EXPLORING THE PASSIVE HOUSE FRAMEWORK IN COOLING-DOMINATED CLIMATES

Damiloju L. Adeyina

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Department of Mechanical Engineering
Faculty of Design and Creative Technologies
Auckland University of Technology
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ABSTRACT

The energy used in buildings, primarily for heating and cooling, represents approximately 1/3 of the world's energy use. In many locations, this is unsustainable as the current energy sources used are non-renewable and often linked to global warming and climate change. This is why it is important to study the Passive House concept (Passivhaus), and certification framework established in 1996. Passive Houses have been reported to save between 70 - 90% of the energy typically used in (residential) buildings, whilst maintaining acceptable comfort conditions. However, whilst such buildings have been demonstrated in heating-dominated climates such as northern and central Europe; there appears to be limited development of the concept in cooling-dominated climates (climates that require significantly more cooling than heating), where approximately 40% of the world's population currently live.

Considering this, this study set out to explore how the Passive House concept might behave in cooling dominated climates. Using computational simulations, the study showed that a certified Passive House could not simply be adopted from another climate and that a Passive House must be designed for the specific climate in which it will be located. Subsequently, parametric computational analyses sought to achieve a Passive House in cooling-dominated climates by implementing four main strategies (super-insulation, highly performance glazing, airtightness, and mechanical ventilation with 'heat' recovery).

It was shown that super-insulation and low-thermal transmission windows could result in energy savings of approximately 30% due to reduced heat transfer. Furthermore, it was shown that such savings could be achieved whilst maintaining comfort conditions considered acceptable to ASHRAE 55. Conversely, airtightness was found to have no significant effect on energy due to the minimal differences in outdoor and indoor temperatures in predominantly hot climates (with no heating requirement). It can, however, ensure a stable thermal condition in a conditioned building.

Furthermore, ensuring the peak load does not exceed 10W/m^2 (a requirement of the Passive House certification), a mechanical ventilation system with ‘heat’ recovery at an average ventilation rate of 1 ACH could be sufficient to maintain acceptable comfort conditions and save up to 50% of the energy used in high-performance buildings. Otherwise, a conventional heating, ventilation, and air conditioning system (HVAC) would be required to maintain thermal comfort range and prevent overheating. Additionally, whilst not considered a primary strategy in heating-dominated climates, it was shown that minimising internal heat gain is a significant factor in meeting the Passive House standard in cooling-dominated climates.

In summary, the research has shown that achieving the Passive House standard in some cooling-dominated climates can be challenging due to extreme weather conditions (i.e., high solar insolation) for most of the year. That said, buildings that incorporate Passive House strategies such as super-insulation, highly insulated windows, and minimal internal heat gain, combined with other strategies such as shading, building orientation, and thermal mass, can save up to 70% of their energy whilst maintaining acceptable comfort conditions.

In conclusion, this work suggests that the Passive House standard could be enhanced with consideration for cooling-dominated climates (PH-CDC). This might include setting a target of saving at least 70% energy when compared to a reference building/s in the specific climate, whilst also requiring it to maintain acceptable comfort conditions throughout the year. Such a modification would ensure energy efficiency and thermal comfort are the metrics, rather than an impractical or generalised kWh/(m^{2}a) or W/m^2 metric.

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LIST OF ABBREVIATIONS

ACH	Air changes per hour
CFM50/sf	cubic feet per minute at 50 pascals, per square foot of building enclosure surface area
c_P	Specific heat capacity of air at constant pressure (J/kg/K)
hr	heat transfer coefficient
HVAC	Heating, Ventilation and Air conditioning;
I_{beam}	Solar flux (W/m^2)
I_{dir}	Direct solar flux (W/m^2)
$J{\cdot}kg^{-1}{\cdot}K^{-1}$	Thermal capacity
kg/m^3	Density
$kJ/(m^2K)$	Thermal mass
kWh	Kilowatt hour
$kWh/(m^2yr)$	Kilowatt hour per square metre yearly
m	Air mass flow rate (kg/s)
m^3/h	Volume per hour
PCTu	Predictive Comfort Temperature
PH	Passive House
PHI	Passive House Institute
PHPP	Passive House Planning Package
PPD	Predicted Percentage of Dissatisfaction
Q	Net heat flow (W)
QH	Heating demand (kWh/a)

QI	Internal heat gains (kWh/a)
QS	Solar heat gains (kWh/a)
QT	Transmission heat losses (kWh/a)
QV	Ventilation heat losses (kWh/a)
T	Temperature
Ta	Room Mean Air Temperature (^{o}C)
Ti	Supply Temperature (^{o}C)
T_{MRT}	Mean Radiant Temperature
Ts	Surface Temperature
U-$value$	Thermal transmittance (W/(m^{2}K))
V	Volume (m^3)
W	Heat flux (W/m^2)
W/m^2	Watt per square metre
η	utilization factor
θ	Angle of incidence
λ	Conductivity W m^{-1} K^{-1}
ρa	Air density (kg/m^3)

ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgments), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Auckland University of Technology Signature_________________

Damiloju Lydia Adeyina

PUBLICATIONS

The following publications have been derived in whole or in part from the work contained within this thesis.

Conference Papers:

Adeyina, D., Anderson, T., & Ghaffarian Hoseini, A. (2021). A Parametric Study of Passive House Design in a Sub-tropical Climate. *Asia-Pacific Solar Research Conference*.

Adeyina, D., Anderson, T., & Ghaffarianhoseini, A. (2022). A Parametric Study of Passive House Strategies in a Cooling Dominated Climate – A Case Study of Algeria. In W. M. Shahzad, E. O. Rasheed, & J. O. B. Rotimi (Eds.), *7th New Zealand Built Environment Symposium (NZBERS)*. The Architectural Science Association (ANZAScA).

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1 Introduction

1.1 Overview

Buildings are essential to our everyday existence, they provide a place of rest, for social gatherings, work, and other physical activity. In fact, approximately 90% of a person's life is spent in buildings (Al horr et al., 2016; Kraus & Šenitková, 2017; Horve et al., 2020). So, in addition to establishing psychological and physical barriers to the environment, they are expected to shield their occupants from weather conditions, such as temperature, wind, humidity and precipitation, which can sometimes be extreme. For instance, the temperature in Romania could go from as low as -35ºC to as high as +40ºC (Dabija, 2006). Therefore, designing a space where the occupant(s) feels a sense of comfort (not too hot or too cold) regardless of the outdoor weather conditions is one of the most critical aspects of building design. This phenomenon which expresses one's satisfaction with the thermal environment, is known as thermal comfort (ASHRAE 55; Md Din et al., 2014; Attia & Carlucci, 2015).

Over the years, building architecture has attempted to address thermal comfort in various ways. In ancient times, simple huts were built in hot climates to provide shelter from the scorching sun (Widera, 2021) (*Figure 1-1, left*) and solid structures in cold climates to keep the heat in (Hoof & Dijken, 2008) (*Figure 1-1, right*).

Figure 1-1: Dagomba House (Left) (Shepherd, 2007), *Traditional Turf House Iceland (Right)*(Chapman, n.d.)

Environmental energies (such as wind and solar) and architectural elements were also used to manage the indoor thermal environment. The architectural features include the shape of roofs (using dome & arched roofs instead of flat roofs); walls (massive and thick walls), materials (including clay, unfired clay bricks, stone, brick, mortar, lime and timber); Godal Baghcheh (lower courtyard); window; and wind tower (badgir). Ventilation was natural and controlled by the building's orientation and placement of windows to catch the prevailing breezes. High ceilings and large open central staircases with ventilated domes also contributed to ventilation (Amirkhani et al., 2010; Hughes et al., 2012; Oxlade, 2012; Matthias Hiebert, 2013; Ionescun et al., 2015; Moldovan et al., 2015; Sangdeh & Nasrollahi, 2022). However, according to Rosenlund (2000), these buildings did not achieve consistent comfort at all times of the day or in all seasons.

One of the early important works that looked at creating comfortable indoor environment, was done by Victor Olgyay and documented in his book, Design with Climate: Bioclimatic Approach to Architectural Regionalism (1963). In his work, Olgyay identifies solar architecture and passive architecture and bioclimatic architecture as design solutions for creating comfortable indoor space in different climates (Olgyay et al., 2015). However, Reyner Banham (Banham's famous collage of an "Environmental Bubble" originally published in Art, 1965) predicted the unavoidable vital role of machinery in building systems to achieve comfort (Napier, 2015; Kallipoliti, 2018); and with the advancement of technologies in air conditioning, humidifiers, and other devices for regulating interior climate in the early 1960s (Kallipoliti, 2018). In the 20th century, the use of mechanical systems to condition buildings using mechanical heating, cooling, and air conditioning (in other words, active systems) for domestic purposes, became widespread (Nicol & Roaf, 2017; Schoenefeldt, 2022).

Today, building occupants rely heavily on mechanical systems for comfort, accounting for approximately 40% of global energy consumption, 40% of which is used for heating and cooling purposes (Yang et al., 2014; International Energy Agency and the United Nations Environment Programme, 2018). This is not sustainable because the primary source of energy generation (fossil fuels) is constrained, and their use has been found to contribute significantly to climate change (Omer, 2008; Höök & Tang, 2013; Lechner, 2014; Johnsson et al., 2019). Hence, in the face of rising energy demand and population growth, buildings must seek ways to maintain thermal comfort without relying heavily on mechanical systems. This is where the Passive House concept has gained traction today.

1.2 Passive House

In 1998, at the 2nd International Passive House Conference in Düsseldorf, "Passive Houses were defined as buildings which have an extremely small heating energy demand even in the Central European climate and therefore need no active heating. Such houses can be kept warm "passively", solely by using the existing internal heat sources and the solar energy entering through the windows as well as by the minimal heating of incoming fresh air" (Feist, 2020).

Passive House, or "Passivhaus" (the original German term) is often defined as "a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions—without the need for additional recirculation of air" (Berge & Mathisen, 2015; Guillén-Lambea et al., 2016; Susanne Theumer (Passivhaus Institut), 2018); Alejandro Moreno-Rangel, 2021).

The term "Passive House" is frequently used interchangeably with "passive design," which describes the use of strategies such as orientation, thermal mass, shading, material selection, insulation, internal layout, window size and direction, and natural ventilation to manage buildings indoor conditions (Lechner, 2014; Kim et al., 2018; Yao et al., 2018). Or passive solar building, which focuses on collecting, storing, and reflecting solar energy from windows, walls, and floors, distributing its heat in the winter and rejecting it in the summer (Bainbridge & Haggard, 2011; Gong et al., 2022; Hachem-Vermette, 2020). However, these concepts differ from Passive House in that Passive House refers to an energy efficiency standard for buildings that reduces their ecological footprint while maintaining an optimal level of thermal comfort (Elsarrag & Alhorr, 2012; Proietti et al., 2013; Chen et al., 2015; Foster et al., 2016; Yao et al., 2018; Tran et al., 2021). Whilst some of the aforementioned strategies can be instrumental in achieving a Passive House, their implementation does not certify a building as a Passive House, which forms the central pillar of this study.

1.2.1 History of Passive House

The genesis of Passive House can be traced to a polar ship, “Fram”, designed in 1883 (*Figure 1-2*). As described by Nansen & Lieut. Sverdrup (2020), “the sides of the ship were lined with tarred felt, then a space with cork padding, next a deal panelling, then a thick layer of felt. Next is airtight linoleum and, last of all, an inner panelling. The skylight most exposed to the cold was protected by three panes of glass, one within the other. The ventilation is excellent, especially since we rigged up the air sail, which sends a whole winter’s cold in through the ventilator” (Passivhaus Institut, 2019).

Figure 1-2:The Research Ship "Fram"(Passivhaus Institut, 2019a).

This design resulted in a thermally comfortable ship; as Fridtjof Nansen (captain of the ship) reports, "The Fram is a warm, cozy abode. Whether the thermometer stands at 22° above zero or 22° below it, we have no fire in the stove. The ventilation is excellent. I am thinking of removing the stove; it is only in the way" (Nansen & Lieut. Sverdrup, 2020). The ship's thermal comfort accomplishment demonstrated that a comfortable indoor environment could be achieved with little or no active mechanical system.

This point was further reinforced with the actualisation of other low-energy buildings, which were noted to require little or no active heating or cooling, such as the DTH zero-energy house built at the Technical University of Denmark in 1973, the first zero-energy house (Burford & Pearson, 2013). The building integrated strategies such as super-insulation, an air-to-air heat exchanger with 80% efficiency, double panel windows, and solar collectors with a water storage tank. Air infiltration in the envelope was considered at values of 0.03 - 0.15 h^{-1} (Ionescun et al., 2015).

Similarly, the Philips Experimental House, built in Germany in 1974, incorporated thermal insulation of walls and windows equipped with ground heat exchangers, controlled ventilation, and solar and heat pump technology ((Bruno et al., 1978; Coma Bassas et al., 2020).

The Saskatchewan Conservation House built in 1977, is believed to be one of North America's first conservation demonstration houses (Wallace, 2018). The house, which is still occupied, demonstrated the benefits of superinsulation and was designed to provide 100% solar space heating in a cold climate. Heating was primarily by passive solar gain and internal heat generation from normal electricity usage and people (Besant et al., 1979; Paehlke, 1981; Wallace, 2018).

According to the Passivhaus Institut (2019a), these constructions laid the foundation for what is now referred to as Passive Houses. Critical lessons were learnt from the low-energy houses, such as the importance of insulation, airtightness, and high-performance windows. In 1991, using the combination of academic and theoretical principles, the world’s first passive house was built by a team in Darmstadt-Kranichstein, Germany, led by Wolfgang Feist (Feist, 2015).

1.2.2 The First Passive House

The first Passive House design (Feist, 2015), was accomplished by using computer simulations to systematically vary the building’s components (insulation, airtightness, window size, glazing quality, internal gain, orientation, and ventilation system). This resulted in a building design that achieved a heating load of 10 W/m^2 of floor area and an energy balance of 10.5 $kWh/(m^2a)$ based on the design parameters shown in *Table 1.1*.

Table 1.1: Design Feature of the Passive House in Darmstadt-Kranichstein (Feist, 2020)

Building component	**Description**	**U-value W/(m²K)**
Roof	Grass roof: Humus, non-woven filter, root protective membrane, 50 mm formaldehyde-free chipboard; Wooden light-weight beam (I-beam of wood, stud link of hardboard), counter lathing, sealing with polyethylene sheeting bonded without jointing, gypsum plasterboard 12.5 mm, wood-chip wallpaper, emulsion paint coating, entire cavity (445 mm) filled with blown-in mineral wool insulation.	0.1
Exterior wall	Fabric reinforced mineral render. 275 mm of expanded polystyrene insulation (EPS) (installed in two layers at that time, 150+125 mm). 175 mm sand-lime brick masonry. 15 mm continuous interior gypsum plastering; wood-chip wallpaper, emulsion paint coating	0.14
Basement ceiling	Surface finish on fibreglass fabric. 250 mm polystyrene insulation boards. 160 mm concrete. 40 mm polystyrene acoustic insulation. 50 mm cement floor finish. 8-15 mm of parquet, adhesive. sealing solvent-free	0.13
Windows	Triple-pane low-e glazing with Krypton filling: Ug-value 0.7 W/(m²K). Wooden window with polyurethane foam insulated framework (CO_2-foamed, HCFC free, handcrafted)	0.7

Heat recovery ventilation	Counterflow air-to-air heat exchanger. Located in the cellar (approx. 9°C in the winter), carefully sealed and thermally insulated, the first one to use electronically commutated DC fans.	heat recovery rate approx. 80%
Airtightness	Air change rate (n50-value)	<0.3 h^{-1}
Thermal bridge-free construction.		

The building is a row of houses, with each accommodation unit having a floor area of 156m^2 occupied by four families (Badescu & Sicre, 2003; Feist, 2014). According to Feist (2014), the building is no different from a conventional building in that no further elements were required to construct the building. Except that the components (floors, outer walls, windows, roofs and ventilation) were of higher quality, and typical of those used in low-energy houses (*Figure 1-3***)**.

Southern view Northern view

Figure 1-3: Passive House in Darmstadt-Kranichstein (Passivhaus Institut, 2019a) *(Feist, 2020).*

1.2.2.1 Performance of the First Passive House

Based on the design of the first Passive House, the building's measured energy consumption was as follows:

- Annual space heating consumption: 11.9 kWh/(m^2 a).
- Hot water: 6.1 kWh/(m^2 a).
- Gas for cooking: 2.6 kWh/(m^2 a).
- Total electricity consumption, including all household applications: 11.2 kWh/(m^2 a) (Schnieders et al., 2015).

This is comparable to the building's simulation value of 10 kWh/(m²a) (Feist, 2020), implying energy savings of about 90% when compared to the conventional building stock, as shown in *Figure 1-4***.**

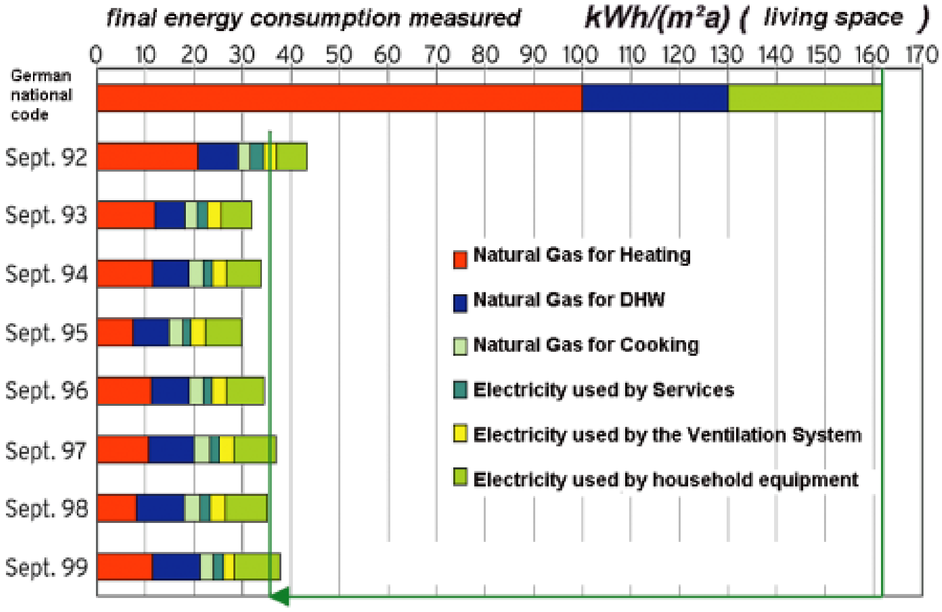


Figure 1-4:Results of the Energy Consumption Measurements in the Passive House in Darmstadt-Kranichstein (Feist, 2020).

Regarding the building's thermal conditions, a thermographic image of the interior surface (*Figure 1-5)*, showed that the surface temperature is high ranging between 22 and 24°C.

Moreover, field measurements, user surveys, and continuous monitoring of indoor air quality have all confirmed the building's high level of thermal comfort (Schnieders & Hermelink, 2006).

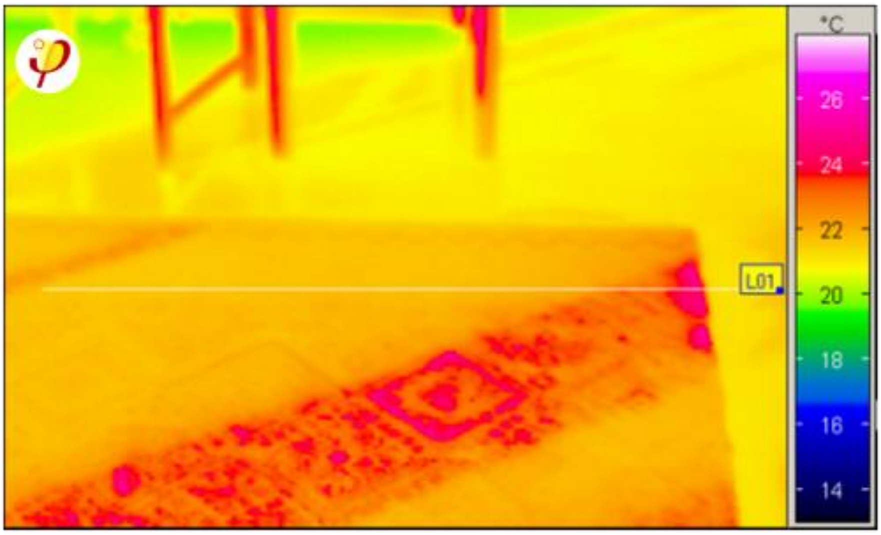


Figure 1-5:Thermographic image of the interior of the First Passive House Wolfgang Feist (2020)

1.3 The Passive House Framework

Following the success of the first Passive House in achieving energy efficiency and thermal comfort, the Passive House Institute (PHI) was established in 1996 as an independent research institute responsible for developing the Passive House framework. The institute was responsible for establishing the Passive House concept, which highlights five fundamental strategies necessary to achieve the Passive House standard: *Super-insulation*, *Thermal bridge free design, Airtight construction, mechanical ventilation systems with heat recovery (MVHR)) and highly insulated window*s, (*Figure 1-6*) (Müller & Berker, 2013; Johnston et al., 2020).

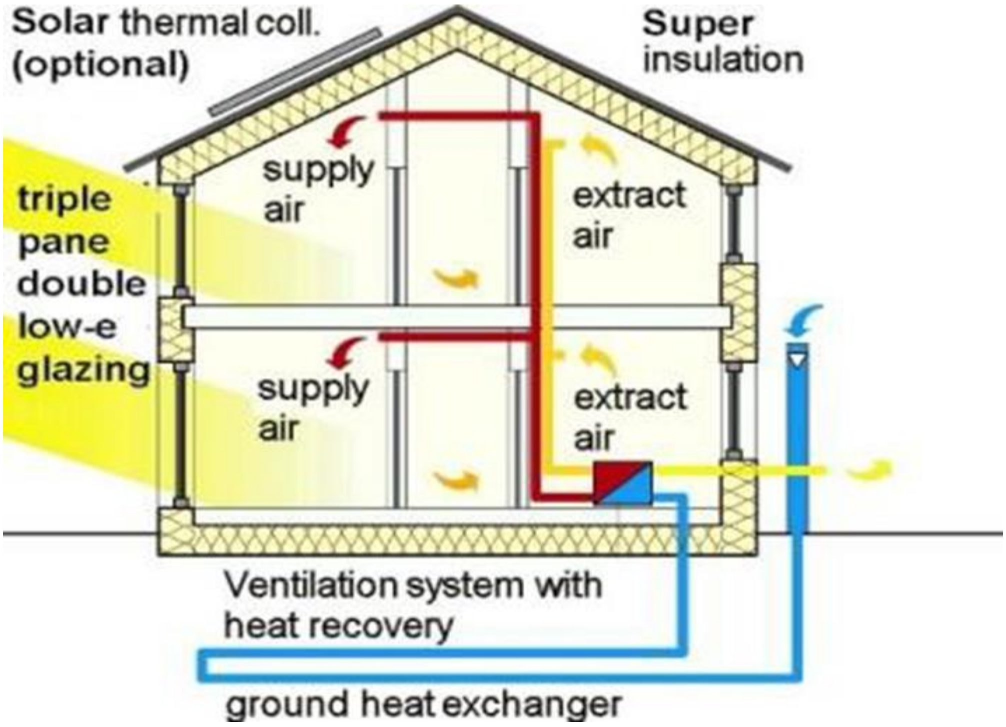


Figure 1-6:Standard Passive House (Passipedia, 2020)

1.3.1 The Passive House Strategies

1.3.1.1 Super Insulation:

Superinsulation is a strategy used in Passive House to achieve its energy efficiency and thermal comfort standard (Wang et al., 2017). Several studies have investigated superinsulation in buildings. For instance, Al-Homoud (2004) studied the effectiveness of thermal insulation in various types of buildings in hot climates. The study found that thermal insulation in building walls and roofs reduced the size of the required air-conditioning systems and annual energy costs. The study also suggests that it helps to extend thermal comfort periods without relying on mechanical air conditioning, particularly during inter-seasonal periods.

Also, in a study by Urban & Roth (2010), it was pointed out that insulation reduces heat losses and gains through the roof in ways other strategies, such as reflective surfaces, cannot. This point was corroborated by Abuseif & Gou (2018), who stated that a typical uninsulated timberframed house in New Zealand loses 30-35% of its heat through the roof. Uninsulated homes in the United Kingdom lose about 25% of their heat, while uninsulated homes in Canberra experience about 40% heat loss. Therefore, super insulation can contribute to keeping the indoor environment pleasantly cool by keeping the heat outside in the summer and inside in the winter.

Accordingly, Passive House uses superinsulation to reduce the thermal transmittance (U-values) of the building envelope (building fabrics, windows, and doors), reducing heat transfer to and from the building and, as a result, delivering high levels of energy efficiency due to lower heating and cooling demand. It is recommended that the building envelope has a low thermal transmittance (U-values), typically in the range of 0.10 to 0.15 W/(m^{2}K) (Johnston & Siddall, 2016), achievable with a wide variety of thermal insulating materials (from strawbale to batts, Structural Insulated Panels (SIP) to Vacuum Insulated Panels (VIP). It is noted that the type of insulation (blanket, rigid, or loose-fill) and material (i.e., glass-fibre, wool, polyester) used in each part of the building can vary depending on client preference, construction type (i.e., timber frame or concrete), and which part of the building envelope is being insulated. However, most studies agree that the most important thing is to keep the heat transfer coefficients of the envelope as low as possible (Almusaed, 2011; Jelle, 2011; Wang et al., 2017; Hailu, 2021).

Passivhaus Institut (2021a) also adds that the thickness of the insulation layer will depend on the form of the buildings, environmental factors, and the type of insulation used. For example, 90 mm of typical wall insulation may suffice for a compact, multi-storey apartment building in Auckland (Passive House Institute New Zealand, 2017; Ministry of Business Innovation & Employment (MBIE), 2021). But in Sweden, to achieve Passive House standards, the insulation thickness would be 335 mm (0.10 W/(m^{2}K)) and the roof 500 mm (U- value 0.066

W/(m²K)) as seen in Passive House school Högåsskolan in Knivsta in Sweden (Imbabi, 2012; Petra Vladykova Bednarova, 2016).

1.3.1.2 Advanced Window Technology:

Another Passive House strategy is to use advanced window technology. Windows are critical for passive indoor climate control depending on their orientation and the prevailing climate conditions. They can let in too much sunlight, causing overheating, just enough to balance the indoor temperature, or not enough, resulting in a heat deficit (Gupta & Gregg, 2020).

Passive House recommends installing highly insulated windows to meet the Passive House standard. The windows are typically thermally broken, airtight, and usually triple glazed (with a good solar heat-gain coefficient, low- emissivity coatings, with the gaps between glass panes filled with argon or krypton gas to reduce heat transfer) (Klingenberg, 2020). The overall window will have a low U-value (typically 0.85 to 0.70 W/(m²K) for the entire window, including the frame) (Johnston & Siddall, 2016).

These Passive House windows are designed to maximise solar gain while naturally minimising heat loss. The objective is to obtain the most energy with the least effort or cost and then maintain it due to the excellent insulation.

1.3.1.3 Airtight Construction:

Passive House also emphasises the need for an airtight construction. Airtightness is defined as the amount of air leakage or infiltration in a building. Gap leaks account for up to 20% of heat loss in buildings and one-third of heat loss in well-insulated structures (Gillott et al., 2016). The most common sources of uncontrolled air leakage are poorly installed suspended floors, ventilation systems, doors, windows, services (pipes and ducts), and internal partitions, as well as poorly designed construction systems and small cracks and holes in the building envelope (Sayigh & Marafia, 1998; Jaggs & Scivyer, 2009; Alejandro Moreno-Rangel, 2021). So, to prevent cold air from entering (and warm air from escaping) uncontrollably through unseen gaps and cracks. Passive House recommends that buildings be airtight to eliminate draughts and allow total control over how much air is let into the building through controlled ventilation systems (with heat exchangers) to achieve energy efficiency and comfort.

Building envelopes under the Passivhaus standard must be extremely airtight compared to conventional constructions. Passive House buildings are required to meet either 0.60 ACH50 (air changes per hour at 50 pascals) based on the building's volume or 0.05 CFM50/sf (cubic feet per minute at 50 pascals per square foot of building enclosure surface area) (Truong & Garvie, 2017; Langmans et al., 2010; Borrallo-Jiménez et al., 2022). To achieve this, Passipedia (2015) recommends that the air barriers (or airtightness line) be continuous and joined up to form a complete loop (*Figure 1-7***)**, that every construction joint in the building envelope is carefully sealed, and that all service penetrations are sealed. Every construction joint may or may not be made of the same material, but it must be continuous and joined together.

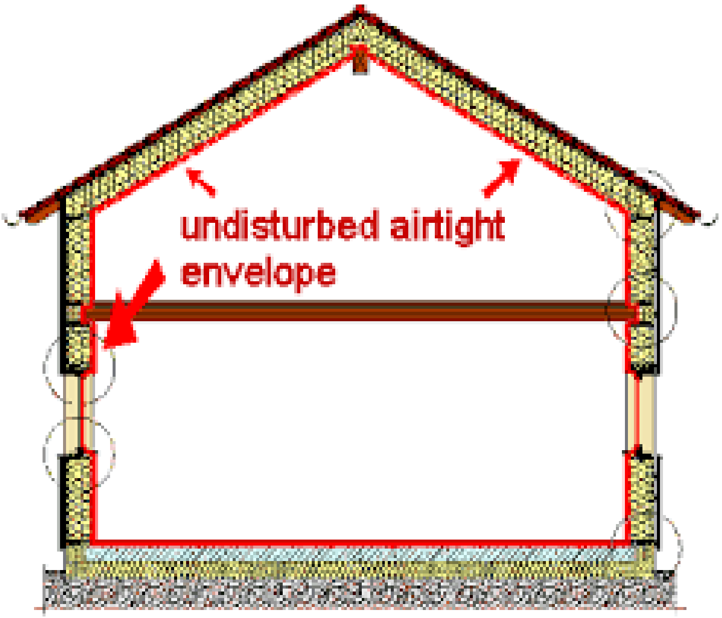


Figure 1-7: Airtight Envelope (Passivhaus Institute, 2019)

Some typical materials used for airtight construction include wet plaster on masonry construction, reinforced concrete, Oriented Strand Board (OSB) of a suitable thickness, and specifically designed airtight membranes. Furthermore, the materials used to construct the building fabric, windows, doors, curtain wall systems, and roof lights must be airtight. In order to achieve the required airtightness levels, air barriers that seal construction joints and penetration across the envelope are also required (Passivhaus Institute, 2019).

The framework recognises that irrespective of the attention to detail when designing and constructing the building, penetrations through the air barrier are possible, so to ensure a building meets the set standard, at mid-construction, the building air barrier enclosure is required to be tested with a blower door (Bohac & Harrington, 2020; Delgado et al., 2021).

1.3.1.4 Heat Recovery Ventilation:

A mechanical heat recovery ventilation system is another strategy the Passive House uses to achieve an energy-efficient, thermally comfortable house. Ventilation is critical in achieving thermal comfort and a healthy indoor environment.

Generally, buildings must have an adequate ventilation system in order to provide oxygen to occupants and remove contaminants from the human body (carbon dioxide, ammonia, benzene, methane, etc.). It is also required to remove chemicals that may remain in building materials and furnishings for many years after installation and remove excess humidity generated by regular human activity (cooking, bathing) (Kukadia & Upton, 2019). Therefore, ventilation in a building is vital and can be achieved naturally, mechanically, or through a hybrid system (mechanical and natural).

Natural ventilation is a low-energy strategy used in many building types (Sharpe et al., 2021). It can sometimes help to achieve a comfortable indoor temperature without using a mechanical system through singular or cross-ventilation from simple openings or enhanced by the stack effect from more minor ingress with more oversized egress windows and/or clerestory-operable skylights (Hughes et al., 2012; Wang et al., 2017). However, because natural ventilation depends on the local climate, the indoor environment suffers when the weather is unfavourable. Thus, Passive House recommends using a mechanical system with at least 80% heat recovery (Dodoo et al., 2011; Wang et al., 2020).

Heat recovery systems typically recover about 60–95% of the heat in the exhaust air and have significantly improved the energy efficiency of buildings (Kamendere et al., 2014; Justo Alonso et al., 2015). It consists of ducts for incoming fresh air, outgoing stale air, and a heat exchanger core. The system's operation transfers heat from one stream to the other, using two blower fans, one to exhaust stale air and the other to supply fresh air through the heat exchanger core. The exhausted air primarily preheats or cools (depending on the season) the fresh air stream before it is delivered to the building. The incoming and outgoing air passes by each other but does not mix in the heat exchanger. As a result, the recovery system reduces the heat content of the air supply during warm weather and increases it during cold weather. The system performs filtration, purification, circulation, and heat recovery (Mardiana-Idayu & Riffat, 2012).

1.3.1.5 Thermal Bridge free construction:

In addition to the previously mentioned strategies, Passive House also pays attention to thermal bridges. According to Rajat Gupta (2018), thermal bridging, both repeating and non-repeating, can account for 20-30% of total heat loss in a new building as heat travels by taking the path of least resistance from a higher to a lower temperature space.

Thermal bridge can occur in a building when there is a significant change in the thermal resistance of part of the building envelope compared to its surroundings (i.e., the presence of materials with a higher thermal conductivity, a change in the geometry of the fabric, as in the case of the junction between roofs, floors, ceilings and walls) (Evola et al., 2011). The most common type of thermal bridge is "constructional," in which a construction material penetrates the insulation. Others include geometric thermal bridges caused by the building's shape (i.e., corners), structural connections or insulation installation. Linear thermal bridges are caused by a gap between two pieces of insulation or where one building material meets another (Cotterell & Dadeby, 2012; Alejandro Moreno-Rangel, 2021).

Thermal bridges can result in heat loss, internal condensation, and dampness in the building envelope as heat is transferred between indoors and outdoors (Hanafi et al., 2018). In Passive House buildings, thermal bridges cause condensation and become a source of unquantified thermal losses, which could be as high as 50% of the heat transmission depending on the indoor air temperature, the surface temperature of walls or windows, and air moisture content (Schnieders, 2003; Šadauskien˙ et al., 2015; François et al., 2021). To achieve thermal bridge-free construction, the Passive House Institute (PHI) (2018) recommends careful planning for the connections between building components, intermediate ceilings, and foundations (Sadineni et al., 2011).

Moreno-Rangel, (2021) concludes that by correctly applying these Passive House principles, the indoor environment, particularly the indoor air quality, is guaranteed to achieve a high level of comfort. Energy-efficient electric appliances and lighting are also essential to achieve the low-primary energy demand required to meet the Passive House standards.

1.3.2 The Passive House Standard

A building is certified as a Passive House based on adherence to the following standard as highlighted in Borrallo-Jiménez et al. (2022);

- Space Heating Demand - not to exceed 15 kWh annually OR 10W (peak demand) per square metre of usable living space.
- Space Cooling Demand - roughly matches the heat demand with an additional, climate-dependent allowance for dehumidification.
- Primary Energy Demand - not to exceed 120 kWh annually for all domestic applications (heating, cooling, hot water, and domestic electricity) per square metre of usable living space.
- Airtightness - a maximum of 0.6 air changes per hour at 50 Pascals pressure (verified with an onsite pressure test in both pressurised and depressurised states).
- Thermal comfort - must be met for all living areas year-round, with not more than 10% of the hours in any given year over 25°C (*Table 1.2*).

Table 1.2:The Passive House Standard according to the PHI.

Energy Demand	**Standards**
Heating energy demand	≤ 15 kWh/(m^{2}a)
Or Building heating load	≤ 10W/m^2
Useful cooling demand	≤ 15 kWh/(m^{2}a)
Primary energy demand	≤ 120 kWh/(m^{2}a)
Excess temperature frequency	$\leq 10\%$
Airtightness	$n50 \leq 0.6/h$
Heat protection (thermal bridge free)	$U \leq 0.15$ W/(m^{2}K), $U_w \leq 0.8$ W/(m^{2}K)
Triple-glazing	$U_g \leq 0.8$ W/(m^{2}K), g-value 50-55%
Ventilation with $\geq 75\%$ heat recovery	

1.4 Passive Houses in Different Climates

Since establishing the framework, Passive House has gained popularity, with over 60,000 residential and non-residential units certified according to Passive House Institute certification criteria (Passipedia, 2018; The International Passive House Association (iPHA), 2021; Passive House Institute (PHI), 2022). The theoretical and practical success of the first Passive House in Germany (with warm temperate summers and cold winters and extreme temperatures sometimes reaching -10° C (5°F) in winter and 35° C (95° F) in summer months) has generated interest in Passive House study and implementation for different locations similar to the initial climate region, but also differing climates. Generally, the Passive House standard is currently considered one of the preferred energy-efficient stanard for architects and researchers in many countries (i.e., Germany, Switzerland, Austria, and Central Europe). Hence, interest in Passive House design continues to grow (Passive House Institute (PHI), 2018).

An extensive analysis of Passive House in South West Europe (with a distinctive Mediterranean climate) was carried out by Schneider (2009) to investigate the performance of Passive House in warmer climates where hot and possibly humid conditions are experienced in the summer. The Mediterranean climate is predominately a heating-dominated climate; however, the warmer and humid conditions experienced in the summer are factors that were examined. Using computer simulations, the study highlighted a few adjustments to the original design of the first Passive House required to achieve the best result in Southwest Europe. It was observed that due to the higher level of solar radiation, single glazing was used on the south facade of the building to provide sufficient solar gain required during heating periods. It also pointed out that orientation has a significant influence on meeting heating demand in the Mediterranean climate of Europe compared to the Passive House in Germany. The study also highlighted the role of shading, and how it can increase the heating demand in winter if not properly managed. Additionally, due to the high humidity of this region, the potential for night ventilation in this region is diminished. However, it was reported that utilizing Passive House strategies, depending on the ventilation technique applied, resulted in thermal comfort at a steady 26°C and, in other cases, reaches an uncomfortable 30°C. It was also noted that the Passive House had a steady temperature pattern compared to a typical conventional building (where the temperature patterns depict the external temperature with high fluctuations).

Following this study, Echarri-Iribarren et al. (2019) applied the Passive House standard in Spain (40.4637° N, 3.7492° W), South West of Europe, evaluating the impact of building envelope heat flows and air infiltration, especially in summer, on the annual energy demand. This is crucial due to high relative air humidity levels and solar radiation in this region. The designed Passive House was constructed, focusing largely on the thermal behaviour of the façade enclosure and the airtightness of the building. Subsequently, using a simulation tool to determine the impact of both parameters on the energy demand; the overall result showed that the annual energy demand of Passive House was 69.19% below the usual value for the buildings in the region. It was concluded that very thick thermal insulation and low airtightness values applied to the building envelope have a significant effect in winter where the annual energy demand is below 15 kWh/(m^2yr), meeting the Passive House standard. However, in summer, to achieve optimum comfort, a well-designed air conditioning system (heat recovery with a VRV system) is required; the annual energy demand for cooling is about 30 kWh/(m^2yr), which is 200% over the passive house requirement but much lower than a conventional building. This is with a setpoint of 21°C in Winter and 24°C in Summer.

In another case, Micheel Wassouf (2015) studied two retrofit Passive House buildings in the Mediterranean summer of Spain. One of the buildings, “MZ House”, previously had a heating demand of 171 kWh/(m^2a) before retrofitting to a Passive House. Afterwards, the heating demand was 17.5 kWh/(m^2a), which is still about 2.5 kWh/(m^2a) above the Passive House standard but about 90% lower than the original building.

Considering the optimistic outlook of the Passive House design with the potential to provide a comfortable indoor environment and achieve this with about 70-90% less energy required than the status quo in a temperate and Mediterranean climate. The potential was also considered for frigid climates, as in the case of Longyearbyen (78.2232° N, 15.6267° E). The monthly average winter temperatures range between –13°C and –21°C, while summer temperature range between –3.5°C and 6°C in summer (Osuch & Wawrzyniak, 2017). This presents a significant challenge as there is a lack of winter sunlight in Longyearbyen, which limits the option of heat gain through solar gain. Furthermore, the winter temperature is also colder than in Germany's temperate climate, and the summer temperature indicates the need for heating. As a result, Longyearbyen residents require heating all year. This is in contrast to Germany, where heating is only needed for seven months (Buijze & Wright, 2021). Considering this, Buijze & Wright (2021) sought to establish the potential for Passive House standard in the high arctic country of Longyearbyen. Using computer simulation, a typical building layout was modelled using both IES (integrated environmental solutions) and PHPP (Passive House Planning Package) software. Two main parameters were the focus, the primary energy requirement of not more than 120 kWh/(m^2a) and the heating demand of 15 kWh/(m^2a). Four variations were considered:

i. the thermal envelope was improved, where U-value was reduced to reduce heat loss and, consequently, heating demand.

ii. the window area was reduced.

iii. the stand-alone (detached) building was modelled as a row of houses. Thus, the ratio of external surface area to floor area in the standalone (variation I and II) is

2.25 (215.52/96), while this ratio is 1.50 (143.52/96) for the row house (variation III and IV).

iv. The fourth case was reducing the set point temperature to 18°C instead of 20°C in variations 1-III.

This study shows that in variations I-III, the heating demand was exceeded. In variation I, primary energy was exceeded. However, in Variation IV, where 2°C reduced the set point temperature, the heating demand met the Passive House standard at 14.8 kWh/(m^2a). Therefore, it was concluded that the only theoretical possibility of meeting the Passive House Standard was by lowering the temperature outside the boundary conditions of Passive House. Also, because heating demand was almost at the limit, in this case, it is uncertain that this will be attainable in actual construction. However, based on this possibility, it was recommended that the PHI considers the approval of contextual, realistic adjustment of the boundary conditions to suit different climates (Buijze & Wright, 2021), which is the case for Passive House standards in countries such as the USA and China.

1.4.1 Passive House Institute in the USA

In March 2015, after three years of research, climate-specific and cost-effective PHIUS + 2015 Passive Building Standard - North America was released. According to Passive House Institute US (PHIUS) (2021), the standard yielded realistic climate-specific building energy performance. The targets substantially cut buildings' carbon emissions and energy consumption to provide excellent comfort, superior indoor air quality, and resilience.

Adaptations were made to three crucial aspects of the Passive House approach;

1. **The airtightness requirement:** With the aim of avoiding moisture and mould risk in the building envelope. It was recommended that airtightness should scale appropriately

based on building size. Therefore, the recommendation for airtightness is 0.05 CFM50, and 0.08 CFM75 per square foot of gross envelope area (PHIUS, 2021) compared to a limit of 0.6 ACH at 50 Pascal set initially by PHI Germany. It was argued that a larger building that met the 0.6 ACH 50 requirement could be seven times leakier in terms of air leakage per unit area through the walls compared to a small single-family home that tested the same volume air change rate.

2. **The source energy limit:** Based on the global CO_2 emission budget, the source energy limit was reviewed based on a per-person limit rather than per square foot of floor area, at least for residential projects. Hence, instead of the requirement which states primary energy not to exceed 120 kWh annually for all domestic applications (heating, cooling, hot water, and domestic electricity) per square metre of usable living space. The PHIUS standard recommends 6200 kWh per person per year and can be tightened back to 4200 kWh in the future as is practical (PHIUS, 2021). Stating that it promotes a fair share principle and a more accurate calculation.

3. **The space conditioning criteria:** The specific annual heating and cooling demands and peak heating and cooling loads were reviewed based on economic feasibility. Thus, it is set at a cost-optimal for the project’s climate (i.e., the energy performance level, which leads to the lowest cost during the estimated economic lifecycle). To ensure efficiency measures will have a reasonable payback relative to operational energy savings, rather than the established target not to exceed 15 kWh annually or 10W (peak demand) per square metre of usable living space (PHIUS, 2021).

Thus, the PHIUS requirements and recommendations are designed to achieve energy efficiency and comfort with respect to the climate zone. It also considers sources of energy and economic factor. Therefore, to achieve successful outcomes using the Passive House standard, design details such as insulation, windows, and ventilation are considered in reference to the designated county's climatic conditions and building tradition. However, the Passive House Institute requires that the goals are the same (which is to build almost self-sufficient houses without compromising the comfort of occupants) in all climates and for all countries (Passivhaus Institut, 2019c). In line with this, Passive House feasibility and achievement continue to be tested and challenged in other climates, such as China.

1.4.2 Passive Houses in China

China is a massive territory with extensive climatic coverage of different complex climatic conditions divided into the north and south region. The North climate is temperate, with summer temperatures around 25 ^{o}C and very cold winters. On the other hand, the south climate is subtropical, with sweltering summers and mild winters. Achieving the Passive House standard could be daunting in this complex climate. However, in 2010 with the certification of the first Passive House in China, the Passive House concept started gaining momentum. At the end of 2018, over 100 Passive House projects have been accomplished, with about 21 certified. Most were in the southern region, with less than 10% in the northern area (Wang et al., 2020). This propelled further study and exploration of the PH concept, and in 2019 the Passive Low Energy Consumption Residential Building Design Standard relevant to the design of Passive Houses in China was published, as shown in *Table 1.3*.

Table 1.3: Designing Standards of Passive Houses in China (Wang et al., 2020)

Parameter	**Unit**	**Maximum**
Heating demand	kWh/m^2	18
Heating load	W/m^2	12
Cooling demand	kWh/m^2	13
Cooling load	W/m^2	20
Frequency of overheating	%	10
Airtightness (n50)	ACH	0.6
Primary energy demand	kWh/m^2	120

This standard shows a deviation from the PHI Germany requirements, as the heating demand allowance has been increased to 18 kWh/m^2 as opposed to 15 kWh/m^2 and the heating load 12 W/m^2 instead of 10 W/m^2. Also, it is observed that the cooling demand and load of 13 kWh/m^2 and 20 W/m^2 instead of 15 kWh/m^2 and 10 W/m^2, respectively. However, the primary energy demand annually remains 120 kWh/m^2. The China standard was advanced to suit the varying complex climate of China.

Evidently, designing to suit the climate and setting an achievable standard that promotes energy-efficient buildings offering thermal comfort for occupants remains the goal that needs to be met. As a result, as Passive House becomes more popular, more deviation from the PHI Germany requirements and standards may be unavoidable. This is considering the framework's requirements and standards were informed by the first Passive House, which was designed to suit the German temperate climate. While the framework may be easily adopted in similar temperate climates, it proves more challenging in other distinct climates.

