

POTENTIAL OF GREEN ENGINEERING SOLUTIONS TOWARD SUSTAINABLE RESIDENTIAL BUILDINGS: A CASE STUDY OF SAUDI ARABIA

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ABDULLAH NASSER S ALSHABANAT

2025976

FACULTY OF ENGINEERING

DEPARTMENT OF ARCHITECTURE AND THE BUILT ENVIRONMENT

UNIVERSITY OF NOTTINGHAM

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Abstract

Efficient green buildings can potentially boost economic growth, enhance social development, and promote environmental sustainability. One of the contemporary challenges in building design is minimising greenhouse gas (GHG) emissions and energy use while delivering thermal comfort. A building environment that is unhealthy and delivers low levels of comfort in an effort to diminish emissions can be viewed as a failed project, similar to how a building with excessively high emissions while providing a quality thermal environment is considered an ethical failure.

The building sector is highly significant in Saudi Arabia because of its impact on the development of other economic sectors and the complex national economy. Additionally, almost half of the total national electricity consumption in Saudi Arabia can be attributed to residential buildings. Therefore, the building sector plays a pivotal role in addressing energy and sustainability issues. One of the current megaprojects of Saudi Arabian Vision 2030 is the Saudi Public Investment Fund's (PIF) ROSHN housing project, which covers an area of 150 million square metres across nine major cities. The first stage involves the SEDRA district in Riyadh, which will eventually have over 30,000 residential units across an area of 20 million square metres. Leveraging the advantages of green engineering solutions to improve the energy consumption and thermal comfort performance of such megaprojects without impacting their architectural values should be a national goal.

Therefore, this research aims to evaluate the potential of green engineering solutions (traditional passive architectural design, energy efficiency measures, and low-carbon technology) in Saudi residential buildings to offer a balanced approach between cooling energy consumption and occupants' thermal comfort within the context of the sustainability concept.

An understanding of the challenges and possibilities associated with integrating green engineering solutions into the design of Saudi residential buildings was essential to this study. Therefore, engaging with key stakeholders who could have provided valuable insights would have been beneficial. Furthermore, to maximise the outcomes, modelling and simulation of a case study involving a residential building from the SEDRA project were undertaken to achieve the aim and objectives of the current research. In light of these factors, the researcher selected a case study analysis and survey research methodology to represent a mixed-methods

approach. The case study methodology consists of computer-based modelling and simulations that constitute the quantitative element, while the expert survey represents the qualitative dimension of mixed-methods research. Furthermore, to ensure that the research project generates new, valid, and reliable information, intense engagement with the theory surrounding research methodologies must be combined with a rigorous consideration of the unique requirements of the research subject. Accordingly, the findings of the literature review and the former and later methods were merged to gain comprehensive insight.

As a result, and after the case study was evaluated, it was evident that the implementation of the proposed green engineering solutions, taking into account the sustainability context for this study, can scientifically enhance cooling energy performance and the thermal comfort levels of the base case building. For instance, moderate implementation, characterised by a balanced application of passive strategies aligning with existing building codes, resulted in mild reductions of up to 16% in cooling energy and 13% in discomfort hours.

In contrast, high-level implementation involving advanced energy efficiency measures and full code adherence achieved notable reductions of up to 28% in cooling energy and 35% in discomfort hours. However, the integrated approach, which combines the three strategies of traditional passive design, energy efficiency measures, and renewable energy, produced the most significant results, with potential reductions of up to 49% in cooling energy load and 73% in discomfort hours.

Publications

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Chapter 1: Introduction

The industrial age has seen the building industry contributing significantly to the consumption of natural resources and it is considered a major contributor to levels of Greenhouse Gas (GHG) emissions in the world's atmosphere. This remains true today, more than 200 years since the industrial revolution began and buildings continue to consume a large amount of energy (RICS, 2020). In recent years, building practices, construction techniques and the resources used have all evolved as the industry has developed new, more sustainable construction methods and now society is more widely focussing on energy conservation and moving to green and sustainable engineering.

The word "green" has become associated with sustainable products and environmental awareness, while the term 'green engineering' refers to building design that seeks to minimise pollution, promote human health, encourage sustainability, and nurture the environment. Sustainability has become a key issue across many sectors, but the building industry is uniquely placed among these with regard to its ability to have a profound effect on how new practices are implemented. While 'green engineering' employs similar construction methods to conventional construction, it differs in terms of focusing on choosing environment-friendly, innovative principles and materials that are designed to minimise energy consumption. According to Samer (2013), sustainable building is being promoted by factors including the increasingly serious problems associated with climate change and environmental issues, new regulations and policies, green building technologies and the relevant evaluation criteria, as well as demands for an improved-quality architectural environment.

In this chapter, Section 1.1 introduces the background of this topic; Section 1.2 presents the significance of the research; and Section 1.3 outlines the research aim and objectives. Meanwhile, Section 1.4 includes the research questions. Finally, Section 1.5 describes the thesis structure, designed to address the relevant research topics.

1.1 BACKGROUND

Al-Kaabi et al. (2009) advise that many nations have adopted the concept of green buildings in an attempt to sustain the environment and preserve the world's resources. However, at the governmental level, such approaches to green buildings must not only include passive strategies but also commit to the use of renewable energy, while buildings should be governed by sustainable principles as well as complying with energy efficiency targets. In Europe, residential buildings make up approximately 75% of building stock, according to Laaroussi et al. (2020), while Pohoryles et al. (2020) add that over 30% of these are more than 50 years old. Santamouris and Kolokotsa (2015) indicate that the age of these buildings means that a large majority of them can be considered energetically obsolete. Meanwhile, Ma et al. (2012) and Gulotta et al. (2021) stated that these energetically obsolete buildings will represent around 70% of the future building stock when the new build construction rate is taken into account. According to Birol and Andersen (2019), cited in Gassar and Cha (2022), around a third of global energy use could be attributed to buildings in 2018, an increase of 1% on the previous year. Moreover, these buildings emitted 37% of energy-related carbon dioxide emissions in 2017 and this rose by a further 2% the following year.

The International Energy Agency (IEA, 2022) indicates that almost 15% of direct CO2 emissions and 30% of global energy consumption can be attributed to buildings and the construction sector combined. As developing countries engage in a greater number of construction projects and the floor area of global buildings grows, they make a greater contribution to these figures. Energy use in these countries is also affected by improved access to energy and the resulting increased ownership of energy-consuming appliances, as well as the growing demand for air conditioning in countries with hot climates. Lahn et al. (2011) explain that developing countries in hot climate regions including Saudi Arabia have also witnessed rapid population growth, which has led to greater resource consumption as a result of the increased demand for new buildings.

