions measured in mm

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