1.4.2.1 Research Problem

In line with the above, it is observed that despite the growth and achievement of Passive House in heating-dominated climates such as the United Kingdom, United States, Australia, and Canada. However, there appears to be limited growth of Passive House in cooling-dominated climates (climates that require significantly more cooling or no heating) such as South-East Asia, South America and northern Australia, as shown in *Figure 1-8*.

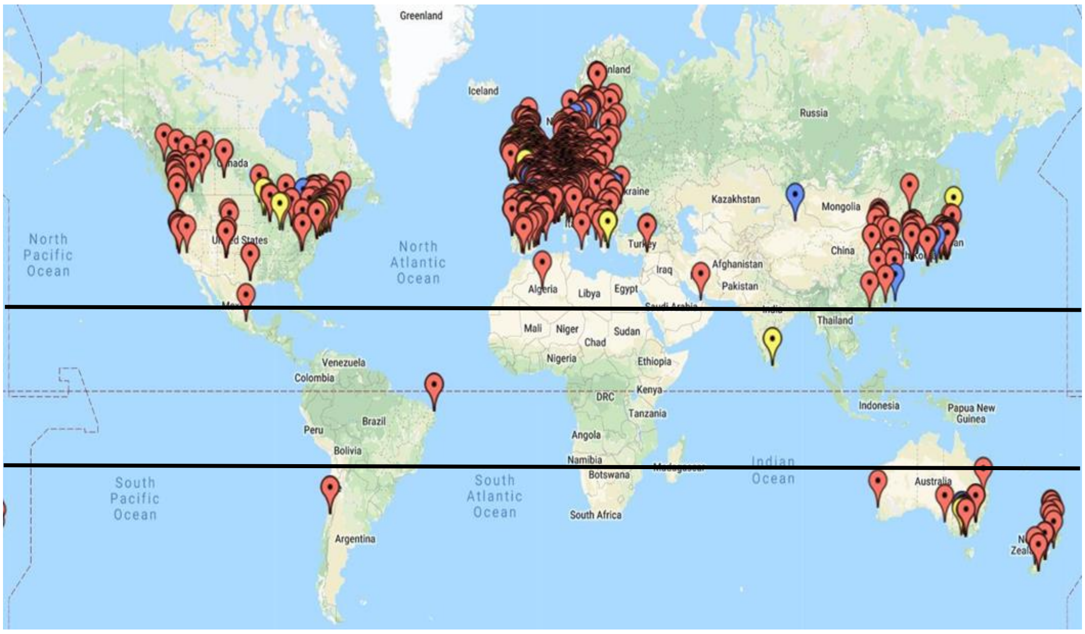


Figure 1-8:Map of Certified Passive House Buildings (The International Passive House Association (iPHA), 2021)

This limitation could be due to recurring issue that has been raised in some Passive Houses, overheating. The issue of overheating has been reported in some heating-dominated climates. Examining this point, in the sub-tropical climate of Cyprus, where the Passive House concept has been utilized, the issue of overheating has been highlighted by Ridley et al. (2013), Fokaides et al. (2016) and Kylili and Ilic (2017). Similarly, Badescu et al. (2010) investigated the first Romanian Passive House office building in south-eastern Europe, which features warm to hot, dry summers. They concluded that the overheating rate and cooling load are higher than for a standard structure. This was further confirmed in the thermal comfort analysis of the same building carried out by Udrea et al. (2016), stating that the calculated indoor temperature using a mechanical cooling system without an HVAC system shows that the indoor temperature was between 20.74^{o}C to 32.7^{o}C, while using HVAC the indoor temperature was between 19.75^{o}C and 27.75^{o}C. The building was confirmed to overheat due to wall thickness and the influence of internal gains. Thus, the office has to use the cooling system from June to August, with a high demand for cooling during July (Udrea et al. 2016). Hence, it was concluded that a Passive House in Romania is a good idea but will need a good mechanical system for cooling the space on warm days (Badescu et al. 2010; Udrea et al., 2016).

In another study, Rhodin et al. (2014) reported on the occupants' experience of nine Passive Houses built in Linköping (Sweden). They compared their thermal comfort and energy use with conventional buildings' indoor conditions. The findings showed that indoor thermal environments were generally found to be good. However, the post-occupancy evaluation revealed occupants' complaints of discomfort, including cold floors in winter and significant air temperature variations. They noted that in summer, the air temperature was discovered to be higher in the Passive Houses.

Further reporting that overheating complaints during summer in Passive Houses were more than in conventional buildings. Certain factors were pointed out to be responsible for these, including the fact that buildings do not have external shading installed by default—also the effect of internal heat gains (such as cooking and other heat-generating activities). Consequently, heat is trapped in the building due to super insulation and airtightness (Rhodin et al. (2014).

Ridley et al. (2013) also found that overheating is a significant issue in climate zones characterized by hot summers and mild winters. According to a performance analysis carried out by Fokaides et al. (2016) on the Tseri passive house, the issue of overheating was recorded in the building before occupancy in August 2014, and overheating was recorded to be higher in August 2015 due to internal loads post-occupancy. This was further exacerbated by the heat spell experienced in August 2015. For the inhabited spaces of the building (living room, master bedroom and dining) where the measurement was done, the indoor temperature readings were between 25.5°C and 31°C for about 80% of the year.

To mitigate this issue of overheating in Passive House, Passivhaus Institut (2019b) proposes some prevention or post-occupancy techniques, such as shading and night ventilation. This was tested in the Tseri Passive House, where Fokaides et al. (2016), using computer simulations, investigated the effect of night ventilation in the building. In modelling the night cooling, all the first-floor zones were assumed to be cross-ventilated with 50% of the window opening used during the night-time (i.e., between 19:00-07:00). The result represented a predicted percentage of dissatisfaction PPD index; where due to the introduction of night ventilation the overheating rate was significantly reduced from 35% to 16% which is still a significant percentage of overheating.

Schnieders et al. (2015) also presented a detailed study about Passive Houses in different climate zones; Yekaterinburg (cold and temperate climate), Tokyo (humid subtropical climate), Shanghai (humid subtropical climate), Las Vegas (hot and dry climate), Abu Dhabi (hot desert climate), and Singapore (hot and humid climate). This work employed hygrothermal dynamic building simulation to prove that the realisation of Passive Houses in climates that differ fundamentally from central Europe is achievable. It was revealed that although annual energy demand for space conditioning of Passive Houses is 75 to 95% lower than that of a traditional building of the same geometry. In a hot and humid climate, the total useful energy demand for sensible and latent cooling may exceed 70kWh/(m^2a) even in a Passive House (Schnieders et al., 2015). It is important to note that the model building was adjusted to suit the climatic condition of each location. However, the result still showed that the cooling load exceeded the standard requirement of 15kWh/(m^2a) in the hot and humid climate by about 300%. Thus, it fails to meet the Passive House standard.

1.5 Research Question, Significance and Objective.

Given the discussions in the literature, which highlights the Passive House framework (based on the European temperate climate), its modification in different climates, as seen with the high arctic country of Longyearbyen, Passive House USA, and Passive House China, and the issue of overheating occurring even in some heating dominated climates; this thesis poses a pertinent question(s):

How can the Passive House standard be achieved in cooling dominated climates?

And, if it cannot, what is required to redefine the standard for feasibility in these climates whilst maintaining the goal of energy efficiency and acceptable/comfortable thermal conditions year-round?

1.5.1 Significance of Study

Due to growing climate change concerns, it is critical to further explore the Passive House concept to determine its potential to achieve energy efficiency and maintain acceptable comfort conditions in the cooling dominated climates as it does in heating dominated climates. This is significant considering currently at least 40% of the world’s population (i.e., tropics) live in cooling dominated climates, where the average temperature is between 25 and 28 degrees Celsius all year. A population that on its own is projected to account for roughly half of the world's population by 2050 if current growth rates continue (United Nations (UN), 2017).

In other words, it is crucial to establish a building methodology for cooling-dominated climates that offers both energy efficiency and acceptable comfort conditions, because failure to do so will inevitably result in more buildings, in addition to the current housing stock where the occupants rely heavily on active cooling systems to meet thermal comfort needs. Consequently, leading to increasing energy demand and carbon emissions which have been identified as a major contributor to the issue of global warming and climate change currently being experienced around the world (Höök & Tang, 2013; Intergovernmental Panel on Climate Change (IPCC), 2021; Johnsson et al., 2019; Kumar, 2018; National Oceanic and Atmospheric Administration (NOAA), 2021; Savo et al., 2016).

Therefore, to mitigate climate change and move toward a sustainable future, sustainable buildings (which serve the occupant's comfort needs, with minimal environmental impact) are critical in all climates.

1.5.2 Research Objective

In summary, the study seeks to establish the feasibility of adapting the Passive House framework for cooling-dominated climates, considering its achievements in heating-dominated climates. The objective is to explore effective strategies which can contribute to achieving an energy efficient, thermally comfortable building that can be referred to as a Passive House in this climate.

2 Computer Simulation for Building Design & Analysis

2.1 Overview

The previous chapter introduced the Passive House concept, methods, and growth in heating-dominated climates. However, its pertinence and applicability in cooling-dominated climates was questioned due to the limited certified Passive House building in this climate and the overheating reported in some Passive Houses. In an attempt to answer the question, this study explored the Passive House framework in cooling-dominated climates using computer simulation.

2.1.1 Computer Simulation

Computer simulation is a tool that allows the imitation of actual or theoretical physical systems (such as a building) and enables the examination of many possible solutions for building geometry and construction (Kaizer et al., 2015). It can be used in the early stages of design, throughout the design phases and all through the life of the building to optimise building components and service systems, thereby increasing the potential for energy efficiency. At the same time, occupant comfort is improved (Nimlyat et al., 2014).

Computer simulation has been used in several studies (Dakwale et al., 2011; Kwong et al., 2014) as a necessary tool to understand a design approach in building construction before implementation. Therefore, there has been substantial reliance on and integration of computer simulation modelling in building architecture and construction to achieve sustainable buildings. The use of computer simulations helps to solve problems that otherwise would be difficult to handle, offering cost-effective and less time-consuming solutions than experimental studies (Dakwale et al., 2011).

According to Nimlyat et al. (2014), computer simulation helps to visualise a system that does not yet exist to achieve the best possible outcomes. This is essentially relevant to understanding the Passive House concept, standard, and practicability in cooling-dominated climates.

Over the years, various software applications for computer simulation and modelling have been developed; utilized in the building and construction industry. They include The Building Loads Analysis and System Thermodynamics (BLAST), US Department of Energy (DOE-2), ESP, TRNSYS, Energy Plus, Design Builder, Passive House Planning Package (PHPP) and Integrated Environmental Solution- Virtual Environment (IES-VE). Of these computer simulation tools, the IES -VE is well-established and widely used for research and industrial applications in the building services industry (Ahmed et al., 2021).

2.2 Integrated Environmental Solution – Virtual Environment (IES-VE)

IES-VE is an in-depth suite for integrated analysis, linked by a common user interface and a single integrated data model for building design and retrofit. It includes ModelIT- geometry creation and editing, ApacheCalc – loads analysis, ApacheSim – thermal analysis, MacroFlo – natural ventilation, Apache HVAC -component-based HVAC, SunCast – shading visualization and analysis, MicroFlo – 3D computational fluid dynamics, FlucsPro/Radiance – lighting design, DEFT – model optimization, Lifecycle- life-cycle energy and cost analysis, Simulex – building evacuation used for research and industrial applications within the building services industry.

2.2.1 Software Consideration

IES-VE is a well-established software in the industry that meets international standards, methodologies, regulations, and rating systems such as the ASHRAE 140, ISO 52000, and CIBSE TM33. It provides an environment for a detailed evaluation of building and system designs, allowing them to be optimized for comfort and energy efficiency (Ahmed et al., 2021). The validation and accuracy of this software have been proven by the BESTEST (Building Energy Simulation Test) standard of the International Energy Agency (IEA), green building rating schemes and numerous studies ((Blight & Coley, 2013; Chen & Yang, 2015; Thomas van Raamsdonk, 2015; Thomas van Raamsdonk, 2015; Kandar et al., 2019; Vidushini Siva, 2017; Zune et al., 2020).

Additionally, the software has been applied in other Passive House studies, such as the work of Bagheri et al. (2018) and the work of Buijze & Wright (2021), where it was stated that IES-VE was used for their study to ensure results were as realistic as possible when exploring more extreme climate conditions, allowing the isolation of single parameters. Therefore, it is a valuable tool for this study investigating the Passive House in cooling-dominated climates as it also follows the same heat balance calculation used by the Passive House Planning Package (PHPP) to calculate the annual heating demand for a Passive House (*Equation 1)* (Feist, 2007; Schoner et al., n.d; Chen et al., 2020).

$$Q_H = (Q_T + Q_V) – (Q_S + Q_I).\ \eta \qquad \text{………………………………… } \textit{Equation 1}$$

Where:

Q_H – heating demand (kWh/a), Q_T – transmission heat losses (kWh/a), Q_V – ventilation heat losses (kWh/a), Q_S – solar heat gains (kWh/a), Q_I – internal heat gains (kWh/a), η – utilization factor.

Accordingly, IES-VE uses dynamic, higher resolution, hour by hour data to calculate the annual energy demand (Buijze & Wright, 2021). The IES apache simulation module also uses the energy balance equations on the internal and external surfaces of the building to calculate the building's thermal performance. The method run in ApacheSim analyses all three modes of heat transfer processes, conduction, convection and radiation of each building element, to calculate the building heat balance *(Equations 2-7)* (Integrated Environmental Solutions Limited, n.d.) (Mushtaha et al., 2021) as follows:

i) Heat conduction out of the building element

$$W = -\lambda \nabla T \qquad \text{……………………………………………………} \quad \textit{Equation 2}$$

Where W (x, y,z,t) – is the heat flux vector (W/m^2) at position (x,y,z) and time t

λ – is the conductivity of the solid (W/(m^{2}K))

T (x, y,z,t) – is the temperature (°C) in the solid at position (x,y,z) and time t

ii) Convection to the surface from the outside air

$$W = h_C (T_a - T_S) \qquad \text{……………………………………………………} \quad \textit{Equation 3}$$

Where W – is the heat flux (W/m^2) from the air to the surface

h_c – is the convective heat transfer coefficient

T_a – is the bulk air temperature (°C)

T_s – is the mean surface temperature (°C)

iii) Thermal Radiation exchanged with the external environment

$$W = h_r (T_s - T_{MRT}) \qquad \text{……………………………………………………} \quad \textit{Equation 4}$$

Where W – is the net radiative loss from the surface

h_r – is surface heat transfer coefficient for the exchange with MRT (Mean Radiant Temperature)

T_s – is surface temperature

T_{MRT} – is Mean Radiant Temperature of the enclosure.

iv) Solar gain absorbed by the surface.

$$I_{dir} = I_{beam} \cos(\theta) \qquad (\cos(\theta) > 0) \qquad \text{…………………………………} \quad \textit{Equation 5}$$

Where I_{dir} – is the direct solar flux (W/m^2) incident on the surface

I_{beam} – is the solar flux (W/m^2) measured perpendicular to the beam

θ – is the angle of incidence

v) Internal/Casual gains, i.e., lighting, equipment and appliances, cooking, computer and people.

Thus, with the thermal model of the building fabric integrated with the heat gain of the building model, the heat transfer by conduction is calculated as

$$Q = c_p \rho_a V dT_a / dt \quad \ldots\ldots\ldots\ldots\ldots \textit{Equation 6}$$

where Q is the net heat flow into the air mass (W)

c_p is the specific heat capacity of air at constant pressure (J/kgK)

ρ_a is the air density (kg/m^3)

V is the air volume (m^3)

T_a is the air temperature (ºC)

and heat transfer by air movement is calculated as

$$Q = mc_p (T_i - T_a) \quad \ldots\ldots\ldots\ldots\ldots \textit{Equation 7}$$

Where m – is the air mass flow rate (kg/s),

c_P – is the specific heat capacity of air at constant pressure (J/kg/K),

T_i – is the supply temperature of the air (ºC), and

T_a – is the room mean air temperature of the air (ºC).

Therefore, *Equation 1* Q_H is solved by subtracting transmission heat loss (Q_T) (which is heat transfer through conduction, convection and radiation) and ventilation heat losses Q_V (which is heat transfer due to infiltration of the building envelope which depends on variables - wind speed, difference between outside and inside temperatures, and ventilation system without recovery) from solar heat gains Qs (which is gains primarily through windows) and internal heat gain Q_I (which is based on internal heat gain from people and equipment) using *Equation 2 – 7* run by IES-VE.

As a final step in the software consideration, a validation analysis was conducted to ascertain the software's methodology in modelling a Passive House and produce results comparable to the Passive House Planning Package (PHPP) used for certification.

2.3 Validation Analysis of the Software Tool

To carry out the validation analyses, a certified Passive House was examined in order to test the software's precision and ensure it was correctly configured for this study. This procedure also made it possible to understand the software dynamics as well as the representation of Passive House inputs and outputs.

Accordingly, a certified Passive House building with sufficient, accessible (i.e., online) and verifiable data was required. After reviewing available pieces of literature on Passive Houses, "The Tseri Passive House", which has been studied by Fokaides et al. (2016) and Kylili et al. (2017), was chosen. Both studies provided simulation data about the building design, architectural layout, and materials, including information on the design output as calculated by PHPP and measured data. Additionally, Milos IIic (one of the authors) of the study "performance of a Passive House under the subtropical climate conditions" was contacted (Personal Communication 8th of April 2020). To gather further data, information, and insight into the building beyond what was initially provided in the paper (i.e., a comprehensive building plan).

This information lent itself to the validation of model simulation in IES-VE. The post-occupancy analysis carried out by Fokaides et al. (2016) also provided detailed data on the actual indoor thermal environment experienced in the building. Therefore, it was possible to compare the simulated output to both the design and measured analysis.

2.3.1 Validation Data

The following information was used to model the building; architectural plan/layout, thermal transmittance of the building elements, window size and transmittance, building orientation, internal heat gain, airtightness, heat recovery ventilation system and weather data.

2.3.1.1 Weather Data

The reference building is in Nicosia, Cyprus. Cyprus has a sub-tropical climate that is both Mediterranean and semi-arid. Nicosia, the island's largest city, is located in the centre, with high temperature fluctuations. It has a cold winter and warm to hot summers. According to Fokaides et al. (2016), it is the warmest climate in the European Union. The temperature typically varies from 6°C to 33°C and is rarely below 2°C or above 36°C. The typical summer lasts for about eight months. In July and August, the mid-summer average daytime temperature reaches 37°C and drops to about 22°C at night.

The weather data on IES-VE was used in modelling the reference building. The data was derived from up to 18 years (1982-1999) of DATSAV3 hourly weather data initially archived at the U. S. National Climatic Data Center. The weather data is supplemented by solar radiation estimated hourly from earth-sun geometry and hourly weather elements, particularly cloud amount information made available by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (ASHRAE, 2001).

However, the weather data, particularly for Nicosia, was unavailable. Hence, the weather data of Larnaca, about 36 kilometres (22 miles) from Nicosia, was used instead. Summers in Larnaca are hot, arid, and clear, and winters are cold, windy, and mostly clear, similar to those in Nicosia. The daily high temperature is above 30°C on average. In August, the hottest month, temperatures range from 33°C to 37°C with a low of 23°C. The average temperature is comparable to Nicosia, which supports the use of this data.

2.3.1.2 Building Description

The Tseri Passive House, shown in *Figure 2-1,* is a detached residential unit located in Tseri (coordinates 35.07°N, 33.32°E), a suburb south of Nicosia, Cyprus (Kylili and Ilic, 2017). It is a two-storey, four-bedroom family house, with a total floor area of 185 m^2 divided into a total floor area of 89m^2 on the ground floor and 94.5m^2 on the first floor and a clear room height of 2.5m. To maximize sunlight during winter, the orientation of the building is east to west (Fokaides et al., 2016).

Figure 2-1: Pictorial View of the Tseri Passive House (Fokaides et al., 2016)

The house has a wooden frame with a slab foundation made of reinforced concrete. The building walls and roof were insulated with mineral wool, incorporating an external wall insulation system and triple-glazed windows made of uPVC-filled argon. The building's window-to-wall ratio (WWR) is shown in *Table 2.1*, and the architectural plan obtained from Kylili et al. (2017) is shown in *Figure 2-2*.

Table 2.1: Window to Wall Ratio of the Tseri Passive House

Orientation	**Glazing size**	**WWR**
North	11.7	12%
East	8.3	10%
South	9.8	13%
West	6.7	16%

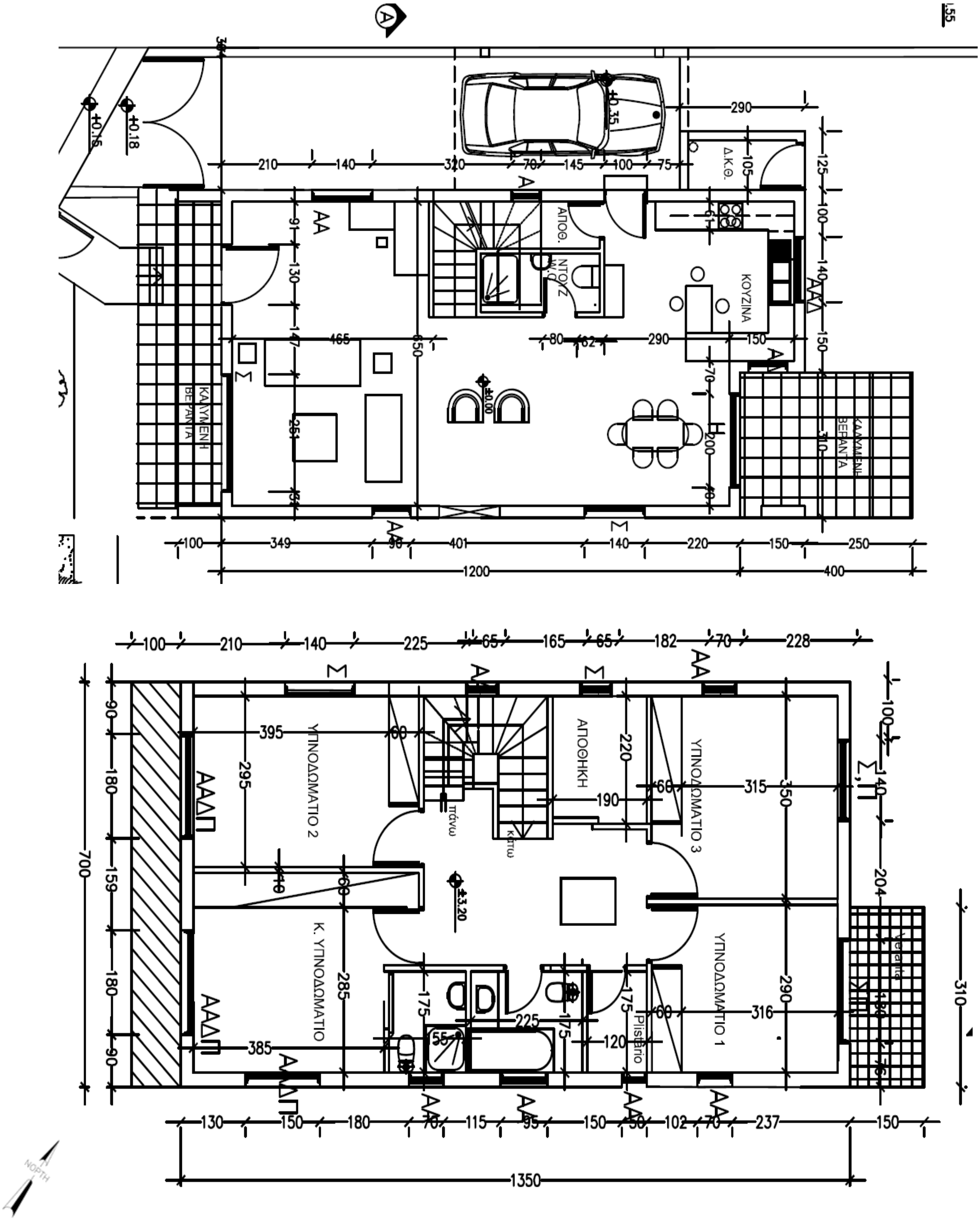


Figure 2-2: Ground/First Floor Architectural Layout of the Tseri Passive House.

2.3.1.3 Thermal transmittance of the Building Envelope

In addition to the architectural plan, the thermal transmittance of each element (external wall, roof, ground slab) is shown in *Table 2.2*.

Table 2.2:Tseri House Thermal Transmittance (W/m^{2}K) according to (Fokaides et al., 2016)

Building Element	**Thermal Transmittance (W/m^{2}K)**
External wall	0.18
Roof	0.15
Ground slab	0.48
Window frame	1.3
Glazing	0.8

2.3.1.4 Internal Heat Gain:

The internal heat gained from household appliances (refrigerator, oven, washing machine, dishwasher), lighting and people is estimated to be 3.1 W/m^2, assuming the appliances are energy efficient (Fokaides et al., 2016).

2.3.1.5 Airtightness

According to the PHI (Passive House Institute (PHI), 2015), airtightness should not exceed 0.6 times a room's volume per hour, and the pressure differential is limited to 50 Pascals. This level of airtightness is advisable to manage indoor conditions i.e., ventilation and temperatures while preventing moisture damage (International Passive House Association (iPHA), 2021). Thus, the infiltration of the Tseri Passive House was inputted as 0.6 ACH.

2.3.1.6 Heat Recovery Ventilation System

The Tseri Passive House uses a heat recovery exchanger ventilation system by Atrea (DUPLEX 370 EC4.D(CF)) combined with a 2.6 kW Mitsubishi Heavy Industries heat pump to supply airflow of 300m^3/h of outside air and maintain the indoor temperature. The heat recovery unit, a Passive House certified component, has an efficiency of 82%.

2.3.2 Validation Result & Analysis

Using the above design data, the Tseri Passive House building was modelled as shown in *Figure 2-3*. Following that, the software thermal and energy analysis was run, and the results were compared to the energy demand calculated by the PHPP (As-designed performance) and measured temperature data in the reference literature (Post-Occupancy Monitored Performance). These were divided into validation 1 & 2.

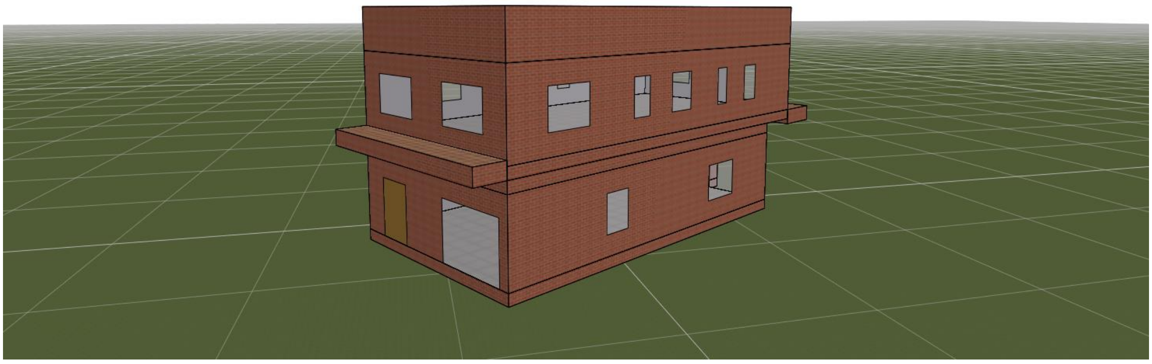


Figure 2-3:IES-VE Model of the Reference Building.

2.3.2.1 Validation 1 - As-designed Performance

The PHPP report calculates the Tseri Passive House certification data, which shows that the space heating load and annual heating demand are 7 W/m^2 and 5 kWh/(m^{2}a), respectively. The specific cooling demand of the building, which is within the Passive House requirement, is 15 kWh/(m^{2}a). Although, the peak load is shown to be 13 W/m^2 which exceeds the required limit by 3 W/m^2. As shown in *Table 2.3*, this data was compared to the IES-VE report.

Table 2.3: The “Tseri Passive House” PHPP and IES Certification Parameters.

PH Certification Parameters	**PHPP**	**IES**
Annual Heating Demand (kWh/(m^{2}a)	5	4
Annual Cooling Demand (kWh/(m^{2}a)	15	10
Peak Heating Load (W/m^2)	7	7
Peak Cooling Load (W/m^2)	13	10
Total Energy (kWh/(m^{2}a)	63	52

Table 2.3 shows that the building's heating demand and peak heating load are comparable to the PHPP's as-designed performance result. On the other hand, there appears to be a variation in annual cooling demand and cooling load, which had an effect on total energy demand.

The differences in cooling demand and load observed between the IES and PHPP simulation results can be attributed to the following factors:

i. The difference in software. The PHPP uses a very simplified design approach, while IES uses a more detailed dynamic hour-to-hour simulation method.

ii. The difference between the microclimates of Larnaca and Nicosia, as highlighted earlier.

iii. The PHPP assumes a generic heat recovery system with a heat pump to examine the building's performance. On the other hand, the IES-VE simulation enabled the design of a ventilation system with heat recovery. Which means the actual design could be different.

Nevertheless, there is a good agreement between simulation results in IES and PHPP, and the results meet the criteria for a certified Passive House. Thus, validating the capacity of the software IES-VE.

2.3.2.2 Validation 2 - Post-Occupancy Monitored Performance

The post-occupancy performance monitored by Fokaides et al. (2016), which presents the building's indoor temperature and humidity, is used for validation. According to the literature, the building was monitored (using relative humidity sensors and data loggers) from April 2014 to September 2015, revealing the thermal conditions of the indoor environment. As shown in *Figure 2-4,* the post-occupancy report was also compared to the predicted average indoor temperature of the building by IES-VE.

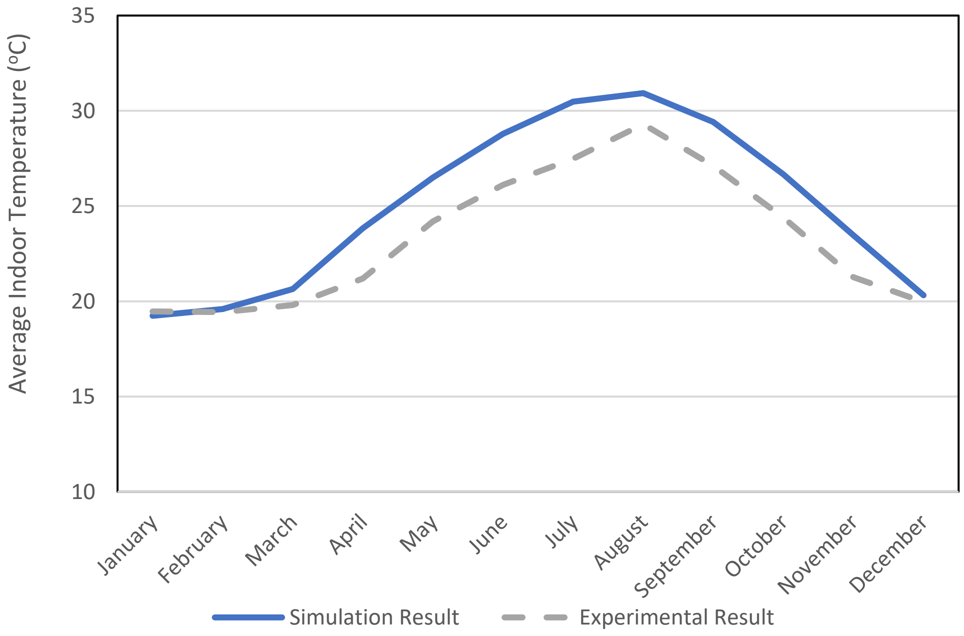


Figure 2-4: Simulated and Measured Temperature (°C).

According to *Figure 2-4*, the temperature projection of the Tseri Passive House simulation in IES is consistent with the measured temperature documented in Fokaides et al. (2016). The disparities observed between the simulation and measured value can be attributed to the difference between the predicted performance of the building design and its actual operational performance (which can be influenced by human behaviour). This is in addition to the other factors mentioned above in Validation 1.

Nevertheless, the software IES-VE shows comparable results to the as-designed and measured building performance in Validation 1 and Validation 2 analysis simultaneously. Thus, the software can be used to model, design and certify a Passive House and, accordingly, to carry out the research study.

It is worth noting that, despite being certified as a Passive House, this building appears to overheat during the summer months (June – October), as the average indoor temperature in these months is above 25ºC (the benchmark comfort temperature for Passive House). However, it is uncertain whether the percentage of overheating hours (hours experiencing temperature above 25ºC) in a year exceeds the Passive House allowance of 10% (Chapter 1.3.2).

2.4 Research Design

Following the software validation, case studies were set up to investigate the Passive House framework in the cooling-dominated climate, classified into hot and humid or hot and arid.

The hot and humid climates lie between the Tropics of Cancer and Capricorn, with maximum temperatures ranging between 27ºC – 32ºC to a minimum temperature between 21ºC – 27ºC. Temperature ranges are very narrow at nocturnal and diurnal times, while humidity remains high at around 75%. (i.e., Singapore, Indonesia, Malaysia etc.) (Triana et al., 2020; Amoabeng et al., 2022; Aryal et al., 2022). On the other hand, hot arid is characterized by a lack of moisture in an area of high temperature where the average temperature can rise to 38ºC, such as Namibia, Algeria, etc.—experiencing huge temperature differences between day and night and Winter and summer (Varzaneh et al., 2014).

2.4.1 Case Studies Approach

The case studies for hot and humid and hot and arid climates were conducted using a parametric analysis, also known as sensitivity analysis. This methodology allows the investigation of the impact of various geometric or physical parameters, or both, on a proposed solution. In this case, to look into the Passive House concept in climates that require significant cooling (i.e., little to no heating all year round). Two approaches to investigating the Passive House framework were attempted for the parametric analysis.

2.4.1.1 Method I- Adaptation of a Certified Passive House in a Cooling-Dominated Climate.

The initial approach to answering the research question was to deploy a certified Passive House to a cooling-dominated climate in order to adapt the building for comparable performance in this climate. Thus, determining whether any certified Passive House could meet both its energy and thermal comfort standards (as stated in Chapter 1.3.2) with little to no modifications in another climate.

Accordingly, for the first case study, the certified Passive House, "The Tseri Passive House" (from a subtropical climate), was deployed to a cooling-dominated climate. The performance of the building in this hot climate was examined, and the key Passive House strategies were investigated by conducting a parametric analysis.

2.4.1.2 Method II – Applying Passive House Strategies to a Conventional Building

The second approach investigated the framework by applying the Passive House strategies to a conventional building (that is a design that is typical and/or common in the region) as means to achieve the Passive House standard in this climate. This is similar to the approach used to design the first Passive House, which was documented in Feist (2020a). To begin, the conventional reference buildings from the cooling-dominated climates were validated, and their results served as a baseline for examining and implementing the Passive House strategies.

The fundamental Passive House strategies were systematically varied and optimised in relation to their efficiency in the building. Given that these techniques have been demonstrated to be effective in heating-dominated climates, the study showed their efficacy in achieving a Passive House in cooling-dominated climates. As a result, this method was studied in both the hot and humid climates and the hot and arid climates in order to provide comprehensive insight into the Passive House framework for cooling-dominated climates (PH-CDC).

This methodology was deemed valuable because it focuses on optimising typical building design in these climates. If successful, it could pave the way for the implementation and expansion of the Passive House framework in hot climates. So, in order to reach a reliable conclusion, the optimised reference models were tested in five additional hot and humid and hot and arid locations.

2.4.1.3 Out of Scope:

As previously mentioned, the practical Passive House framework, which encompasses the five main strategies, is evaluated in the cooling-dominated climate. However, in this study, only four (insulation, highly insulated windows, airtightness, and mechanical heat recovery system) of the fundamental Passive House strategies are considered. The thermal bridge-free strategy was not considered in this study.

A thermal bridge occurs in an area of the building envelope with the least resistance to heat flux due to the presence of material with higher thermal conductivity. A thermal bridge lowers the affected area's internal surface temperature, increasing the risk of condensation and mould and fungi growth, resulting in poor air quality. The effects of thermal bridges become more pronounced when moisture transfer in building envelopes is considered, which is beyond the scope of this study (Feist et al., 2005; Brás et al., 2014; Sierra et al., 2015; Moumtzakis et al., 2022; Xue et al., 2022).

Furthermore, Feist (2001) and Alejandro Moreno-Rangel (2021) state that thermal bridge is primarily a construction concern. Thus, to prevent thermal bridges during construction, Johnston & Siddall (2016) recommend that the thermal envelope at design is not interrupted (that is, to have a continuous flow of the building geometry). When the insulating layer must be interrupted, the thermal resistance should be as high as possible (this indicates using, e.g., aerated concrete or timber instead of regular concrete or sand-lime bricks).

Also, insulating layers should meet without gaps or misalignment at junctions when it comes to the building geometry. It is assumed that if these guidelines are followed for building design and construction, thermal bridge losses will be minimal, resulting in a thermal bridge-free construction (Feist, 2001).

Finally, Feist et al. (2001) and Alejandro Moreno-Rangel (2021) also noted that super insulation and airtightness in a Passive House with an extremely good thermal envelope would prevent thermal bridging and air leakage. Thus, the issue of thermal bridge was not considered in this study.

3 Performance of a Certified Passive House in a Cooling Dominated Climate – Case Study of Singapore

3.1 Introduction

In the previous chapter, the research tool was validated by modelling and confirming the certified Passive House in the subtropical climate of Cyprus. In this chapter, the certified Passive House (the “Tseri Passive House”) is deployed in the cooling-dominated climate of Singapore to explore the possibility of achieving the Passive House standard in this climate.

The Passive House's idea for achieving a low energy, thermally comfortable building is to minimise heat transfer across the building envelope, such that the indoor environment is insulated from the sometimes-extreme outdoor weather conditions. As a result, requiring minimal energy to achieve and maintain comfort range in the building. With this approach, it can be assumed that a Passive House, particularly a certified Passive House, would perform similarly in any climate, assuming comparable internal heat gain (from people and equipment). This necessitates the need for this case study.

Furthermore, given the performance of the reference building in its design climate, where it appears to overheat during the summer months, establishing the building's performance in a climate requiring cooling all year is critical.

3.2 Location of Study - Singapore

3.2.1 Climate of Singapore

Singapore is a tropical country located at 1°20′N latitude and 104°E longitude. It is characterised as a hot and humid climate with uniformly high temperatures, high humidity, and abundant rainfall throughout the year. The average temperature ranges from 23^{o}C to 32^{o}C

(*Figure 3-1*), which could go as high as 34°C with an average high relative humidity of 84% for the whole year (Hien, 2007; Weather Atlas, n.d.).The high temperature recorded in this climate suggests that it requires cooling all year, making it an ideal cooling-dominated climate.

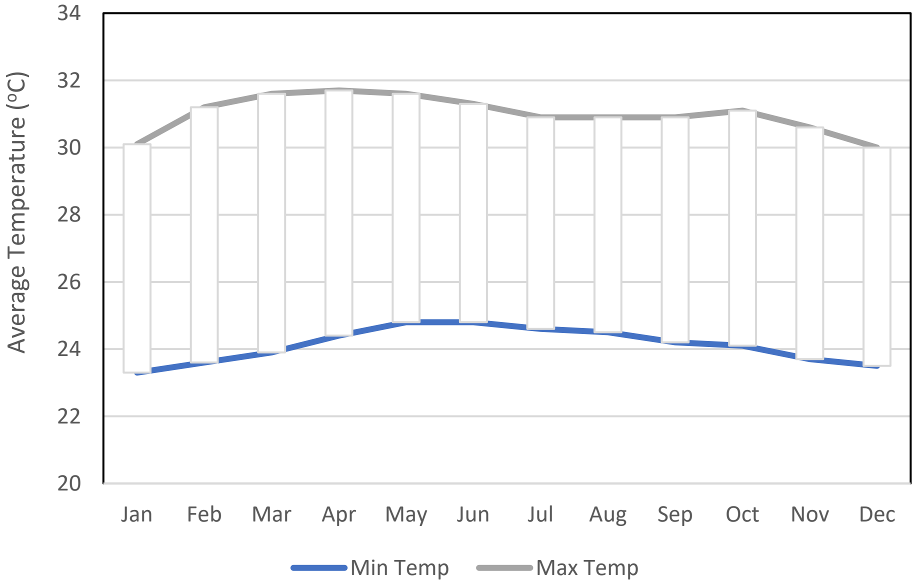


Figure 3-1: Average Temperature, Singapore (Weather Atlas, n.d.)

3.2.2 Energy Consumption of Buildings in Singapore

According to Chuan & Ukil (2015), the building sector (residential, commercial and industrial) consumes over half of Singapore's electricity generation. In residential buildings, about 40-50% of electricity is consumed to operate the heating, ventilation, and air-conditioning (HVAC) system (Chou, 2010; Heng & Chow, 2019; Wu et al., 2017). Thus, in an effort to reduce greenhouse gas GHG emissions by reducing energy demand in the building industry, the government of Singapore seeks a transformation of the sector by targeting 80% of buildings to be green certified by 2030 (Vidushini Siva, 2017).

To accomplish this transformation, the Building and Construction Authority of Singapore ((BCA), 2014) recommends the reduction of heat gain through the building envelope. Since a significant part of the cooling energy consumption is attributed to the heat gain through the building envelope (Wu et al., 2017). Thus, buildings are required to focus on thermal insulation, glazing, shading devices, and other design parameters such as window-to-wall ratio, massing, and orientation to achieve low-energy building design. In line with this, the BCA seeks to modify and adopt the Passive House Standard to achieve its low energy goals.

3.2.3 Previous Study of Passive House Framework in Singapore

Currently, no building has been certified as a Passive House in Singapore. Also, at the time of this study, there were limited resources on the analysis of Passive House in Singapore except for the PHI study by Schnieders et al. (2015). The study, which concluded that the Passive House is achievable in all the world's major climates, highlights that in Singapore, the total practical energy demand for sensible and latent cooling may exceed 70 kWh/(m^2a) in Passive House. This energy demand exceeds the Passive House recommendation of 15 kWh/(m^2a).

In addition, while the average cooling load was recorded, the peak load required for Passive House certification was not. The study, which also did not provide detailed information on the applicability of Passive House strategies in this climate, indicated the need for further research.

3.3 Design of Study

In this study, the Tseri Passive House is investigated for the Singaporean climate, as earlier stated. The study commenced by determining the building's performance in this climate, as it had been validated in the previous chapter.

Whilst attempting to adapt the building to this climate, a parametric analysis was performed, which examined each of the fundamental Passive House strategies. This included varying the thermal transmittance/insulation of each building envelope element, the building's airtightness, and the ventilation rate of the mechanical heat recovery system. In this regard, the building's preliminary performance in this climate was useful as it served as the baseline for the parametric study.

3.3.1 Summary of Design Parameters

The reference building is a two-storey building with a total area of 185 m^2 and a clear room height of 2.5m. The internal gain is computed as 3.1 W/m^2 as the reference building. Further information about the building can be found in Chapter 2.3.1.

More specifically, for this study, a simple constant volume energy recovery system was used to provide ventilation in the building to analyse the effect of a heat recovery ventilation system. The energy recovery system technical data includes an efficiency of 82%, as in the reference building design data. The ventilation rate of the system was calculated based on 0.35 ACH, which is the minimum ventilation acceptable to human occupants under the ASNI/ASHRAE Standard 62.1 guidelines (ASHRAE, 2022).

3.3.2 Assessment of Results

The result analysis focused on the main Passive House objectives, energy efficiency and thermal comfort. Thus, the building's energy demand was analysed, including the peak heating and cooling load, annual heating and cooling demand, and annual total energy.

The peak heating or cooling load – corresponds to an “ideal heating and cooling system” that keeps the indoor air conditions within the “indoor comfort range.” The annual heating and cooling demand – is the sum of energy that needs to be added or removed from the conditioned space to maintain a constant/specified temperature all year. Meanwhile, the total energy is the annual energy consumption for systems, lighting, and other appliances. These energy results are benchmarked against the Passive House standard (see Chapter 1.3.2).

Also, the indoor condition is analysed using the comfort graph, as shown in *Figure 3-2*. This graph is based on the Passive House Institute recommendations (Schneider, 2009) following the ASHRAE 55 and EN 15251 standards. Hence, as shown on the graph, the inner and extended comfort range are referred to as the acceptable comfort range or comfortable conditions in this study. Accordingly, the temperature and humidity are plotted to view the indoor thermal condition of the building throughout the year.

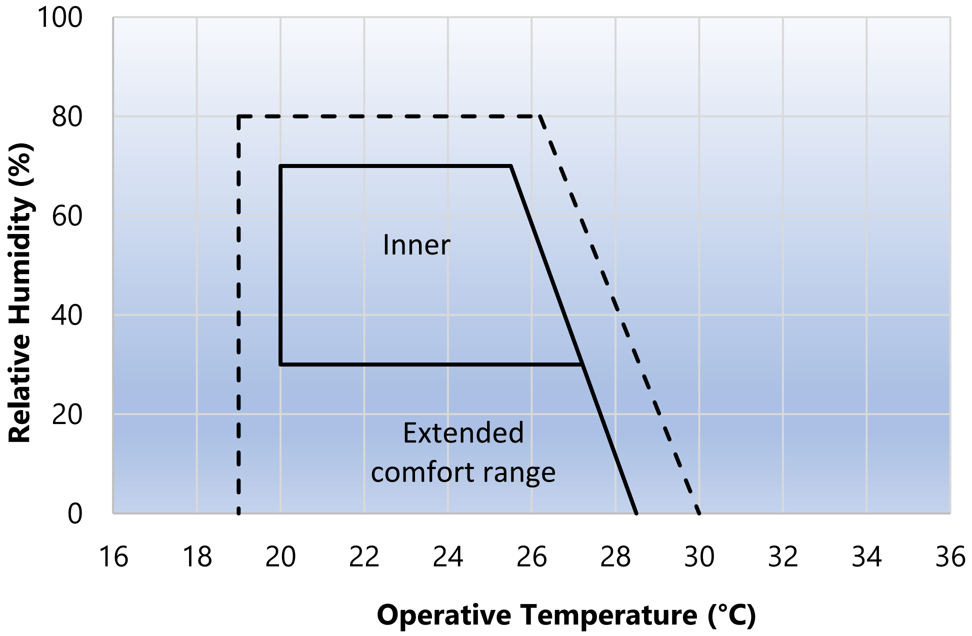


Figure 3-2: Comfort Range for Dynamic Simulations (Schnieders et al., 2015).