The building sector is highly significant in Saudi Arabia because of its complex national economy and the fact that its development rests on the development of other economic sectors. There are currently over 5,000 ongoing construction projects in Saudi Arabia, and these are valued at a total of 819 billion US dollars. Moreover, leadership has led to both economic growth and social development in the country, including Vision 2030 (2022), which

sets out Saudi Arabia's future and includes significant plans for new housing and other real estate projects. Major projects include the ROSHN housing project, the Neom project and the Ministry of Housing Projects. Between 2017 and 2021, there were 156 housing projects in Saudi Arabia with over 160,000 units of mixed villa, house, and apartment developments, with over 55,000 of these being villas. The Housing Program is resuming its efforts to increase the percentage of Saudi families owning houses to 70% by 2030. Hence, to achieve the aims of Vision 2030, the Saudi Ministry of Housing targets 70% homeownership among the Saudi population by 2030. However, the latest report from the Saudi General Authority for Statistics (2022) states that Saudi homeownership was 54% in 2019.

On the other hand, the Saudi Energy Efficiency Centre (SEEC) seeks to rationalise energy production and consumption. The buildings and transport sectors account for 90% of domestic energy consumption in the country; almost a third of which is consumed by the building sector; as a proportion, this represents approximately 75% of Saudi Arabia's electricity production. As shown in Figure (1.1), the Saudi residential sector consumes almost half of the total national electricity consumption, so it plays a pivotal role in addressing energy issues. Furthermore, Ochsenwald et al. (2024) state that the desert climate prevalent in Saudi Arabia means that it has hot, dry summers, with temperatures reaching up to 38°C in coastal regions and 45°C in inland areas, sometimes reaching as high as 54°C. It is therefore essential that Saudi Arabia considers energy efficiency measures and adheres to sustainability principles.

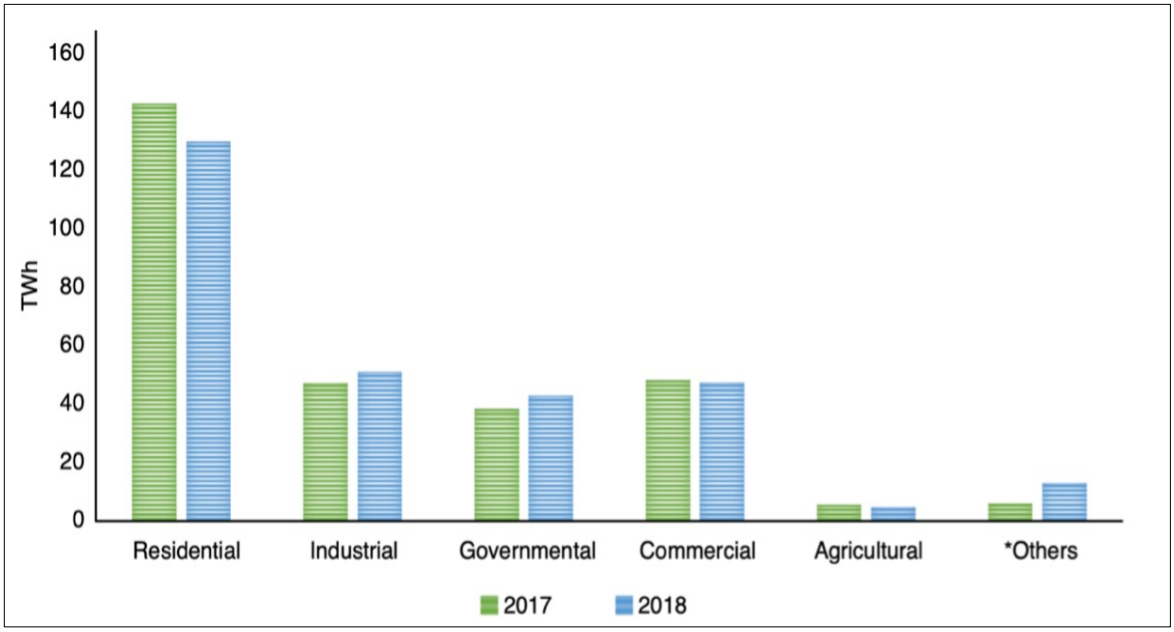


Figure 1.1. Electricity Consumption by Sector (2017-2018). (Source: Saudi Energy Efficiency Centre (SEEC) 2020).

1.2 RESEARCH IMPORTANCE

The International Energy Agency (IEA, 2022) speculates that energy efficiency improvements in buildings could reduce global energy demand by about a third by 2050, which would have a significant impact on reducing global GHG emissions. However, such changes require the building sector to adopt then implement relevant energy consumption principles; for example, if the stated project goal is to implement sustainable design and preserve the environment around a development, then the most effective strategic solution would involve reducing the usage of non-renewable resources and increasing the use of renewable resources.

Saudi Arabia's Vision 2030 has set out several goals for the country to achieve by the stated date. The government's vision is particularly focused on environmental considerations and implementing more sustainable methods of buildings, industrialisation, and service delivery. As part of this vision to progress towards more sustainable development, the government not only intends to improve standards in the building industry in Saudi Arabia but also aims to make it more efficient and cost-effective. The improvements involve new regulations and codes of new building projects however the existing approach in Saudi Arabia tends to have scant regard for architectural design parameters and renewable energy usage and instead focuses on the building's thermal transmittance values for the opaque and transparent elements, aiming to meet the minimum requirements of the building envelope. According to Chwieduk (2003); Alrashed and Asif (2014), the three core principles of sustainable energy buildings are sustainable design solutions, renewable energy technologies and energy-efficiency measures. As a result of the demand for more sustainable and energy-efficient architecture that meets community needs, interest in 'comprehensive design' is growing, while designers involved in the built environment including architects and engineers are pivotal to the achievement of the government's goals.

As one of the current Saudi Arabian 'megaprojects', the Saudi Public Investment Fund's (PIF) ROSHN housing project mentioned previously involves 150 million square metres across nine major cities and four Saudi regions, Asir region, the Eastern region, Riyadh region and Makkah region. The design's configurations are identical across the development, with the first stage involving the eight-phase development of the Sedra district in Riyadh city which will eventually have over 30,000 units across a 20 million square metre area. As shown in Figure

(1.2), the first phase comprises 4,500 units that are still under construction. However, part of the first phase (residential buildings) had been finished and was handed over to the clients in September 2021. Part of the present research project's importance is evaluating the PIF's claim that the ROHSN housing project constitutes sustainable buildings, using various methods to investigate the design and performance of one of these finished residential buildings. Additionally, exploring how the application of green engineering solutions could enhance energy consumption and thermal comfort performance in these residential buildings without affecting their architectural values. Hence, the research outcomes might allow the designers involved in the project, including architects and engineers, to improve the building design and avoid repeating the current drawbacks in the subsequent phases of such a megaproject.