3.4 Performance of Reference Passive House Building in Singapore

Having simulated the reference building in Singapore, its performance, which comprises the annual cooling demand, peak cooling load, and total energy of the building, is shown in *Table 3.1*.

Table 3.1: Energy Summary of Reference Building

Energy Analysis	**Reference Building**	**Passive House Standard**
Peak Cooling Load (W/m^2)	8	10
Annual Cooling Demand $kWh/(m^2a)$	37	15
Total Energy $kWh/(m^2a)$	59	120

In *Table 3.1*, it can be seen that the building meets the peak cooling load standard of the Passive House but exceeds the annual cooling demand by over twice. Since Passive House requires that the building meets either the peak cooling load or annual cooling demand standard, the building could be considered to have met the energy standard of Passive House.

However, another criterion for certifying that the building meets the Passive House Standard is meeting the indoor thermal conditions. This is evaluated by *Figure 3-3*, which showed that the thermal condition of the building is well outside the recommended comfort range, presenting a case of severe overheating.

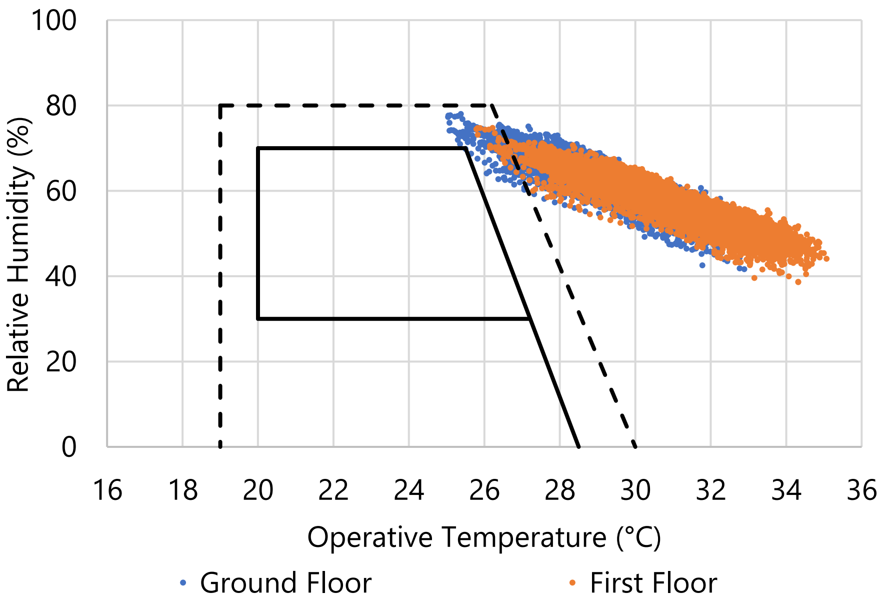
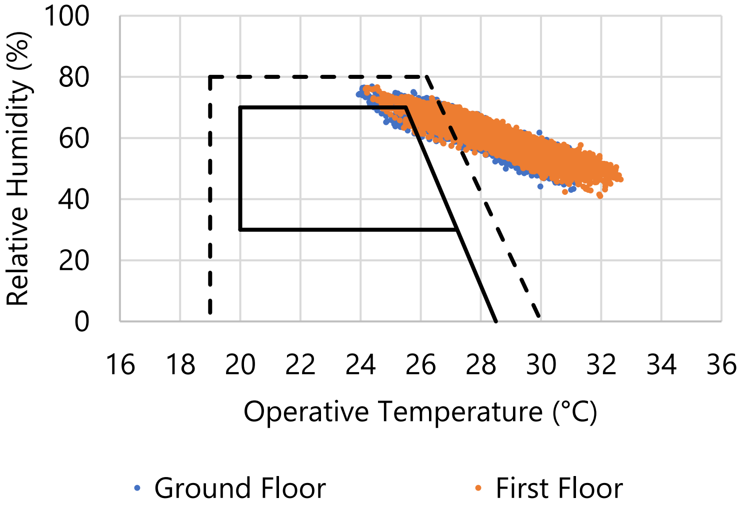


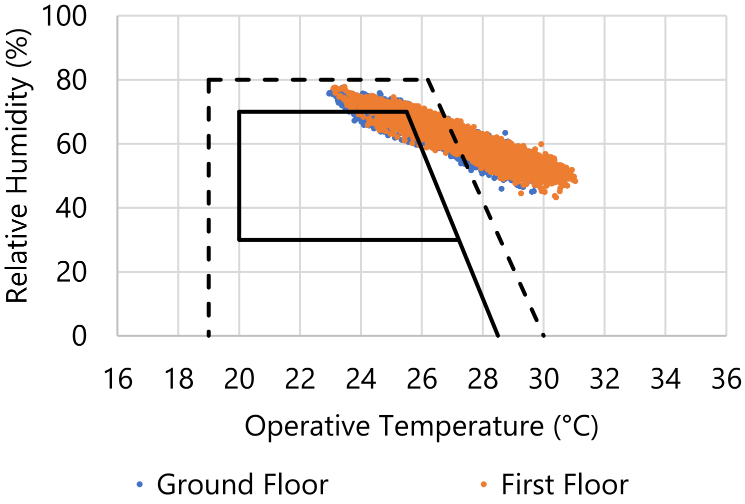
Figure 3-3: Indoor Temperature and Humidity of Reference Building @ 0.35 ach

It was evident that the designed mechanical ventilation system was inadequate to manage the thermal conditions of the building. Therefore, the first attempt to solve the issue was to increase the ventilation rate of the mechanical system. Since the building relies on the supply air to provide cooling, increasing the controlled ventilation rate was intended to improve the building's thermal condition.

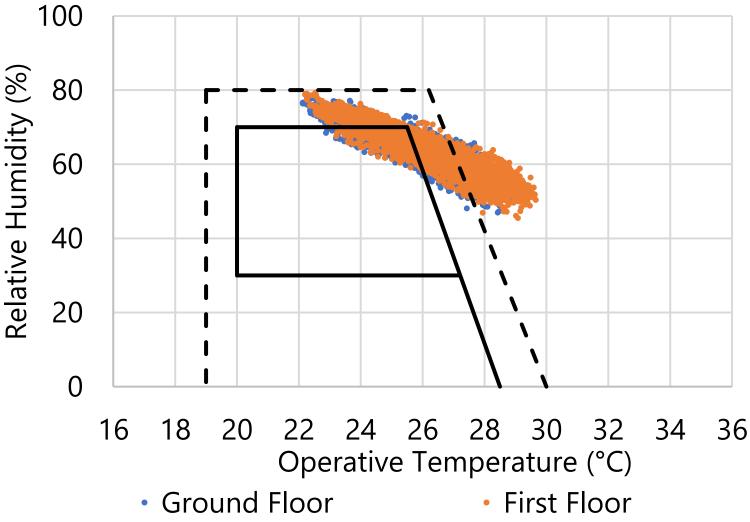
Additionally, the PHI institute recommends outdoor airflow of 5–10 L/s per person (~0.3–0.6 air changes per hour or equivalent to 18–36 m^3/h per person) for mechanical systems based on the ASHRAE 62.1 & 62.2 (2019) (Feist et al., 2005; Robertson, 2021). Feist et al. (2005) also highlighted that 0.30 ACH (the lower air change rate) might deliver fresh air into the building but would not be sufficient to provide cooling, as shown in *Figure 3-3*. Therefore, the next step was to explore the upper limit of 0.60 ACH recommended ventilation rate. *0.6 ACH* The resultant indoor condition of the building is shown in *Figure 3-4 (a)*.



a. *0.6 ACH*



b. *0.8 ACH*



c. *1 ACH*

Figure 3-4: Indoor Temperature and Humidity of Reference Building at 0.6 ach (a), 0.8 ach (b), 1.0 ach (c).

Since the increasing ventilation rate of the system to 0.6 ACH appeared to improve the thermal conditions of the building, the ventilation rate was subsequently gradually increased by 0.2 ACH to monitor its effect on the building performance. This was considered under the ASHRAE 62.1 & 62.2 (2019) guidelines of ASHRAE, where the recommended air ventilation rate in residential can range between 0.35-1 ACH (Martin, 2014; Robertson, 2021). Therefore, an air change rate of up to 1 ACH was considered, and the thermal condition of the building was observed to improve significantly (*Figure 3-4,c)*.

Increasing the ventilation rate of the mechanical ventilation system with heat recovery was shown to improve the building's indoor thermal conditions. Consequently, resulting in increasing the cooling load of the building because more outdoor air was introduced to the system. Hence, additional energy was required to overcome the load, increasing the building's energy demand (*Figure 3-5*). Also, increasing the airflow rate in humid climates like Singapore would mean increased indoor humidity, as shown in *Figure 3-5*. Thus, the building did not meet the Passive House standard, as the peak cooling load and annual cooling demand exceeded the criteria.

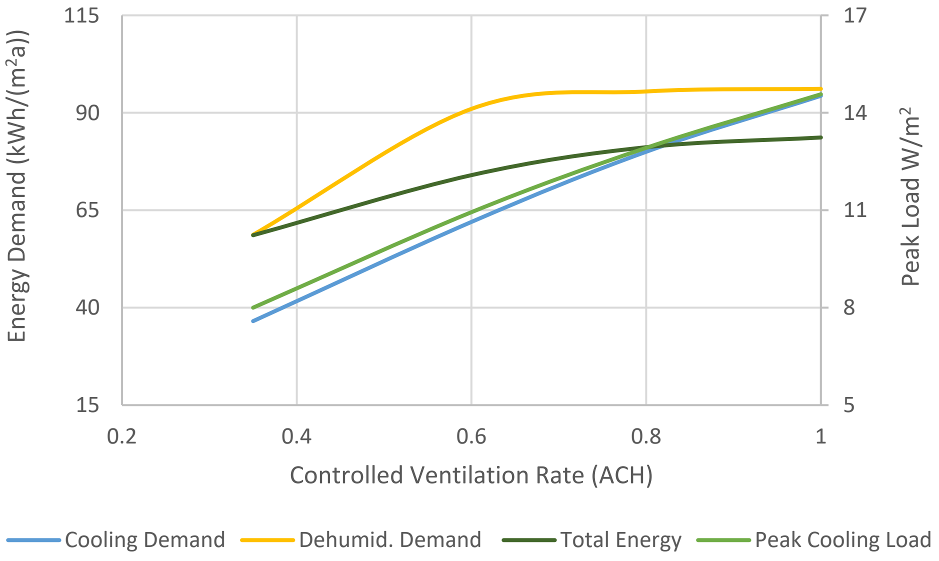


Figure 3-5: Energy Demand of Reference Building for varied Controlled Ventilation Rate

Since the Passive House standard was not met, it was inferred that the building did not perform similar to its original design climate. Primarily, because acceptable comfort conditions were not attained for a significant period of the year, and an attempt to improve the conditions by increasing the mechanical ventilation rate increased the cooling energy demand significantly. Thus, setting it outside the Passive House standard.

3.5 Parametric Assessment of the Reference Building

As demonstrated above, when the reference Passive House was applied to Singapore’s hot and humid climate, either the energy demand criterion or the thermal comfort criteria were met rather than both simultaneously as per the Passive House framework. This outcome could be attributed to climate-related factors such as high temperatures and super-insulation. As a result, a parametric analysis was conducted to investigate methods for optimising and adapting the reference model.

Firstly, the parametric exploration investigated the Passive House strategies (i.e., super-insulation, advanced window technology), which influence the building envelope’s thermal transmittance. Thereafter, given that an increased controlled ventilation rate above 0.35 ACH significantly increased the energy demand of the building, increasing uncontrolled ventilation rate was also explored as a means to improve building indoor conditions. To explore other strategies, the mechanical system’s ventilation rate of 0.35 ACH was maintained. This ventilation rate is also recommended by the building and construction authority Green Mark (an internationally recognised green building rating system tailored for the tropical climate) of Singapore (Building and Construction Authority (BCA), 2022).

3.5.1 Super-Insulation & Low Thermal Transmitting Window Analysis:

The performance of the reference building in Singapore corroborates the report of overheating from other performance analyses of Passive House buildings, even in heating-dominated climates, including the reference building (Tseri Passive House) (see Chapter 1.6.1 and Chapter 2.3.2). Although the high external temperature throughout the year in Singapore could be considered a significant factor for overheating in the model Passive House; other studies have identified low thermal transmitting or highly insulated windows and super-insulating building envelopes as contributing factors in overheating. Therefore, optimising the building envelope was considered to enhance internal conditions since external conditions cannot be changed, and increasing the ventilation rate of the mechanical system would increase energy usage. As a result, the building envelope's insulation (thermal transmittance) was assessed.

Super-insulation aims to reduce heat transfer between internal and external boundaries; as such, heat gained from internal and solar heat sources can be trapped in the building. Thus, reducing insulation or increasing the thermal transmittance of the building envelope – wall, roof, and floor is explored as a means to improve the building's performance.

The PHI recommends that the building heat transfer coefficient for a Passive House should range between 0.10- 0.15 W/(m^2K) (Passivhaus Institut, 2021a). To achieve this, the building envelopes need to be well insulated. The thermal value of the envelope is expected to be below 0.10 W/(m^2K) (International Passive House Association (iPHA), 2021). However, in the case of this reference building, the thermal value for the building component varies slightly; external wall – 0.18 W/(m^2K), roof – 0.15 W/(m^2K), floor – 0.48 W/(m^2K) as calculated by the PHPP. Also, in the study by Schnieders et al. (2015), the Singapore reference design had a thermal value higher than the recommended value of 0.10- 0.15 W/(m^2K);where the thermal transmittance of the wall and roof were 0.20 W/(m^{2}K) and 0.28 W/(m^{2}K) respectively, and the ceiling/floor 0.36 W/(m^{2}K).

Thus, to optimize the performance of the reference building, the thermal transmittance for the wall, roof and floor is increased simultaneously. The insulation of the reference building is reduced to about half (low insulation) and a quarter (lower insulation), with the corresponding U-value increased by 100 and 200 percent simultaneously (*Figure 3-6)*. This distinct range was set to observe its influence on the performance of the reference building.

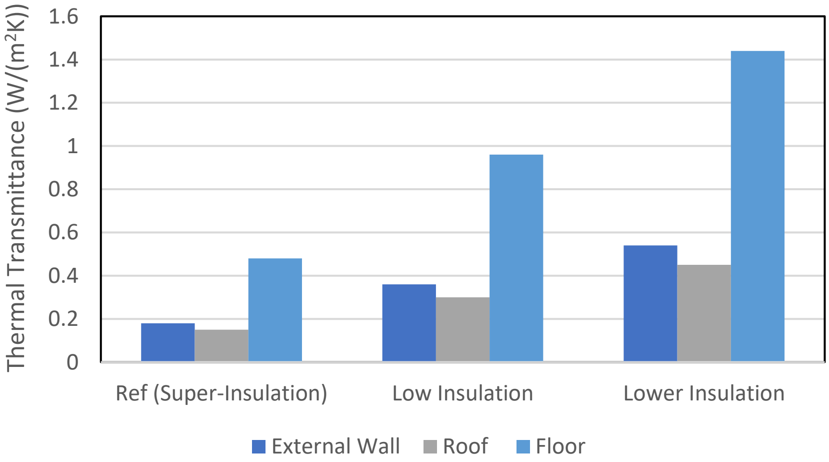


Figure 3-6: Thermal Transmittance of the Varied Building Envelope.

Additionally, in a Passive House, a highly insulated window is recommended to allow sufficient heat gain whilst significantly preventing heat loss. The Passive House Institute recommends that the entire window, i.e. glazing and frame, have a U-value of 0.80 W/(m^{2}K) or less (International Passive House Association (iPHA), 2021). However, standard double-glazed windows can vary between 1.6 W/(m^{2}K) and 2.1 W/(m^{2}K)). So as an attempt to manage overheating in the building, these higher thermal transmitting windows were considered.

3.5.1.1 Results and Discussion

This section analyses the effect of a lower insulated envelope on the building's performance. It was assumed that the wall, roof, floor, and window had a thermal transmittance twice and thrice that of the reference building. The effect on the indoor temperature is shown in *Figure 3-7*.

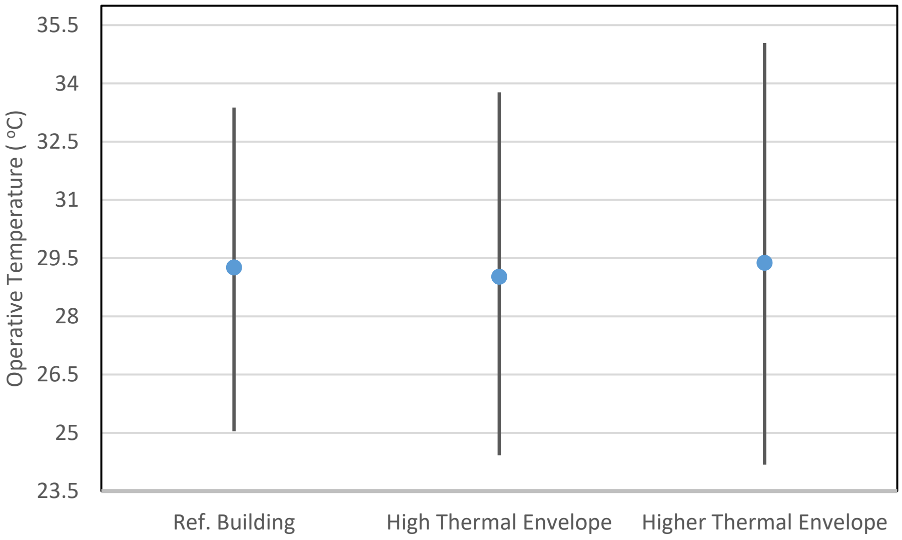


Figure 3-7: Indoor Operative Temperature of Reference Building with High(er) Thermal Transmitting Envelope.

Figure 3-7 shows more heat transfer with the higher thermal transmitting envelope(s). Thus, the indoor environment responds more when the external temperature was higher or lower. As observed, the minimum temperature measured in the high thermal transmitting envelope is about 1°C lower than the reference building. Due to less insulation, the indoor environment can experience heat loss when the outdoor temperature is lower, thereby slightly affecting the building's average temperature. The same phenomenon was observed in the higher thermal transmitting envelope experiencing a higher indoor temperature, presumably gaining more heat and increasing the indoor temperature when the outdoor temperature is high. However, the average temperature experienced in the building is similar in all instances.

This corresponds to the outcome of the building energy demand shown in *Figure 3-8*, except that the peak cooling load of the less insulated building increased due to the increased heat gain because of the higher thermal transmittance of the building envelope.

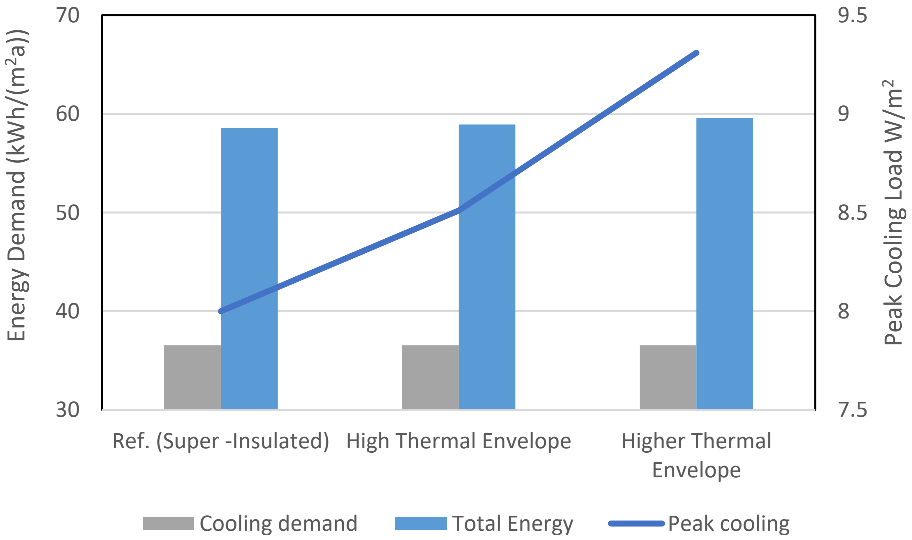


Figure 3-8:Energy Demand for Reference Building with Higher Thermal Transmittance

Therefore, the alteration of the building insulation did not enhance the building's performance, as the thermal conditions shown in *Figure 3-9* still present an uncomfortable indoor environment as the operative temperature and humidity were largely outside the acceptable thermal comfort range.

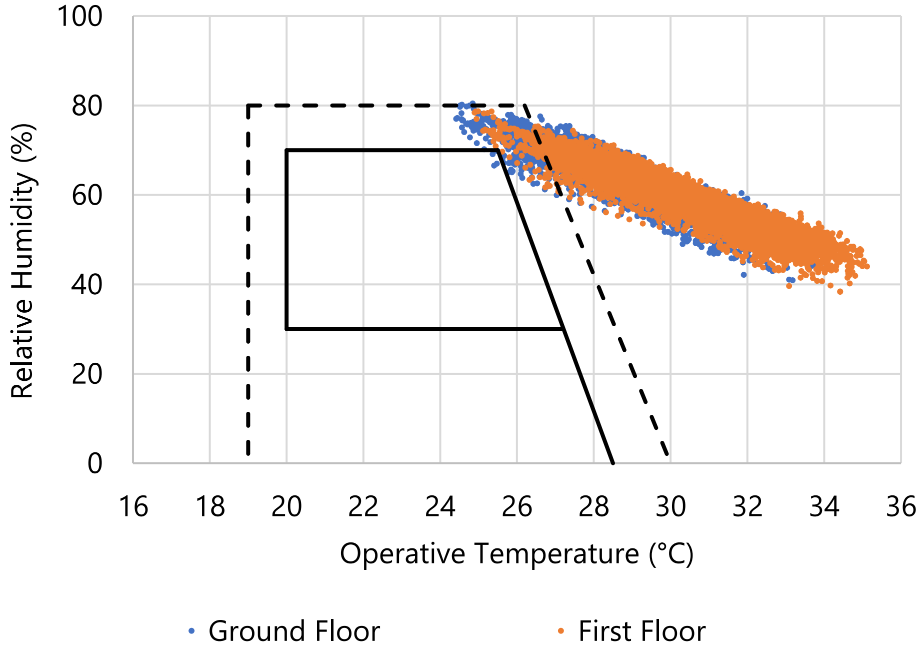


Figure 3-9:Indoor Temperature and Relative Humidity of High Thermal Transmitting Reference Building

3.5.2 Airtightness Analysis

Another strategy Passive House uses to reduce heat transfer and save energy is ensuring airtightness does not exceed 0.6 ACH at 50 Pascals. Also, uncontrolled infiltration or leakages in building envelopes have been linked to several building problems, including condensation water damage (Vornanen-Winqvist et al., 2018; Younes et al., 2012). Accordingly, Gonzalo et al. (2022) state that "ventilation through gaps and cracks provides no reliable contribution to indoor air quality, as it is subject to extremely large fluctuations". In the study carried out by Feist et al. (2001), where 221 Passive Houses were studied, it was reported that ventilation through gaps and cracks provided no benefit and had significant disadvantages such as condensation water damage, draughts, and elevated energy consumption.

However, U.S. Department of Energy (2014) noted that because of the low temperature differential between the outside and inside environment in a hot climate, the issue of condensation and energy increase due to infiltration is insignificant. Thus, the building infiltration was explored as a means to improve the indoor temperature. The uncontrolled ventilation rate of the reference building was increased from the set 0.6 ACH to 1- 5 ACH.

3.5.2.1 Results and Discussion

Having considered increased uncontrolled ventilation for the reference model, the temperature of the building is shown in *Figure 3-10*, where the minimum indoor temperature recorded in the building gradually reduces as the air infiltration increases. This was due to increased air flow through openings, gaps and cracks, which resulted in heat loss in the building when the outdoor temperature was lower. Thus, the average indoor operative temperature dropped up to 1°C at 5 ACH; however, the maximum temperature experienced in the building remained high.

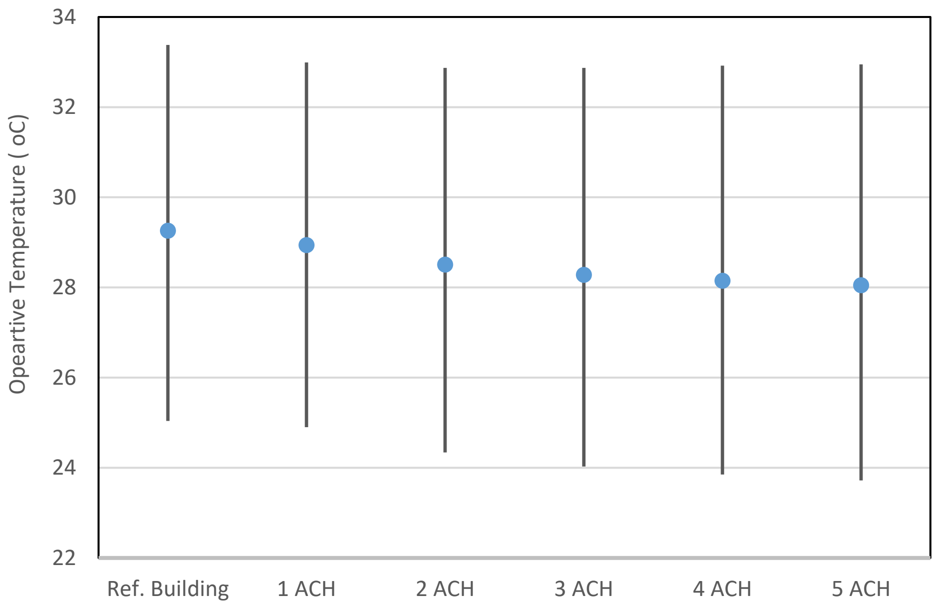


Figure 3-10:Indoor Operative Temperature of Reference Building with Increased Infiltration.

As a result, while uncontrolled ventilation aided heat loss in the building (presumably when the outdoor temperature is lower), thereby lowering the average temperature, it was insufficient to overcome overheating. Similarly, while infiltration reduced the cooling load slightly, the energy demand of the building remained constant even at higher infiltration *Figure 3-11*. This could be due to the low temperature differential between the outside and inside environments in a hot climate and/or heat transfer associated with increased infiltration.

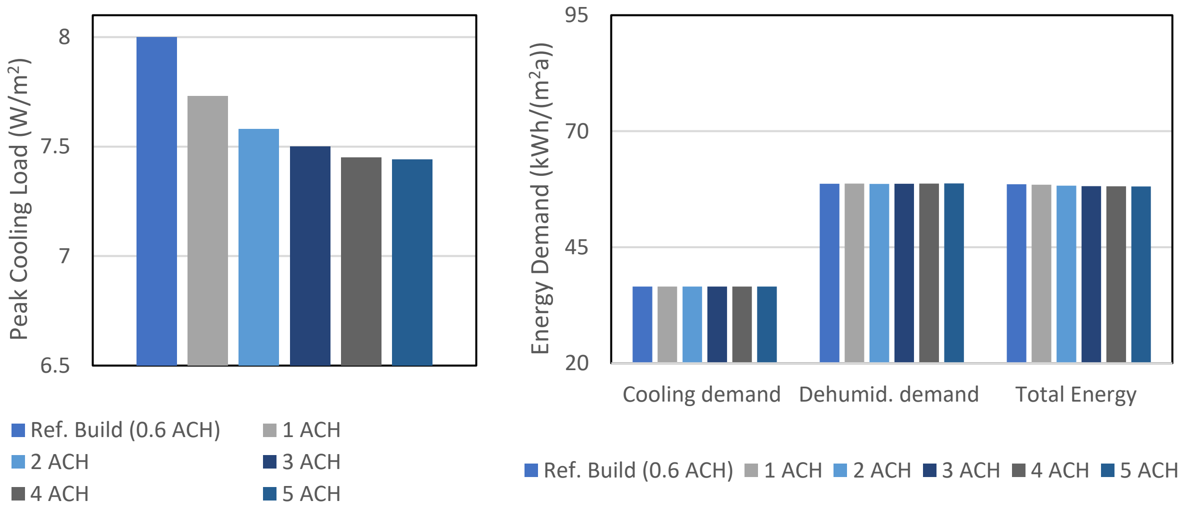


Figure 3-11: Energy Demand of the Reference Building with Increased Infiltration

Therefore, increased infiltration did not significantly affect the building’s energy and thermal condition. This result is in line with the report of the U.S. Department of Energy (2014), as it was observed that the effect of airtightness on energy demand was not as significant in cooling-dominated climates as reported in heating-dominated climates.

3.6 Conclusion

In this study, a certified Passive House was considered for the cooling-dominated climate of Singapore. It was observed that the Passive House building in its initially designed climate of Cyprus (Sub-tropical climate) satisfied the Passive House standard. However, when applied in Singapore's hot and humid climate, the building did not meet the Passive House standard, mainly due to overheating.

Conclusively, the approach of adapting the reference building to the cooling-dominated climate of Singapore proved unsuccessful, and any attempt to modify the building by focusing on the

Passive House strategies proved ineffective. Hence, an alternative approach is taken in further studies to achieve the research objective.

4 Exploration of the Passive House Framework in Hot and Humid Climates

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4.1 Introduction

In the previous chapter, a certified Passive House from a sub-tropical climate was explored for adaptation in Singapore's tropical hot and humid climate. The building, however, did not meet the Passive House criteria because the indoor thermal condition was primarily outside the acceptable thermal comfort range. It was therefore inferred that modifying a Passive House designed for a different environment might be challenging. Thus, another approach to achieving a Passive House in hot and humid climates was investigated in this chapter.

This approach involved applying the Passive House strategies to a conventional building in an effort to reach the Passive House standard rather than adapting a Passive House from another climate. This methodology was decided considering that the Passive House strategies have been fundamental in achieving a Passive House in heating-dominated climates.

This method was also used in designing and achieving the first Passive House. According to Feist (2001), using computer simulation, the first Passive House was accomplished by systematically varying the building’s components (insulation, airtightness, window size, glazing quality, internal gain, orientation, and ventilation system).

Moreover, choosing a conventional building allows the evaluation of the influence of Passive House strategies on building performance. If successful in attaining the Passive House standard, it can increase the chance of practical adaptation in this climate. Since the building would be no different from a typical conventional building except that it is built to a higher standard. To this end, a conventional building in Indonesia's hot and humid climate was evaluated.

Though it would have been useful to use the exact location as the previous chapter, there appears to be insufficient data to enable and support accurate modelling for a conventional building in Singapore. Thus, given that both Indonesia and Singapore are both hot and humid and share comparable weather data (*Figure 4-1*). It was decided to use a conventional building in Indonesia with sufficient data to allow the modelling and representation of a typical building in this climate.

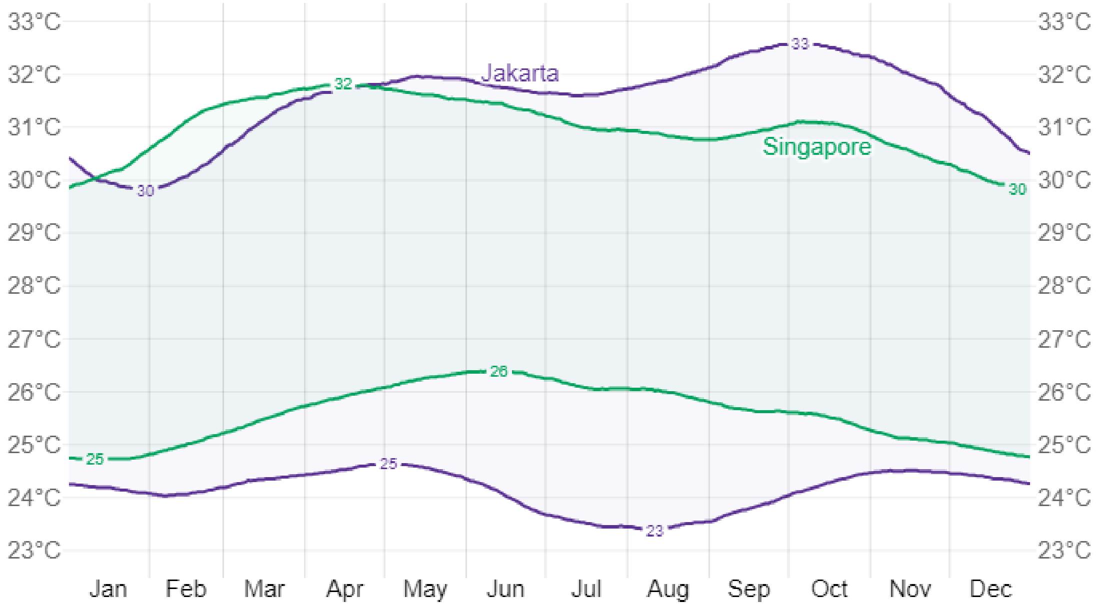


Figure 4-1:Comparing the Average High and Low Temperature in Jakarta, Indonesia and Singapore (WeatherSpark.com, n.d.)

4.2 Location of Study – Indonesia

4.2.1 The climate in Jakarta, Indonesia

Indonesia, located in South-east Asia between 6°08′ N–11°15′ S and 94°45′–141°05′ E, has only two seasons each year, a dry and a wet season. The average and maximum outdoor temperatures are 26ºC and 37ºC, respectively, while the average relative humidity ranges between 73% and 100%. Indonesian regions experience rainfall between 1000 and 4000 mm/year. The climate is generally hot and humid, with only a slight temperature variation throughout the year.

4.2.2 Energy Use in Indonesia

Indonesia currently relies heavily on fossil fuels for its energy generation. According to (*Indonesia Energy Sector Assessment, Strategy and Road Map Update*, 2021), as of 2019, the country's primary energy supply mix consisted of oil 35%, coal 37.3%, gas 18.5%, and about 9.2% from new and renewable energy (which includes geothermal, biofuel, biogas, hydropower etc.) making Indonesia, the 10th largest greenhouse gas emitter and 19th highest country in terms of CO_2 emissions per capita.

It is reported that the following sectors are the primary consumers - transport, industry, and residential building, where residential buildings consume about 14% of the country's total energy for lighting (lamps), entertainment (television), and space cooling (refrigerator and air conditioning systems). Space cooling ranks first among the other consumptions, consuming about 35% of total consumption (Hilmawan, 2011; Santy et al., 2017).

This percentage of space cooling consumption is projected to continuously increase as the sales and use of fans, refrigerators and air conditioning systems are increasing due to heat waves. Batih & Sorapipatana (2016) explains that because the ambient temperature is relatively hot all year-round and buildings are thermally uncomfortable, low-income earners typically rely on an electric fan. But as soon as income increases, appliances for increased comfort, i.e., air conditioners, are purchased.

The current policies in Indonesia expect the delivery of 2% reduction in energy use by 2025, with the expectation of energy-saving up to 10% and 35% across residential, municipal and others (*Indonesia Energy Sector Assessment, Strategy and Road Map Update*, 2021).

4.2.3 Previous Study of Passive House concept in Indonesia

To tackle this issue of uncomfortable indoor conditions, causing a massive reliance on air-conditioners and contributing to energy use in residential buildings. Santy et al. (2017) attempted to explore the Passive House idea of post-heating and post-cooling to design a thermally comfortable house that does not require mechanical HVAC system for heating and cooling purposes. The design of the building, which considers the Indonesian climate, was intended to lay a foundation for developing a Passive House in this climate. Thus, it investigated the effectiveness of strategies such as heavy walls, roofs, and window openings proposed by bioclimatic analysis.

This research, however, focuses on the applicability of the Passive House framework in this climate. Nevertheless, Santy et al. (2017) provided substantial data used in this study to model a typical residential building in Indonesia. The literature was chosen because it provided adequate information to simulate and validate the building.

4.3 Design of Case Study

Firstly, a validation assessment was carried out to ensure that the building and its characteristics have been accurately represented in the software package IES-VE. The evaluation relies on the performance of the building in contrast to the reports in the reference literature and other secondary sources.

Following this, an analysis of the building began with establishing the performance of the reference building by assessing the building’s performance (indoor conditions and energy demand). The result provided the baseline for further investigation, where super-insulation, advanced window technology, airtightness and heat recovery ventilation were explored for the building.

Given that the previous study in Chapter 3 demonstrated that simply adhering to the Passive House recommendation of thermal transmittance for building envelopes could be problematic. In this Chapter, investigations of thermal transmittance using insulation followed a more in-depth method where each component of the building envelope (i.e., wall, floor roof) was analysed independently. This provided guidance for applying insulation and establishing its effectiveness and role in achieving a Passive House for this climate. Insulation was applied at different thicknesses from a minimum of 2 cm to 10 cm, representing a spectrum of thermal coefficients from minimal to super insulation as recommended by Passive House.

Subsequently, as part of the building envelope, highly insulated windows were examined for the reference building instead of only considering the Passive House standard window. A standard double-glazed window with U-value higher than the Passive House standard window but lower than a typical conventional window was also analysed. The assessment was to scrutinise the application and impact of low thermal transmitting windows whilst assessing the necessity for Passive House standard windows in a hot climate. The parametric analysis informed the modification of the reference building toward designing a Passive House in this climate.

Finally, to examine the last fundamental strategy that is, mechanical ventilation with a heat recovery system (MVHR) - a simple Constant Air Volume (CAV) system was applied to the building. The technical data of the CAV system followed the Passive House recommendation with a ventilation rate of 0.35 ACH and heat recovery of 85%. The CAV system was intended to provide ventilation and supplement cooling in order to manage the indoor temperature. The Passivhaus Institut (2019) indicated that such a system would be more functional and suitable in a building with a minimal cooling load. Therefore, the MVHR system and its effectiveness could only be investigated after the other strategies had been applied. Prior to this, the study assumed a conventional air conditioning system to achieve the set point temperature of 25^{o}C.

In addition to investigating the Passive House strategies, other passive techniques such as building orientation, external shading, and energy-efficient appliances commonly recommended to improve building performance were assessed. The study of these strategies was essential to show their efficacy in achieving a thermally comfortable, energy-efficient building in this climate.

4.4 The Reference Building

4.4.1 Building Design, Envelope & Material, Ventilation, Occupancy and Other Details.

According to Santy et al. (2017), a typical residential house in Indonesia has two bedrooms (one main bedroom and one child’s bedroom, one kitchen, one living room and one bathroom) depicted in *Figure 4-2*. The residential reference building has a total floor area of 54 m^2 and an occupancy of four (4). The materials and properties of the building envelope are detailed in *Table 4.1*. *Table 4.2* shows the electrical appliances frequently used by the occupant, including time usage. The building orientation is in the north direction, and the air change rate is set as 1/ach.

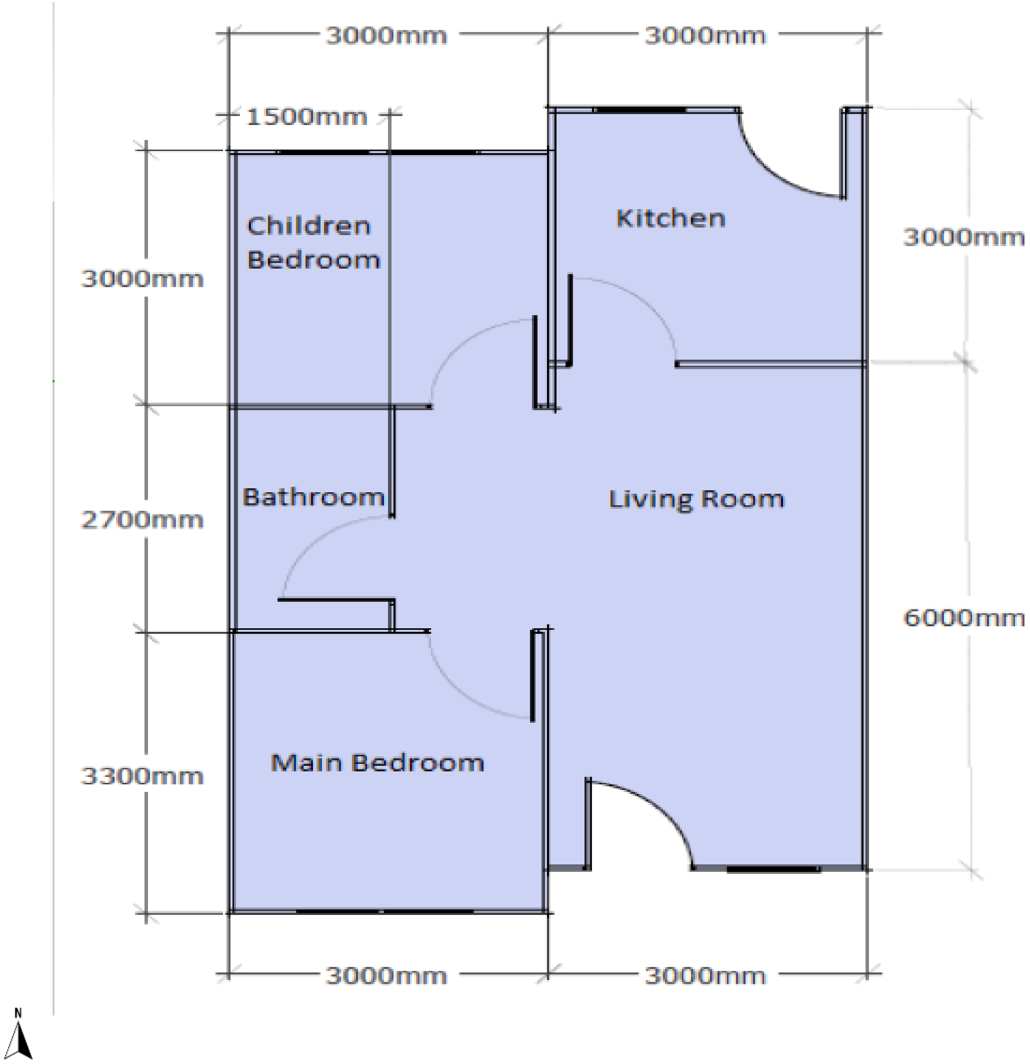


Figure 4-2: Typical Building in Indonesia (Santy et al., 2017)

Table 4.1: Building Envelope and Thermal Properties of each Layer.

House Envelope Elements	**Layer Name**	**Thickness (mm)**	**Density (kg/m3)**	**Specific Heat (J/kgK)**	**Thermal Conductivity (W/mK)**	**U-value (W/m^2 K)**
Roof	1. Clay tiles	10	1922	590	0.69	2.2063
	2. Air gap		Thermal resistance: 0.18 m^2. K/W			
	3. Gypsum plaster board	19	800	1090	0.16	
Wall	1. Cement and sand plaster	10	1858	837	0.6918	1.8087
	2. Concrete block	120	2200	750	0.339	
	3. Cement and sand plaster	10	1858	837	0.6918	
Floor	1. Ceramic tile	10	2390	730	1.5	0.4913
	2. Concrete screed	20	2000	656.9	0.753	
	3. Soil	1500	1300	1046	0.837	
Window	Tinted Single glazing (wood frame)	3			0.9	5.2353
Door	Wood	30	0.6	1500	0.147	2.6732

Table 4.2: Lighting, Electrical Appliances List and Usage.

Room	**Lighting Power (Watt)**	**Electrical Appliances**	**Appliance Power (Watt)**	**Appliance Usage**
Main bedroom	40	Fan Laptop Handphone	100 100 20	8 h/day 2 h/day 2 h/day
Bathroom	25	Washing machine	250	4 h/week
Children bedroom	40	Fan	100	8 h/day
Living room	40	Television Fan	240 100	8 h/day 8 h/day
Kitchen	40	Refrigerator Rice cooker	120 100	24 h/day 24 h/day

4.4.2 Validation of Model

Using the data above, the reference building was modelled in IES-VE, as shown in *Figure 4-3*. The building is initially simulated as a free-running house without an air conditioner, just as in the reference paper (Santy et al., 2017), in order to validate the model. Accordingly, the thermal condition of the simulated building is compared to that of the reference literature. The thermal comfort analysis is based on predictive comfort temperature (PCTu), with a comfort limit of 26.8 ± 1.5^{o}C. The total discomfort hours within the year in the three habitable rooms (living room, main bedroom, and children’s bedroom) is considered. This is based on the occupancy profile of 8 hours per day in the bedroom from 9 pm – 5 am and 16 hours per day in the living room from 5 am – 9 pm.

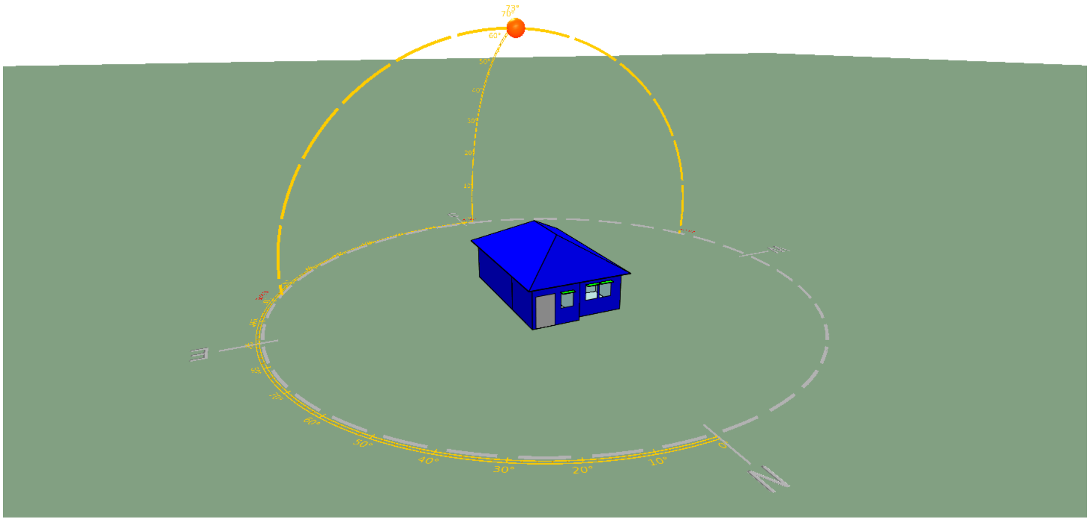
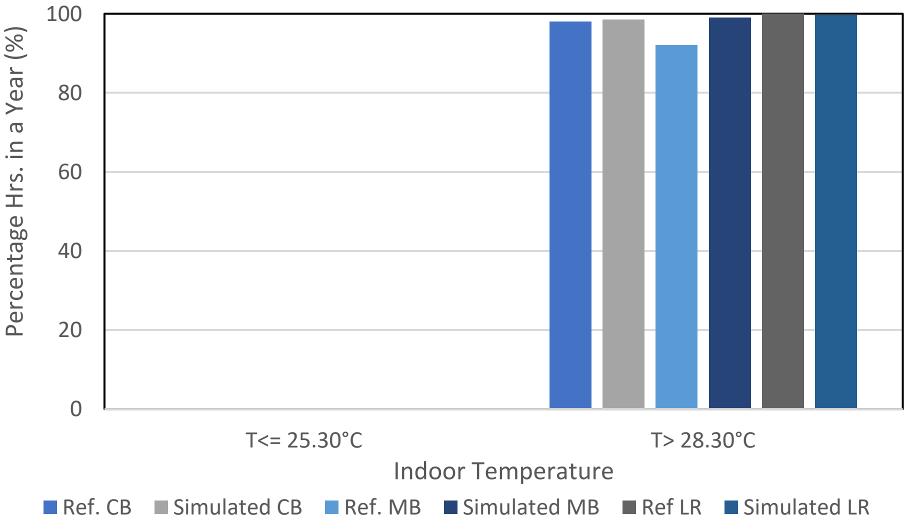


Figure 4-3: Indonesian Conventional Reference Building as Modelled in IES-VE.

4.4.2.1 Validation Results & Analysis

The analysis concentrated on the habitable room, as shown in *Figure 4-4*. It shows the building does not present a comfortable indoor environment in line with Santy et al. (2017); the discomfort hours are almost 100% of the habitable room's total hours in a year. This result establishes that the model depicts the temperature experienced in a typical Indonesian residential building (per the reference literature).



CB- Children's Bedroom, MB -Main Bedroom, LR -Living Room

Figure 4-4:Indoor Temperature Range in the Habitable Rooms of the Reference and Simulated Model.

Additionally, Sukarno et al. (2013) investigated the energy consumption of the residential sector in a local city (Padang City) in Indonesia. Based on the data collected, the electricity consumption in a typical Indonesian house ranges between 300-400 kWh/month. This was also confirmed by Matsumoto et al. (2016), studying 18 homes in another Indonesian city (Depok City). *Figure 4-5* shows the building's average monthly electricity is 404 kWh, which is in line with the report of Sukarno et al. (2013) and Matsumoto et al. (2016)—suggesting that the model is representative of reality.

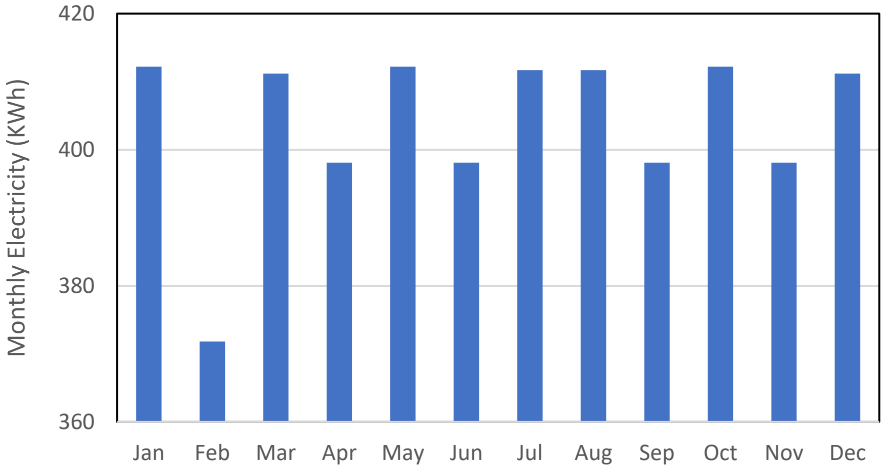


Figure 4-5: Monthly Electricity Consumed (kWh) in the Reference Building.

4.4.3 Baseline Performance of the Reference Building.

Given the high temperature recorded in the building, an air conditioner was introduced to improve thermal conditions and meet the acceptable thermal comfort range presented in Chapter 3.3.2. The setpoint temperature was 24 °C with a setback of 26 °C and relative humidity not to exceed 80%. The performance result of using the mechanical system is shown in *Figure 4-6* and *Table 4.3* noting that heating is not required in this climate.

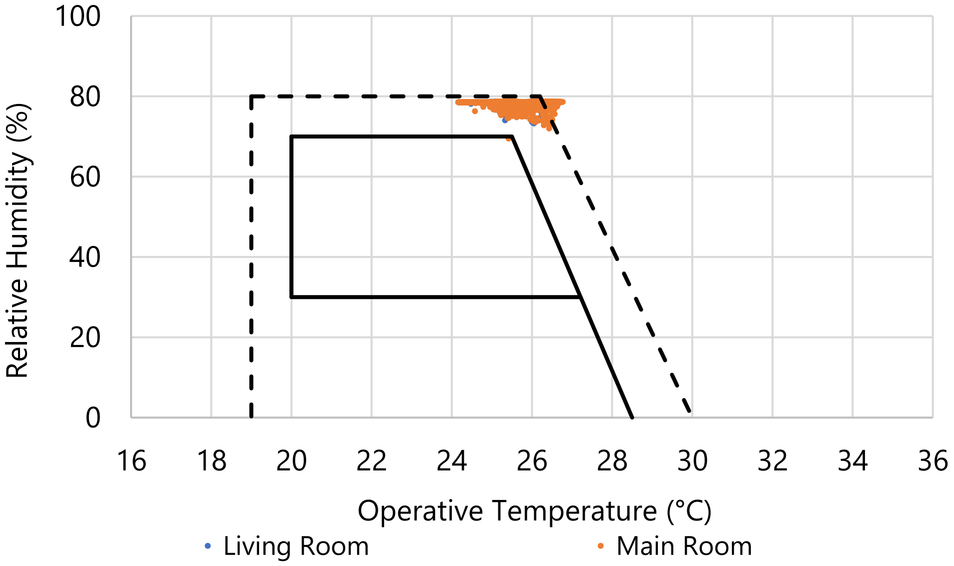


Figure 4-6:Indoor Operative Temperature and Relative Humidity of the Conditioned Conventional Building in Indonesia.

Table 4.3:Energy Demand of the Conditioned Reference Building.

Energy Demand	**The Conditioned Reference Building Indonesia**	**The Passive House Standard**
Cooling Demand (kWh/(m^2a)	294	15
Total Energy (kWh/(m^2a)	341	120
Peak Cooling Load (W/m^2)	34	10

The results show that the cooling required in the conventional reference building is nearly 20 times the allowable energy demand of a Passive House. The peak cooling load is also well above the standard. This comparison provided context for the energy demand of the building and served as a baseline for future studies.

4.5 Application of the Passive House Strategies

Having validated the reference building and estimated the baseline performance, the systematic application of the fundamental Passive House strategies is evaluated to guide the successful implementation of each technique. At the same time, its impact and effectiveness in maintaining the acceptable thermal comfort range and saving energy are also analysed.

4.5.1 Super Insulation

The first strategy introduced to the building envelope was super-insulation, and to effectively use this technique, the insulating material was applied individually to each component of the building fabric at different thicknesses (i.e., wall, roof, and floor). This was to ensure that insulation was being applied appropriately for this climate. The Passive House does not specify insulation to be used. The essential factor to consider was the building thermal transmittance between 0.10 – 0.15 W/(m^{2}K), which is achievable using an insulating material. In this study, polyurethane (insulating material) was applied at thicknesses from 2cm – 10cm, allowing the analysis of each component's thermal transmittance up to the Passive House recommendation for building envelope, as shown in *Figure 4-7.*

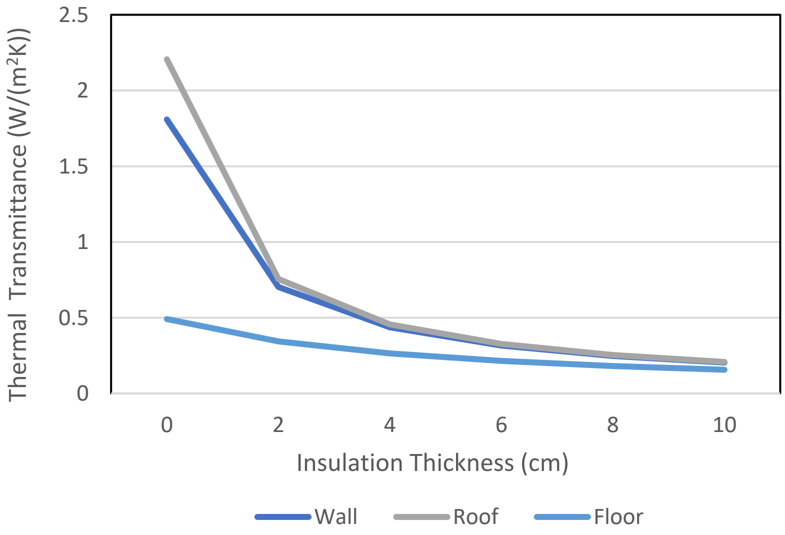


Figure 4-7: Thermal Transmittance of Wall, Roof & Floor with Different Insulation Thickness.

4.5.1.1 Results and Discussion

The results of applying insulation to each element (wall, roof, and floor) and its effectiveness on the building performance are presented as follows.

4.5.1.1.1 External Wall Insulation

The wall is the largest building envelope area constantly exposed to external conditions. So, having an uninsulated wall like the reference building, where there is minimal resistance to heat flow, it is likely for indoor thermal conditions to imitate external conditions—increasing the building's cooling demand. Therefore, it is expected that by introducing insulation to the wall, the heat transfer rate would slow down and progressively as insulation increases, thereby preserving indoor conditions and reducing cooling demand. However, the result presented in *Figure 4-8* shows a slightly different outcome.

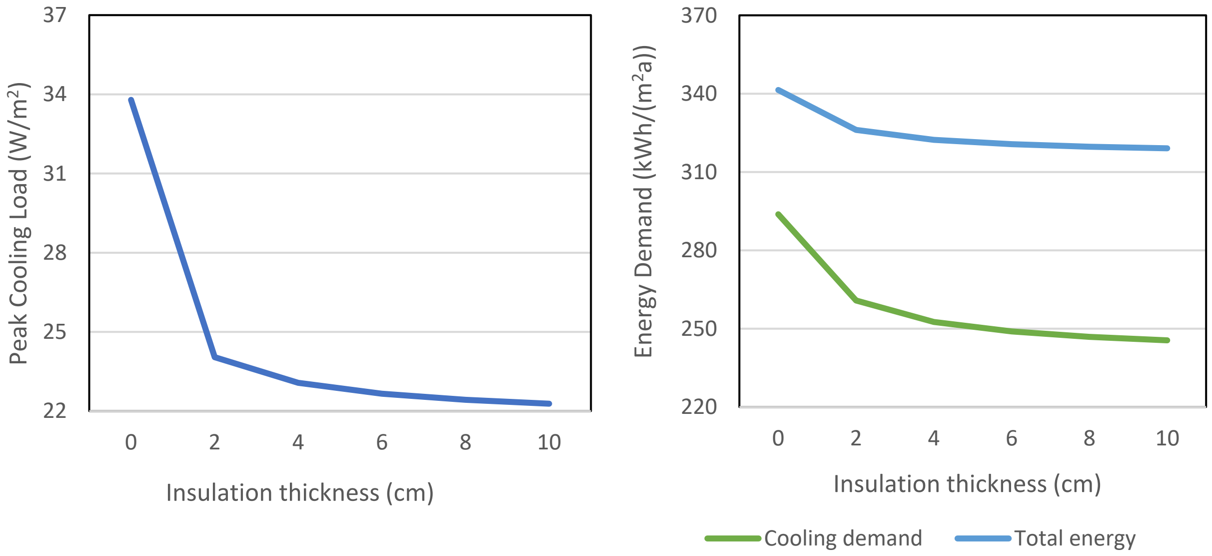


Figure 4-8: Energy Demand of the Reference Building with varied Wall Insulation/Thermal Transmittance.

The introduction of insulation to the wall, at a minimum of 2cm (0.70 W/(m^{2}K)), significantly impacted the building as insulation prevented excessive heat gain. The peak cooling load is reduced by 29% compared to the reference building with the uninsulated wall, which simultaneously resulted in the decline of the cooling needs by 11.24%—saving about 4.5% of the building’s total energy at minimum insulation of 2 cm. Though, this phenomenon did not continue as the insulation thickness increased; no significant effect was observed with the energy demand.

This shows that applying insulation to the wall to hinder external heat gain can be beneficial. However, increasing the thickness becomes insignificant when other sources (e.g., heat gain from roof, windows) and/or internal heat gain is the primary influence of heat gain in the building, as shown in *Figure 4-8*, with the discontinuity in the peak cooling load reduction.

Nevertheless, at the insulation thickness of 10 cm (0.20 W/(m^2K)), the influence of external heat gain was significantly minimised such that the peak cooling load was reduced by 34%. Consequently, reducing cooling demand by 16%, saving about 7% of the building’s total energy. However, its influence on indoor thermal conditions was negligible.

Super-insulating the wall (as Passive House suggested) does not appear to offer an outstanding advantage in this climate, as minimum insulation is sufficient to preclude external heat gain. This also explains the outcome in Chapter 3, where reducing the certified Passive House's insulation to improve the building performance was unsuccessful and had no significant effect, possibly because internal heat gain had become the leading cause of overheating.

4.5.1.1.2 Ground Floor Insulation

Following the analysis of the wall insulation, the floor insulation at various insulation thicknesses was investigated. The thermal transmittance of the building's ground floor, which is in constant contact with the soil providing some insulation, is 0.49 W/(m^2K). *Figure 4-9* shows the results of insulating the ground floor.

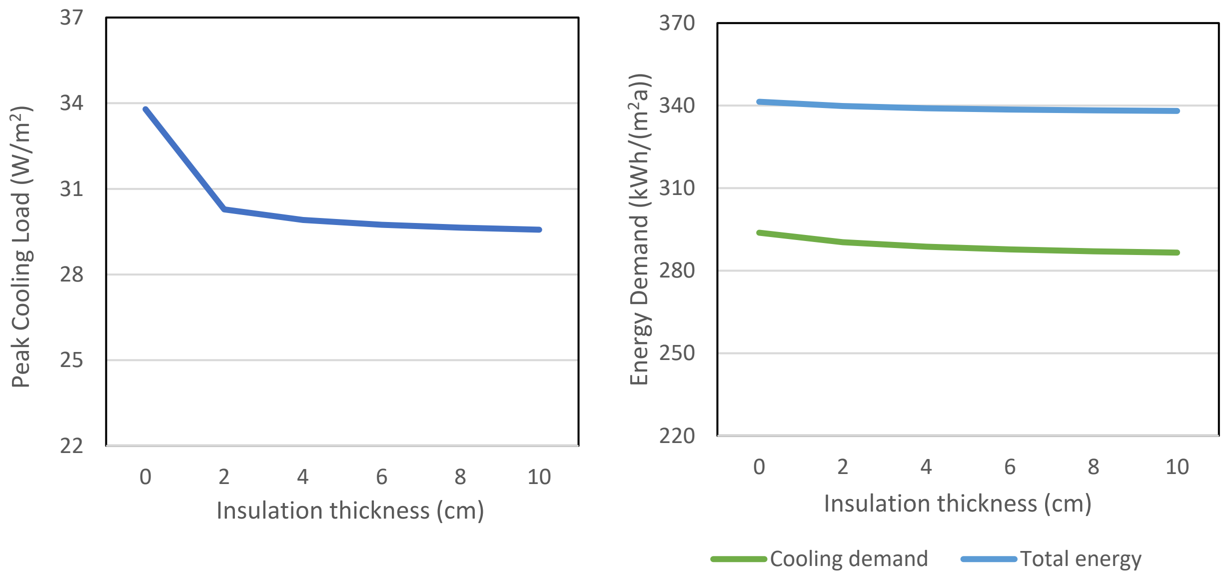


Figure 4-9: Energy Demand of the Reference Building with Varied Floor Insulation/Thermal Transmittance.

The introduction of floor insulation only slightly impacted the building's peak cooling load, with no significant effect on the building's energy demand. As previously stated, the ground floor has some insulation from the soil beneath it. As a result, the insulating material has little effect because the energy gained from other sources remains. Therefore, the energy required to maintain thermal conditions remains constant. Nonetheless, its initial impact on the cooling load highlights the benefit of insulation. The insulation thickness of 2cm (0.34 W/(m^2K)) further reduced heat transfer, reducing the peak cooling load by 10% compared to the reference building with an uninsulated floor.

4.5.1.1.3 Roof Insulation

The roof of the building is the most exposed to direct solar radiation. So, with an uninsulated roof, as in the reference building, it can be anticipated that the heat gain would be significant due to the roof's thermal transmittance (2.2 W/(m^2K)). On the other hand, the building's roof is made of clay tiles. According to Abas & Abd Rased (2016), clay has a high thermal mass, which allows it to retain heat and release it over time, presumably when the surrounding temperature is lower. This can be beneficial in this hot climate to reduce direct heat gain. As a result, it is uncertain how insulating the roof will affect the performance of the building. *Figure 4-10* depicts the outcome of insulating the roof.

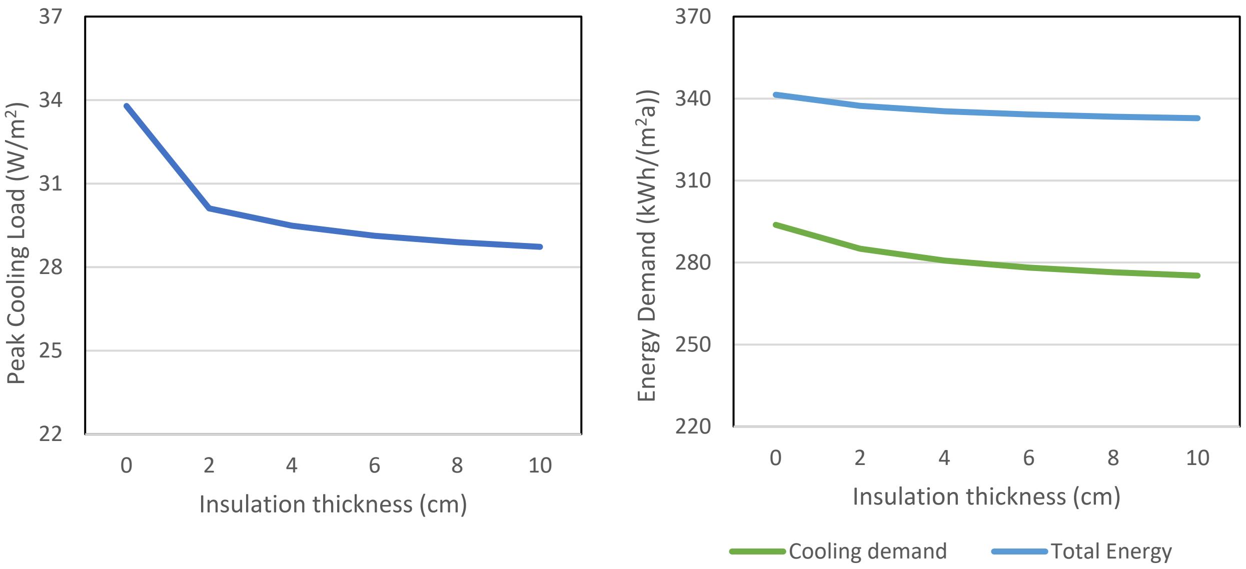


Figure 4-10: Energy Demand of the Reference Building with Varied Roof Insulation/Thermal Transmittance

Figure 4-10 shows that, despite the roof's thermal mass, adding insulation reduced peak load by 11% at the lowest insulation level (0.7 W/(m^{2}K)). The effect is less than the 25% reduction estimated for wall insulation of comparable insulation thickness and thermal value (0.7 W/(m^{2}K)). The peak cooling load was only reduced by 15% when the insulation thickness was 10 cm and the roof thermal transmittance 0.21 W/(m^{2}K). Due to the roof's thermal mass, which slows heat gain, the contribution of insulation appears minimal.

4.5.2 Advanced Window Analysis

The window, which is also part of the building envelope, is treated differently, forming another primary Passive House strategy. The reference building only has a few windows, with a window-to-wall ratio (WWR) of 6%. This design is possibly to manage heat gain as no window is located on the east and west side of the building.

In most conventional buildings, the windows are standard single-glazed windows with high thermal transmittance of 5.2 W/(m^{2}K). Therefore, as a means to improve performance and investigate its effectiveness, low thermal transmitting windows are explored for the reference building. Two insulated windows are examined: the standard double-glazed window of 1.4 W/(m^{2}K) and the Passive House Standard Window of 0.8 W/(m^{2}K).

4.5.2.1 Results and Discussion

Since the building has limited windows and no windows on the east and west side of the building, the impact of low thermal transmitting windows on the North and South windows was uncertain and investigated, as presented in *Figure 4-11***.**

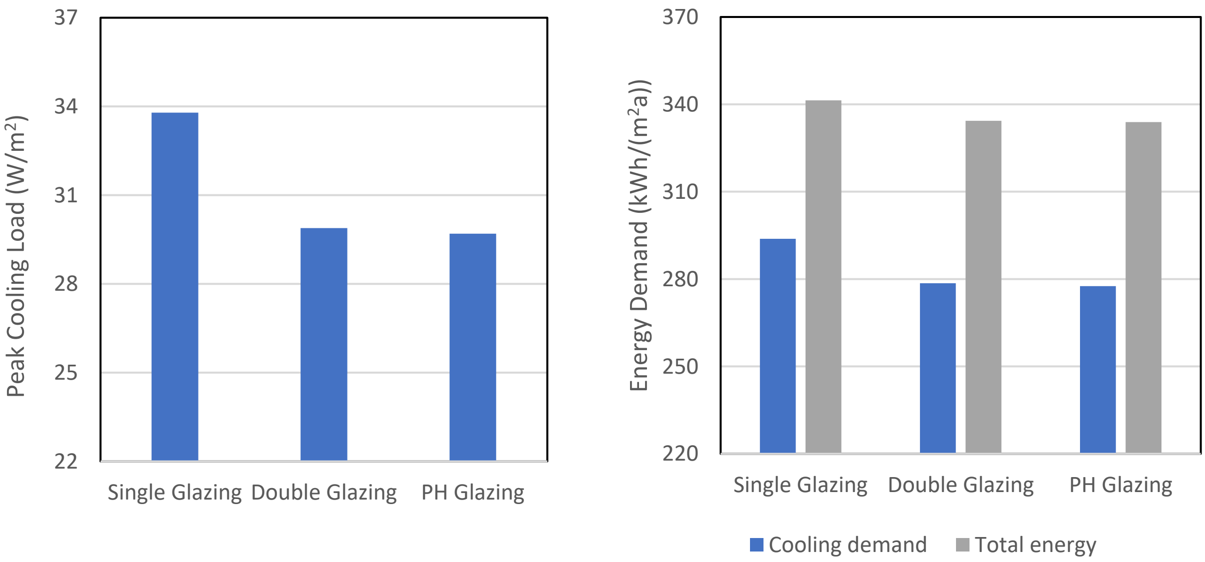


Figure 4-11: Energy Demand of the Reference Building with Low Thermal Transmitting Windows.

*Figure 4-11***.** shows the peak cooling load reduced by 11.5% for the double-glazed window and 12% for the Passive House standard window. The resultant effect on cooling demand is only about 5% and 2% on the total energy demand in both cases. Also, considering the limited window and the negligible contribution of the Passive House window (lower thermal transmittance) compared to a standard double-glazed window, a Passive House standard window might not be necessary for this building in this climate. Its insignificance is also emphasised in the building's thermal condition, which had no effect. However, considering its impact on peak cooling load, using a low thermal transmitting window proves to offer some benefits and might have more impact in a building with more window access.

In summary, insulating the building components positively (even though minimal) affects the building’s energy demand. The wall insulation is observed to have the most significant impact reducing peak load up to 34% and 11% on average for the other element with minimal effect. Overall, it is concluded that even in a building designed for optimal performance (by engaging strategies like thermal mass and minimal glazing area) in this climate, insulation still offered an additional advantage of further reducing heat transfer with an average of 10% reduced peak load.

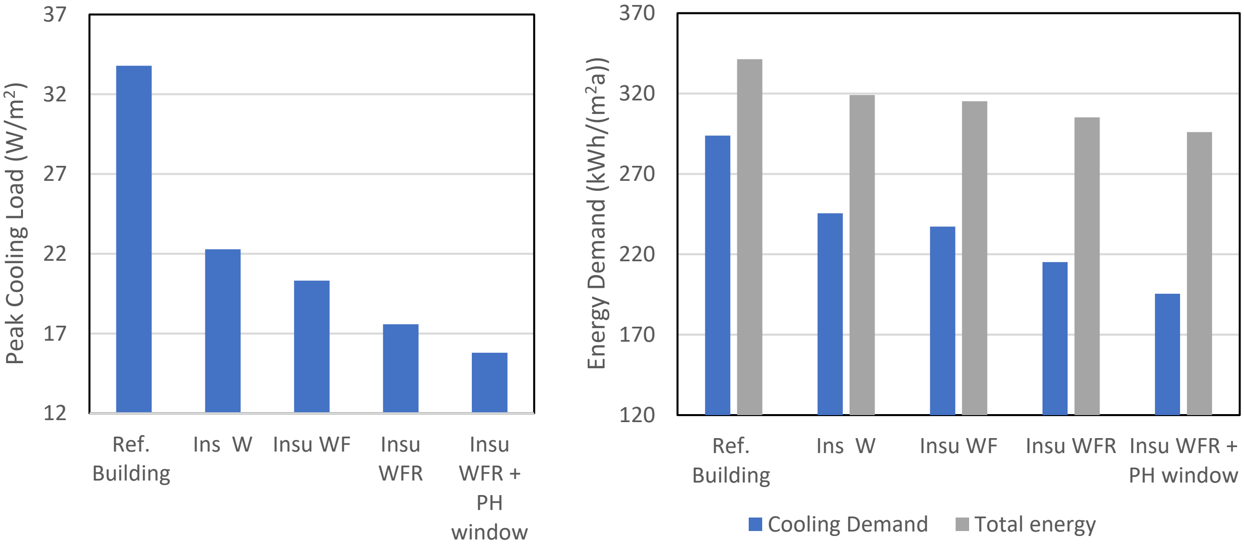
However, the cumulative effect is unknown when the building envelope is simultaneously insulated (at maximum insulation of 10 cm) and applies the Passive House window. Thus, the analysis of super-insulating the whole envelope is presented in the following section, with a Passive House window applied simultaneously.

4.5.3 Insulated Envelope – Wall, Roof, Floor and Advanced Window Technology.

Having observed the effect of insulating each building component from the preliminary analysis, it was necessary to evaluate the combined effect of insulating the building elements having a Passive House standard window. To carry out this investigation, insulation was progressively applied to the building to keep track of the corresponding impact of each component. Thus, insulation began with wall insulation, which had the most effect, to low thermal transmitting windows in this climate.

4.5.3.1 Results and Discussion

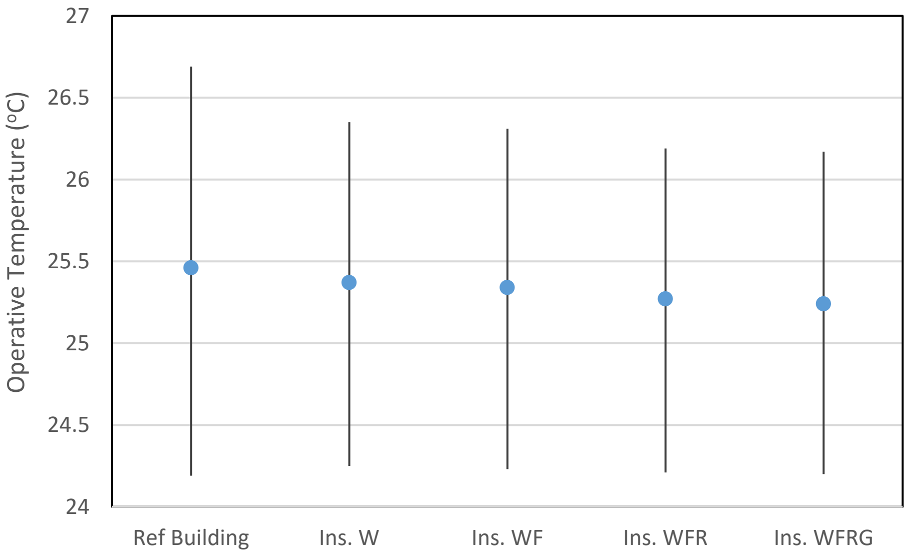
This section presents the results of progressive insulation of the building envelope from the wall to the window, as expressed in *Figure 4-12***.**



Insu -Insulated, W-Wall F-Floor R-Roof

Figure 4-12: Energy Demand of the Insulated Building Envelope

Figure 4-12 shows a continuing positive impact of insulation on the building's energy demand. The application of insulation to each element progressively minimised peak load to a significant cumulative drop of 50%. Consequently, minimising cooling needs by 33.5% and saved about 13% of the building's total energy. Although each element on its own seemed not to have had an enormous impact, except for the wall, the implication of insulating the building envelope with a Passive House window proved beneficial even in a building designed for optimum performance in this climate. This outcome shows that these Passive House strategies further ensured that the indoor environment was thoroughly isolated from the external conditions beyond the influence of the other passive methods that were in place. Thus, having an effect on the indoor operative temperature (*Figure 4-13).*



Insu -Insulated, W-Wall F-Floor R-Roof G -Glazing

Figure 4-13: Indoor Operative Temperature of the Insulated Reference Building.

The effect on the indoor operative temperature shows the average operative temperature in the building gradually decreases toward 25 ºC as insulation progressed because external influence was continuously minimised and heat transfer diminished (keeping cool in). Hence, the indoor thermal condition is maintained with less energy using a significantly smaller system, about half the size required in the reference building, as the peak cooling load is minimised to 50% and cooling demand to about 30%. The indoor operative temperature experienced in the building is maintained and slightly improved.

This achievement is with the application of two of the Passive House principles. The contribution of the other strategies, such as airtightness, mechanical energy recovery ventilation, and some energy-efficient appliances in the building, are investigated in the following section.

4.5.4 Airtightness

According to the reference building design, airtightness was set to 1 ACH, which is outside the Passive House recommendation for infiltration. The Passive House standard requires airtightness to be less than 0.6 ACH at 50 pascals. According to the Passive House Institute (2006), this level of infiltration will limit energy loss and maintain the air quality in the building. It also stated that, although air tightness is not the most important requirement for energy-efficient buildings, it is still advisable for Passive House buildings and even conventional buildings. To validate this point, the infiltration of the reference buildings is first set to the Passive House standard to account for its contribution to the building's performance before applying it to the super-insulated model as a continuing approach for adapting the Passive House principle to the reference building.

4.5.4.1 Results and Discussion

Assuming that the reference building is designed and built to be airtight to the Passive House recommendation of 0.6 ACH and that only this strategy is employed to improve the building, the corresponding energy performance of the building is shown in *Figure 4-14*.

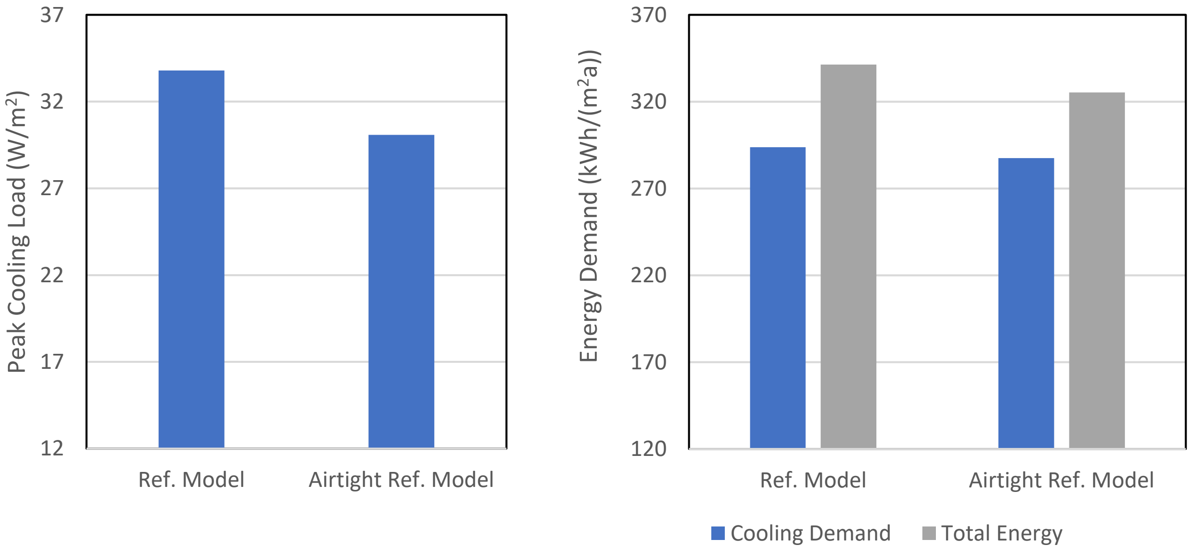


Figure 4-14: Energy Demand of the Reference Building Envelope with Airtightness of 0.6 ACH

The results show that airtightness, which limits infiltration in the building, positively affects energy demand even in a conventional building. The peak cooling load in the airtight conventional reference building was reduced by more than 10%, saving at least 5% of the building's energy. It also results in lowering the indoor temperature of the building, as shown in *Figure 4-15*.

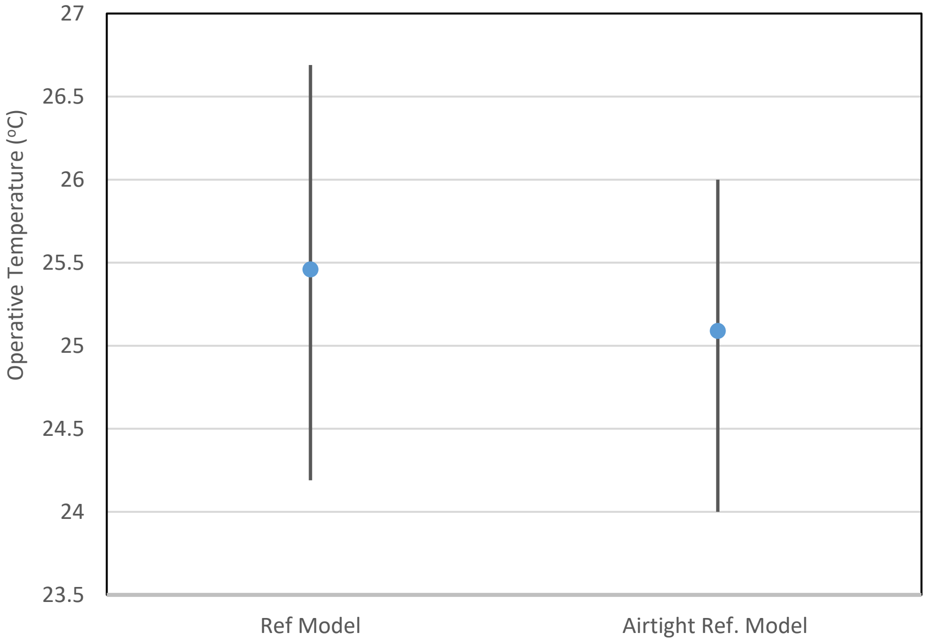
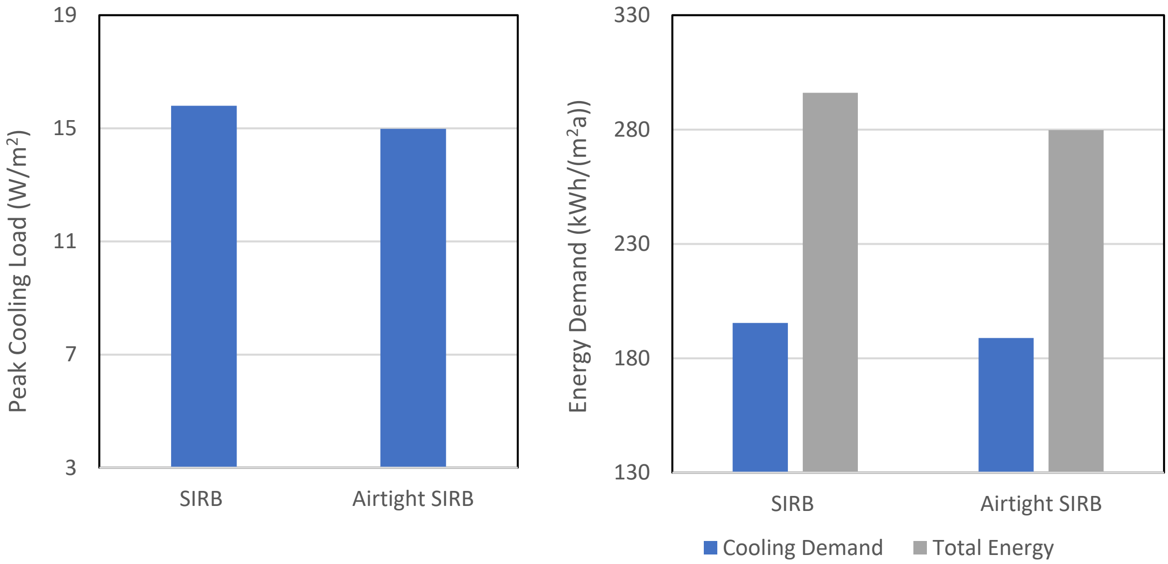


Figure 4-15: Indoor Operative Temperature of the Reference Building with Airtightness of 0.6 ACH

As shown above, making the building more airtight not only lowered the indoor operative temperature but maintained the temperature at the set point range of 24-26 °C, causing the average temperature in the building to be about 25°C, achieved with less energy. Thus, limiting uncontrolled air supply in a conventional (uninsulated) building can contribute to energy savings and improve comfort due to limited heat transfer.

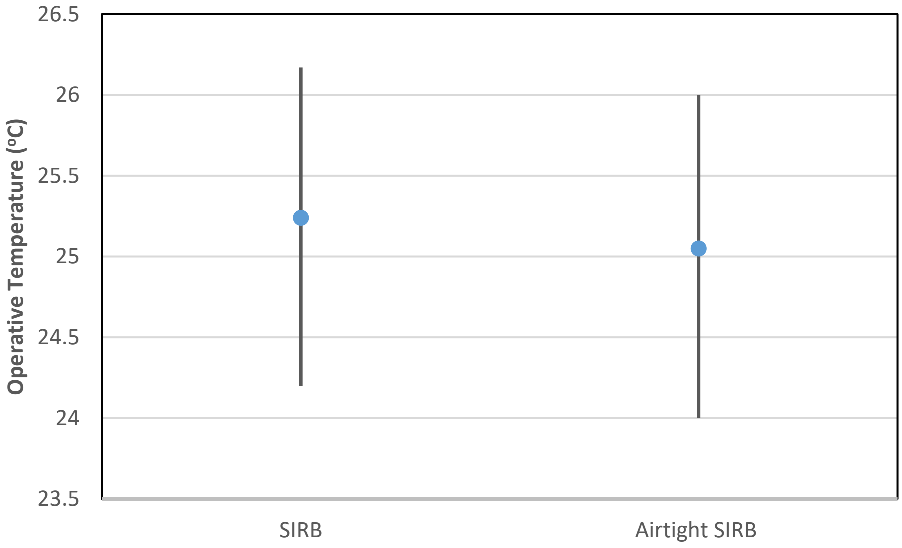
As intended, this infiltration of 0.6 ACH was also analysed for the super-insulated envelope with the Passive House standard window, hereon referred to as SIRB (Super-insulated reference Building). The effect on the energy demand is shown in *Figure 4-16*.



SIRB – Super Insulated Reference Building

Figure 4-16: Energy Demand of the Super-Insulated Building Envelope with Airtightness of 0.6 ACH

The result shows that it affects the building energy demand, but its impact is minimal compared to the uninsulated envelope. The peak cooling load is only reduced by 5% compared to the 11% in the uninsulated model. The reduced influence of airtightness on the peak cooling load in the insulated building is attributed to the impact of the super-insulated envelope, which already limits the uncontrolled airflow path in the building envelope. However, the influence of the external conditions on the cooling load was further mitigated. Overall, airtightness saves about 5% of the building's total energy demand and maintains the indoor temperature within the set range of 24- 26 ^{o}C in both the uninsulated and insulated envelope, as shown in *Figure 4-17*.



SIRB – Super Insulated Reference Building

Figure 4-17: Indoor Operative Temperature of the Super-Insulated Reference Building with Airtightness of 0.6 ACH

Therefore, the Passive House recommendation of airtightness proves beneficial in saving some energy and maintaining the acceptable comfort conditions in this climate. At this point, three (3) of the Passive House strategy have been investigated and successfully applied to the reference building. However, it is observed that the peak cooling load is yet to meet the Passive House Standard of 10 W/m^2 recommended before a mechanical ventilation system can be sufficient to provide heating/cooling and maintain a comfortable indoor condition in a Passive House (Wall, 2006; Passivhaus Institut, 2019). Hence, other strategies to limit heat gain in the building are explored before investigating the use of mechanical ventilation with energy recovery.

4.6 Additional Strategies Explored

Several passive strategies have been used in hot tropical climates (cooling-dominated climates) to improve and manage the indoor environment and limit heat gain in order to reduce energy demand and achieve comfort conditions. These strategies include building orientation, shading, and the use of energy-efficient appliances, etc. Accordingly, Passivhaus Institut (2019d) advises shading in all summer climates with high solar radiation and energy-efficient equipment and controls to reduce internal heat loads from appliances and lighting.

4.6.1 Shading Analysis

Solar heat gain and internal heat gain (i.e., people and equipment) both contribute to heat gain in a building. Thus, in cooling-dominated climates such as Indonesia, providing adequate shading to protect building envelopes (particularly openings) against direct sunlight is highly recommended (Chen et al., 2020; Jakarta Green Building User Guide - Vol. 1, n.d.). In the reference building (*Figure 4-18)***,** it can be seen that apart from the roof, which is always directly exposed to the sun with 100% exposure, the wall exposure to the sun is less than 50%. In addition, the windows in the structure, which are only on the North and South side of the building, have less than 30% of solar exposure and have also been provided with overhangs to limit heat gain further.

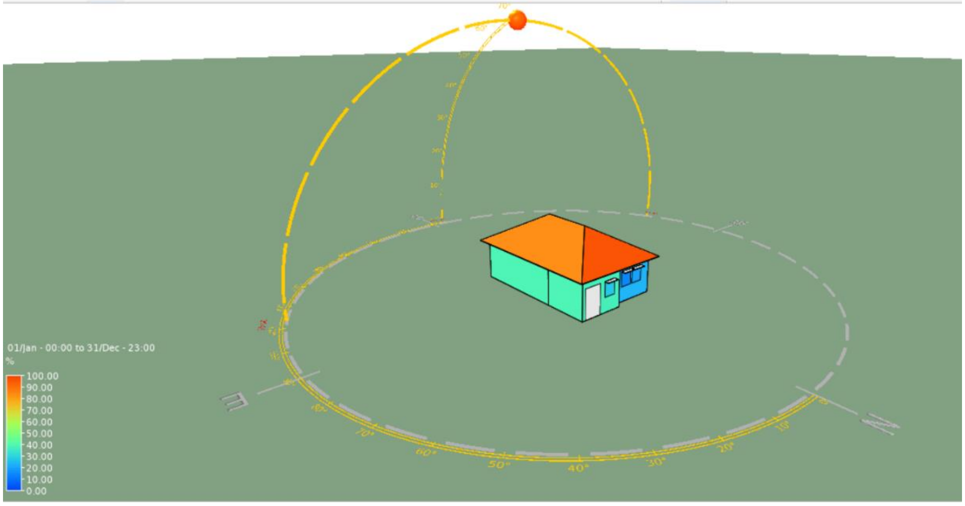


Figure 4-18: Percentage Hours of Solar Exposure of Reference Building

However, as a means to optimise building performance, that is, to reduce energy demand and improve thermal conditions, additional shading was applied to the building façade.

Accordingly, an overhang of 1.5m was added to the roof with a roof canopy to limit solar exposure and an additional perimeter shade for the wall to provide ample shade for the building envelope (*Figure 4-19*).

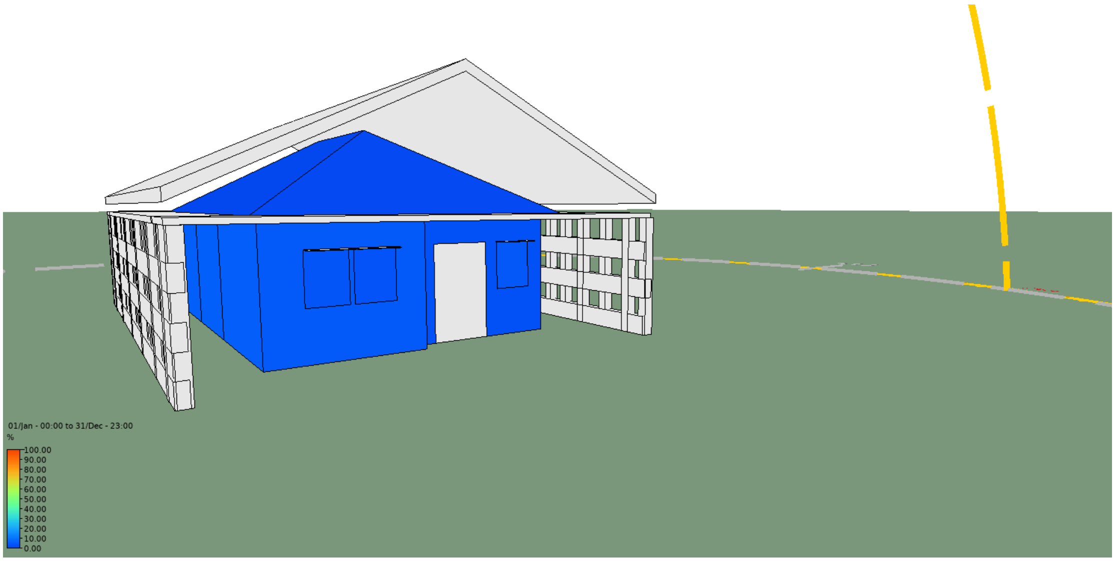


Figure 4-19: Hours of Solar Exposure of Shaded Reference Building

Having shaded the building extensively, the solar exposure of the building façade is reduced to less than 20% throughout the year. Thus, it can be expected that the performance of the building would be improved. As in previous cases, the analysis is evaluated in two (2) scenarios to validate the influence of shading in the uninsulated reference building and the super-insulated model.