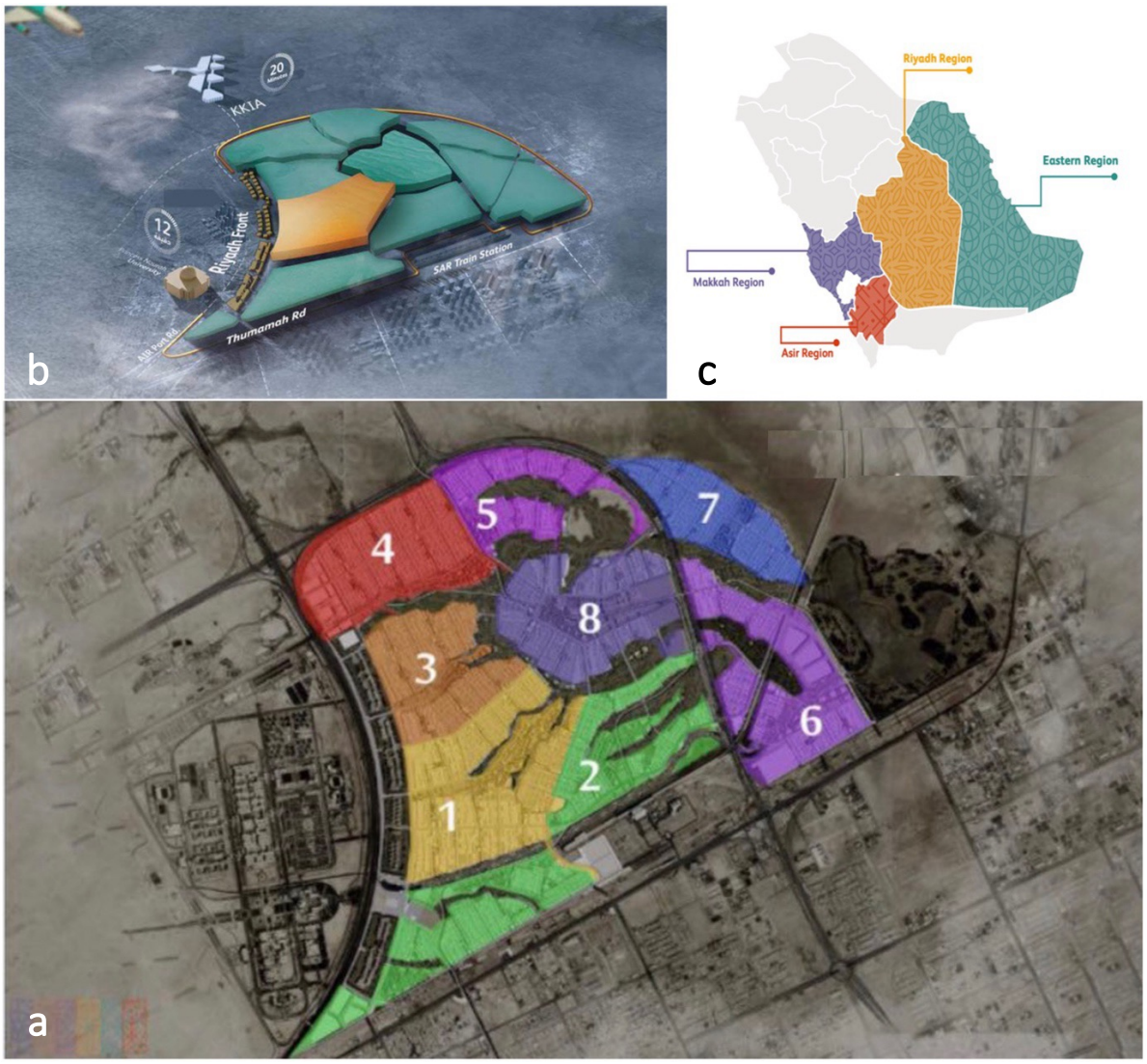


Figure 1.2. (a) Stages 1 to 8 of The ROSHN Housing Project in Riyadh City; (b) The Designated Site for Stage 1; (c) Additional Proposed Construction Sites for the Project. (Source: www.roshn.sa/en, Accessed April 23, 2022)

Moreover, researchers around the world are evaluating various forms of sustainable residential buildings, including Plus-Energy Homes, Low-Energy and Zero-Energy buildings (ZEBs) and Passive houses. These forms of sustainable development have all been based on simulations of energy performance in an individual building, while the majority of extant studies on sustainable building development have largely focused on either single existing building structures or a subset of building components. Other studies have investigated the parameters of heating or cooling systems that are most associated with energy efficiency. Less scholarly attention has been directed towards investigating how energy efficiency measures, renewable energy and traditional passive architectural design can be combined in one model.

Furthermore, previous studies have used case studies focused either on old buildings or those that have been built without claims to the use of sustainable principles. Therefore, this study tries to offer a comprehensive perspective on sustainable development by casting light on the three dimensions of sustainability.

However, this research will not include any economic or environmental analyses, such as Life Cycle Cost Analysis (LCCA), Cost-Benefit Analysis, or Life Cycle Assessment (LCA). Its primary focus is on the technical aspects of green engineering solutions in buildings. Nonetheless, sustainability dimensions (Environmental, Economic, and Social) will be considered in the selection of these solutions for examination, particularly in relation to their potential impact on balancing energy consumption and thermal comfort, as energy efficiency and occupants' comfort can indirectly contribute to environmental and economic benefits. Moreover, the choice of specific building components within the context of Saudi architecture that aligns with its heritage and social values could thereby contribute to the social dimension of sustainability.

To sum up, reducing energy consumption in residential buildings in Saudi Arabia, given its significant contribution to overall energy use, is a critical goal for aligning with the targets of Saudi Vision and promoting sustainable development. Despite growing awareness of energy efficiency by Vision 2030, the residential building industry struggles with implementation due to a lack of clear, coherent frameworks and the absence of comprehensive guidance. Moreover, examining ongoing schemes can be beneficial, as they can clarify the necessary actions for achieving the aforementioned targets. Furthermore, there are current research trends that focus on the energy performance of residential buildings and explore innovative strategies and technologies. These aspects represent the fundamental elements that shape the importance of the current research.

1.3 AIM AND OBJECTIVES

According to the United States Environmental Protection Agency (2022), "Green engineering solutions are the design and use of strategies and measures in a way that reduces pollution promotes sustainability and minimises risk to human health and the environment without sacrificing economic viability and efficiency". In line with this, Figure (1.3) illustrates the current research project area, which was focused on these three fundamental dimensions.