4.6.1.1 Results and Discussion

In the previous analysis, investigating different strategies for the uninsulated and the insulated envelope has consistently shown that the uninsulated building appears to respond more than the insulated model. The energy demand of the uninsulated reference model is shown in *Figure 4-20* to determine the impact of extensive shading.

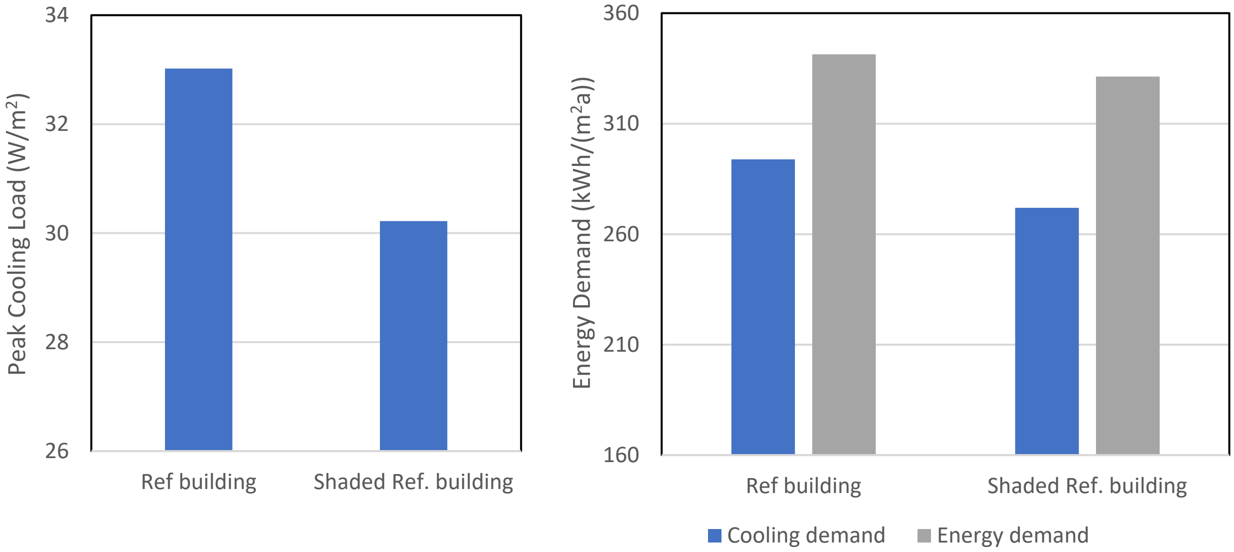


Figure 4-20: Energy Demand of the Reference Building with Extensive Shading.

The effect of extensive shading, which dropped the solar exposure of the wall and roof to less than 20% from 50% and 100%, respectively, reduced the peak cooling load by about 12% in the uninsulated envelope— with a corresponding 12% influence on the cooling demand, saving 5% of the building's total energy. This effect does not have a significant impact on indoor temperature. Furthermore, when compared to the insulated reference envelope, the shading effect had roughly half the impact of the uninsulated model case (*Figure 4-21*).

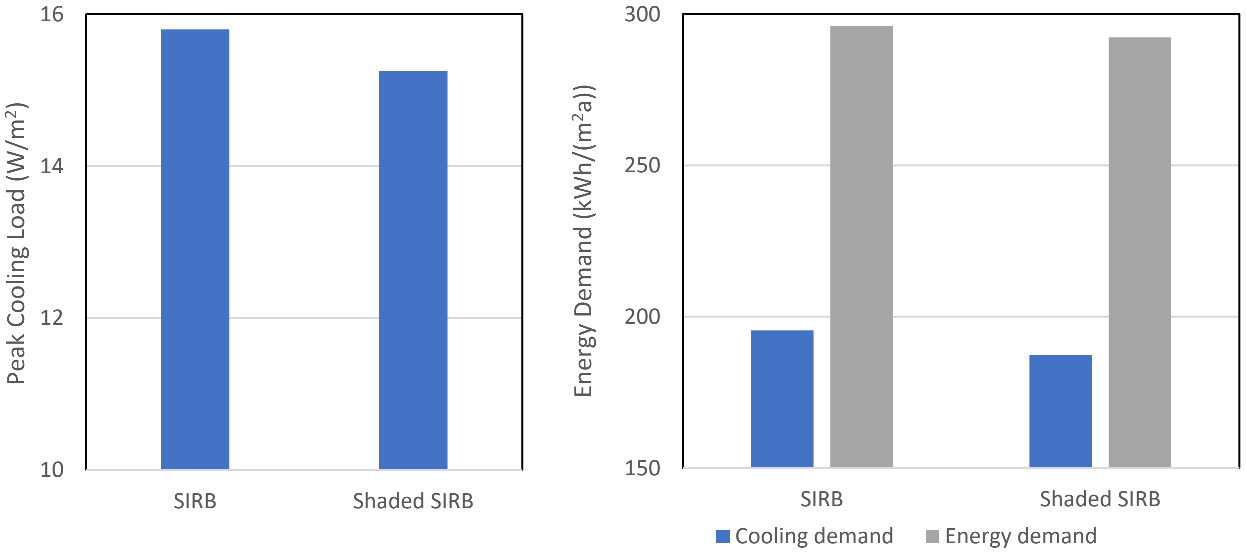


Figure 4-21: Energy Demand of the Super-insulated Reference Building (with extensive shading).

It is worth noting that the peak cooling load and demand were only reduced by about 6%, and the total energy saved was about 2%, with no effect on the indoor thermal conditions. The outcome once again demonstrates that using insulation and other strategies -advanced windows and airtight envelopes- improves building performance to the point where other techniques could become less effective against external conditions.

Overall, this shading analysis shows the building design already receives minimal heat gain from sunlight, as such extensive shading did not significantly affect the building. Also, insulation appears to have played a pivotal role in limiting heat gain in the building such that the effect of additional shading is negligible. This is considering that shading had more impact on the energy demand of the uninsulated reference building, where the energy saved is twice that of an insulated building. Even at this, the energy saved is not significant. This result is consistent with the findings of Noaman et al. (2022), who explored passive-designed façades in a hot climate. Thus, additional shading as means to further improve performance is ignored.

4.6.2 Internal Heat Gains Analysis

The fundamental requirements for estimating heat gains in buildings are the solar heat gain and internal heat gain (Monstvilas et al., 2010; IS EN ISO 52016-1:2017). Since the effect of solar heat gain appears to be minimised due to the high-performing envelope, reducing other sources of internal heat gain, such as using energy-efficient appliances, was explored.

Internal heat gain (IHG) can change over the service life of a building (based on occupancy and appliances). Internal heat gain value in Passive House analysis is based on the PHPP calculation, which considers the varying availability of dissipated heat in a building. Based on people, equipment usage, lighting, and other factors in correlation with dwelling unit size given in Grant et al. (2014) as shown in *Figure 4-22*. The internal heat gain is largely based on having energy-efficient appliances, as shown in the PHPP analysis presented in *Appendix B.*

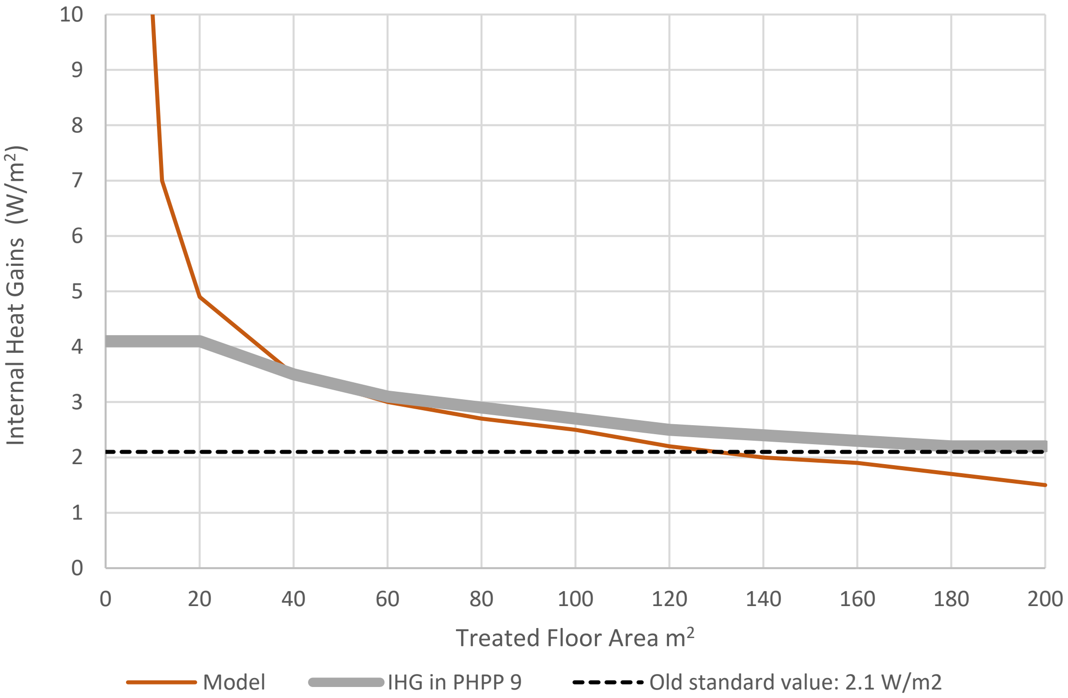


Figure 4-22: Internal Heat Gains Depending on Living Area (Passivhaus Institut, 2021b)

Internal heat gain can be expected to vary across countries based on occupancy density. According to Benjamin Krick et al. (2014), there is no relationship between the average living area per person and electricity consumption. Also, the difference in cold water temperatures based on climate may be significant when considering factors such as cold water and hot water usage (gain & losses) and evaporation. However, Passivhaus Institut (2021b) states that this variance can be ignored for simplicity. Furthermore, the Passive House standard tool PHPP has been used to design Passive Houses in various climates without identifying the internal gain value as a problem. Thus, based on *Figure 4-22*, the reference building's internal heat gain was assumed to be 3.1 W/m^2 based on the treated floor area (TFA) or conditioned floor area. TFA measures the usable internal floor area contained within the heated thermal envelope (Feist, 2020).

4.6.2.1 Results and Discussion

The specified internal heat gain (IHG) value is first evaluated for the conventional reference building to establish its influence on the building performance, as shown in *Figure 4-23*.

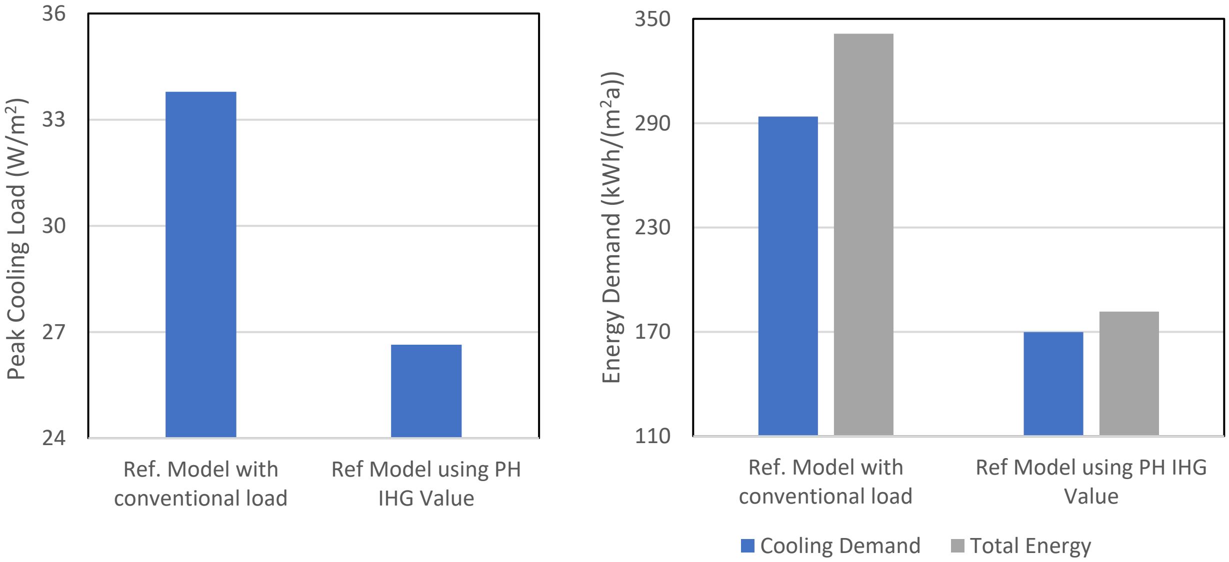


Figure 4-23: Energy Demand of the Reference Building using Passive House Internal Heat Gain Value.

Figure 4-23 shows that the specified internal heat gains significantly reduced the building's energy demand in the uninsulated model. The peak load was reduced by 20%, cooling demand by 42%, and over 45% of total energy was saved. This outcome demonstrates the impact of using energy-efficient appliances in the building. The lighting in the conventional building, for example, was 40 W, whereas energy-efficient bulbs would use 1/3 of this power, resulting in less energy and heat generated within the building. However, no significant effect on indoor temperature was observed. The internal heat gain value is evaluated for the super-insulated envelope.

Figure 4-24 shows the internal heat gain value had a comparable impact on the building energy demand saving about 42% of the building’s total energy.

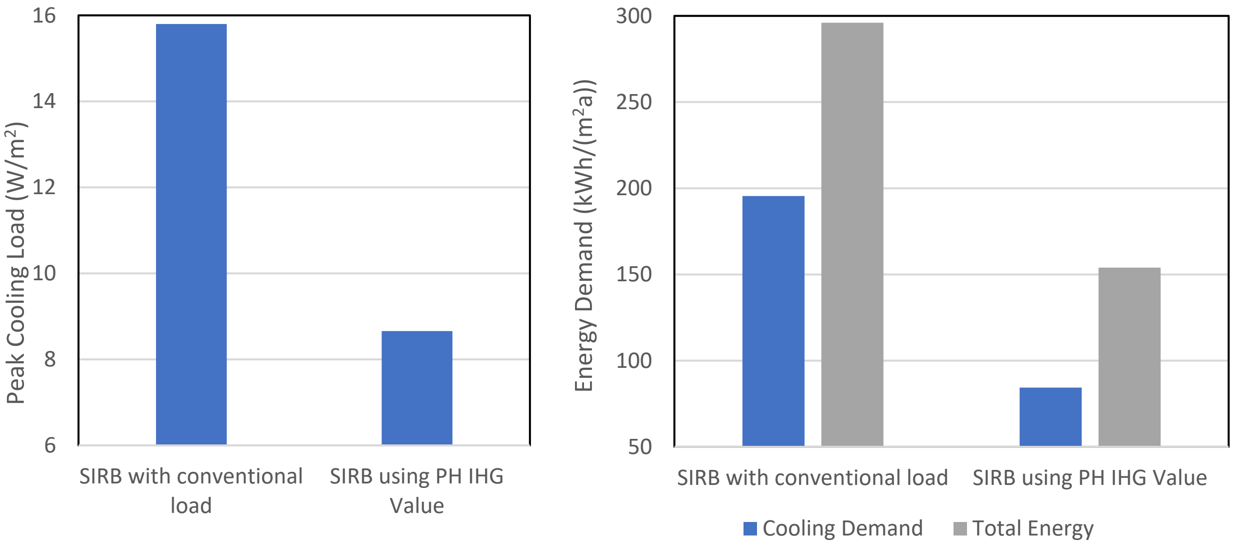


Figure 4-24: Energy Demand of the Super-insulated Reference Building (SIRB) with Passive House Internal Heat Gain Value.

This finding backs up Passipedia's (2020) claim that energy savings in Passive House buildings are achieved through the use of energy-efficient building components and an excellent mechanical ventilation system. In the insulated building, the peak cooling load and demand were reduced by more than 45% and 57%, respectively. Although, it did not affect the building's indoor thermal conditions as in the uninsulated reference building.

Table 4.4 summarises the super-insulated reference model (SIRB) performance to the Passive House standard. At this stage, the SIRB model represents the application of super-insulation, PH windows, airtightness of 0.6 ACH, and using energy-efficient appliances (represented by the PH internal heat gain value). *Table 4.4* shows the SIRB exceeds the Passive House cooling demand requirement by over five (5) times; however, it meets the peak cooling load standard. *Figure 4-25* also shows that the building meets the Passive House thermal comfort range. As a result, the building could be said to have met the Passive House standard.

Table 4.4: Energy Demand of the Super-Insulated Reference Building (SIRB)

Energy Demand	**SIRB**	**PH standard**
Cooling Demand (kWh/(m^{2}a))	84.42	15
Total Energy (kWh/(m^{2}a))	154	120
Peak Cooling Load (W/m^2)	8.66	10

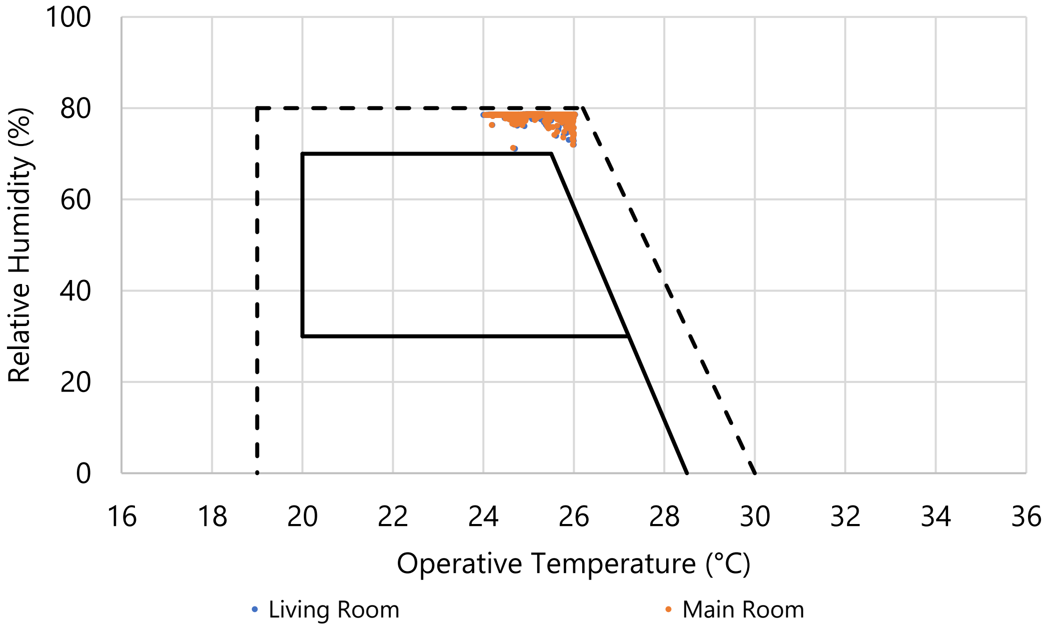


Figure 4-25: Indoor Operative Temperature and Relative Humidity of a PH Building in Indonesia Using a Conventional Air-Conditioner.

Despite the fact that the Passive House standard appears to have been met after specifying the Passive House internal heat gain value, the building is assumed to be using a conventional air conditioning system, which could be the cause of the building's high energy demand, as shown in *Table 4.4.* As a result, the following section investigates the use of a mechanical ventilation system with energy recovery to reduce energy in the building.

4.7 Mechanical Ventilation with Recovery System

Based on the airtightness of Passive House buildings, a mechanical ventilation system with heat recovery (MVHR) is used to supply fresh air in order to maintain excellent air quality without causing draughts. In addition, coolth can be recovered from the outgoing/exhaust air and transferred to the incoming air, saving energy. Passivhaus Institut (2020b) suggests that in a well-insulated building with a heating/cooling load of about 10 W/m^2, the supply air can be used to keep the thermal conditions of the building within the comfort range. Therefore, since the peak cooling load of the building is less than 10 W/m^2, as shown in *Table 4.4*. A constant air volume system with 85% energy recovery is specified for the super-insulated reference building, hereafter referred to as Passive House (PH). An energy recovery ventilation (ERV) system is used instead of a heat recovery system to pre-cool and remove excess moisture from the incoming air due to the high humidity level of the study climate - Indonesia.

4.7.1.1 Results and Discussion

Unlike previous analyses in which the strategy was applied to the uninsulated reference building before the super-insulated reference building, the ERV system was only applied to the Passive House because the peak load indicated its applicability. *Figure 4-26* and *Figure 4-27* depict its effectiveness at the recommended 0.35 ACH (44 m^{3}h).

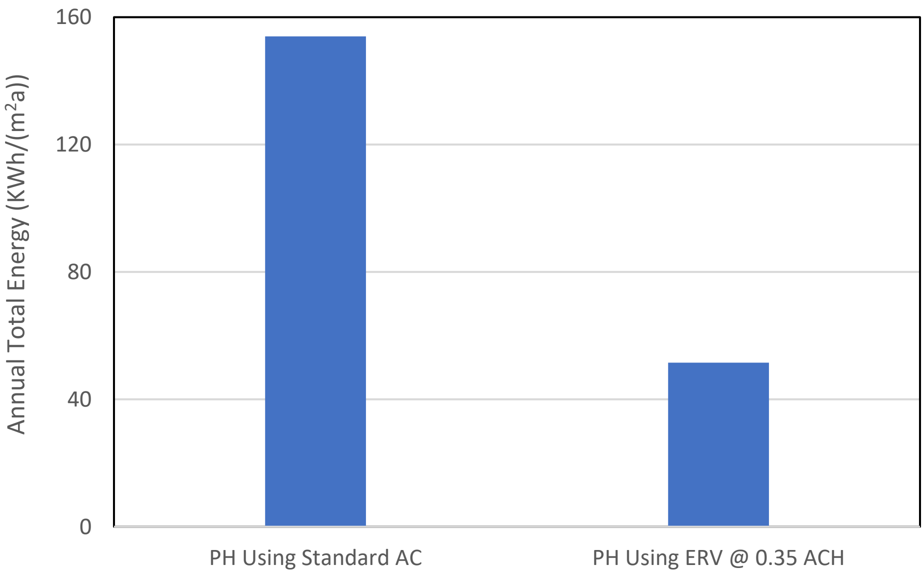


Figure 4-26: Energy Demand of the PH Building using Standard Air-Conditioner versus Mechanical Ventilation Energy Recovery System

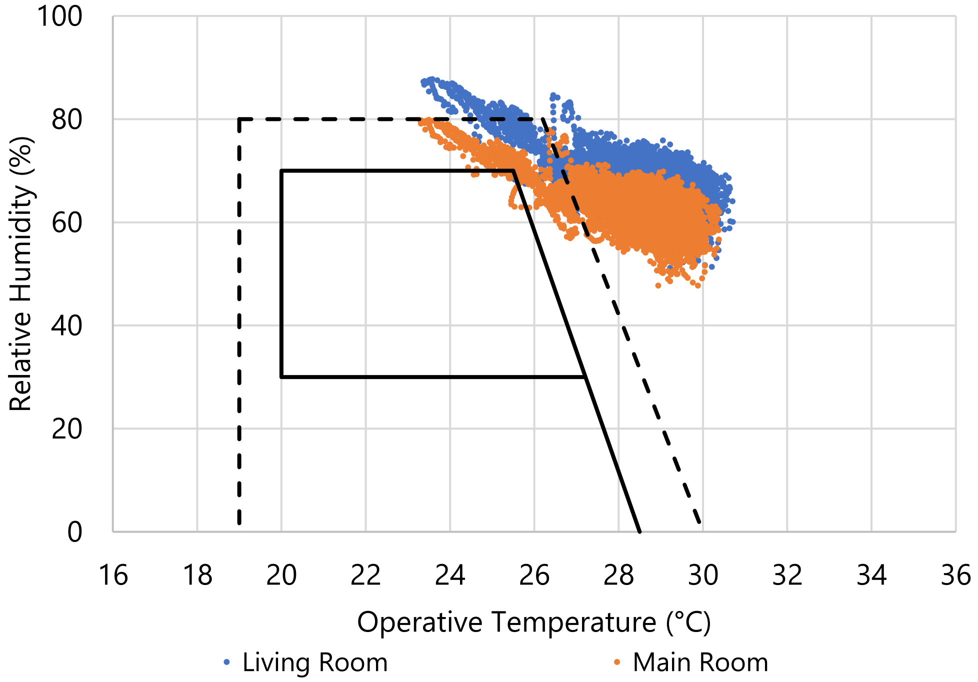


Figure 4-27: Indoor Operative Temperature and Relative Humidity of a PH Building in Indonesia using Energy Recovery Ventilation system at 0.35 ACH.

The energy demand analysis in *Figure 4-26* shows that the ERV system saves approximately 67% of the total energy used by the building when compared to an air conditioner but results in an indoor environment significantly outside the comfort range, as shown in *Figure 4-27*. The energy recovery ventilation system at the specified ventilation rate is insufficient to provide cooling and achieve indoor thermal condition within the comfort range. The outcome is comparable to the Singapore analysis presented in Chapter 3.4. As a result, similar to the Singapore analysis, the building shows to be outside the acceptable comfort conditions until the ventilation rate was increased to 1.0 ACH (145 m^3h). *Figure 4-28* and *Figure 4-29* depict the performance of the building at a ventilation rate of 1.0 ACH.

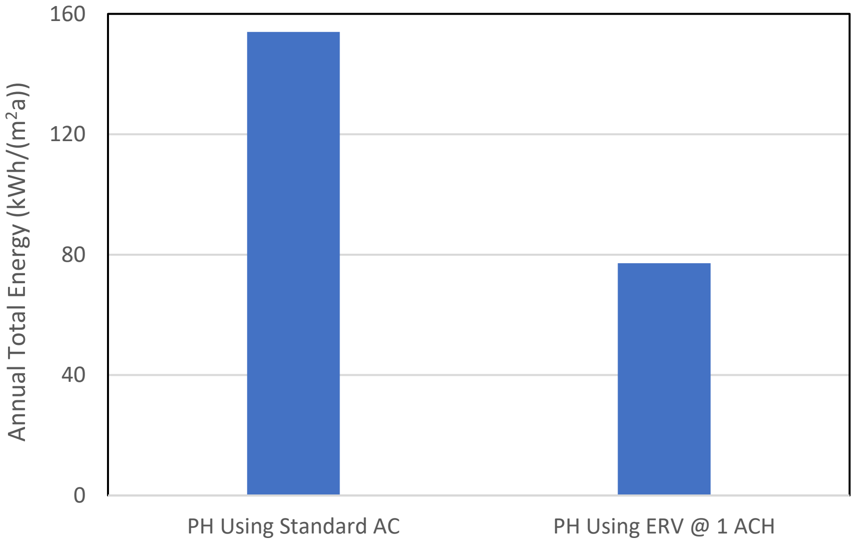


Figure 4-28: Energy Demand of the PH Building with Air-Conditioner versus Energy Recovery Ventilation System at 1 ACH Airflow Rate.

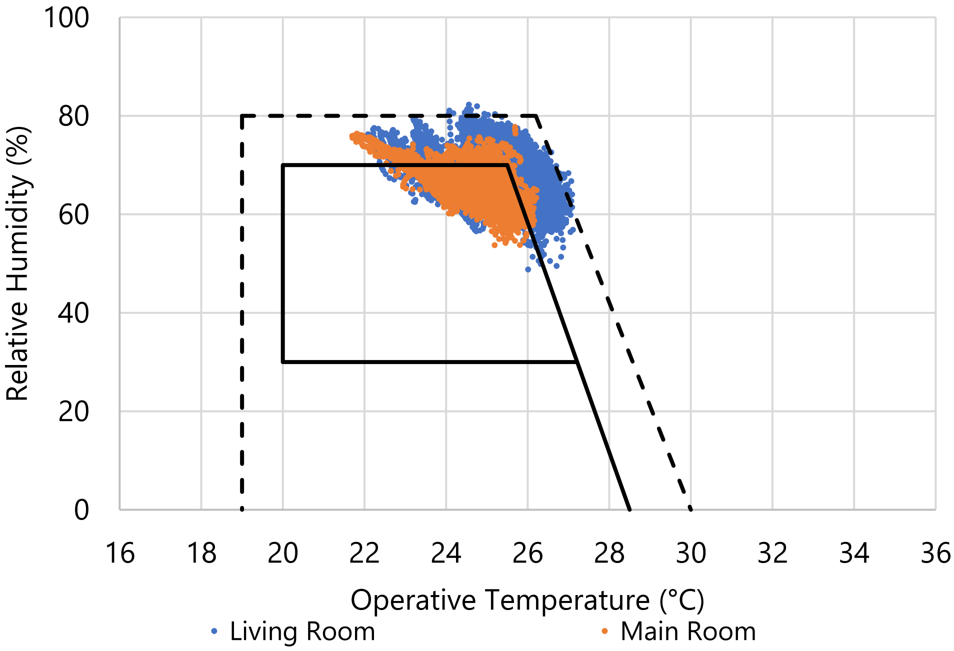


Figure 4-29: Indoor Operative Temperature and Relative Humidity of a PH Building in Indonesia with Energy Recovery Ventilation system at 1 ACH.

According to the evaluation, an energy recovery ventilation system operating at 1 ACH is adequate for ventilation and cooling to achieve and maintain a comfortable indoor environment. When compared to a conventional air conditioning system, it saves approximately 50% of the building's energy consumption, as shown in *Figure 4-29*. The system saves energy by precooling- and removing excess moisture from the incoming air with the exchanger. Thus, an energy recovery ventilation system contributes significantly to energy saving in Passive House buildings and is useful in cooling-dominated climates.

In summary, the study discovered that the reference building saved approximately 77% of its total energy by implementing Passive House strategies. This result is comparable to the work of Schnieders et al. (2015) on a Passive House in Singapore, which has a similar climate to Indonesia. In the following section, the performance of the realised Passive House is evaluated in other hot and humid climates.

4.8 Adaptation of the Optimised Model in Other Hot and Humid Locations.

Having achieved an energy efficient model within the thermal comfort range in Indonesia – “A Passive House" by applying Passive House strategies to a conventional building (i.e., super-insulation, highly insulated windows, airtightness, efficient appliances, and energy recovery ventilation system). It was critical to investigate the performance of this model in other similar climates to determine its functionality and adaptability before reaching a conclusion to answer the research question.

Accordingly, the optimised model was tested in five (5) other hot and humid locations, including Dodoma, Tanzania; Kinshasa, Congo; Bangkok, Thailand; Darwin, Australia; Kuala Lumpur, Malaysia. *Figure 4-30* depicts the average minimum and maximum temperatures of the hot and humid locations considered.

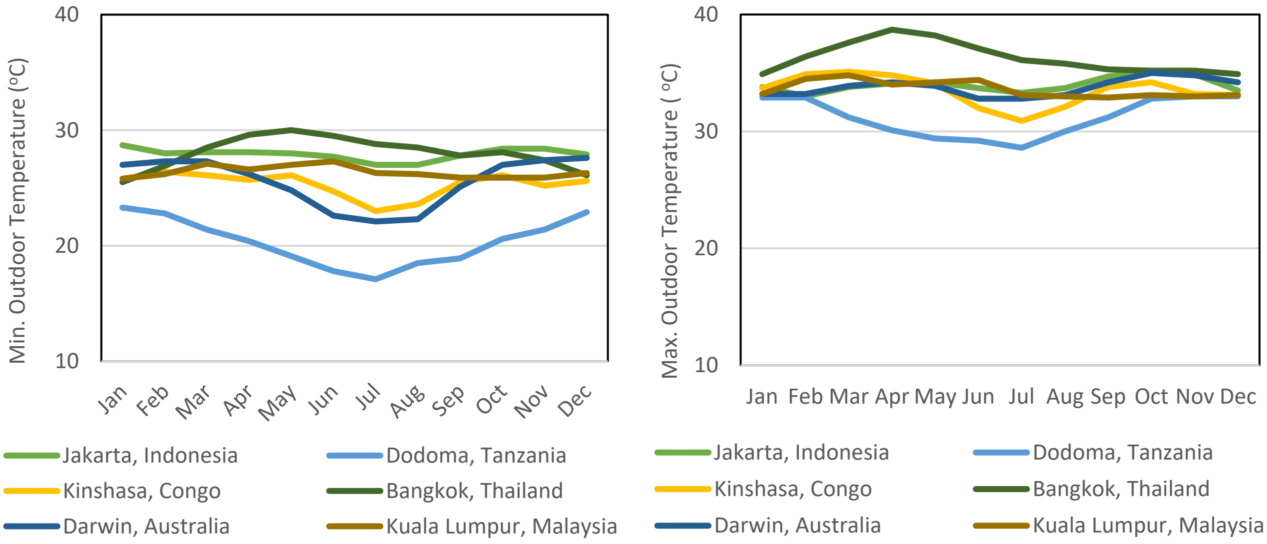
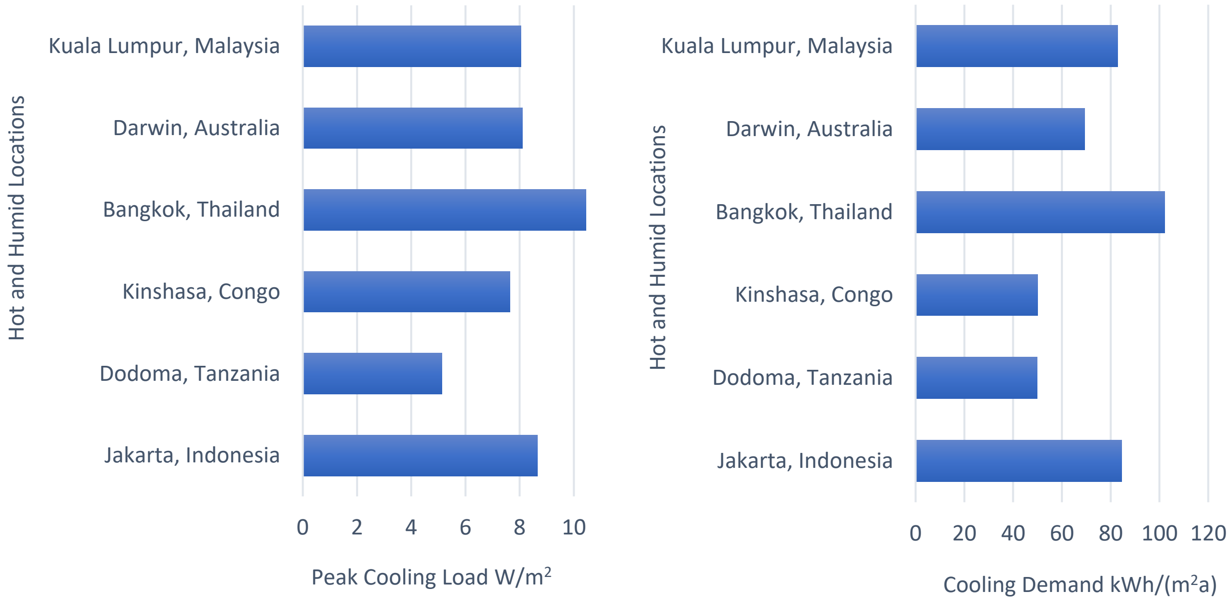


Figure 4-30: Average Minimum (left) and Maximum Temperature (right) of the Hot and Humid Locations (IES Weather Data)

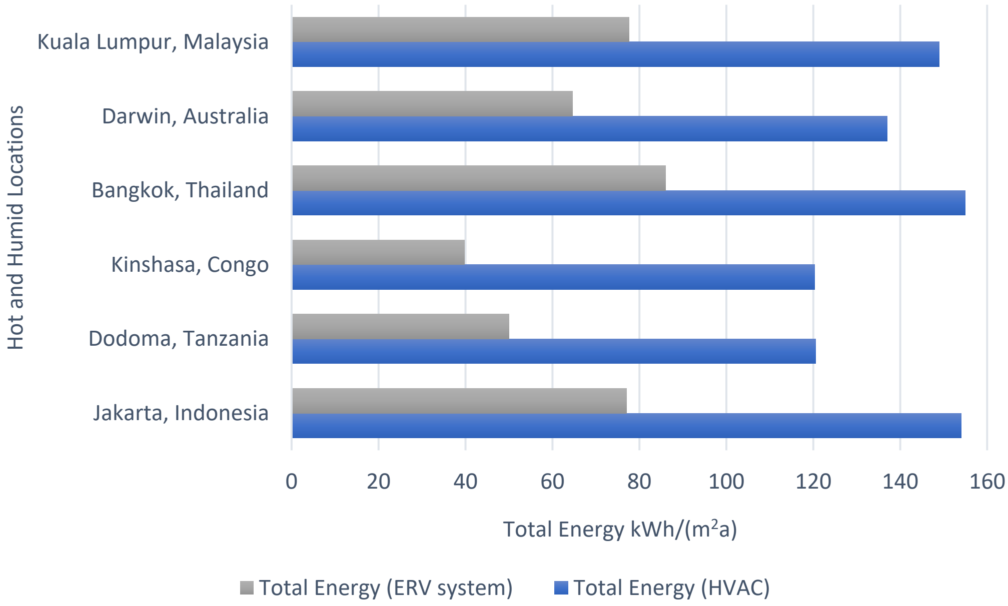
4.8.1.1 Results and Discussion

For the model Passive House, the peak load, cooling demand, and total energy consumed by using a standard HVAC system or energy recovery ventilation system were investigated in each location. *Figure 4-31* depicts the performance outcome in these hot and humid locations.



a. Peak Load

b. Cooling Demand

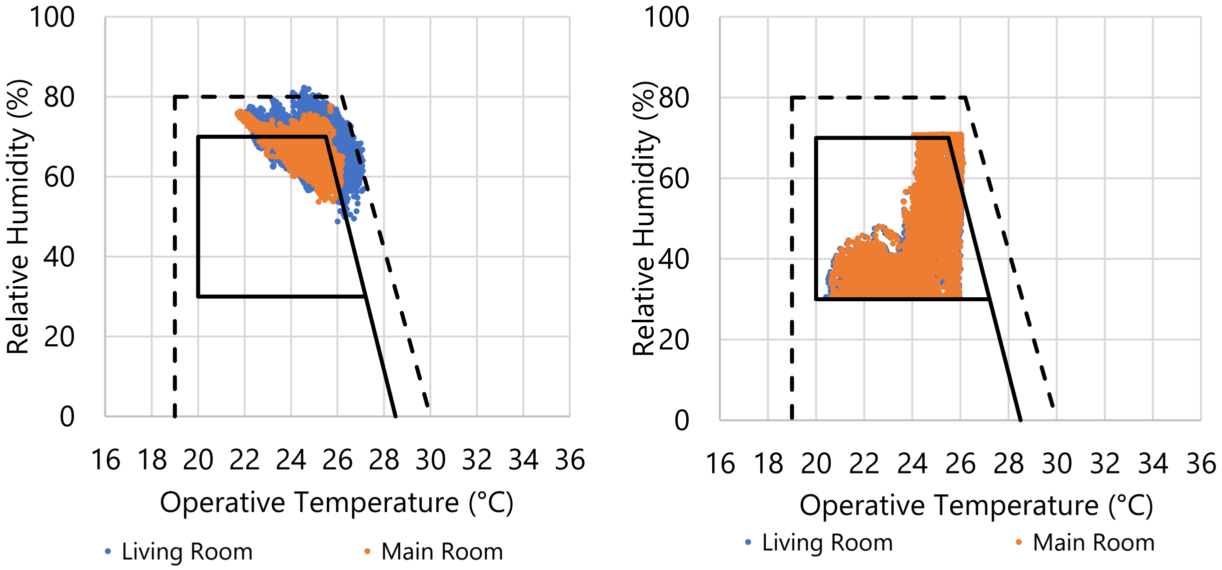


c. Total Energy

Figure 4-31: Energy Demand of the Reference Passive House in other Hot & Humid Locations.

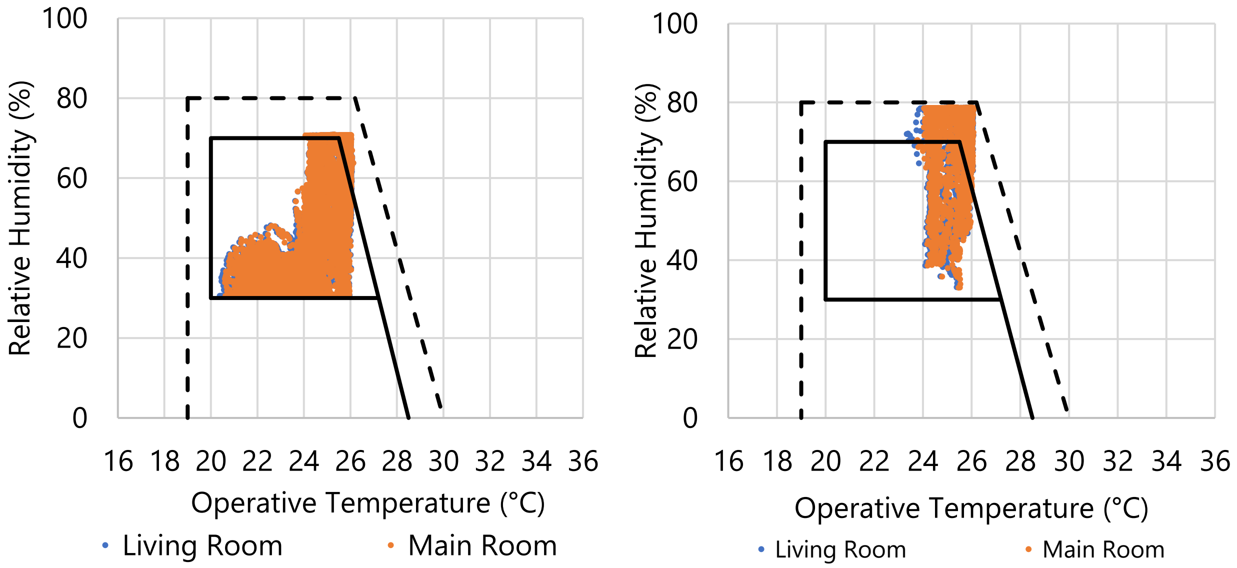
The results of *Figure 4-31*a show that peak load is comparable in all locations studied due to the high-performing envelope, which prevents excessive heat gain from the external environment, even in Bangkok, Thailand, where the average maximum temperature can reach 40 degrees Celsius.

On the other hand, building cooling and energy demand reflect the local climate's cooling requirements, as locations with higher temperatures throughout the year require more cooling. Bangkok, Thailand, for example, has the highest temperature and thus the most cooling requirements (*Figure 4-31*b). The ventilation rate required to achieve a comfortable thermal environment in each location also indicates this in *Figure 4-32*.

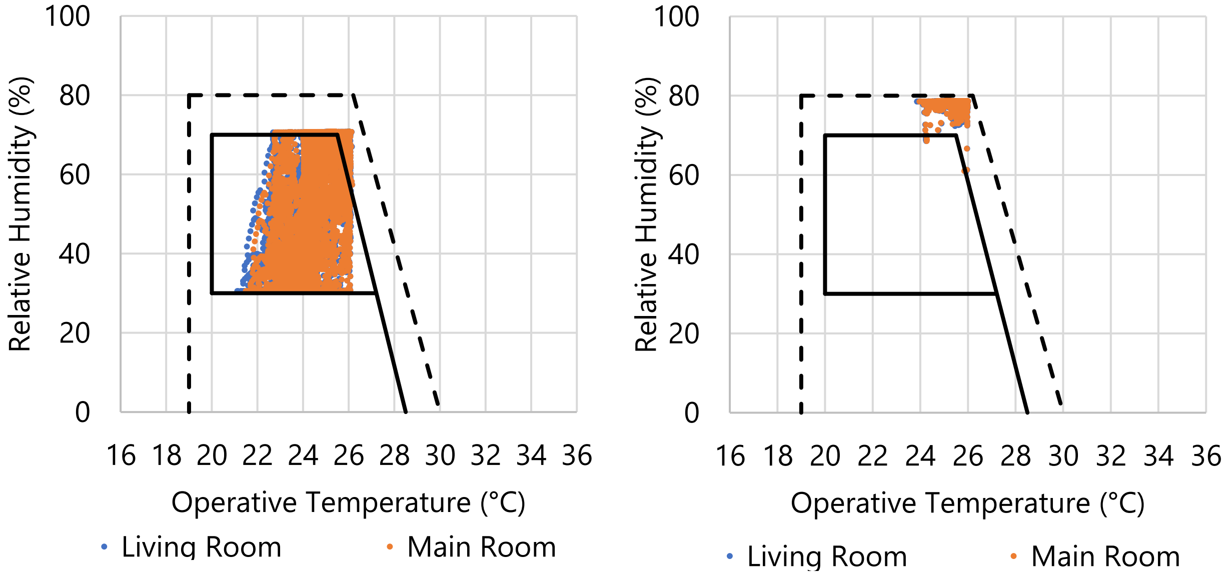


a. Jakarta, Indonesia @ 1 ACH

b. Dodoma, Tanzania @ 0.8 ACH



c. Kinshasa, Congo @ 0.6 ACH d. Bangkok. Thailand @ 1.5 ACH



e. Darwin, Australia @ 1 ACH f. Kuala Lumpur, Malaysia @ 1 ACH

Figure 4-32: Indoor Operative Temperature and Relative Humidity of the Reference Passive House in other Hot and Humid Locations.

Figure 4-32 shows that the ventilation rate required to achieve a comfortable indoor environment varies by location, ranging from 0.6 ACH in Kinshasa, Congo, to 1.5 ACH in Bangkok, Thailand. This also confirms that the local climate significantly impacts building performance, even in well-insulated buildings. As observed, the higher the average temperature in the location, the greater the cooling required. However, using an ERV system instead of a standard HVAC system resulted in an average of 50% energy savings in all study locations, even at a higher ventilation rate.

Thus, the study shows the building meets the Passive House standard, given that the peak load and acceptable comfort conditions were met in all hot and humid locations studied.

4.9 Conclusion

In this chapter, the Passive House framework was investigated for hot, humid cooling-dominated climates. The objective was to determine if it was feasible to use the PH strategies to reduce energy demand and maintain the building within the acceptable comfort conditions.

The study discovered that a building that could be considered suitable for this climate, having implemented passive strategies (such as thermal mass for the roof and window size and placement based on building orientation) to manage solar gain, could optimise its performance by integrating the Passive House techniques.

It was found that by incorporating super-insulation and Passive House standard windows, buildings in hot, humid climates can save up to 30% of their energy demand. Due to reduced heat transfer, which ensures the coolth indoor air stays inside and the exterior heat stays outside. Thus, reducing the peak cooling load by about 50%.

In addition, airtightness, a primary strategy used in heating-dominated climates to reduce heat loss and save energy, was discovered to be primarily useful in maintaining indoor temperatures between the set point (24 and 26 ^{o}C). It further excludes the influence of external conditions and ensures a stable, comfortable indoor environment. However, it does not significantly impact energy demand in this climate due to the slight difference between indoor and outdoor temperatures.

On the other hand, it was observed that minimising internal heat gain, which is not a primary strategy in heating-dominated climates, is significant in achieving the Passive House standard in this climate. This strategy is critical because of its propensity to contribute considerably to cooling load, especially in a super-insulated building, where the heat gained would be trapped due to a slow heat transfer rate. Therefore, specifying Passive House internal heat gain value (which is based on occupancy density and energy-efficient appliances) substantially reduced internal heat gain with a corresponding effect on the building's cooling and energy demand. Noting its influence in achieving the Passive House standard in this climate, it is recommended that this IHG value be re-evaluated for reliability in hot and humid climates.

Nevertheless, the study found that once the heat gained in the building was reduced, a ventilation system such as an energy recovery ventilation (ERV) system at a ventilation rate of about 1ACH is adequate to manage indoor temperature and prevent overheating. The recovery system further saves energy in the building by recovering the cool from the outgoing air.

Finally, the study discovered that the Passive House strategies are valuable for achieving the Passive House standard in hot, humid, cooling-dominated climates; and that buildings appropriately designed for this climate (having deployed other passive strategies, i.e., shading) can optimise their performance using the Passive House strategies highlighted above.

5 Exploration of the Passive House Framework in the Hot and Arid Climates.

5.1 Introduction

The previous chapter investigated the Passive House framework in hot and humid climates. In this Chapter, the framework was evaluated in hot and arid climates with intense sunshine and a large portion of direct radiation, but where some heating is also required. This ensures a well-rounded understanding of the concept in cooling-dominated climates. As in the previous Chapter, Passive House techniques were first applied to a conventional building in order to determine the feasibility of achieving the Passive House standard in hot and arid climates.

5.2 Location of Study – Algeria

5.2.1 The Climate in Ghardaia- Algeria

Algeria, officially the People's Democratic Republic of Algeria, is a country in North Africa's Maghreb region. It is the largest country in Africa and, by extension, the Arab world in terms of land area. It is bounded on the north-east by Tunisia, on the east by Libya, on the south-east by Niger, on the south-west by Mali, Mauritania, and Western Sahara, on the west by Morocco, and on the north by the Mediterranean Sea.

The country has a semi-arid climate, with the majority of the population living in the fertile north and the Sahara dominating the southern geography. Algeria is the ninth-most populous country in Africa, with a land area of 2,381,741 square kilometres and a population of 44 million people. Algiers, the capital and largest city, is located far north on the Mediterranean coast.

However, the location of study is Ghardaia in Algeria. Ghardaia has a hot, dry, desert climate (latitude 32.48°N, longitude 3.80°E). It is distinguished by large temperature differences between day and night and summer and winter. Ghardaia has three (3) months of winter, from December to the end of February, and nine (9) months of summer, from March to the end of November. The average temperature in the summer is around 38°C in July. The average maximum temperature recorded was 40°C (*Figure 5-1)*. The humidity is relatively low, ranging between 23% and 27% during drought periods, with minimum rates ranging between 2 and 6% (Ali-Toudert & Weidhaus, 2017; Boukhelkhal & Bourbia, 2016; Cherier et al., 2018).

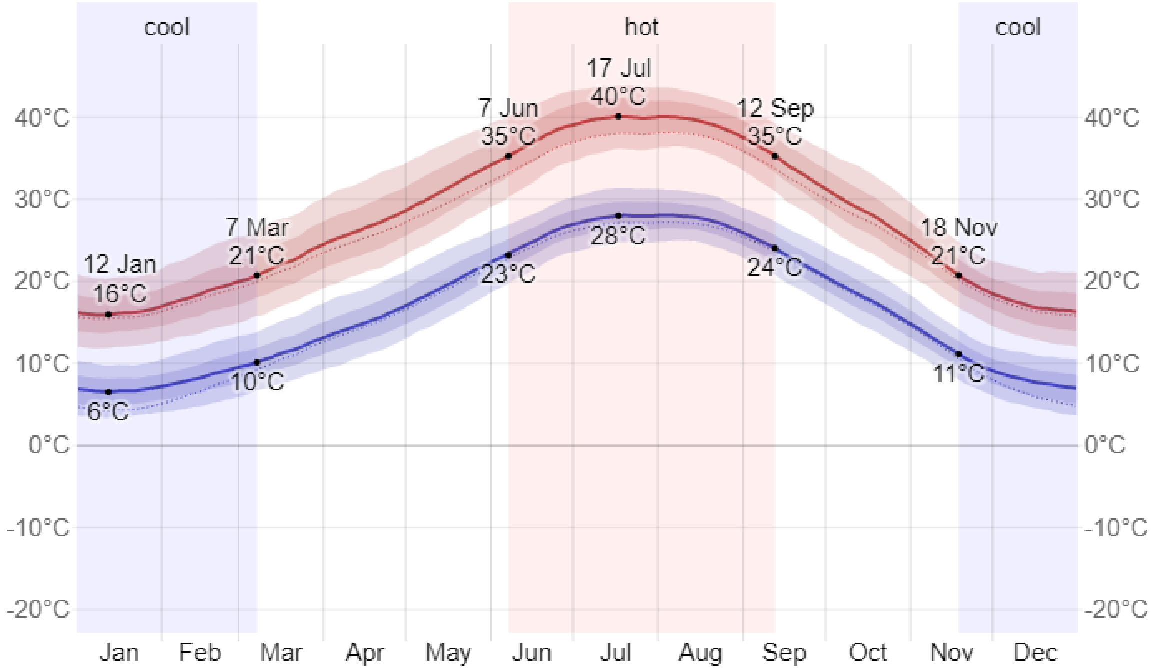


Figure 5-1:Average High and Low Temperature in Ghardaia, Algeria (WeatherSpark.com, n.d.)

5.2.2 Energy Use in Algeria

Buildings are the most energy-intensive sector in Algeria, accounting for more than 41% of total national end-use energy consumption. According to Ghedamsi et al. (2016), total energy consumption in the Algerian residential sector will rise from 73 TWh in 2008 to 180 TWh in 2040, representing a 147% increase in energy demand in about 30 years. In the Algerian construction industry, fossil fuels are primarily used to meet heating needs (in particular natural gas). Space heating accounts for 46% of total building energy consumption (Kerfah et al., 2020). As a result, Algeria's sustainable energy consumption is inextricably linked to improving the thermal performance of its existing and future building stock (Kerfah et al., 2020). Thus, the significance of this study.

5.3 Design of Case Study

The design of this study was similar to that of the previous chapter in that a conventional building from Algeria's hot arid climate was identified, evaluated, and validated. Following that, the reference building analysis commenced by assessing super-insulation, advanced window technology, and mechanical ventilation with heat recovery ventilation. This study did not evaluate airtightness because the infiltration rate of the reference building corresponds to Passive House recommendations. Furthermore, as demonstrated in previous chapters, uncontrolled ventilation had little effect on a building's energy demand or thermal comfort range in a predominately hot climate. As a result, there was no need for this study to delve deeper into it. Other strategies, such as shading, internal heat gain (using energy-efficient appliances), and night cooling, were considered for building optimisation.

5.4 The Conventional Reference Building

The building is a single-story family house with no basement, oriented toward the south; its living area is approximately 70 m^2. According to Ali-Toudert & Weidhaus (2017), the space is enough for a typical family of 4-6 persons in Algeria. *Figure 5-2* depicts the layout of the building with the living room and one bedroom located in the southern part of the building. The other bedroom and lavatory are on the north-western area orientation. The kitchen has a porch and two windows facing east on the east side of the building. The reference building, which depicts a conventional residential building in Algeria, has a flat roof with an uninsulated building envelope. The exterior walls are constructed with double hollow brick walls with an air layer. The windows are made of wooden frames, single glazing, and wooden window shutters. *Table 5.1* summarises the quantitative data for the conventional building components and layers.

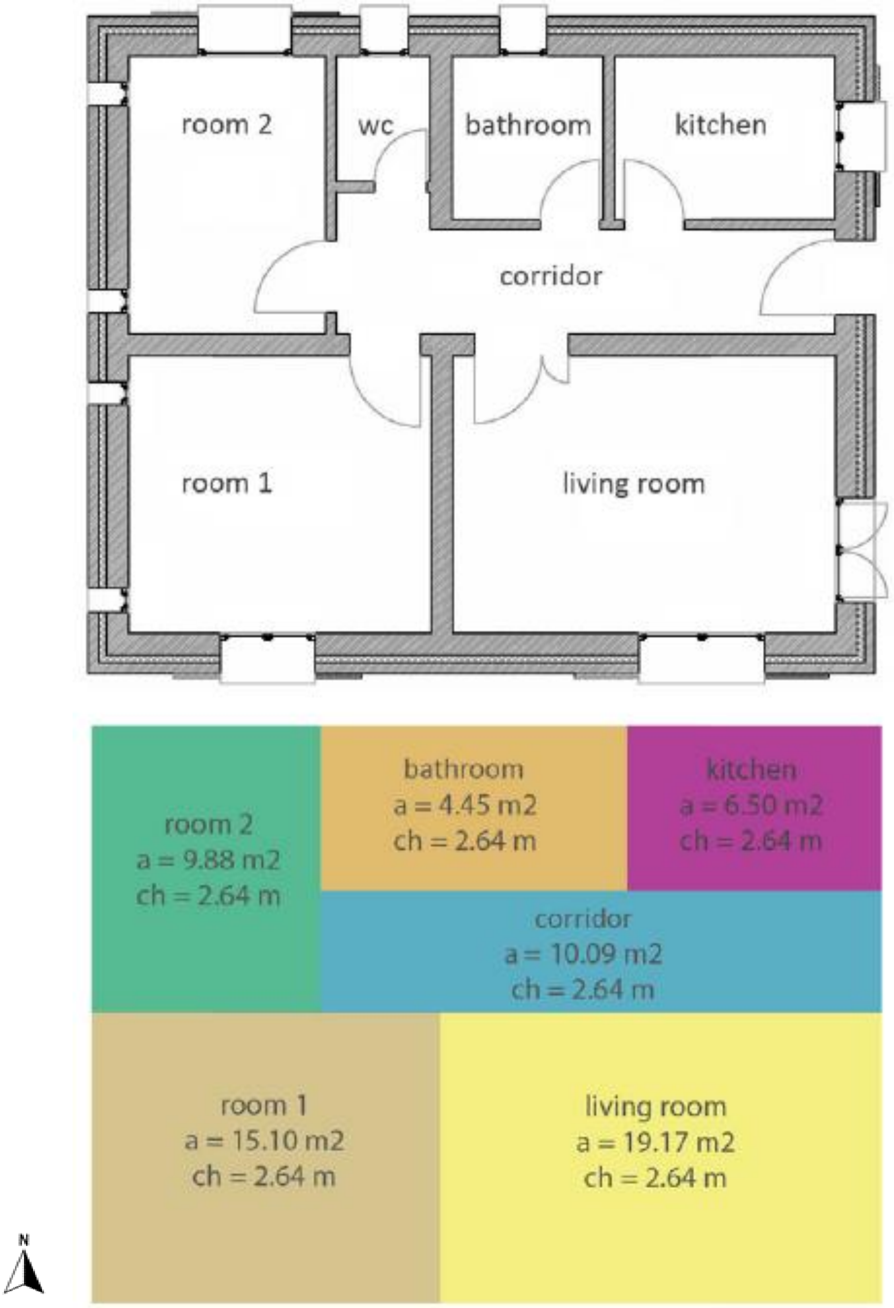


Figure 5-2: Architectural Layout and Dimension of the Reference Building.

Table 5.1: Properties of Building Components the Reference Building.

Building component	**No.**	**Structure**	**Thickness (cm)**	**Thermal conductivity W m^{-1} K^{-1}**	**Thermal capacity $J{\cdot}kg^{-1}{\cdot}K^{-1}$**	**Density (kg/m^3)**	**Thickness building component (cm)**	**U-value $W/(m^2{\cdot}K)$**	**Thermal mass ($kJ/(m^2K)$)**
Floor construction	1	Glazed tiles	2	1.7	1000	2000	15	2.64	165 (medium weight)
	2	Sand-mortar-floor screed	3	1.15	1000	2000			
	3	Reinforced concrete floor	10	0.76	1000	2200			
Ceiling Construction	4	Reinforced concrete ceiling	20	1.78	1000	2400	22	2.93	220 (heavyweight)
	5	Plaster	2	0.7	1000	1400			
External wall	6	Plaster	2	0.7	1000	1400	34	1.15	124 (lightweight)
	7	Brick	10	0.54	1000	1200			
	8	Air layer	5	0.047	1000				
	9	Brick	15	0.54	1000	1200			
	10	Plaster	2	0.7	1000	1400			
Internal wall	11	Plaster	2	0.7	1000	1400	15.5	1.89	
	12	Brick	11.5	0.54	1000	1200			
	13	Plaster	2	0.7	1000	1400			
Window		Single glazing					3	5.47	
		Wooden sash							

Table 5.2 shows the building's thermal profile and simulation settings typical of a conventional building in Algeria. The heating and cooling set points for the building were 20°C and 24°C, respectively, based on the local standard, as reported by Sami-Mecheri et al., (2015).

Table 5.2: Thermal profile and Simulation Setting of the Conventional Reference Building (Ali-Toudert & Weidhaus, 2017).

Thermal Profile		**Simulation Setting**
Heating set temperature	20°C	According to local regulation DTC 3-2: living rooms 21°C, secondary rooms 18°C. Room one, two, living room and bathroom are heated. Kitchen, corridor, and roof floor are not heated.
Cooling set temperature	24°C	According to local regulation DTR C3-4; cooling in rooms.
Ventilation rate	Daytime ventilation rate	Infiltration: 0.5 vol/h. Additional for preventing overheating: 1.4 vol/h (temperature dependent with lower threshold 21°C and higher threshold 24°C. Period: 6 a.m. – 7 p.m.
	Night-time ventilation rate	Infiltration: 0.5 vol/h. Additional for preventing overheating: 2.4 vol/h in the summer (May 15th to September 15th). Period: 8 p.m. – 5 a.m.
Heat gains	Persons	One person per space (except corridor) (seated, light work, after DIN EN ISO 7730).
	Equipment	50 W, continuous (24 h) in kitchen and living room
	Lighting	2 x 19 W/m^2 (rooms) 1 x 19 W/m^2 (bathroom) 1 x 13 W/m^2 (Kitchen, corridor)

5.4.1 Validation of the Reference Building

Using the data above, the reference building was modelled in IES-VE, as shown in *Figure 5-3*. To validate the building, the energy demand of the simulated building is compared to that of the reference literature.

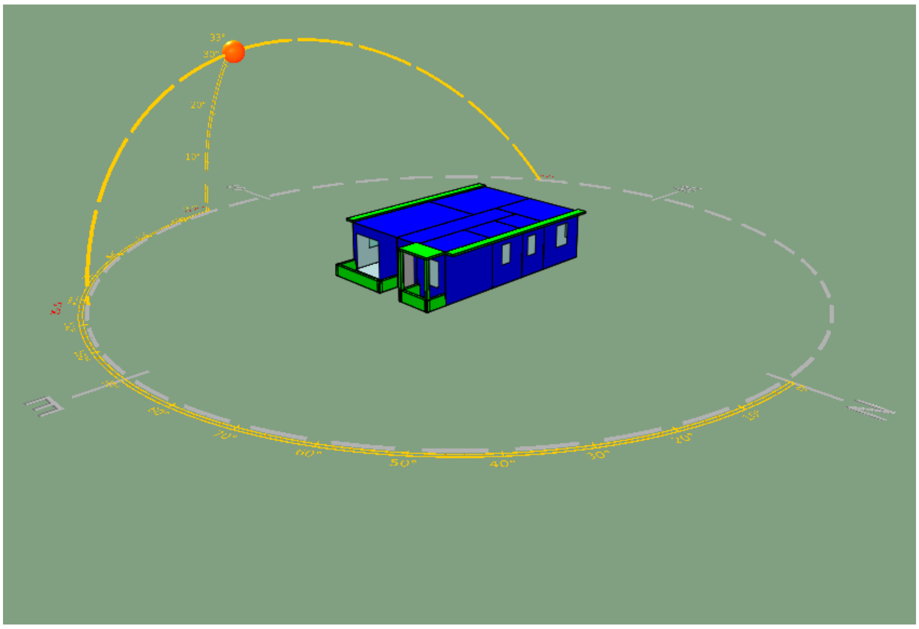


Figure 5-3: Algerian Conventional Reference Building as Modelled in IES-VE.

5.4.1.1 Validation Results & Analysis

The analysis of the cooling and heating demands of the conventional building as simulated in IES-VE software against Ali-Toudert & Weidhaus (2017) is presented in *Figure 5-4*. The result shows good agreement between the simulated energy demand and the reference paper. The observed marginal variance was attributed to differences in the software application and weather data. This completes the model validation. However, in order to establish a baseline for future analysis, the thermal condition of the building was also examined, as illustrated in *Figure 5-5*.

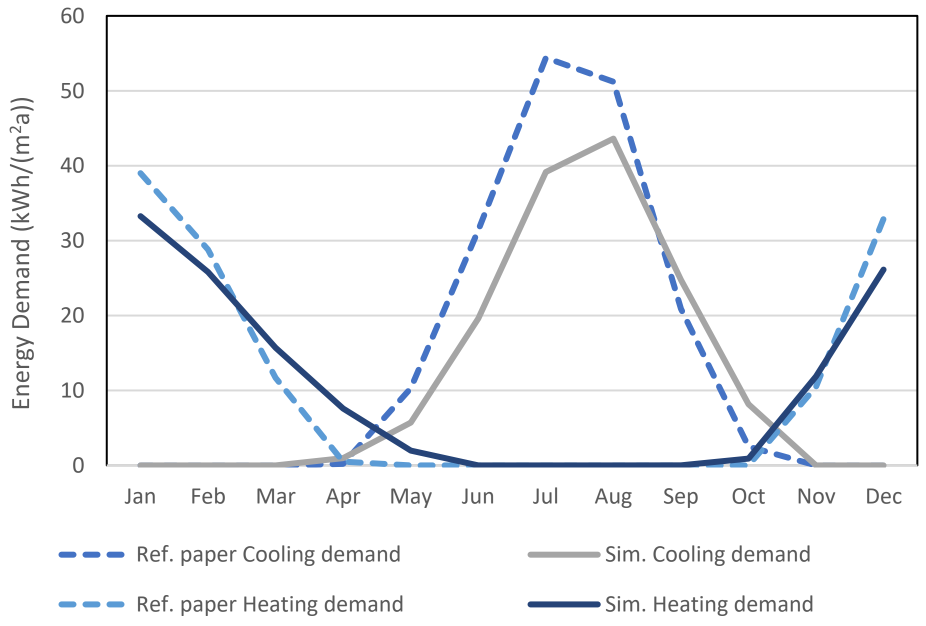


Figure 5-4: Monthly Heating & Cooling Demand of the Reference Building

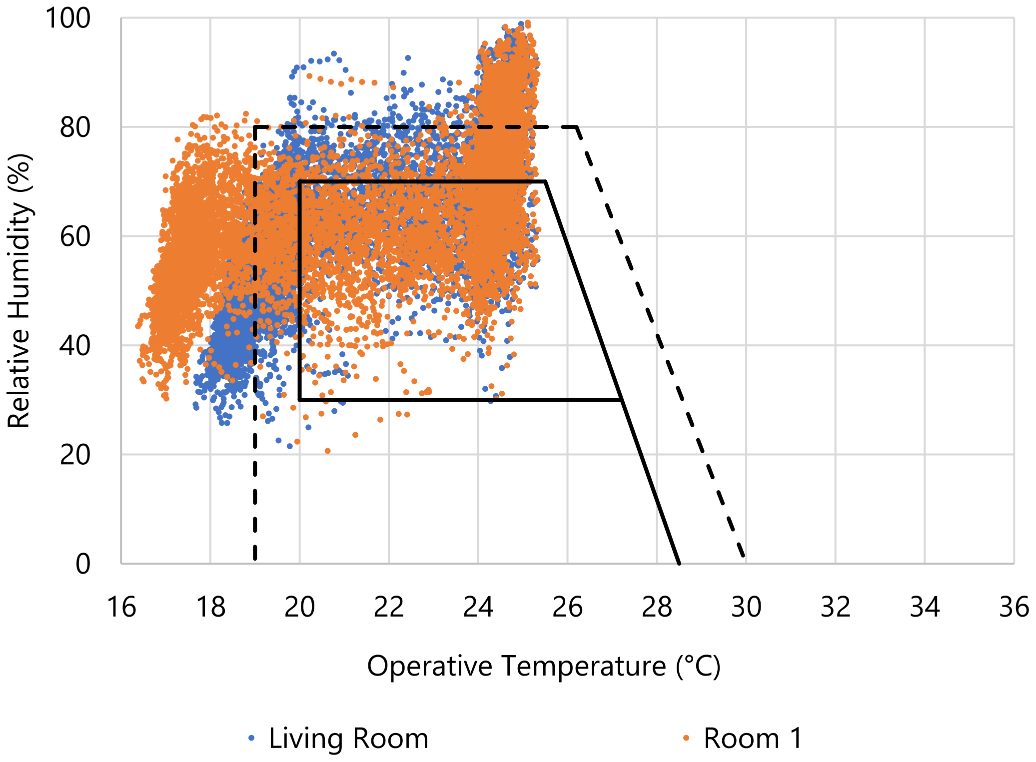


Figure 5-5: Indoor Temperature and Humidity of Conventional Reference Building

Figure 5-5 shows that, despite using an active system, the building still has some periods outside the comfort range. Notably, the indoor conditions fall below the setpoint temperature due to rapid heat loss in the uninsulated reference building, presumably during the colder season. The reference building's performance is useful for further analysis in the following section.

5.5 Application of the Passive House Strategies

The Passive House strategies were implemented after the validation of the reference building, which confirmed the performance of the conventional building. Thus, as described in the previous chapter, each Passive House strategy was investigated independently to determine its contribution to the building's performance in this climate and guide its implementation and effectiveness in meeting the Passive House standard.

5.5.1 Super Insulation

Insulation is not mandatory in Algeria (Kerfah et al., 2020). However, according to Derradji et al., (2017), the optimum insulation thickness for heating in this climate is between 1cm and 7cm, while the thickness for cooling varies between 1cm and 2.5cm. Passive House, on the other hand, only recommends that the building (walls, roof, and floors) be super-insulated in order to achieve a thermal transmittance between 0.10 - 0.15 W/(m^{2}K). The significance of insulation is highlighted in this study by the systematic analysis of insulation to the wall, roof, and floor. It also emphasises the building envelope element that requires insulation and the optimum thickness based on the chosen material -polyurethane. The thicknesses considered ranged from 2cm to 10cm. At 10 cm, the thermal transmittance of each component would represent the Passive House recommendation for the building envelope, as shown in *Figure 5-6.*

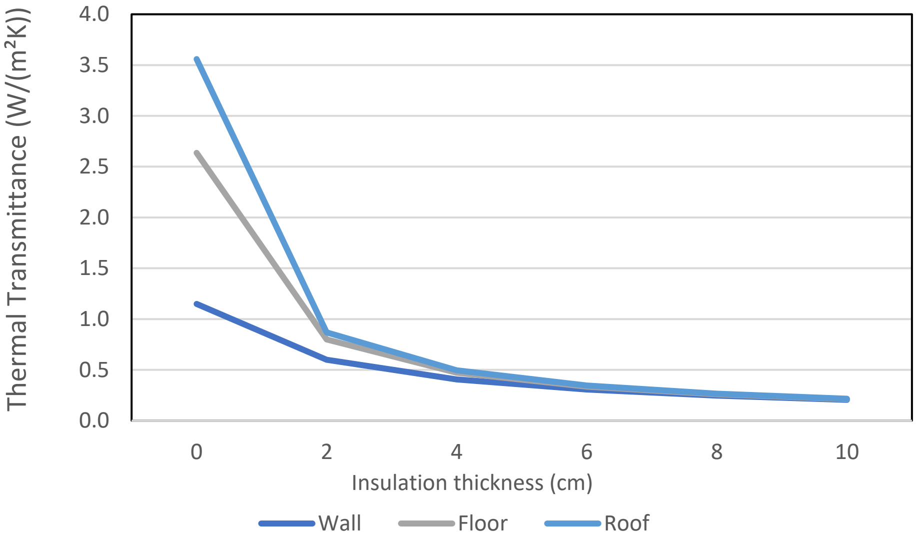


Figure 5-6: Thermal Transmittance of Wall, Roof & Floor with Varied Insulation Thickness.

5.5.1.1 Findings and Discussion

This section discusses the performance implications of insulating each building component. The total energy, heating and cooling demand, peak heating and cooling load, and indoor thermal conditions were analysed.

5.5.1.1.1 External Wall Analysis

The external wall of the building is a double brick wall with a 5cm airgap. Brick, like clay, has a high thermal mass capacity and can thus absorb and store heat, which is useful in both hot and cold seasons to slow heat gain and passively heat the building, respectively. In addition to this, the air trapped between the bricks, being a poor heat conductor, also acts as a barrier to heat transfer (Alhefnawi et al., 2017; Khan et al., 2020). Thus, this wall composition could be considered an effective strategy for preventing heat transfer and maintaining indoor conditions. As a result, it is uncertain what contribution insulation would have on the building's performance. *Figure 5-7* depicts the effect on the building’s energy demand, where 0 represents an uninsulated wall.

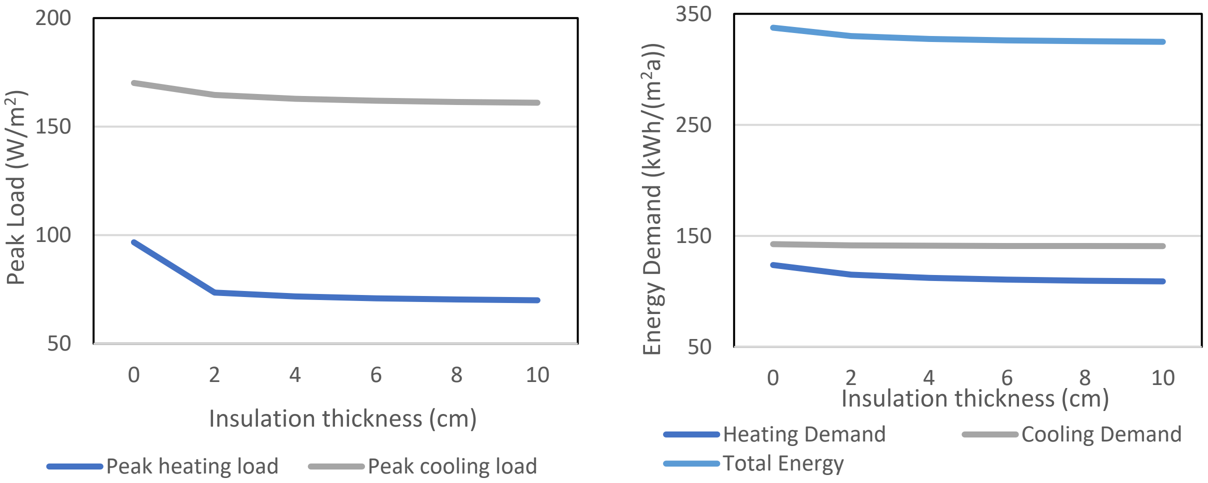


Figure 5-7: Energy Demand for Wall Insulation -Peak Load (Left), Annual Energy Demand (Right)

Figure 5-7 shows that the only noticeable effect of wall insulation is on peak heating load, which is reduced by 24% at a thickness of 2 cm (0.60 W/(m^2K)). Though the wall composition could support passive heating and slow heat transfer during the winter, it appears inadequate to manage heat loss; thus, the introduction of insulation was beneficial in this regard. However, no notable effect was observed beyond the 2cm thickness.

Regarding the cooling demand of the building, the introduction of insulation to the wall composition had no apparent effect. This suggests the wall composition was appropriate to manage the influence of extreme external conditions in summer, and the heat gained in the building is from other sources (as a result of local climate and internal load from equipment's and people), which remains in the building. Thus, the indoor thermal conditions were unaffected.

5.5.1.1.2 Ground Floor Analysis

The ground floor of the building, although not directly exposed to solar radiation, can facilitate heat transfer. Thus, the effect of insulation on the building energy demand is presented in *Figure 5-8*.

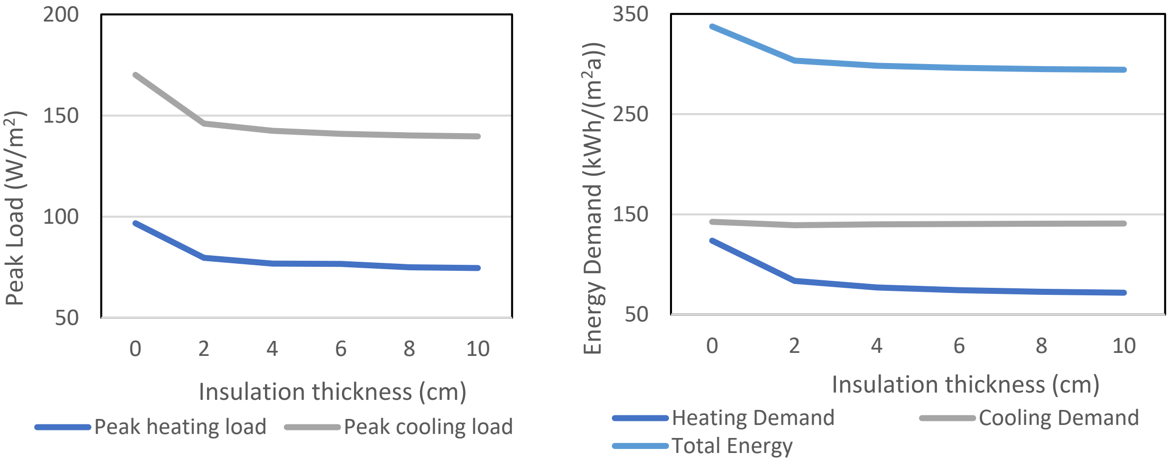


Figure 5-8: Energy Demand for Floor Insulation

The analysis of floor insulation at various insulation thicknesses yields slightly different results on the building's energy demand than the wall insulation. The ground floor insulation isolates the internal environment, preventing heat loss while impeding conductive heat transfer with the ground (see *Figure 5-8).* As a result, the minimum insulation of 2 cm (0.80 W/(m^2K)) reduced peak heating and cooling loads by 18% and 14%, respectively, and the load continues to fall slightly as insulation increases. However, beyond 4cm insulation thickness, no noticeable effect was observed for the peak load as heat transfer is diminished.

Overall, insulating the floor reduced energy demand by 13% because the insulation prevented heat transfer in the building, resulting in a 16% reduction in peak heating and cooling load. The most significant effect is a 40% reduction in heating demand, indicating that significant heat is lost to the ground during winter. However, the cooling demand remained constant as insulation slows heat transfer and retains the heat gained in the building. As a result, floor insulation, like wall insulation, had little effect on the indoor environment of the building.

5.5.1.1.3 Roof Analysis

Of the building envelope, the roof element is the most exposed to external conditions. The reference building, with an uninsulated roof, is prone to significant heat transfer in both seasons. *Figure 5-9* depicts the effect of roof insulation on the building's energy performance.

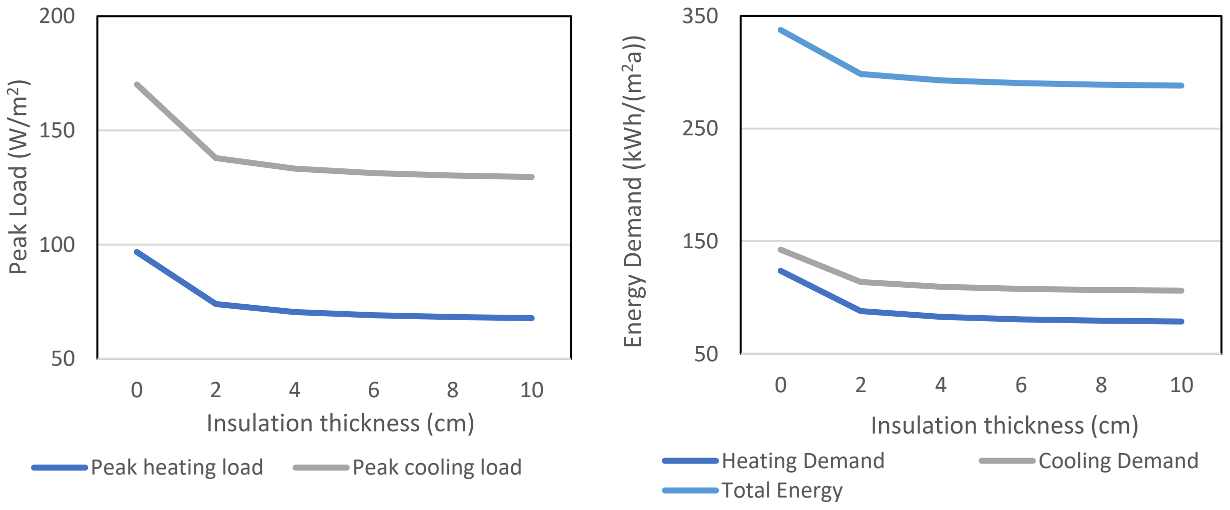


Figure 5-9: Energy Demand for Insulated Roof

Figure 5-9 confirms that the uninsulated roof causes significant heat transfer. Considering that the introduction of insulation at the minimum of 2cm (0.87 W/(m^2K)) resulted in a 19% reduction in cooling load, indicating that significant heat is gained from the sun during the summer months. Similarly, during winter, the building loses significant heat, resulting in a 24% reduction in peak heating load. Consequently, the demand for heating and cooling is reduced by 29% and 20%, respectively. Notably, as with the wall and floor insulation, the significance of insulation decreases beyond 2cm, implying that simply introducing insulation into the building envelope is more important in this climate than thickness. The roof, however, had the most significant impact on the building's energy demand, saving approximately 15% of the total energy demand. Regardless, its effect on indoor temperature is negligible.

5.5.2 Advanced Window Technology

The window is an integral part of the building envelope. The reference building has a wall-to-window ratio (WWR) of 15%, with single-glazed windows of 5.5 W/(m^2K).

To assess the impact of low thermal transmitting windows ranging from 0.7 to 1.8 W/(m^2K) in triple and double-glazed windows (where a lower U-value denotes better performance) (Aguilar-Santana et al., 2020); a double-glazed window with a thermal transmittance of 1.4 W/(m^2K) and a Passive House standard window with a thermal transmittance of 0.80 W/(m^2K) are explored. *Figure 5-10* depicts the corresponding energy performance.

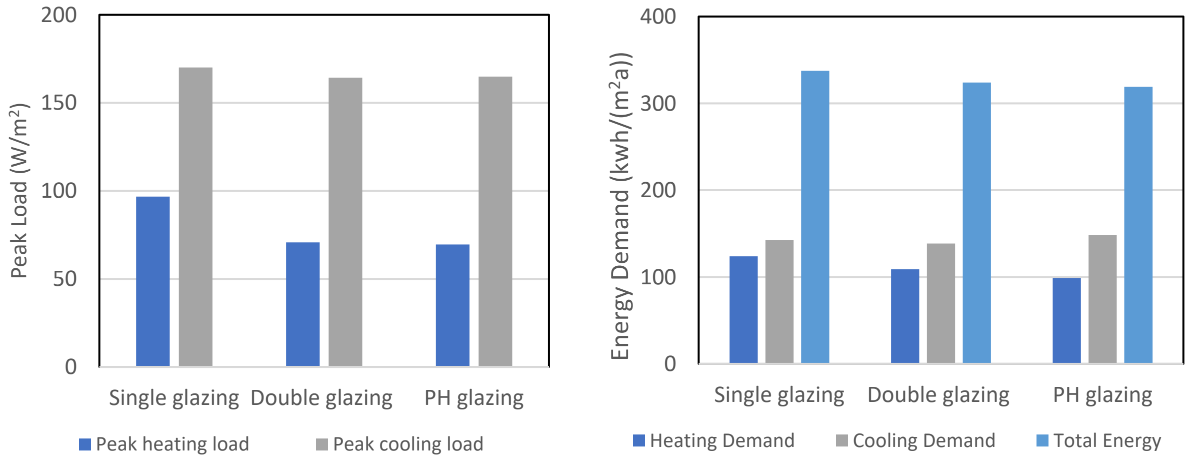


Figure 5-10: Energy Demand Low Thermal Transmitting Windows.

Figure 5-10 shows that having low thermal transmitting windows, such as double-glazed windows (1.4 W/(m^2K)) or Passive House windows, does not affect the building's cooling demand. This could be attributed to the window's limited solar gain due to its size and orientation.

However, because the low thermal transmitting windows can trap heat in the building, the heating demand is reduced by 12% and 21%, respectively. It was also observed that with the Passive House standard window, the cooling demand increased by 7% compared to the single-glazed windows in the model.

In summary, the effect of insulation and low thermal transmitting windows was more pronounced on the building's heating demand due to heat loss prevention. In the case of cooling demand, the effects were minimal due to other strategies such as a high thermal mass wall and small windows, as well as the building's orientation, where the short side of the building was oriented East and West to reduce heat gain. Despite this, the use of insulation had an impact on peak cooling load, particularly with floor and roof insulation, resulting in a 20% reduction in cooling demand. At the same time, it was also observed that super-insulating the building envelope to meet the Passive House thermal transmittance value could be problematic as it negatively impacts the cooling demand. For example, the cooling demand of the reference building with a Passive House standard window exceeds using a conventional single-glazed window. Therefore, to ascertain the best thermal value for the building performance, two scenarios were investigated in the following section.

5.5.3 Insulated Envelope – Wall, Roof, Floor and Advanced Window Technology.

This section covers the result of considering two cases of insulation or thermal transmittance for the building envelope. Initial insulation analysis on each building component suggests that the most significant impact on the energy demand for heating and cooling was achieved at minimum insulation. Increased insulation would mostly benefit the heating demand but have less impact on the cooling, in some cases leading to an increase in demand, even though the peak cooling load may slightly reduce.

The outcome posed a challenge as to what level of insulation should be recommended for a hot and arid climate where although there are heating needs, the cooling need is substantially higher. Hence, to understand the impact of thermal transmittance or insulation thickness of building envelope on the building performance, it was decided that the building envelope be analysed as follows;

(i) Case 1 – Insulated Envelope: In this scenario, the thickness of the insulation chosen for each component supports both heating and cooling; or appears to no longer have a significant impact on the building's energy. Also, the advanced window technology utilized is the low thermal double-glazed window.

(ii) Case 2 – Super-Insulated Envelope: The thickest insulation of 10 cm is applied for all components in this scenario. Additionally, the PH standard window is used. In this case, the building envelope and window technology are similar to a prototype Passive House as shown in *Table 5.3*.

Table 5.3: Characteristics of the Reference Building and Alternative Case Studies.

The Reference Building		**Case 1**		**Case 2**	
Building Component	U-value (W/(m^{2}K))	Insulation thickness (cm)	U-value (W/(m^{2}K))	Insulation thickness (cm)	U-value (W/(m^{2}K))
Roof	3.56	6	0.41	10	0.21
Wall	1.15	4	0.35	10	0.21
Floor	2.64	2	0.8	10	0.21
Glazing	5.4		1.4		0.8

5.5.3.1 Results and Discussion

This section presents the result of both scenarios as insulation was progressively applied to the building envelope, and its impact on building performance evaluated (i.e., energy demand and indoor condition).

5.5.3.1.1 Case 1- Insulated Envelope of the Reference Building.

In *Figure 5-11*, the energy demand of the building is presented from the largest surface area exposed to external conditions (the wall) to the least area (the windows). Firstly, it was observed that insulation had a continuous significant effect on the peak load for both heating and cooling. Due to the reduced influence of external conditions as insulation minimises heat flow resulting in the reduction of peak heating load by 91.5% and cooling load by 51%.

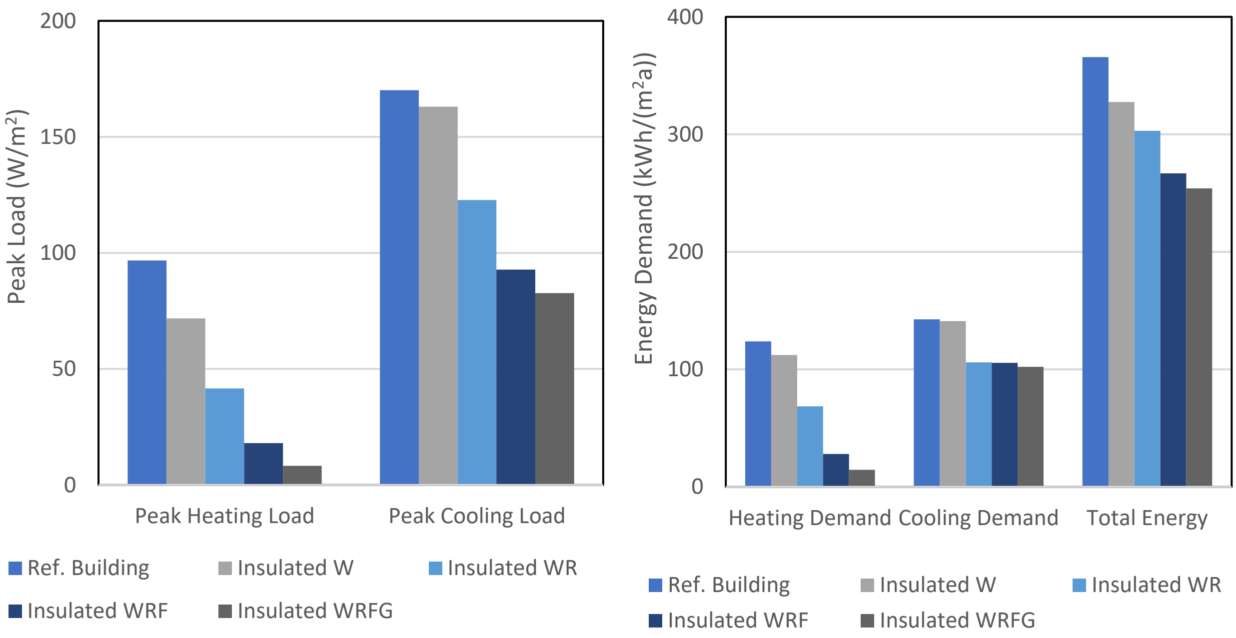


Figure 5-11: Energy Demand for Case 1

Insulation had more effect on the heating demand because heat gained in the building is conserved, and heat loss is prevented when the external temperature is low, thereby keeping the building within the comfort range. Meanwhile, even though external influence is reduced, heat gained in the building is retained; as shown in *Figure 5-11* (right), cooling demand would only reduce when the external primary heat gain source (the roof) is insulated. Otherwise, heat gain in the building appears constant; thus insulation, other than that on the roof, had a lesser impact on the cooling demand.

However, case one (1) shows that with the building envelope insulated, heating demand is almost eliminated and, if necessary, can be handled by a small heating source of less than 10 W/m^2. It was also observed that half the size of the initial mechanical system could be used to provide cooling. Thus, the insulated envelope requires about 88% and 28.5% less heating and cooling demand, respectively, compared to the reference building. Therefore, saving about 31% of the building's total energy in the lightly insulated envelope.

5.5.3.1.2 Case 2- Super-Insulated Envelope of the Reference Building.

Figure 5-12 shows the energy performance of the super-insulated envelope, including a Passive House standard window. In this case, it was observed that although the peak heating load remained the same as the lightly insulated building, super-insulation further prevented heat loss. Thus, heating demand appears to have been eliminated in the building (*Figure 5-12, right*).

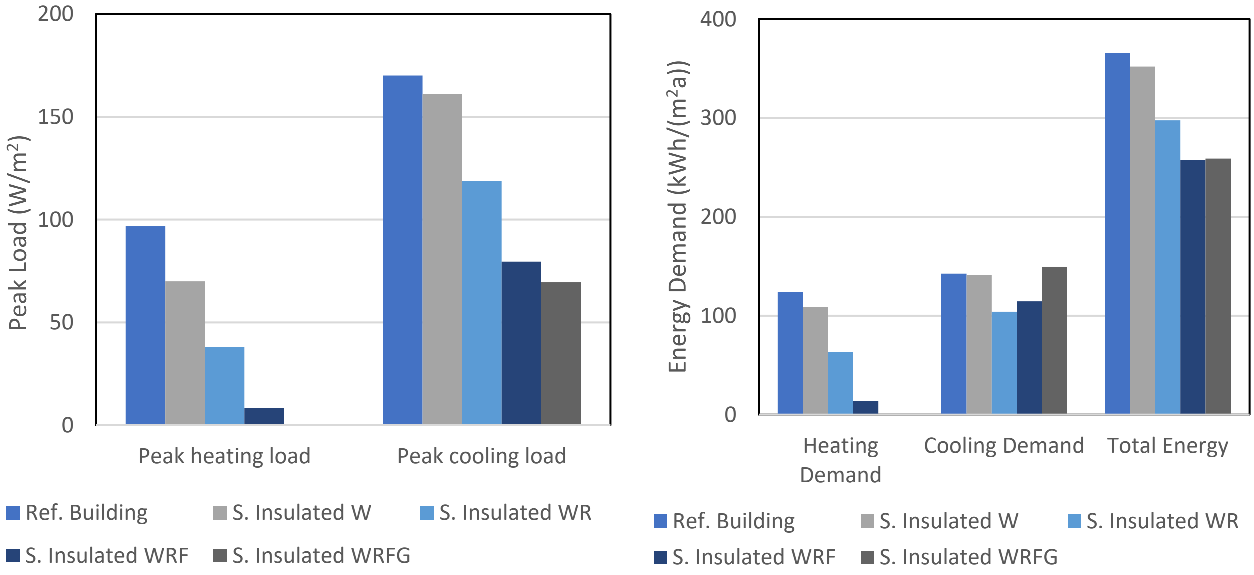


Figure 5-12: Energy Demand for Case 2

Additionally, the increased inhibition of heat transfer by super-insulation reduced the peak cooling load further up to 60% beyond the lightly insulated envelope. Although, it increased the cooling demand slightly beyond the uninsulated reference building by 5%. The total energy saved was 29%, which is comparable to the energy saved in the lightly insulated envelope. The indoor thermal conditions are also evaluated, as shown in *Figure 5-13*.