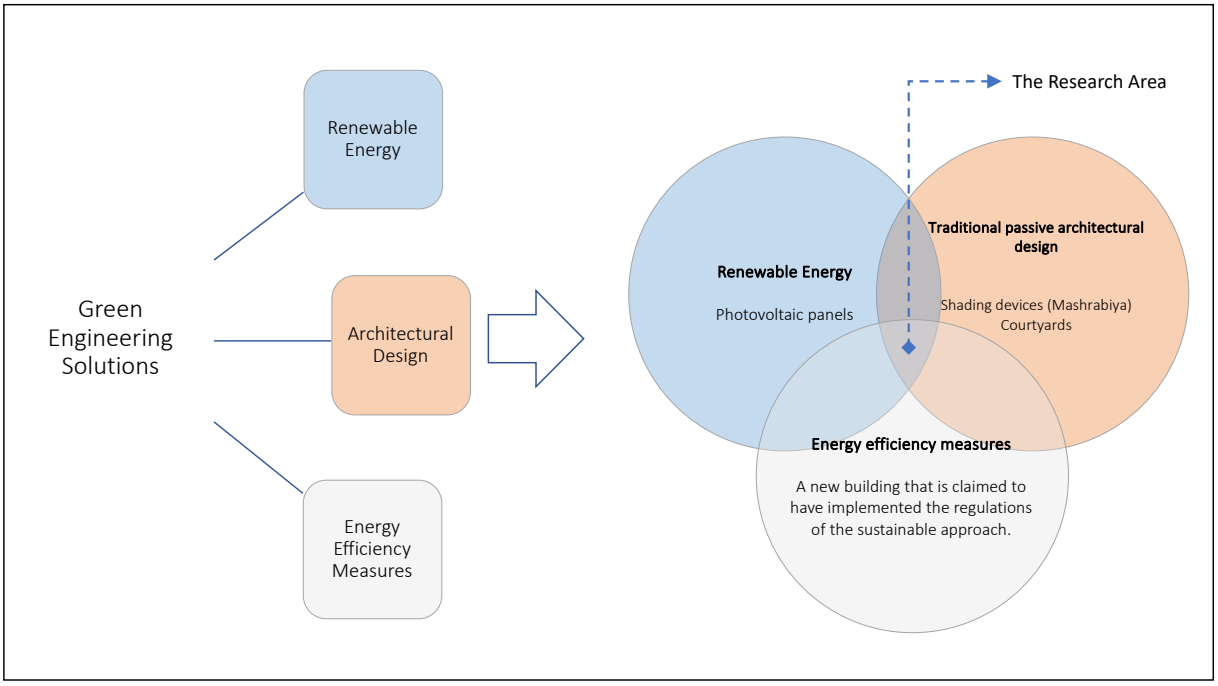


Figure 1.3. The Research Area.

Therefore, this research aims to evaluate the potential of green engineering solutions (traditional passive architectural design, energy efficiency measures, and low-carbon technology) in Saudi residential buildings to provide a balanced approach between cooling energy consumption and occupants' thermal comfort within the context of the sustainability concept. To accomplish this goal, this research establishes the following five key objectives:

1. Develop an understanding of building energy consumption patterns, sustainable approaches, the current state of the Saudi building industry with its challenges and potential, and the influence of climate on Saudi building design and performance.
2. Explore traditional passive architectural design, energy efficiency measures, and renewable energy in the context of Saudi Arabia's sustainable buildings and assess the feasibility of

implementing a complex improvement strategy for new Saudi residential buildings without compromising their architectural values.

3. Investigate the barriers preventing the implementation of proven green engineering solutions—such as passive traditional architectural design, energy-efficient measures, and low-carbon technology—in new residential building projects in Saudi Arabia, despite their demonstrated benefits in enhancing energy performance and thermal comfort.
4. Analyse the potential improvements in energy consumption and thermal comfort in Saudi buildings using DesignBuilder software, with a base case building from the ROSHN housing project, by developing a unique integrated model that combines energy efficiency measures, renewable energy, and traditional passive architectural design.
5. Develop a future roadmap for enhancing new Saudi residential building performance beyond the limitations of the current building code by evaluating the proposed green engineering solutions of the case study in order to achieve a sustainable approach.

1.4 RESEARCH QUESTIONS

This research will address several questions associated with the aims and objectives set out above and the study will aim to answer the following research questions:

Research Question 1: What is the state of the Saudi building industry, including its current challenges and problems? How can the new KSA residential building be classified in a sustainability context? Recently, many developers have claimed that their projects constitute sustainable buildings, including the Saudi-based ROSHN housing project; are they really 'green' or sustainable?

Research Question 2: How can new buildings apply energy efficiency measures, renewable energy, and traditional passive architectural design? Would it be possible to implement a complex retrofitting strategy without affecting a building's architectural values?

Research Question 3: To what extent can energy consumption and thermal comfort be enhanced by a single unique integrated model that combines energy efficiency measures, renewable energy, and traditional passive architectural design for the case of Saudi Arabia?

Research Question 4: Even though the simulation results of the current research project and most of the previous studies evaluated through the literature review confirm that green

engineering solutions (such as passive traditional architectural design, energy-efficient measures, and low-carbon technology) have a significant positive impact on energy performance and thermal comfort, why have these proposed green engineering solutions not been implemented in new residential building projects in KSA to exploit their benefits?

Research Question 5: How can this research help develop a future roadmap for enhancing new Saudi residential building projects by going beyond the current building code to explore the potential of comprehensive, sustainable design?

1.5 THESIS STRUCTURE

In order to achieve the aim and objectives of the research project, in line with the research questions highlighted in Sections 1.3 and 1.4, respectively, the following thesis structure was designed to address the relevant topics.

Chapter 1 Introduction: Presents the background information, context and importance of this research. It states, research aim, objectives, and the questions.

The foci of this research project are supported by a literature review that would be critically discussed in chapters 2, 3, and 4 to provide comprehensive discussions with regard to the subject of inquiry. The formulation of the central research objectives and hypotheses is facilitated by the construction of a theoretical framework that stems from the demarcation of multiple conceptual approaches outlined in the literature, as per the objective of the literature review.

Chapter 2: Describes global energy consumption, building energy consumption in Saudi Arabia, the three fundamental elements of sustainability within the context of the Saudi building industry, and the effect of climate on Saudi buildings.

Chapter 3: Discusses the domain of passive contemporary and traditional architecture design, along with an elementary comprehension of the behaviour and comfort of a building with respect to variables. Additionally, it evaluates the historical Saudi traditional passive architectural design.

Chapter 4: Examines the implementation of energy-efficient measures, and prior academic works on Saudi energy conservation measures. Additionally, it evaluates the extant building regulation codes, the newest innovations in the field of green engineering solutions, and the possibility of renewable energy and the existing sources of renewable energy.