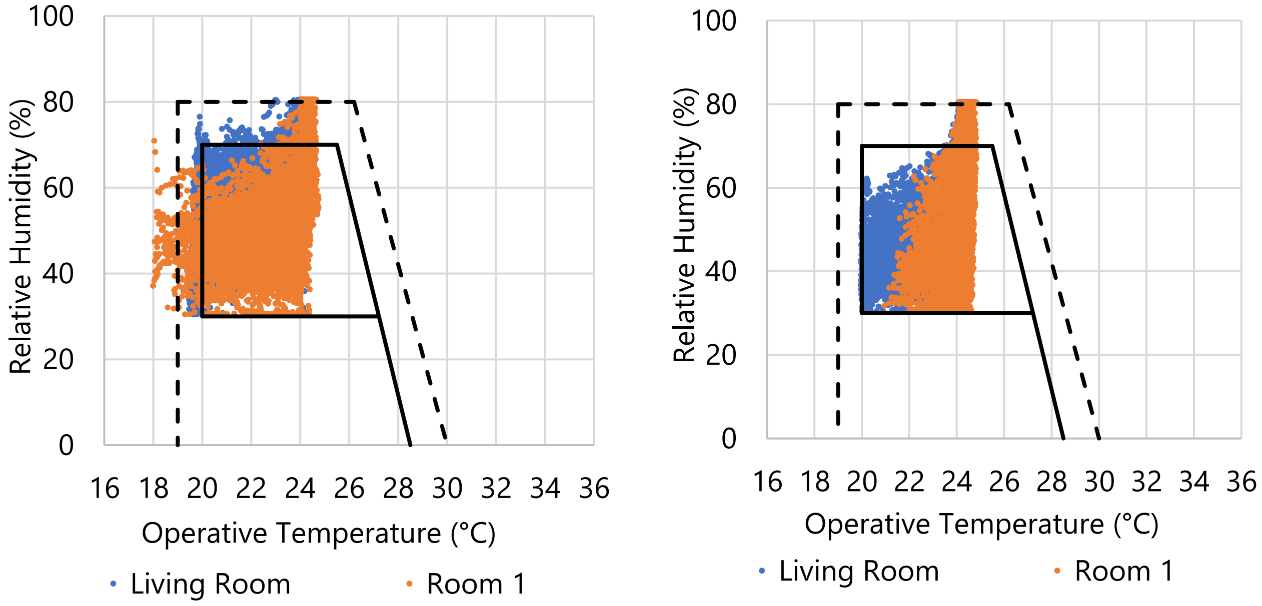


Figure 5-13: Indoor Operative Temperature & Relative Humidity for Case 1 (left) & 2 (right).

The super-insulated envelope (*Figure 5-13*, right) presented a more comfortable indoor environment, particularly in the colder season, due to more insulation hindering heat loss. On the other hand, the building conditions fall slightly outside the inner and extended comfort range in the lightly insulated envelope (*Figure 5-13*, left) with less insulation. However, both conditions can be deemed acceptable and presented better comfort conditions than the reference building.

In conclusion, buildings in hot and arid climates can benefit from insulation and advanced window technology as both cases present their advantages. In Case 1, even though heating and cooling demand are reduced significantly, there is a need to maintain thermal comfort during heating and cooling seasons. Whereas in Case 2, the heating need is removed, allowing focus on cooling needs which can then be delivered with a cooling system less than 50% required for the reference building.

Thus, since this study aims to develop a Passive House, which is highly energy efficient and thermally comfortable, Case 2, hereon referred to as the “Super-Insulated Reference Building”

(SIRB), was chosen for further research. It presented a better indoor condition based on the thermal comfort graph and would mainly require cooling because heating demand was eliminated. Case 2 (SIRB) analysis also shows that the peak cooling load has diminished by 60%, which is desirable to meet the Passive House standard. However, the peak cooling load of the SIRB is still about seven times above the standard. Therefore, other strategies are explored to further reduce the peak cooling load before evaluating the last main Passive House principle – mechanical ventilation with heat recovery.

5.6 Additional Strategies Explored

Several strategies have proved helpful in reducing cooling load/demand in buildings. These strategies include orienting a building to minimize the wall area facing east or west and clustering buildings to provide some degree of self-shading (as in many traditional communities in hot climates). Using high-reflectivity building materials, providing fixed or adjustable shading, avoiding excessive window area (particularly on the east- and west-facing walls); and utilizing thermal mass to minimize daytime interior temperature peaks (Metz et al., 2007).

As noted in the preceding analysis, some of these strategies have already been implemented and proved useful in the reference building. For instance, the building is oriented such that the wall area facing east, or west is smaller than that of the north and south walls. Also, the building wall used thermal mass to control interior peaks. Therefore, it is established that the reference building had considered some passive strategies. However, more avenues are explored to reduce cooling load/demand further.

As stated in the previous chapter, Passive House proposes that cooling demand can be minimised through shading and is necessary for all climates with high solar radiation during summer (Passivhaus Institut, 2019c). In addition, efficient equipment and controls are recommended to reduce internal heat loads from appliances and lighting. Night purging and natural cross-ventilation through open windows are also encouraged during summer.

5.6.1 Shading Analysis

This section, like in the previous chapter, examines the effect of solar heat and considers possible interventions. The studied building has a flat roof with approximately 0.2 m of overhang on the north and south sides, as well as a covered porch on the east side that provides shade to the window and that portion of the building. So, before pursuing additional shading innovations, it was necessary to assess the building's solar exposure. As a result, as shown in *Figure 5-14*, a solar analysis is performed on the conventional building.

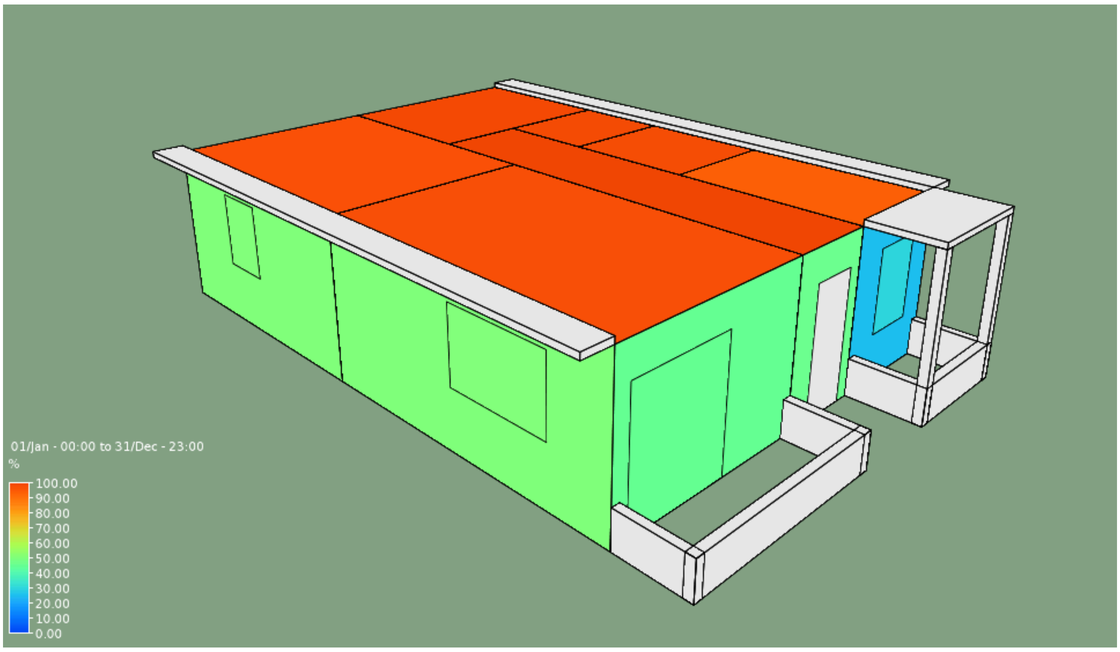


Figure 5-14: Solar Analysis of the Building (South-East View).

As expected, it was observed that the roof had the highest exposure throughout the year. Followed by the East and south side of the building for about half the year, the north side receives the least amount of sun. Thus, to reduce the solar gain, the building envelope is shaded as follows, the application of a double roof with a 1.5 m overhang on all sides of the building.

Additional shade was provided for wall and glazing with trees on the East wing and perforated wall shade on the building's West, North and South. The model is referred to as shaded SIRB, shown in *Figure 5-15*.

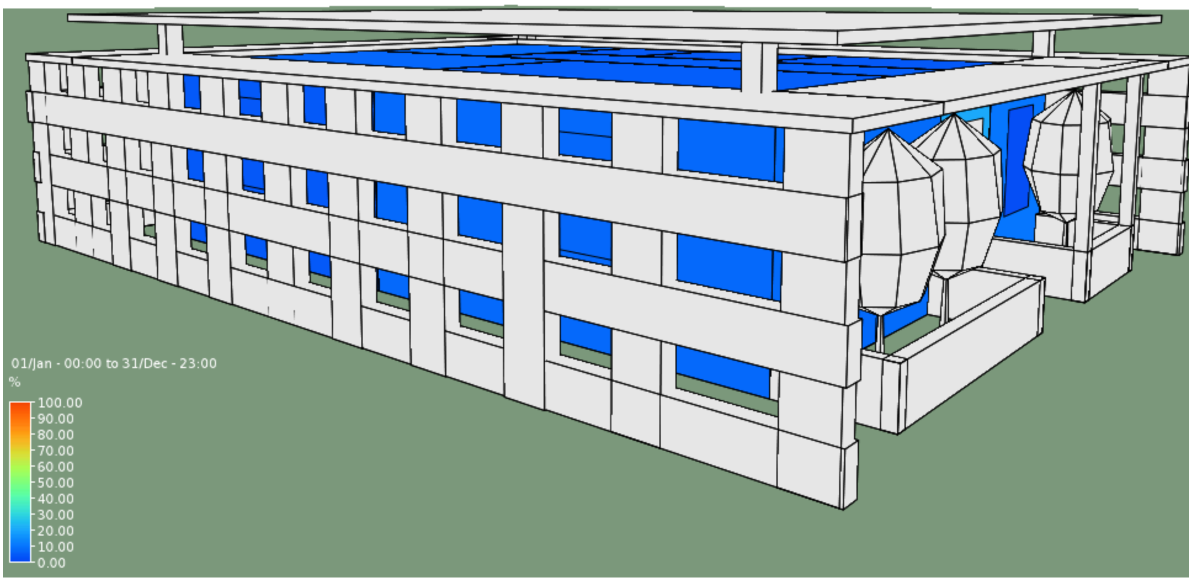


Figure 5-15: Solar Analysis of the Fully Shaded Building.

5.6.1.1 Results and Discussion

Based on the previous study (see 4.6.1.1), the additional shade is expected to further reduce cooling demand in the uninsulated envelope. Thus, was not considered in this case, however, its effect in the super-insulated building is uncertain and was investigated to establish its influence on the cooling demand. *Figure 5-15* shows that due to extensive shading, the building, including the roof, now has direct solar exposure for less than 20% of the year. Thus, its impact on the super-insulated envelope energy demand, mainly the cooling load, was investigated and presented in *Figure 5-16*.

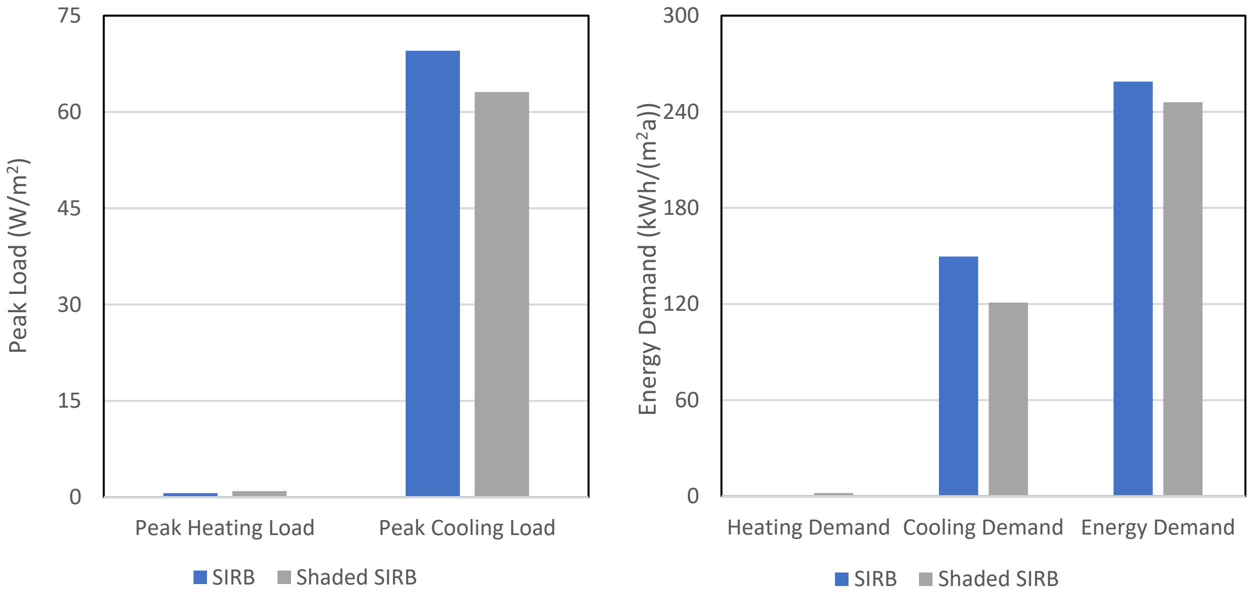


Figure 5-16: Energy Demand of the Fully Shaded SIRB

It was observed that although the shade applied significantly reduced the building's solar exposure, consequently reducing solar heat gain, the peak cooling load was reduced by only 9%, increasing the heating load by 47%. It corresponds to a reduction in cooling demand by 19% and increasing heating demand. Overall, saving only 5% of the total energy demand for the building and its effect on the indoor conditions is insignificant.

Finally, it is important to note that although the heating demand increased, the heating energy demand is still very low (1.97 kWh/(m^{2}a)) compared to a cooling demand of 121 kWh/(m^{2}a), even with 19% savings. Therefore, according to the Passive House standards, the cooling demand is still significantly high, and the impact of the additional shading was insignificant. Thus, as in the previous chapter, another avenue to reduce the cooling demand (i.e., using energy-efficient appliances) was explored.

5.6.2 Internal Heat Gain Analysis

The Passive House guidelines published by International Passive House Association (iPHA) (2021) stated that reducing internal heating loads could facilitate passive cooling. The preceding analysis also shows that the cooling load/demand might not be due to solar heat gain as additional shade did not significantly affect the cooling demand. Therefore, an internal heat gain of 3.1 W/m^2 is applied to the building based on the conditioned floor area, as in the previous chapter.

5.6.2.1 Results and Discussion

5.6.2.1.1 Energy efficient load in the Conventional Reference Building

Firstly, the internal heat gain value is applied to the conventional building to analyse its impact on the building performance compared to the super-insulated model, as shown in *Figure 5-17*.

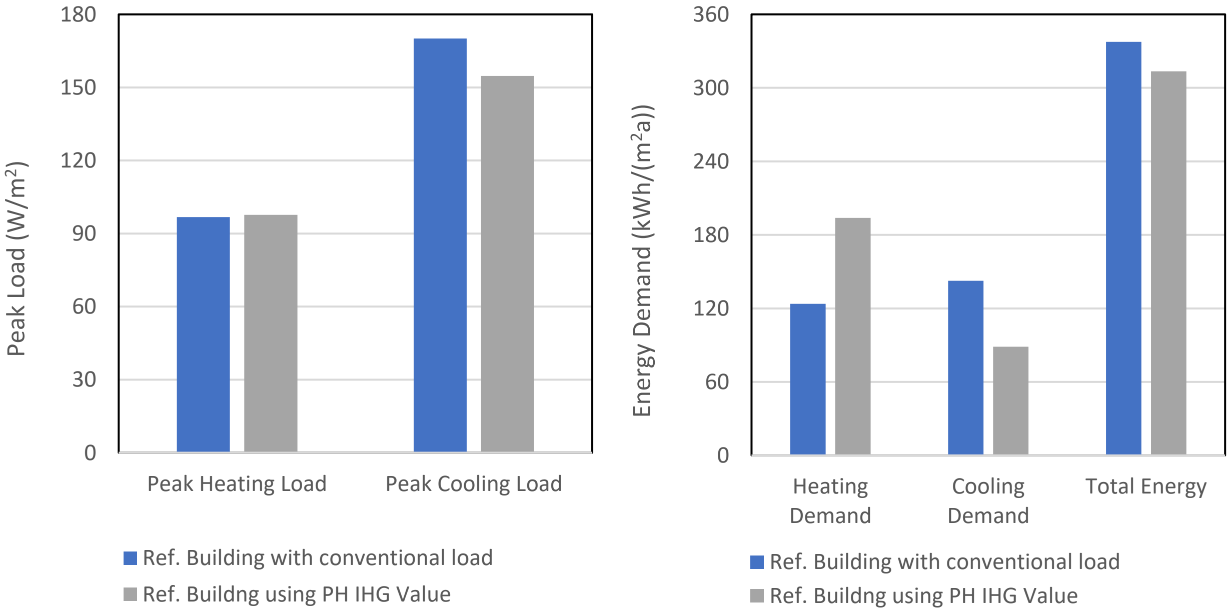


Figure 5-17: Energy Demand of the Conventional Reference Building using Passive House Internal Heat Gain Value.

Figure 5-17 shows that the peak heat load in the building when considering conventional load and energy efficient load (estimated by Passive House), is comparable because of the influence of external conditions (solar gain) in the uninsulated building. However, the impact of the energy-efficient load is observed in *Figure 5-17* (right), as the heating demand in the building is increased by 36% due to reduced internal heat gain. This result is substantiated, as the cooling demand is observed to have decreased by about 38%, with only a 9% reduction of the peak cooling load compared to having conventional loads. With this trade-off between heating and cooling demand, the influence of internal heat gain was limited in the uninsulated reference building, saving only 7% of the building's energy. Also, the effect on the indoor thermal conditions was insignificant. The influence of energy-efficient load is investigated in the well-insulated building (SIRB), considering its insulation from the impact of external conditions.

5.6.2.1.2 Energy Efficient Load in a Super-Insulated Reference Building (SIRB)

After noting its impact in the uninsulated reference building, which proved to have some effect but was insignificant because of heat transfer and influence from the external conditions, the effect of the energy-efficient load is investigated in the super-insulated reference envelope (SIRB)as shown in *Figure 5-18*.

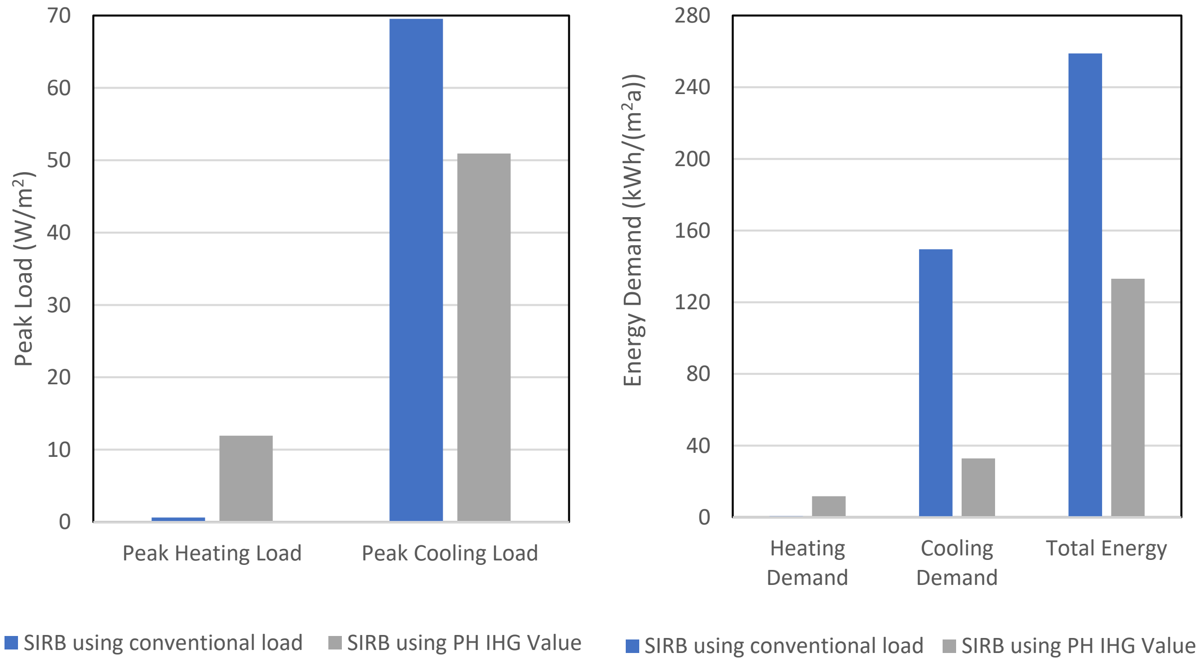


Figure 5-18: Energy Demand for SIRB using Passive House Internal Heat Gain Value.

In contrast to the uninsulated reference building, the energy-efficient load significantly impacted the building's total energy, where almost 50% savings was achieved. Firstly, it was observed that the peak heat load and demand increased due to reduced internal heat gain in the building. Nonetheless, the demand is still low (approximately 12 kWh/(m^2a)), which meets the Passive House standard.

On the other hand, the cooling demand plummeted to 33 kWh/(m^2a) as demand was reduced by 78%, with a peak cooling load reduction of 27%. This is double its effect in the uninsulated reference building, emphasising the benefit of insulating the building envelope even in a hot climate which led to significant total energy savings achieved; while the effect on the indoor conditions was negligible.

Due to the use of insulation, low thermal transmitting windows and assuming Passive house internal heat gain value based on energy-efficient appliances and variability of occupants, the heating and cooling demand of the reference building has been reduced by over 75%. However, the peak cooling load and demand are yet to meet the Passive House standard. Next, mechanical ventilation with heat recovery (another main Passive House) strategy is considered for complete evaluation of the Passive House strategy.

5.7 Mechanical systems

5.7.1 Using Mechanical Ventilation with Recovery

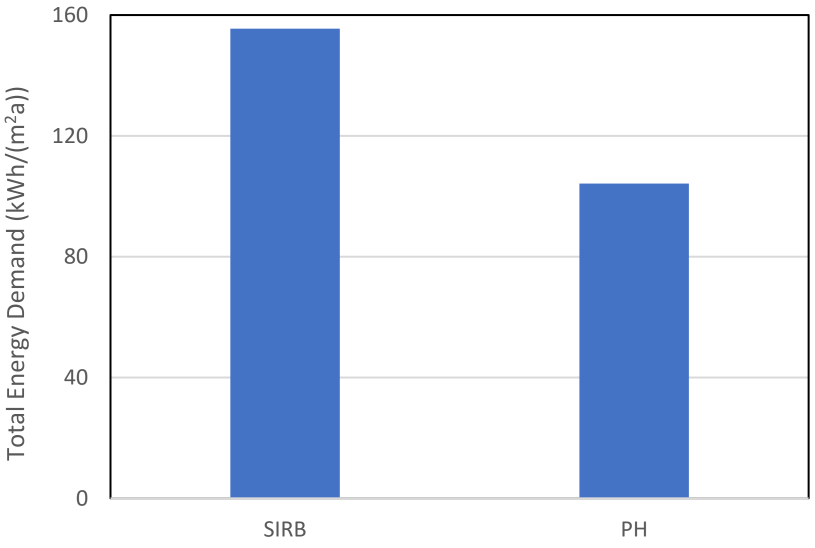
The last primary Passive House strategy yet to be evaluated is mechanical ventilation with a heat recovery system. According to Passipedia (2020), "A Passive House is a building in which thermal comfort can be achieved solely by post-heating or cooling of the fresh air mass, which is required for sufficient indoor air quality without the need for additional recirculated air".

Hence, it is crucial to ensure the heating and cooling requirement in a Passive House is reduced to the point where a traditional heating system is no longer considered essential.

In this instance, after applying the other strategies, the building did not meet the recommended peak load to rely on a mechanical ventilation system with heat recovery to maintain thermal comfort conditions. However, to establish this, a heat recovery ventilation system supplying air at 0.35 ACH is specified for the building.

5.7.1.1 Results and Discussion

The result analysis is presented in *Figure 5-19*, comparing the total energy of the building when using a standard air conditioning system to maintain indoor temperature to mechanical ventilation system with heat recovery.



SIRB- Super-insulated reference building, PH- Passive House

Figure 5-19: Energy Demand of Insulated Reference Building with MVHR

The result shows using MVHR further saves the building's total energy up to 33%. However, when the indoor thermal analysis was carried out, *Figure 5-20* indicates that indoor conditions fall significantly out of the comfort range during both winter and summer.

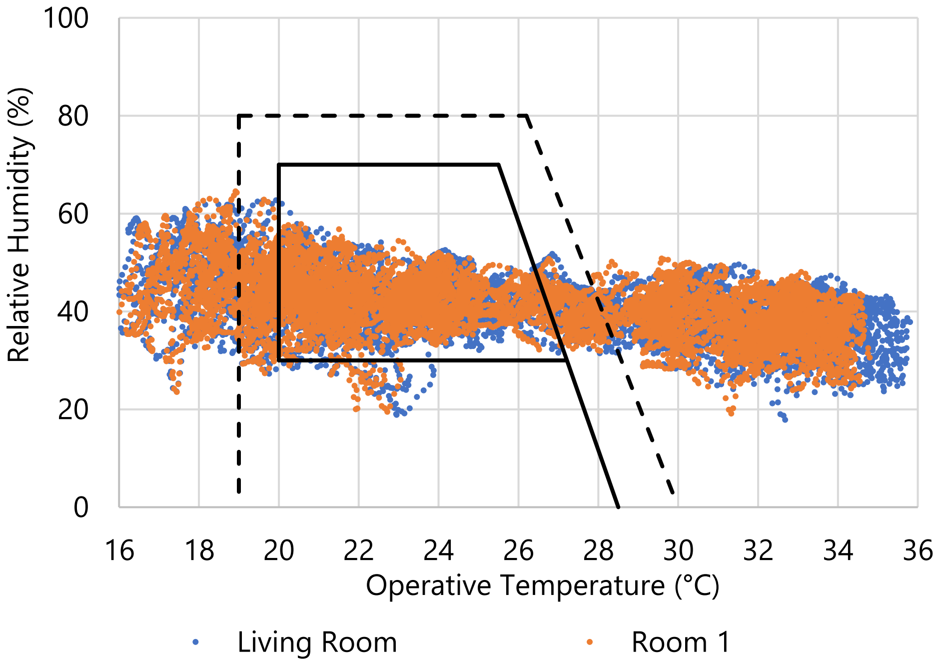


Figure 5-20: Indoor Operative Temperature and Relative Humidity *of the SIRB using MVHR*

The indoor conditions indicate that the ventilation system with heat recovery at the specified airflow rate is insufficient to provide a comfortable indoor environment with a significant case of overheating. As in the previous chapters, the ventilation rate was increased in an attempt to improve the indoor environment. It was discovered that increasing the ventilation rate slightly improved the summer period but had a negative effect in the winter period and overall did not keep the building within the comfort range. As a result, it was confirmed that this system is inadequate to manage indoor conditions due to the high peak load and extreme weather conditions in this climate. Thus, a conventional HVAC (heating, ventilation, air conditioning) system is specified to provide and maintain comfortable indoor conditions throughout the year in winter and summer.

5.7.2 Rationale for HVAC System

In Passive House, the idea of post-heating and cooling appeared to have been successful because, in winter, the building envelope is optimised to take advantage of solar heat gain where possible and rely on internal gains while minimising heat loss. Thus, additional heating via supply air is sufficient to keep the building thermally comfortable. Also, the requirement for such a system to be practical was for the peak load to be < 10W/m^2, the peak cooling load of this building after applying other strategies is more than five times the recommended standard.

Thus, although the other strategies significantly reduce energy demand by minimising heat transfer, a conventional HVAC system appears to still be required, even in a building referred to as Passive House in the cooling-dominated climate. The energy demand of the building is discussed below.

5.7.2.1 Results and Discussion

Assuming the use of an HVAC system instead of relying on MVHR in the building with the application of the other Passive House strategies. The resultant energy demand of the building, hereon referred to as 'The Algeria Passive House', is shown in *Figure 5-21***.**

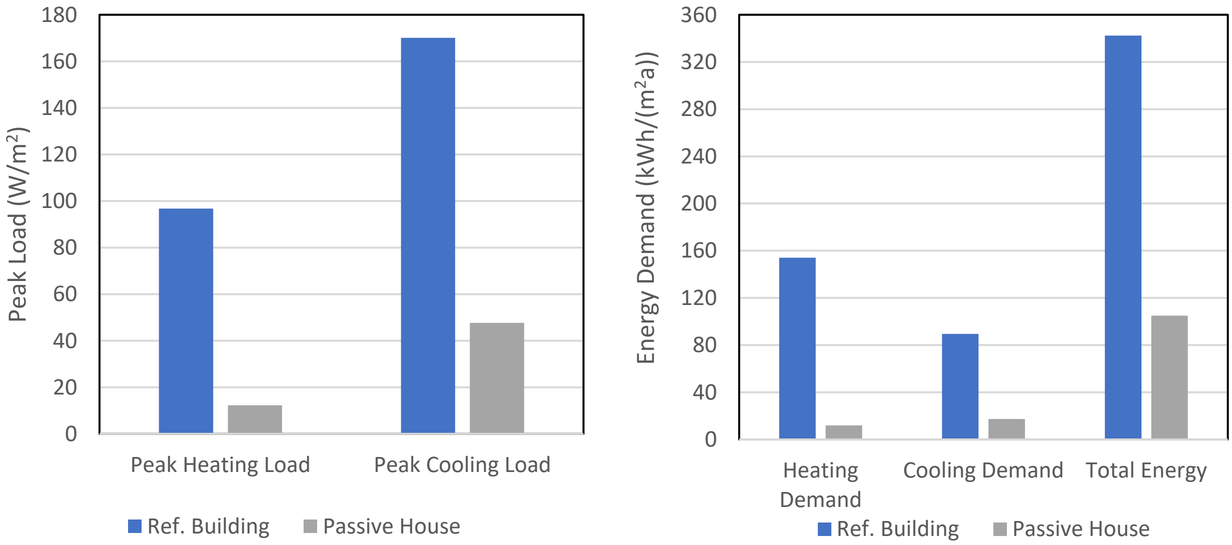


Figure 5-21: Energy Demand of the Algeria Reference Building and Passive House

Figure 5-21 shows that significant energy savings are achieved in the building using Passive House strategies even when the HVAC system is used. It can be observed that implementing strategies such as super-insulation, double-glazed windows, and using energy-efficient appliances reduced peak heating and cooling load by 87% and 72% respectively. Consequently, reducing heating and cooling demand by 92% and 81% respectively, leading to an overall energy savings of about 69% whilst maintaining a comfortable indoor environment (*Figure 5-22)*.

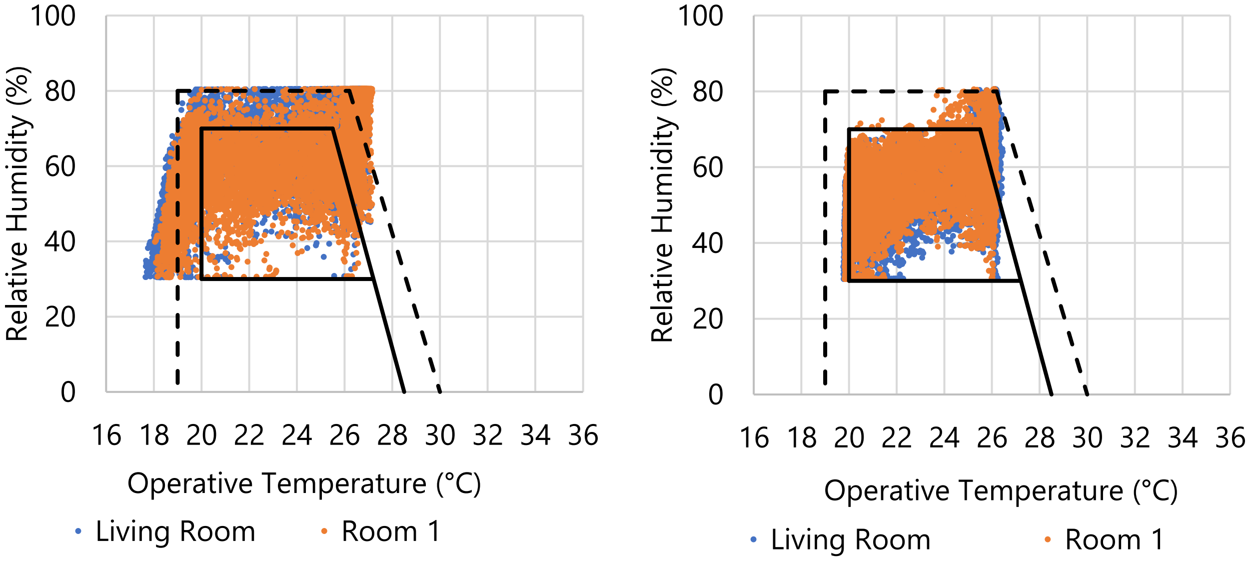


Figure 5-22: Indoor Operative Temperature & Relative Humidity in the Reference Building (left) and Algeria Passive House (right).

Additionally, it can also be observed that although the set point temperature for both buildings is the same, the Passive House reference building (on the right) offers a more comfortable thermal condition as temperature and humidity are well within the thermal comfort range. This further validates and reiterates the advantages of strategies employed by the Passive House, considering the reference building already implemented other passive approaches. Furthermore, as observed in *Figure 5-22,* the use of an air-conditioner enables a more stable and comfortable indoor condition than relying solely on MVHR. Since heat transfer is significantly reduced in the building due to the strategies implemented, less energy is required to maintain comfortable indoor conditions, even with the use of air conditioners.

The energy demand of the optimised reference building, referred to as the “Algeria Passive House” is compared to the Passive House standard (*Table 5.4)*.

Table 5.4: Energy Demand of the Algeria PH

Energy Demand	**The Alegria PH**	**The PH Standard**
Heating Demand @ 20°C (kWh/(m^2a))	12	15
Annual Cooling Demand @ 26°C (kWh/(m^2a))	17	15
Total Energy (kWh/(m^2a)	105	120
Peak heating load (W/m^2)	12	10
Peak cooling load (W/m^2)	48	10

Table 5.4 show that the building struggles to meet the standard because the annual cooling demand, peak heating loadand peak cooling load all exceed the criteria. The Passive House standards require that either peak load or demand standard is met. However, it was observed that the Algerian Passive House building met the heating demand and exceeded the cooling demand by only 2 kWh/(m^2a) with an energy savings of about 70% and maintained a comfortable indoor environment; the building should still be considered a Passive House. However, to ascertain its performance, the building is tested in other locations with similar climates in the following section.

5.8 Adaptation of the Optimised Model in Other Hot and Arid Locations

Finally, as previously done in Chapter 4, the model Passive House for Algeria, having attained the Passive House standard, is analysed for five (5) other hot and arid locations – Alice springs

Australia; Tehran, Iran; Riyadh, Saudi Arabia; Khartoum, Sudan, Assuit, Egypt (*Figure 5-23.*). To check the optimised building performance in these locations, thereby validating the Passive House framework in this climate type.

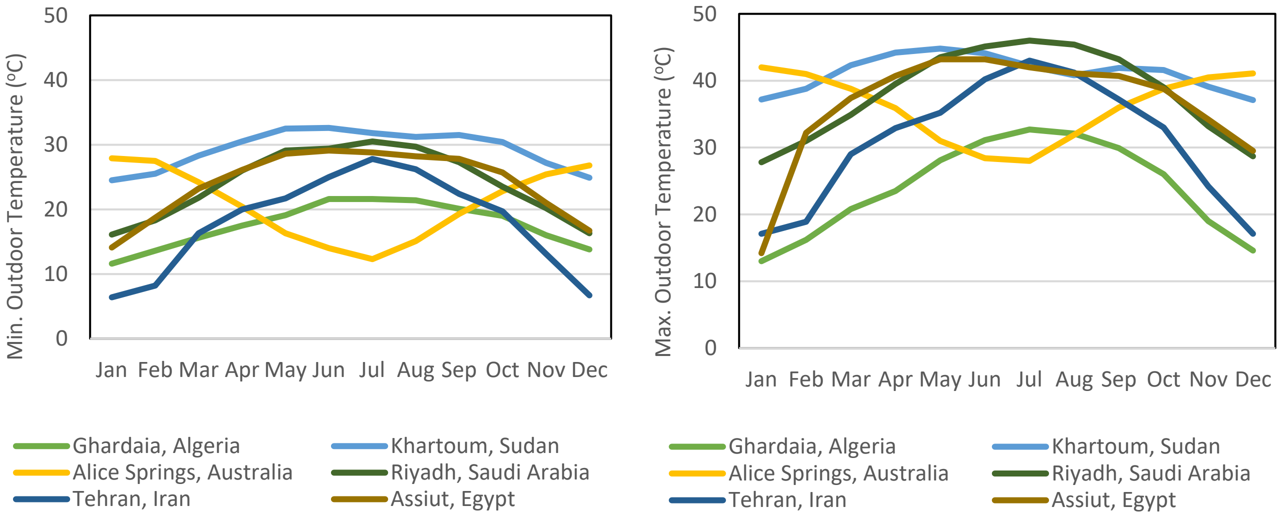


Figure 5-23: Average Minimum (left) and Maximum Temperature (right) of the Hot and Arid Locations (IES Weather Data).

5.8.1 Results and Discussion

This section evaluates the prototype "Algeria Passive House" building for other hot and arid locations, including peak heating load, peak cooling load, heating demand, cooling demand and total energy shown in *Figure 5-24*.

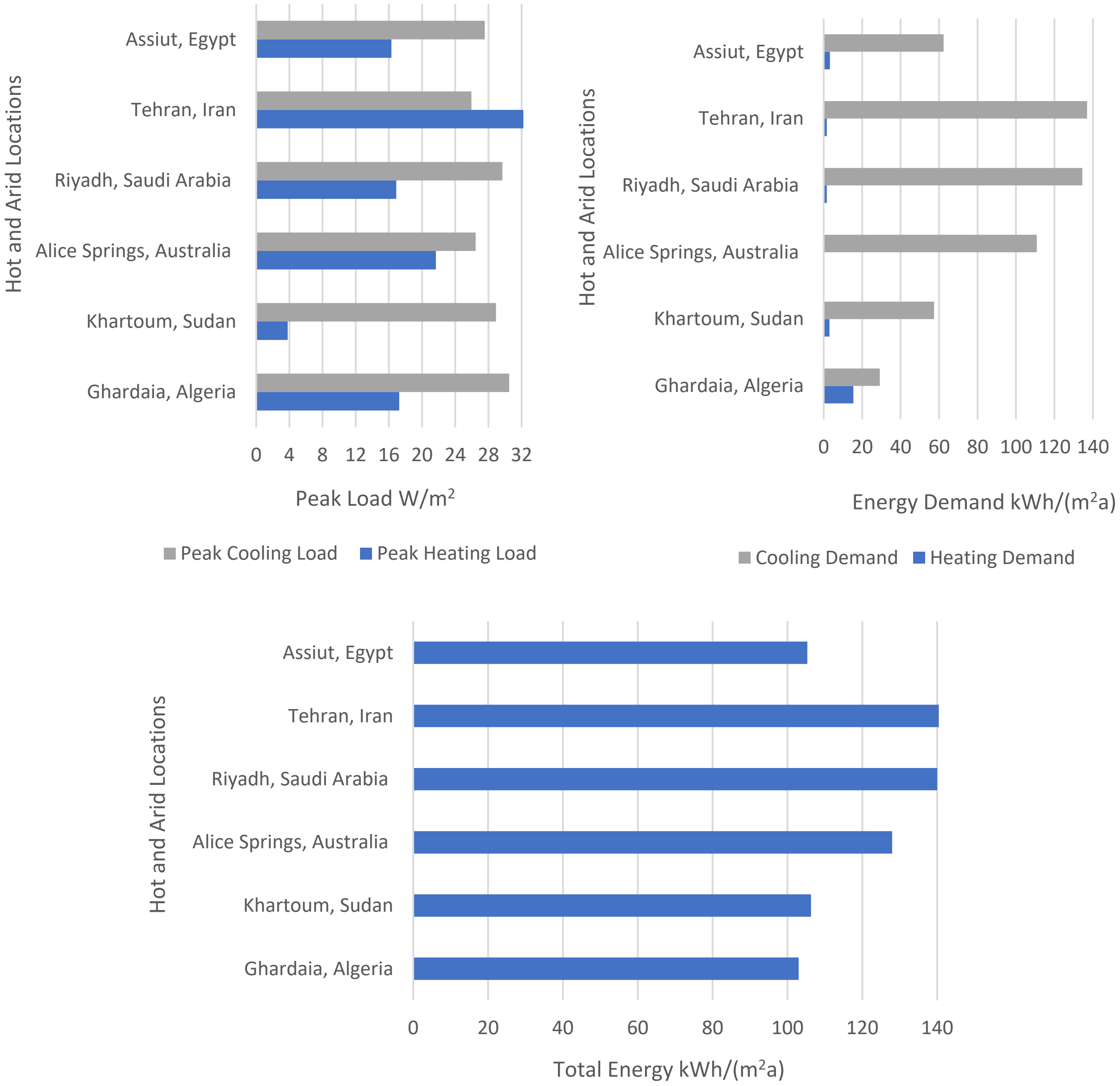
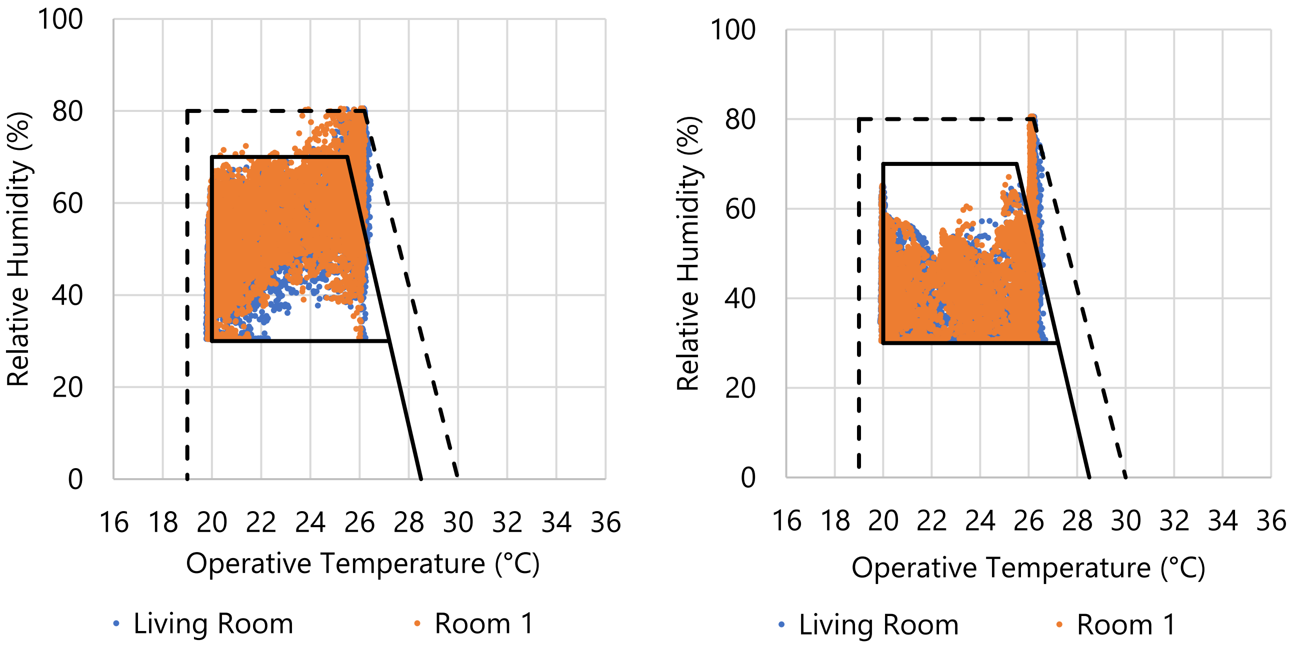


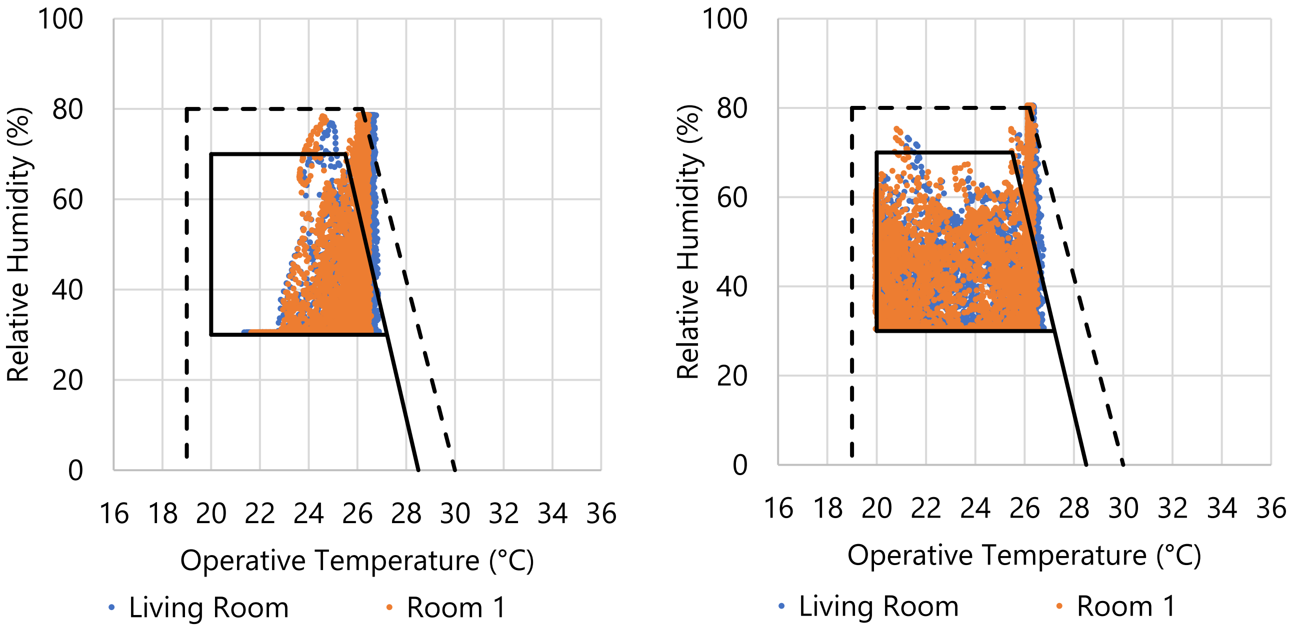
Figure 5-24: Energy Demand for Hot and Arid Locations

The results show that the energy demand of the building in different locations reflects the prevailing weather conditions where locations with high temperature for most of the year require more cooling. On the other hand, the peak cooling load is comparable even in Khartoum, a city regarded as one of the hottest major cities on earth, with annual mean temperatures hovering around 30 °C (86 °F). Since the influence of external conditions is reduced when Passive House strategies such as super-insulation, etc., are implemented. Thus, solar heat gains with the assumed internal heat gain value resulted in a comparable peak cooling load. However, the peak load and demand did not meet the Passive House standard of 10 W/m^2 and 15 kWh/(m^{2}a) at a set point temperature of 20°C in Winter and 26°C in Summer with humidity not exceeding 80%. The corresponding indoor temperature conditions are shown in *Figure 5-25*.



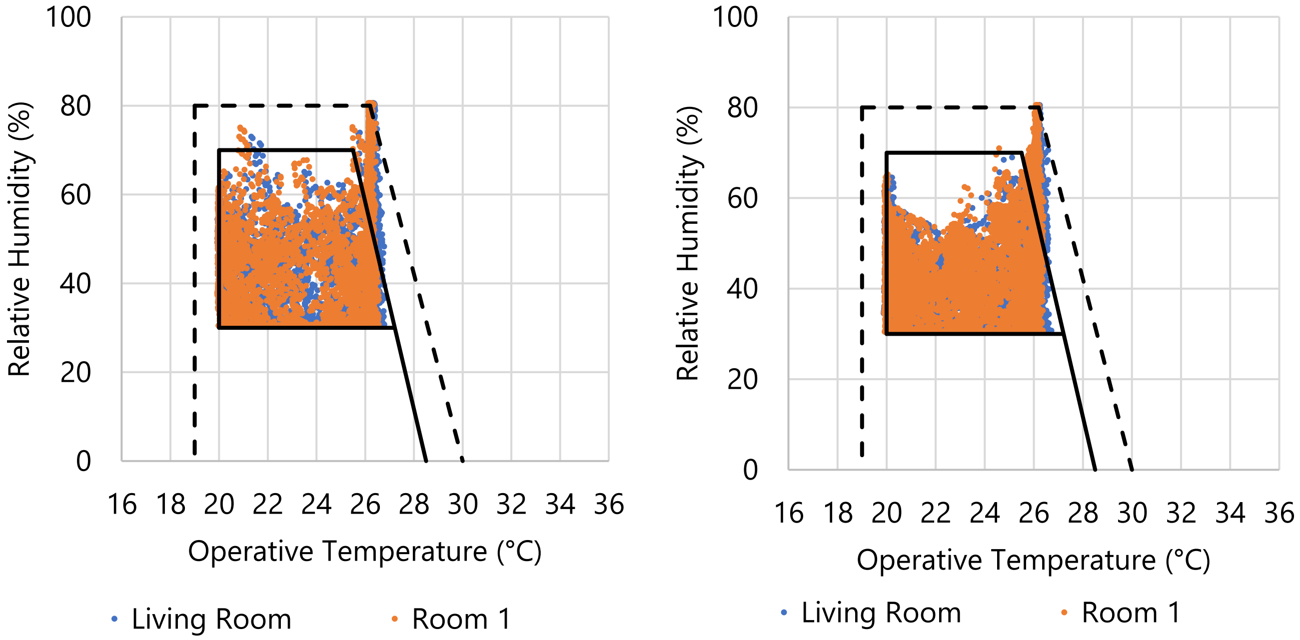
a. Ghardaia, Algeria

b. Khartoum, Sudan



c. Alice Springs, Australia

d. Riyadh, Saudi Arabia



e. Tehran, Iran

f. Assiut, Egypt

Figure 5-25:Indoor Operative Temperature and Relative Humidity of the Reference Passive House in other Hot and Arid Locations.

The results show that the peak load (where the average temperatures are similar) is comparable regardless of the distinct prevailing weather condition in all these locations proving that the Passive House strategies minimise heat transfer and minimise the influence of external conditions. However, the cooling demand differs based on the prevailing ambient temperature throughout the year.

5.9 Conclusion

This study explored the Passive House framework in hot and arid climates to ascertain the effectiveness of the Passive House strategies in achieving the Passive House standard in this climate.

It was found that insulation and low thermal transmitting windows significantly reduced peak loads by an average of 55% as these strategies limited heat transfer in the building thereby saving up to 30% of the building's energy. This outcome is comparable to the energy savings realised when these strategies are used in hot, humid climates. However, in this hot and arid climate, these strategies were mostly useful for lowering heating demand because heat loss was reduced, which meant that in summer, heat is trapped in the building therefore the cooling demand remained high.

This is where the advantage of using energy-efficient appliances to reduce internal heat gain becomes critical. It was discovered that when the internal heat gain value per Passive House assumptions was specified, the cooling demand in the building was significantly reduced. Similar to the hot, humid climate, this specified IHG value proved beneficial in substantially reducing cooling demand and, consequently, total energy demand in the super-insulated envelope.

This same effect was not observed in the uninsulated conventional building. It was found that when this value was specified, it resulted in a heat transfer trade-off. The reduced heat gain, which resulted in energy savings for summer cooling, was required for winter heating due to heat loss. Thus, having no significant effect on the building's energy performance. Meanwhile, in the super-insulated building, the heat gained during winter is conserved to maintain indoor comfort conditions, while the cool is preserved during the summer. As a result, less energy was needed to maintain acceptable thermal comfort conditions, although, not to the point where a mechanical ventilation with heat recovery system would be effective because of the high peak load.

As a result, a conventional HVAC system is required to reduce overheating risk and ensure optimal thermal comfort conditions. This may suggest high energy demand; however, this was not the case as the above strategies implemented limited the external influence on the indoor environment. Thus, the building's energy demand remains significantly lower than that of a conventional building.

Overall, the study found that buildings in hot and arid climates could use Passive House strategies to save energy and maintain indoor conditions but might struggle to meet the Passive House standard due to the high temperatures experienced in hot-arid climates. However, the building embodies the Passive House concept, with energy savings of approximately 70% and an average savings of 80% on heating and cooling demand while maintaining acceptable thermal comfort range.

6 Conclusion

In many climates, growth in sustainable buildings and energy efficiency is expected to be the primary driver of new and existing buildings. As a result, the Passive House framework, which has gained popularity in heating-dominated climates due to its energy efficiency and thermal comfort achievement, was investigated for possible adaptation in cooling-dominated climates.

In this study, it was found that a certified Passive House building in one climate could not simply be adapted in another climate because a Passive House is no different from a conventional building that needs to be designed based on the local climate only to a higher standard.

In line with the foregoing, and as has been observed with Passive House in the United States and China, the Passive House framework should be revised if it is to be adapted for cooling-dominated climates. According to this study, the standard developed for heating-dominated climates may struggle to comply in cooling-dominated climates, particularly in hot and arid climates.

The main issue is that cooling-dominated climates have high insolation and temperatures for most of the year, resulting in high cooling demand. Even when the buildings are shielded from the effects of sometimes extreme solar radiation or temperatures. The heat in the indoor environment must still be removed. This becomes a critical issue in a well-insulated building because heat is trapped due to the slow transfer rate, even when the outside temperature is lower. So, it was found that when the peak cooling load does not exceed $10W/m^2$, a mechanical ventilation system with recovery at an average ventilation rate of 1 ACH could be sufficient to maintain comfortable indoor thermal conditions and contribute to energy savings. Otherwise, a conventional heating, ventilation and air conditioning system (HVAC) would be required to maintain acceptable thermal comfort range and prevent overheating.

Furthermore, because of the distinct characteristics of this climate, the Passive House strategies to be focused on differ slightly from those engaged in heating-dominated climates. It was discovered that the combination of super-insulation and low thermal transmitting windows was the most effective of the four main Passive House strategies (super-insulation, low thermal transmitting windows, airtightness, and mechanical ventilation with heat recovery) studied for the cooling dominated climates. It inhibits heat transfer, thereby limiting the influence of external conditions and preserving indoor conditions. On the other hand, airtightness did not significantly affect the energy and temperature of the building due to minimal variation between indoor and outdoor conditions. However, it can ensure a stable comfortable indoor thermal environment as it further reduces the influence of the external environment.

The single most impactful strategy which improved the building's performance was minimising internal heat gain by assuming the Passive House internal heat gain value. This strategy which is not a primary strategy in heating-dominated climates had a significant impact on building performance in cooling-dominated climates. This is meaningful in this climate because of the high solar radiation, which causes averagely high temperatures throughout the year. As a result, if the internal heat gained from both people and equipment is also substantial, it could result in thermal discomfort and increase overheating risk, especially in a super-insulated building. Thus, in cooling-dominated climates, this strategy should be considered a primary strategy to reduce cooling/energy demand or toward achieving the Passive House standard. Although, the PH internal heat gain value used in this study (calculated based on average occupancy and energy-efficient appliances in heating-dominated climates) may need to be re-evaluated, and its accuracy determined for this climate.

It is important to note that the Passive House strategies highlighted in this research are not intended to replace other techniques, such as shading, orientation, and thermal mass, which can help reduce heat gain in a building. Instead, they should be regarded as techniques for optimising building performance such that as heat gained in the building is reduced, and comfortable indoor condition can be achieved and maintained with minimal energy.

Finally, it was established that while buildings in cooling dominated climate can improve their performance, saving up to 70% of their energy demand compared to conventional buildings and maintain the indoor environment conditions within an acceptable comfort range they may fail to meet the Passive House standard (Germany) of 10W/m^2 for peak heating and cooling load and/or 15kWh/(m^{2}a) for heating/cooling demand.

However, because this PH standard appears to be based on the achievement of the "first Passive House" design, which corresponds to about 90% heating demand savings compared to the conventional building in its design climate -Germany (Chapter 1.2.2); and other PH buildings in heating-dominated climates that achieve this standard have also reported energy savings of 70- 90% (Chapter 1.4). This study, therefore, proposes that the Passive House standard in cooling-dominated climates (PH-CDC) be set to achieve a minimum of 70% energy savings for cooling demand and total energy, when compared to conventional buildings in its location while maintaining acceptable thermal comfort range throughout the year. This is a more practical standard for this climate and should be encouraged. Since energy efficiency and thermal comfort are the primary goals that need to be achieved.

Accordingly, PH-CDC would then be able to achieve this goal using these five main strategies; super-insulation, low-thermal windows, mechanical ventilation with heat recovery where feasible or an energy-efficient HVAC system, minimizing internal heat gain using energy-efficient appliances and other climate-relevant strategies such as shading which have been demonstrated in this study to be effective for this climate.

It is crucial to emphasise that special consideration must be taken to minimise internal heat gain, as it had the most significant impact on the building's performance. This may also be useful for Passive Houses in heating-dominated climates to avoid summer overheating issues, as highlighted in other Passive House studies (Chapter 1.4.2).

The study findings and recommendations are summarised below in *Table 6.1*.

Table 6.1:Findings and Recommendations for Passive House in Cooling Dominated Climates (PH-CDC).

Energy Demand and Strategy	**PHI Standards and Recommendation**	**Thesis Findings for** **PH-CDC**	**Recommendation for PH-CDC**
Heating energy demand	≤15 kWh/(m²a)	Achievable where required	No change
Peak heating load	≤10W/m²	Achievable where required	No change
Cooling energy demand	≤15 kWh/(m²a)	Not achievable in all cooling dominated climates.	70% ≤ the reference building for the specific location.
Peak Load	≤10W/m²	Not achievable in all cooling dominated climates.	70% ≤ the reference building for the specific location.
Annual Primary energy demand	≤120 kWh/(m²a)	Not achievable in all cooling dominated climates.	Location specific target.
Excess temperature frequency	≤10%	Yes	No change
Airtightness	n50 ≤ 0.6/h	No significant impact on cooling.	Recommended, particularly in climate requiring some heating.

Super Insulation	U ≤ 0.15 W/(m²K)	Beneficial to reduce cooling load.	Insulation recommended, but not necessarily to the Passive House standard especially in climates with no heating needs.
Thermal bridge	Thermal bridge free	Not tested	Not tested
High performance window	Ug ≤ 0.8 W/(m²K), g-value 50-55%	No Significant Impact on cooling.	Minimum double glazing would be sufficient and recommended in cooling dominated climate.
Ventilation	≥ 75% heat recovery	Yes	At minimum 1ACH where ventilation system is relied on to maintain acceptable thermal comfort condition.
Mechanical Cooling	No requirement	Yes	Recommended to achieve ASHRAE 55 and maintain comfort all year round.
Internal Heat Gain	No requirement. However, average of 2.1 W/m^2 for household dwellings or higher based on floor area.	This assumption needs to be verified and likely inaccurate for cooling dominated climates.	Critical in cooling dominated climate and should be calculated. In any case, energy efficient appliances are highly recommended

6.1 Limitations and Recommendations

Firstly, the study was unable to use primary data; as a result, only secondary data were used. Literature excerpts and meteorological information from the software programme were used to create the building model. This might be inaccurate or misrepresented, whereas obtaining primary data might be more dependable but was not practical in this situation.

Also, the thermal bridge free construction strategy was not evaluated in this study, mainly because, as mentioned above, thermal bridge is an issue that occurs primarily in the construction phase of buildings. Moreover, the effect of thermal bridges in cold climates have been associated more with condensation issues which is outside the scope of this study. However, considering its emphasis in heating-dominated climates, this concept should be investigated for cooling-dominated climates.

Airtightness in this study was found to have the least significant impact on the energy consumption and temperature of the building of all the evaluated techniques. Nevertheless, it is recommended to investigate its contribution to moisture issues, especially for highly insulated buildings in hot, humid climates.

Furthermore, the Passive House recommendation was used to determine internal heat gain, which had the most significant impact on the building's performance. As stated above, this assumption needs to be verified for applicability in cooling dominated climates.

Finally, it was inferred that a higher ventilation rate creates a comfortable indoor environment for buildings in hot, humid regions. However, it is advised to be cautious when implementing in this climate due to high humidity. In the hot and arid climate, although the MVHR system seemed unsuitable to maintain a favourable environment, further investigation is recommended to explore a lower ventilation rate for colder months (preventing heat loss) and a higher ventilation rate for summertime (to prevent overheating). This approach may help save energy and maintain the building's thermal comfort, and where possible, buildings should take advantage of natural ventilation (Appendix D).

6.2 Future Work

Considering that about half of the world’s population lives in cooling-dominated climates, and even colder climates are becoming warmer, it is essential to continue exploring means to attain and maintain thermal comfort in buildings with little or no energy. Thus, further study would seek to discover more strategies to optimise building performance in hot climates.

In line with the above, the internal heat gain value which resulted in significant savings would be studied further to provide clarity on its accuracy and applicability for the cooling dominated climate. Also, it would be interesting to determine the role of thermal bridge-free construction, if any, in these climates. Since Passive House emphasises this technique to lessen heat transmission and prevent cold spots in buildings.

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APPENDICES

A. The Passive House Planning Package and Shortcomings

Several software tools and programs are available in the building and construction industry. In 1996, however, when the Passive House Institute in Darmstadt, Germany, was established with the aim to develop and promote the Passive House concept. The design of the Passive House Planning Package tool was how it intended to do this so that PH can be consistently replicated in other areas. Thus, the PHPP is the standard package used for Passive House design and certification (Leardini et al., 2015) (Renata Dalbem et al., 2016).

It is a simplified quasi-steady-state building simulation tool primarily targeted at assisting architects and engineers in designing Passive Houses. The software prepares energy balance and calculates the annual energy demand of the building based on the user input relating to the building's characteristics. Accordingly, it calculates the annual heating demand by monthly heat balances. The heat balance is calculated by subtracting the building heat losses from internal and solar heat gains equation (1) (Feist, 2007) (Schoner et al., n.d.) (Chen et al., 2020).

$$Q_H = (Q_T + Q_V) - (Q_S + Q_I) \cdot \eta \qquad (1)$$

Where:

Q_H – heating demand (kWh/a), Q_T – transmission heat losses (kWh/a), Q_V – ventilation heat losses (kWh/a), Q_S – solar heat gains (kWh/a), Q_I – internal heat gains (kWh/a), η – utilization factor.

Thus, the excel-sheet-based energy modelling tool calculates key Passivhaus certification parameters (that is space heating demand, space cooling demand, primary energy demand, and airtightness) (McLeod et al., 2012).

The main results provided by PHPP include;

- The annual heating demand [kWh/(m^2a)] and peak heating load [W/m^2]
- Summer thermal comfort with active cooling: annual cooling demand [kWh/(m^2a)] and peak cooling load [W/m^2].
- Summer thermal comfort with passive cooling: frequency of overheating events [%]
- Annual primary energy demand for the whole building [kWh/(m^2a)].

When studying the potential for a Passive House in the Australian climate, Gaekwad & Adams (2019) pointed out that PHPP's approach of treating the entire thermal envelope as a single zone may be oversimplified.

The Passive House Institute (PHI) did however, provide some justification for the above simplification. Gaekwad & Adams (2019) report, that after reviewing the justification documentation, PHPP proved correct for Passivhaus buildings designed for a heating-dominated climate (such as Germany). However, the improved accuracy may not apply to Passive House buildings intended for a cooling-dominated or dehumidification-dominated climate.

Similarly (Bagheri et al., 2018) stated that while PHPP is a powerful tool for Passive House energy estimation and breakdown; its method for calculating heating and cooling demands is not as accurate as an hourly simulation software tool that takes into account a variety of important factors, such as the effects of thermal mass, hour-by-hour variations of outdoor and indoor conditions, transient hourly solar heat gain by envelope components, realistic operation of HVAC systems, and so on. To that end, the difference between the PHPP and other dynamic modelling tools such as IES-VE is further detailed in *Table A.1*. As shown in the table, the dynamic simulation system, IES-VE, among other benefits, provides more accurate thermal comfort modelling. Thus, it is beneficial to use a dynamic simulation tool, such as IES-VE, which allows for the assessment of the energy balance for each building zone.

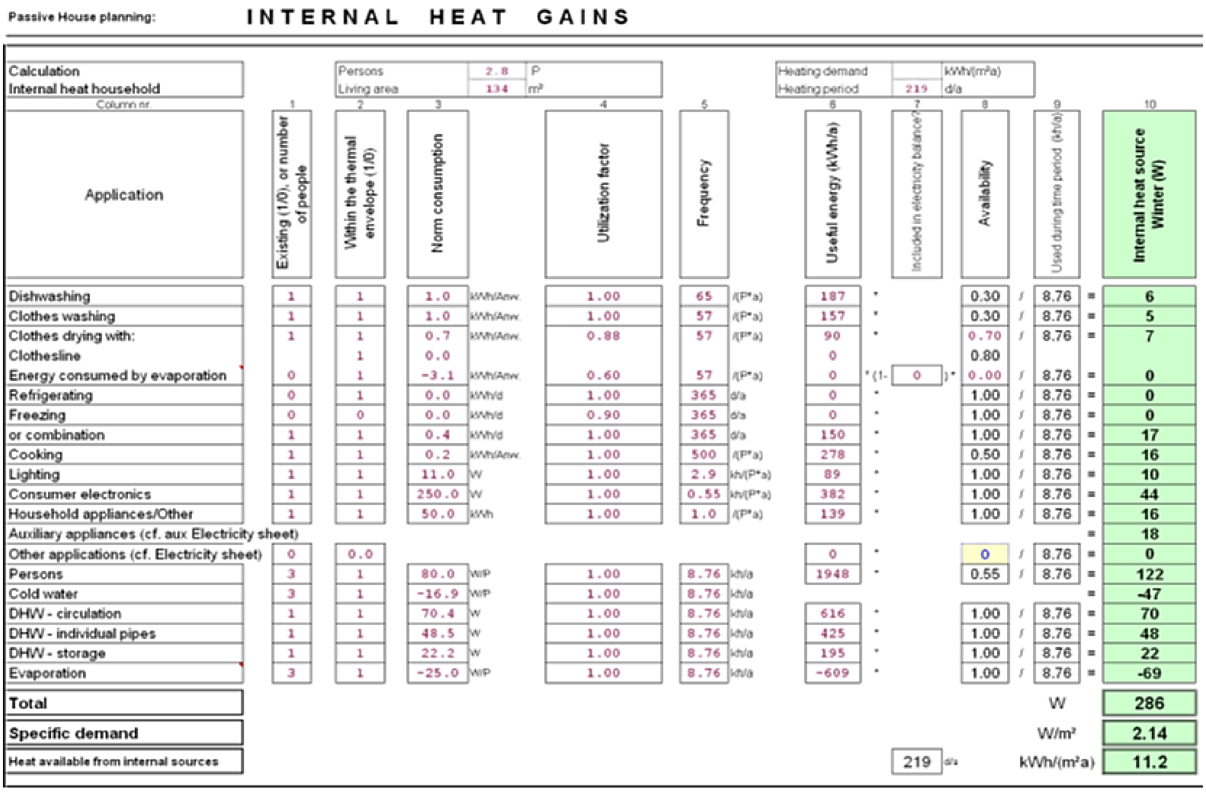
Table A.1:Comparison between Steady State System (PHPP) and Dynamic system (IES-VE) (Menzel & Ploennigs, 2015) (Karlapudi, 2020)

Steady-State	**Dynamic**
Internal Gains + Temp Set Point remain static throughout the entire simulation period.	Uses both the external boundary conditions from climate/weather file input, as well as data from previous simulation steps to create a more detailed (hourly, sub-hourly) model.
Climate/ Weather files supply ALL the inputs into the simulation.	Design of the system based on hourly weather and occupancy data
Fast, Flexible, Simple to use	Can provide more accurate thermal comfort modeling, as well as moisture movement.
May not be as accurate in very complex situations, i.e., with more than one thermal zone, in shoulder season, etc.	Optimized systems
Calculations based on the estimated peak loads.	Allows for load variations over the period of time.

B. Internal Heat Gain

Internal heat gain (IHG) can change over the service life of a building (based on occupancy and appliances). Thus, Passive House, based on the varying availability of dissipated heat in a building, conducted an in-depth analysis of internal heat gain appliances, which might realistically contribute to the total heat gain based on usage of people, equipment, lighting and other factors in correlation with dwelling unit size.

The electrical appliances considered include energy-efficient household appliances, dishwashers with cold water connection, 0.69* kWh per rinse cycle, washing machine with cold water connection 0.66* kWh per wash cycle, heat pump dryer, 1.0 kWh per use with 7 kg, Fridge-freezer, table-top (120 l) and standalone (280 l) identical consumption, 150 kWh/a, Induction cooker, 0.2 kWh per use. Where appliances indicated with a *denotes consumption was multiplied by 1.5 to compensate for standby losses and potential optimisation of the appliances. In addition, other electrical appliances considered were lighting using 100% energy-saving lamps, electronics 250 W during 550 hours per person per year, and small devices 50 kWh per person per year. Auxiliary electricity includes an underfloor efficient heat pump of $10W/100m^2$, hot water circulation of 5 W per dwelling unit, operating 24 h/d, hot water storage tank charging pump of 1 W per person, running 24 h/d. Heat gain from people is estimated as sensible (body) heat per person at 80 W, assuming they are present in the building 55% of the time. Other factors considered in the heat gain calculation include cold water and hot water usage (gain & losses) and evaporation, calculated by the Passive House Planning Package as shown in *Figure B-1*. The IHG is an average of 2.1 W/m^2 for household dwellings (Wolfgang Feist et al., 2007).



Passive House planning: INTERNAL HEAT GAINS

Calculation
Internal heat household

Persons 2.8 P
Living area 134 m²

Heating demand kWh/(m²a)
Heating period 219 d/a

Column nr.	1	2	3		4	5		6		7		8		9		10
Application	Existing (1/0), or number of people	Within the thermal envelope (1/0)	Norm consumption		Utilization factor	Frequency		Useful energy (kWh/a)		Included in electricity balance?		Availability		Used during time period (kh/a)		Internal heat source Winter (W)
Dishwashing	1	1	1.0	kWh/Anw.	1.00	65	/(P*a)	187	*			0.30	/	8.76	=	6
Clothes washing	1	1	1.0	kWh/Anw.	1.00	57	/(P*a)	157	*			0.30	/	8.76	=	5
Clothes drying with:	1	1	0.7	kWh/Anw.	0.88	57	/(P*a)	90	*			0.70	/	8.76	=	7
Clothesline		1	0.0					0				0.80				
Energy consumed by evaporation	0	1	-3.1	kWh/Anw.	0.60	57	/(P*a)	0	* (1-	0	)*	0.00	/	8.76	=	0
Refrigerating	0	1	0.0	kWh/d	1.00	365	d/a	0	*			1.00	/	8.76	=	0
Freezing	0	0	0.0	kWh/d	0.90	365	d/a	0	*			1.00	/	8.76	=	0
or combination	1	1	0.4	kWh/d	1.00	365	d/a	150	*			1.00	/	8.76	=	17
Cooking	1	1	0.2	kWh/Anw.	1.00	500	/(P*a)	278	*			0.50	/	8.76	=	16
Lighting	1	1	11.0	W	1.00	2.9	kh/(P*a)	89	*			1.00	/	8.76	=	10
Consumer electronics	1	1	250.0	W	1.00	0.55	kh/(P*a)	382	*			1.00	/	8.76	=	44
Household appliances/Other	1	1	50.0	kWh	1.00	1.0	/(P*a)	139	*			1.00	/	8.76	=	16
Auxiliary appliances (cf. aux Electricity sheet)															=	18
Other applications (cf. Electricity sheet)	0	0.0						0	*			0	/	8.76	=	0
Persons	3	1	80.0	W/P	1.00	8.76	kh/a	1948	*			0.55	/	8.76	=	122
Cold water	3	1	-16.9	W/P	1.00	8.76	kh/a								=	-47
DHW - circulation	1	1	70.4	W	1.00	8.76	kh/a	616	*			1.00	/	8.76	=	70
DHW - individual pipes	1	1	48.5	W	1.00	8.76	kh/a	425	*			1.00	/	8.76	=	48
DHW - storage	1	1	22.2	W	1.00	8.76	kh/a	195	*			1.00	/	8.76	=	22
Evaporation	3	1	-25.0	W/P	1.00	8.76	kh/a	-609	*			1.00	/	8.76	=	-69
Total														W		286
Specific demand														W/m²		2.14
Heat available from internal sources										219	d/a			kWh/(m²a)		11.2

Figure B-1: Example of Internal Heat Gain Calculation by PHPP (Passivhaus Institut, 2021b)

However, a recent document on the Passipedia website (Passivhaus Institut, 2021b) cited that the occupancy density of smaller units tends to be higher than larger units globally (Grant et al., 2014). Thus, the internal heat gain is based on the treated floor area, as shown in *Figure B-2.*

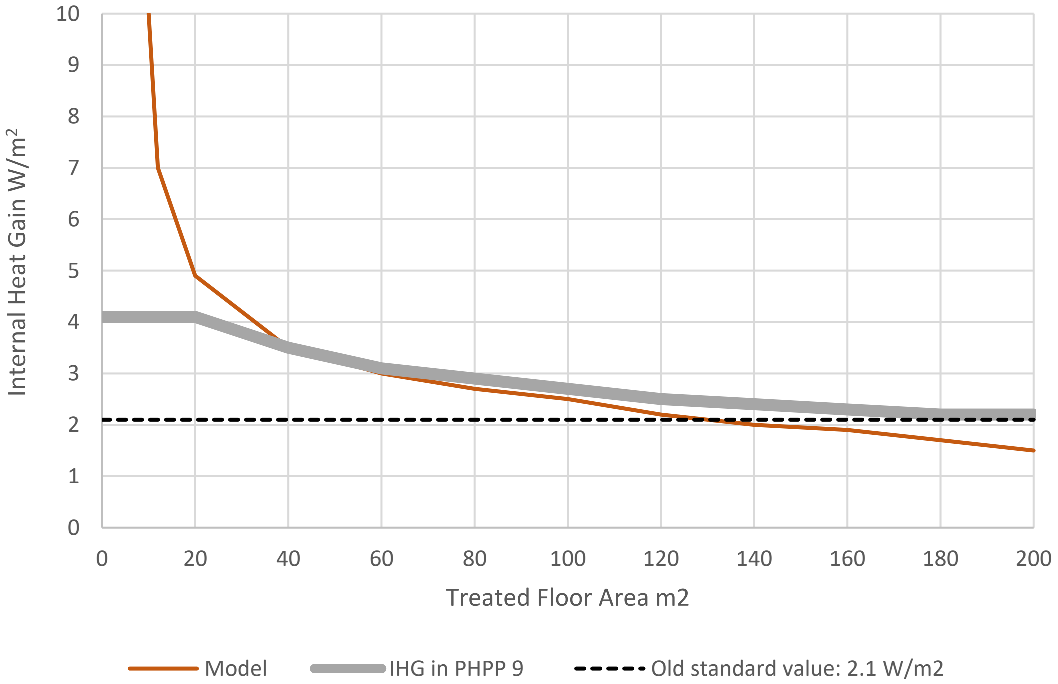


Figure B-2: Internal Heat Gains Depending on Living Area (Passivhaus Institut, 2021b)

C. Building orientation Analysis in Hot Humid Climate- Indonesia

There are several reasons why building orientation is important and considered in building design; however, a key factor is to maximize or minimise solar gain, which can determine window placement and size. In a hot, tropical climate, it is recommended to orient buildings with longer sides facing north-south (long axis east-west). However, there could be restrictions to design based on orientation, even though exposure can significantly impact heating and cooling and energy use in buildings (Andersson et al., 1985; Jaber & Ajib, 2011; Abanda & Byers, 2016; Ghassan et al., 2021). Regarding the reference model in the hot humid climate of Indonesia, the building is oriented toward the North (0^o) (*Figure C-1)*, which goes against the popular recommendation for buildings in the tropics (in the Southern hemisphere) to face longer sides of the building toward the North or South to avoid high-intensity solar radiation from the East and West (Ng et al., 2014; Raji et al., 2017; Ghassan et al., 2021).

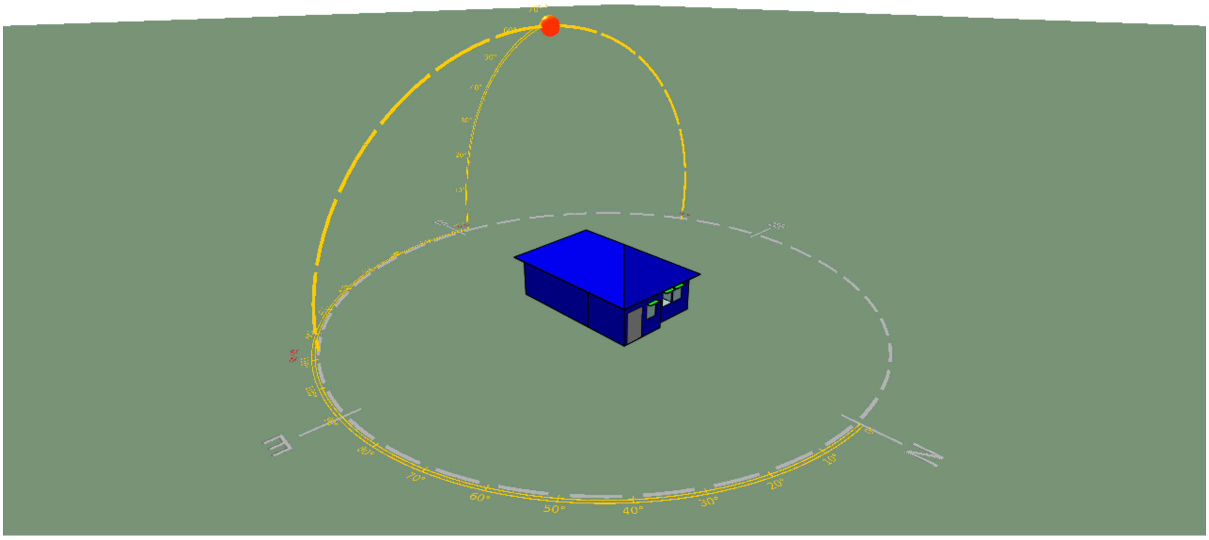


Figure C-1: Orientation of the Reference Building.

As seen in *Figure C-1*, there are no windows on the east and west side of the building (longer side) to limit solar gain in this building design. Nevertheless, different orientations 90^o (East), 180^o (South) and 270^o (West) were explored to consider an opportunity to further minimize solar gain and energy demand in the building, assuming there were no design restrictions. The analysis follows a similar approach as the preceding study, with the initial evaluation of each strategy in the as-designed reference building before implementation in the super-insulated model.

C.1. Results and Discussion

This section presents the results of orienting the building in different directions from its original design orientation for both the conventional (uninsulated) and insulated envelope. Accordingly, the energy result of orienting the reference building in various directions is shown in *Figure C-2*.

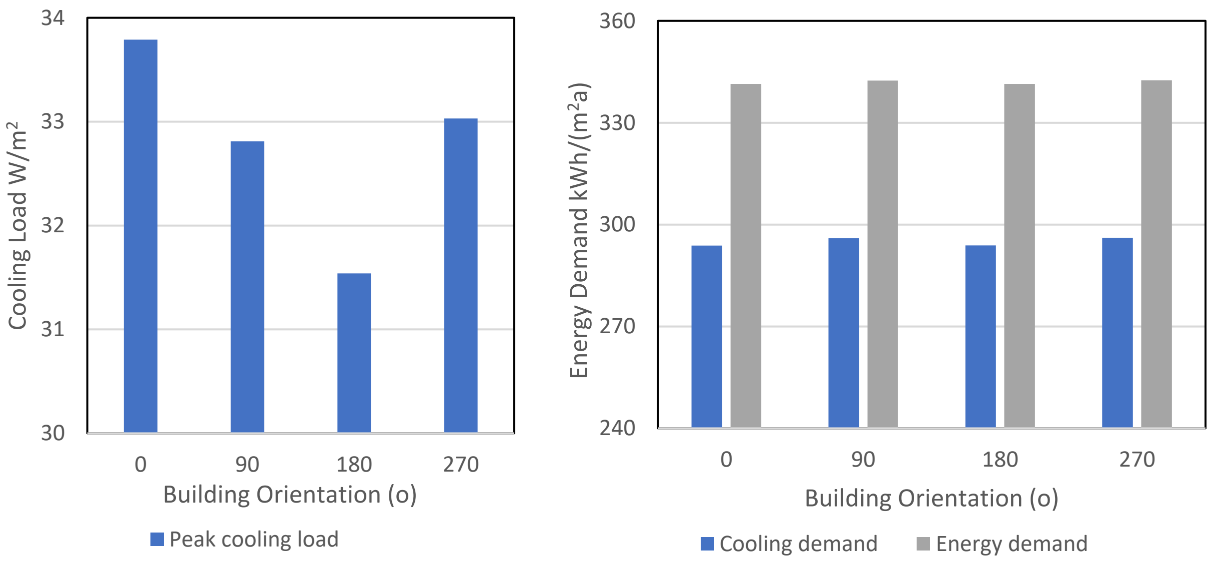


Figure C-2: Energy Demand of the Reference Building at Different Orientations.

Figure C-2 broadly shows that the energy demand of building at different orientations is constant. Although, it was observed that the reference orientation resulted in the most heat gain in the building because the north window (in the southern hemisphere) would likely receive the most heat at noon when the sun peaks. At 180° direction, the building gets the least solar gain with minimal solar exposure. Consequently, the peak cooling load at 180° was 7% lower than at 0° (reference building orientation) and on average lower by 2.5% in the other orientation, 90°, 270° (where the long side of the building faces the North-South direction). However, the heat gain was not significant to cause an impact on the building's energy demand or the indoor conditions.

On the other hand, the building orientation in the super-insulated reference building (SIRB) had a slightly different outcome as the peak load and energy demand at 0° and 180° are comparable and lower than the other orientation, 90° (East) and 270° (West) with windows facing the sun directly in the morning and evening respectively (*Figure C-3)*.

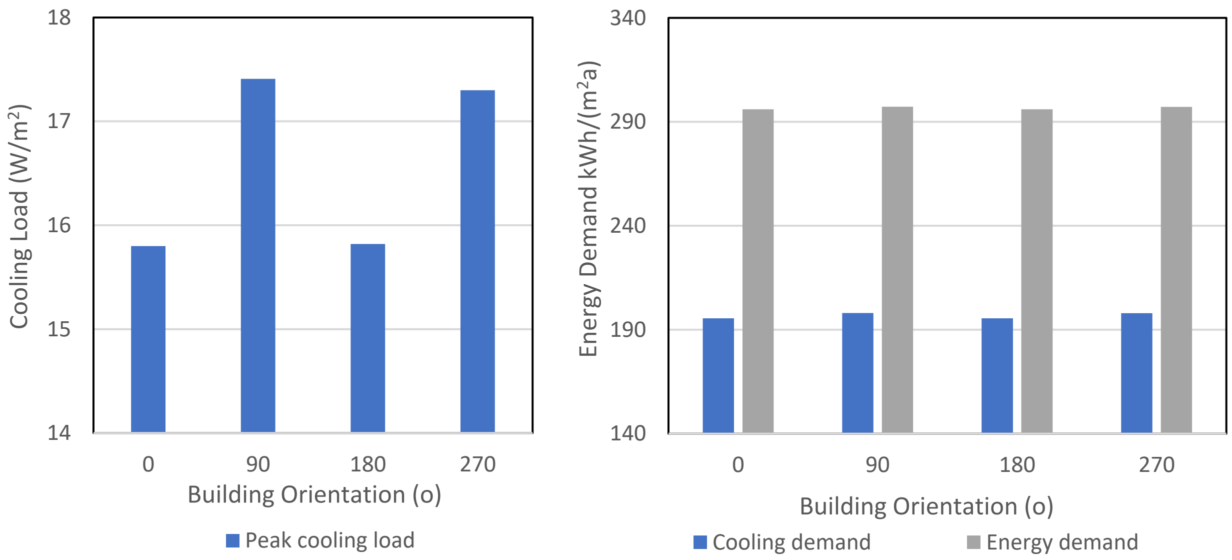


Figure C-3: Energy Demand of the Super-insulated Envelope at Different Orientations.

However, as in the reference uninsulated building, this slight difference in cooling load did not influence the building's energy demand and the indoor temperature in all directions.

The results show the influence of orientation on the building performance was insignificant both in the uninsulated and well-insulated model. This outcome could largely be due to limited windows, which are only about 6% of the envelope and are also shaded. Therefore, heat gain from windows at different orientations is limited and insignificant. This also reflects that the reference building had been designed with consideration for its climate. Thus, there was no need to change the building orientation.

D. Using Hybrid System -Natural Ventilation in Hot Arid Climate - Algeria

The primary aim of considering the PH framework in a cooling dominated climate is to achieve a building that uses less energy to achieve a comfortable indoor environment. Thus, this study explores night cooling to further reduce energy demand, particularly in summer.

Night cooling is a known strategy used to lower indoor temperature by removing excess heat at night when the outdoor temperature is lower than the indoor temperature. Hence, in a hot and arid climate where there can be significant differences between day and night time temperatures, it is essential to explore its contribution.

Accordingly, the working profile set for this building is changed from heating and cooling continuously using a mechanical system to engaging natural ventilation in spring and fall from 10 pm to 7 am (9 hrs) whilst maintaining continuous heating in winter and cooling in summer. This was done to ensure the building retains a comfortable indoor condition in the harsh weather. In Ghardaia, Algeria, the winter (December-February) is cold and dry, especially at night, when the temperature could fall as low as 5°C; thus, continuous heating is maintained. Additionally, continuous cooling is maintained in summer (June-August) when the weather is sweltering and dry, with temperatures as high as 40°C in the day to a low of 23°C. In the spring (March-May) and fall seasons (September – November), the average high and low temperatures are between 10°C and 34°C, with the average night temperature of 18 °C - 24 °C (Weatherspark, n.d.).

Thus, natural ventilation was explored to achieve comfortable indoor conditions at night time (10 pm to 7 am) in the spring and fall seasons, as shown in *Table D- 1* and the results discussed.

Table D- 2: Annual Profile Set for Night Cooling in 'The Algeria Passive House'.

Annual Profile	**System Type**
January 1- March 14	On continuously (HVAC system)
March 15 – June 14	Both active (HVAC) and passive (night cooling) systems.
June 15 – September 14	On continuously (HVAC system)
September 15 – December 14	Both active (HVAC) and passive (night cooling) systems.
December 15- December 31	On continuously (HVAC system)

D.1 Results and Discussion

To investigate the contribution of night cooling, the results were expressed as ‘The Algeria PH’ and the ‘The Passive House with night cooling’. The Algeria PH results represent the situation where the building relies continuously on an HVAC system, whilst the other is the result obtained from utilizing natural ventilation at certain times of the year, as specified above. The energy demand is shown in *Figure D-1***,** where it was observed that night cooling saved 14% of the building’s total energy because active cooling was off for some period.

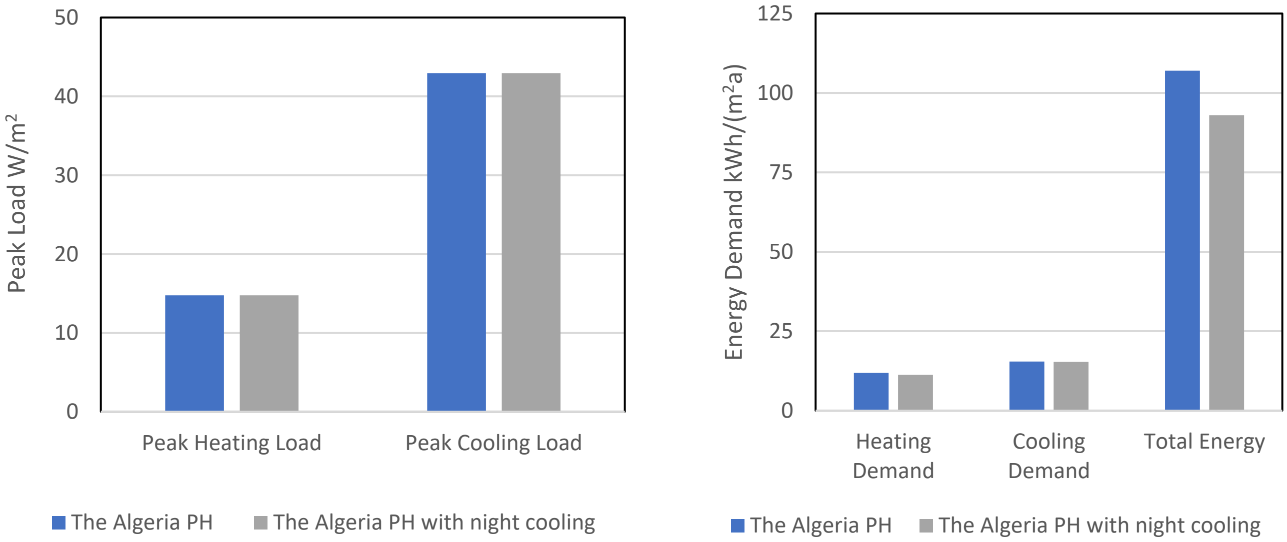


Figure D-1: Energy Demand for the Algeria PH with Night Cooling.

The building's peak heating and cooling loads remained constant because they are factors affected by solar and internal heat gain, which appear to stay the same in this instance. However, its effect on indoor thermal conditions is also presented in *Figure D-2***.**

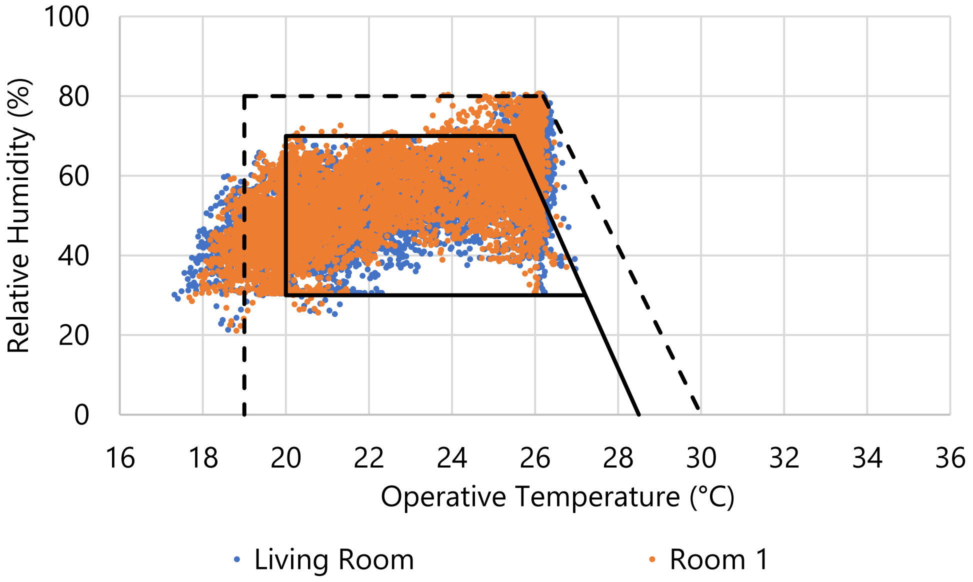


Figure D-2: Indoor Operative Temperature and Relative Humidity of the Algeria PH with Night Cooling.

It was observed that the indoor thermal conditions in the building fall slightly outside the comfort zone due to heat loss when the indoor temperature is higher than the outdoor temperature. However, considering the 14% energy saving with the thermal conditions mainly within the comfort range, night cooling could still be a viable option.