Chapter 5: Discuss the philosophies and hypotheses of designing research to build a theoretical foundation. This includes research approach, methodological choice, research strategies, procedure and timeline, and ethical considerations. Additionally, it outlines a summary of research methodology. However, each method used in the research was discussed deeply in its associated chapter.

Chapter 6: Discusses the various dimensions of conducting the experts' survey in this research project. It explores the sample selection criteria and discusses the procedure for designing the interview questions survey. It examines the thematic analysis technique for survey and its outcomes. Lastly, provides a summary of the experts' interview survey results.

Chapter 7: Provides comprehensive discussions with regard to the subject of climate analysis of the case studies and the choice of base case building. This includes the data and construction specifications related to the base case building. Followed by the evaluation and justification for selecting the simulation software. Highlights the use of modelling data, including occupant profiles, to simulate energy consumption, as well as the free-running simulation of the baseline model to evaluate its performance. Additionally, it examines validation and calibration criteria of the base case to ensure the base case model accuracy. Lastly, it proposes different green engineering solutions for the case study improvements.

Chapter 8: Analyses the parametric of the modelling and simulation development outcomes in terms of both building cooling energy and thermal comfort. This includes examining the effects of traditional passive architectural designs (Courtyards and Mashrabiya as shading devices), energy efficiency measures for the building envelope, and an analysis of potential photovoltaic (PV) energy generation

Chapter 9: Presents all the previous processes in a holistic analysis through the optimisation analysis in order to nominate the final strategic solutions. Additionally, it examines the performance of these final strategic solutions in different Saudi climate zones. Followed by the integration of the thematic and simulation analyses.

Chapter 10: Concludes this research by critically evaluating the extent to which the aim and objectives have been fulfilled. It includes a discussion of the answers to the research questions in the context of the research project outcomes. It highlights the contributions of this research to the broader scholarly community and provides key recommendations to all parties involved in the Saudi building industry. Additionally, it presents a detailed outline of the limitations encountered during the PhD research journey and explores how the outcomes of this thesis may offer valuable insights for future research.

Chapter 2: Energy Consumption Levels: Sustainability and Climate Effects on Saudi Building

This chapter provides an overview of the study's context by examining key trends in global energy consumption, with a particular focus on the significant role that buildings play in driving energy demand. This chapter then investigates the current state of building energy performance in Saudi Arabia and identifies which sector consumes a substantial portion of the nation's electricity. In addition, the Section 2.2 explores the critical aspects of sustainability approach in the Saudi building industry. It highlights how the integration of environmental, economic, and social principles is essential. Section 2.3 focuses on the influence of Saudi Arabia's climatic conditions on building design and energy use; and outlines the climate principles that should be considered in building design.

2.1 ENERGY CONSUMPTION LEVELS

2.1.1 Global Energy Consumption

Improvements in decarbonisation and energy efficacy have been offset by the comparatively faster increases in demand for energy services in buildings, such as electricity for electronic devices, appliances, and cooling equipment, since 2010. The International Energy Agency (IEA, 2022) reports that an 8% increase was observed between 2010 and 2020 regarding the proportion of households with space cooling worldwide, rising from 27% to 35%. In addition, due to the rise in electrification of heating and rapid growth in demand for electricity, especially in developing economies, by 2050, a 70% rise in electricity demand within the building sector is expected, irrespective of enhancements to appliance efficacy (International Renewable Energy Agency 2018). Each individual's use of energy worldwide in 2020 is demonstrated in Figure (2.1). Notably, Canada, Saudi Arabia, and Norway exhibit the greatest quantity of energy use. Furthermore, upon comparison with other countries, in 2021, a value of 15,000 kWh was surpassed in the mentioned countries in terms of their electricity production per capita, as portrayed in Figure (2.2).

Nonetheless, while fossil fuels are heavily relied only upon by Saudi Arabia, the generation of electricity is supported by multiple sources in the majority of high energy consumption nations. As shown in Figure (2.3) in 2021, renewable, fossil fuel, and nuclear energy source proportions.

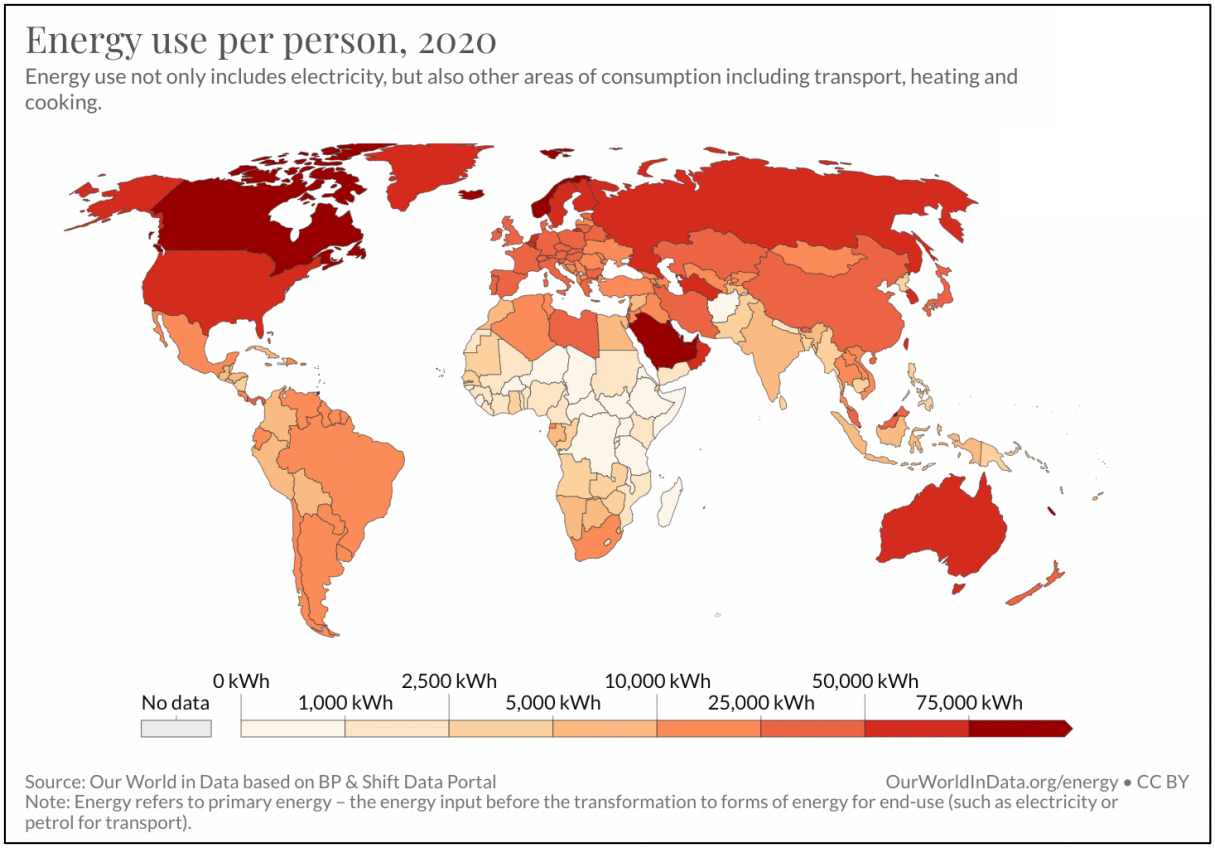


Figure 2.1. Each Individual's Use of Energy Worldwide in 2020.

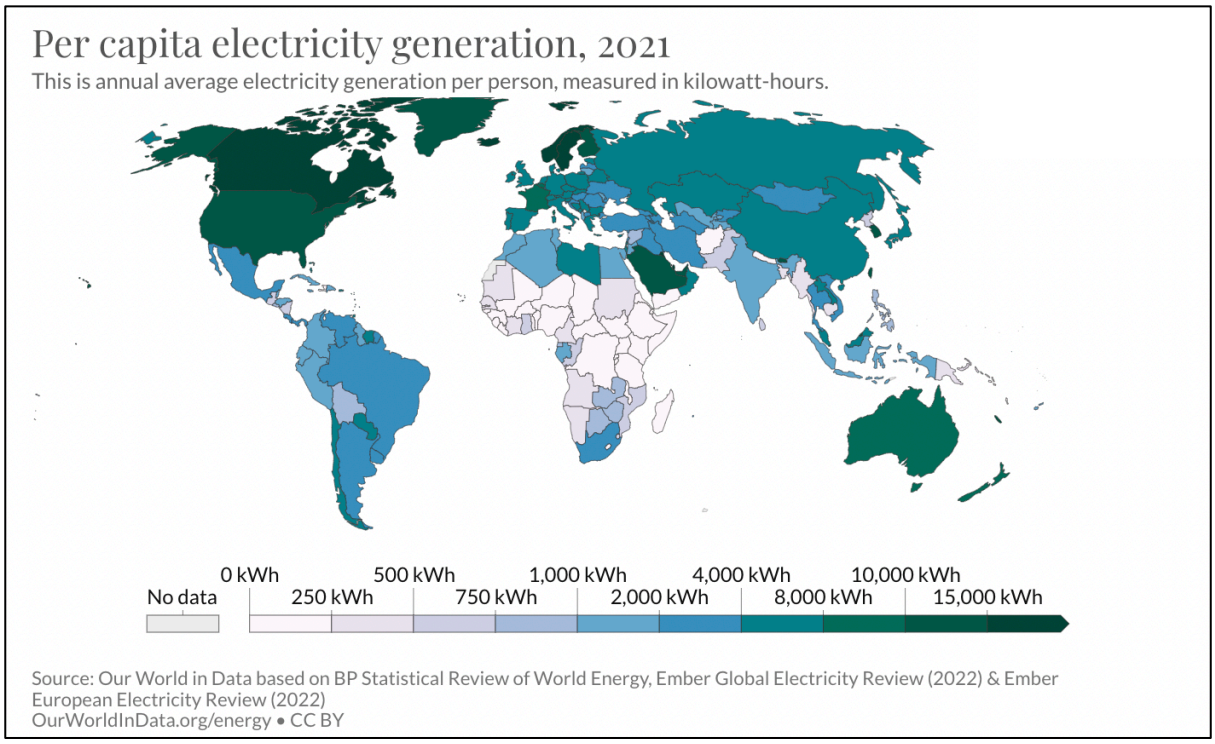


Figure 2.2. Global Electricity Production Per Capita 2021.

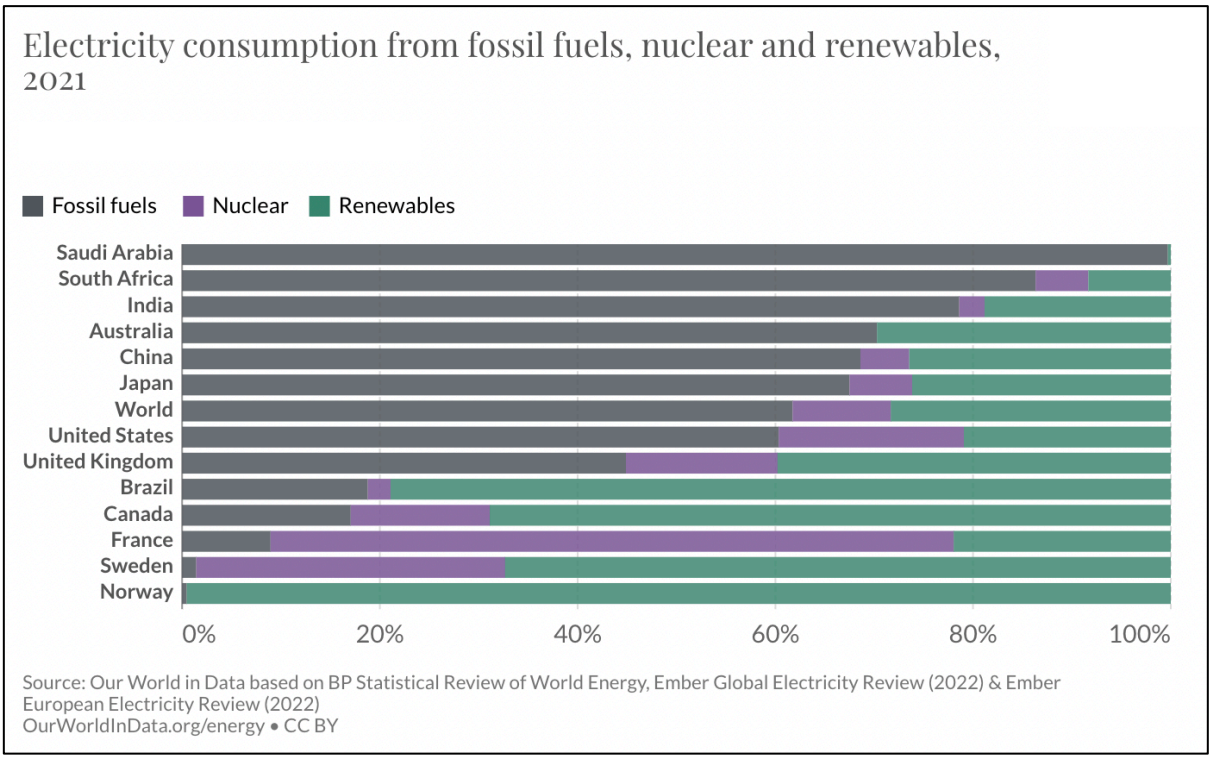


Figure 2.3. The Proportions of Electricity Use Based on the Source.

2.1.2 Building Energy Consumption in Saudi Arabia

As the Saudi Electricity Company (2022) observe, the rise in the adoption of high-energy appliances, urbanisation, rapid population growth, subsidised tariff, and other such aspects, in Saudi Arabia, have contributed to the substantial elevations in energy consumption which principally rely upon fossil fuels. By 2025, a twofold increase in electricity demand is forecasted as a result of the aforementioned factors (Obaid and Mufti 2009). As illustrated in Figure (2.4), data collected by the King Abdullah Petroleum Studies and Research Centre (KAPSARC) between 2005 and 2020 on electricity consumption reflects the findings above. Significant quantities of electricity are consumed by air-conditioning units, and many contemporary buildings in Saudi Arabia intensively rely upon such cooling units, thereby ignoring fundamental sustainable design principles. Consequently, refrigeration and air-cooling functions comprise almost 70% of household electricity due to the inadequately designed buildings in GCC nations like Saudi Arabia (Jamil et al. 2018).



Figure 2.4. Electricity Consumption by Sector for Saudi Arabia from 2005-2020. (Source: KAPSARC)

The energy consumption of 191 houses in Saudi Arabia was statistically analysed to determine the most significant energy consumption markers in an academic work (Esmaeil et al. 2019). Electrical energy consumption per unit area per inhabitant, and per house were among these markers. In addition, analysis was carried out upon water heating, appliances, lighting and other such distinct high-energy domestic tools to ascertain their efficacy. Their findings held that 92.6 kWh/m^2, 4704 kWh/capita, and 30,031 kWh/dwelling comprised the mean annual consumption energy performance parameters. Air conditioning, water heaters, lighting, and household appliances drew values of 66.5%, 10.3%, 8.5%, and 14.7% respectively, which signify the end-use and kind of each domestic energy consumption source. They add that a 43% decrease in the air-conditioning demand can be enabled by envelope insulation. Moreover, as the subsidised Saudi electricity tariff of 0.048$/kWh and the worldwide power cost of 0.15$/kWh produce an anticipated average simple payback time of 6.8 years and 2.2 years, respectively. Similarly, a 3% decrease in overall household energy consumption can occur via the adoption of efficacious lighting systems. Furthermore, a rapid payback period between 0.45 and 3.2 years is demonstrated in this area. However, advanced optimisation, simulation, and geometry generation were not undertaken in this study. Moreover, given that comparisons with published data and individual questionnaire responses serve as the basis for energy consumption reduction values and energy consumption results respectively, such results may not be entirely trustworthy.

Al-Tamimi (2017) notes, Saudi buildings waste a substantial quantity of energy, as per his examination of the energy-saving techniques adopted in the Saudi building sector and the concurrent difficulties and prospects therein. Hence, renewable energy sources, such as wind and solar energy, energy-efficient conservation and design, green technology, and other such energy-efficient practices should be implemented by the national government. Taleb and Sharples (2011) also stated that the link between the significant levels of energy consumption in the country and the hot climate it experiences is provoking high usage of air-cooling systems. Hence, solutions to diminishing energy consumption in buildings must factor in the distinct policies, economy, climate conditions, culture, and raw material availability in Saudi house design in order to maintain high levels of efficacy.

2.2 SUSTAINABILITY APPROACH

The United Nations Brundtland Commission (1987) states that the capability of future generations to fulfil their own needs following development that fulfils the needs of the current generation encapsulates the traditional meaning of sustainable development. Upon assessing any element of life, the process of achieving equilibrium within social, economic, and environmental sustainability represents the sustainable approach (Adewunmi et al. 2012). Hence, as Paredes and Herrera (2020) outline and Figure (2.5) illustrates, the equilibrium between the three domains of economy, society, and environment provides a framework to comprehend sustainability. Notably, a technological dimension was incorporated into this framework by a certain academic comprising the adoption of novel technologies in building regulations, the promotion of green buildings, the utilisation of raw materials, and the enhancement of energy efficacy within the process of research and development regarding novel technologies and materials (Mjakuškina et al. 2019). Nonetheless, each of these fundamental dimensions works in tandem, strengthening their overall stability rather than negatively impacting one another, irrespective of whether there are three or four of them.

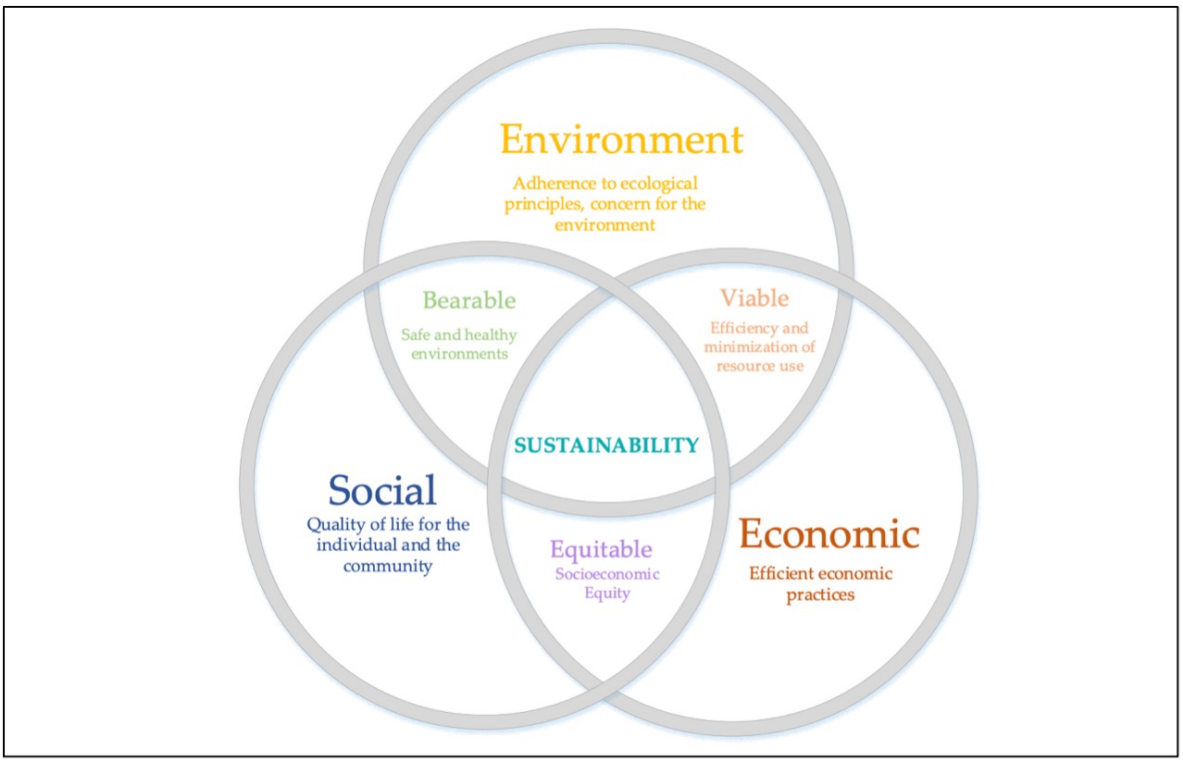


Figure 2.5. Three Fundamental Dimensions of Sustainable Development (Source: Paredes and Herrera, 2020).

The production of a safe environment safeguarded from external climes and appropriate conditions for human activity and life are among the core objectives of any building. Irrespective of the kind of building and its function, if the aforementioned fundamental dimensions are taken into account, the building that could be a community centre, office, or home can be sustainable. Bielek (2016) notes that within the building planning procedure, an auxiliary decision-making tool now exists in the form of a formalised evaluation of the sustainability of buildings enabled by initiatives developed for said purpose. This led to a method, as Rabenseifer et al. (2022) observe, for evaluating the environmental, social, and economic sustainability of buildings, outlined by the EN 15643 European standards. This standard similarly highlights the three aforementioned key dimensions as pillars in the evaluation of building sustainability. Promoting enhanced focus upon sustainable development with the key decision-making and planning processes is the objective of this evaluation, rather than simply certifying the sustainability of buildings. Nevertheless, contesting aims exist between environmental conservation and sustainable social and economic development within the domains of architecture and buildings. Given the variances in Saudi Arabia's community culture, location, environment, and economy, distinct priorities are held by the nation in its outlook on building sustainability (Alulayet et al. 2012). Therefore, in line with such an outlook, an equilibrium must be found between the economic, social, and environmental performance within construction in the country in order to construct sustainable buildings. An academic work undertaken in Saudi Arabia put forward a model for cementing assessment criteria regarding sustainable buildings through the use of the Analytical Hierarchy Process (AHP), survey questionnaires, and semi-structured interviews (Banani et al. 2016). The categories, principal features, and application techniques comprised the criteria through which five key building evaluations were compared. Cultural elements, land and waste, quality of service, indoor air quality, water efficacy, whole-life cost, effective management, materials selection, and energy efficacy made up the nine criteria deemed to be the most suitable assessment criteria, complemented by a further 36 sub-criteria. Given the significant influence exerted upon the core dimensions aforementioned as a result of climate change, the most significant criterion is generally perceived to be energy performance upon evaluating building sustainability. Therefore, Saudi buildings and their sustainability will be explored in the subsequent section in terms of the above three fundamental dimensions.

2.2.1 Environmental sustainability

A positive track record of environmentalism is not displayed by Saudi Arabia which, as Taher and Hajjar (2014) highlight, elevates the severity of the environmental difficulties the nation faces in line with the growth of industrial activity and population. As a result of the country's significant dependence on oil, the development of environmental policy has been stifled. Multiple environmental problems have arisen as a by-product of excessive fossil fuel use. Nearly two-fifths of the overall energy consumption in Saudi Arabia is attributed to its buildings whose carbon emissions also contribute to most of the overall pollution in most cities (Balabel and Alwetaishi 2021). A certain study evaluated the Saudi building's environment utilising renowned international systems—LEED and BREEAM (Alyami et al. 2013). The Saudi building environment was found to be incompatible, to an extent, with such international assessment systems. Due to the hot climate in the country, a low-energy design framework was proposed by another academic (Aldossary et al. 2015). Moreover, analyses were undertaken regarding inhabitant lifestyles, building fabric, massing, on-site renewable possibilities, space arrangement, and landscape. While considering the policies and low-carbon techniques put forward, these academics emphasised the requirement of a novel system to evaluate and approve the design and planning of future buildings. In addition, the significance of diminishing energy consumption, in terms of both economic and environmental outcomes, should be publicly conveyed alongside the implementation of strict guidelines and policies that stimulate low-carbon domestic building designs by the Saudi Arabia government.

However, the fulfilment of environmental sustainability is planned via fomenting diminished energy consumption in buildings, within its continued development of cities, and reliance on oil, as per the country's Vision 2030. Moreover, since the local climate of a given region should predicate the construction and design plans of buildings, thereby enabling optimal sustainability, novel and contemporary Saudi buildings are being assessed by a new rating system established by the government known as "Mostadam". The standards and goals of Vision 2030 are matched by this system that was formulated to work in tandem with extant legislation. Furthermore, the status of sustainable buildings in Saudi cities was evaluated in academic work by applying the mentioned rating system to generate the principal categories of sustainable buildings (Balabel and Alwetaishi 2021) They indicated that "Mostadam" rating system revealed high standards compared to LEED. Thus, the consciousness of environmental concerns within the building sector is gaining traction in present times due to the efforts of Saudi Arabia Vision 2030.

2.2.2 Economic sustainability

As Alaidroos and Krarti (2015) observe, the ability of the Saudi Arabia economy to depend upon oil export revenue would be infringed and put at risk by an extended period of increasing local building energy consumption. Nonetheless, Krane and Wilson (2019) and Our World in Data website (2021) highlight how fossil fuels contribute to 99% of the generated electricity in the country in the form of diesel, crude oil, natural gas, crude oil and other widely available non-renewable low-cost resources despite the prevalence of renewable energy sources like solar energy. This remains to be true, as King Abdullah City for Atomic and Renewable Energy (K.A. CARE, 2013) demonstrates, despite the plans of generating 9 GW of wind power, 17.6 GW of nuclear power, 41 GW of solar power, and 16 nuclear plants by 2032. However, Krane and Wilson (2019) stated that "those unrealistic and expensive plans have since been scaled back, only partly due to falling oil prices. Saudi Arabia now plans just two nuclear power plants of 1.4 GW each. The renewables target has been reduced to a modest 3.45 GW of renewables capacity by 2020 and 9.5 GW by 2023".

Resultantly, given that the generation of energy for buildings and most sectors completely relies upon fossil fuels, the economy of the country would be at risk. Moreover, irrespective of the negative influences on the environment and the volatile oil prices, Vision 2030 catalysed the rapid growth in residential buildings and rising levels of energy consumption which will be reflected negatively on the country's economy if the aspects of economic sustainability are not considered.

2.2.3 Social sustainability

Distinct building techniques and architectural designs stemmed from distinct climatic conditions in the country, as previously mentioned. The sentiment of self-identity and devotion to the Islamic religion is embodied and mirrored among the inhabitants of residential buildings, as per the Islamic culture of the nation. In addition, in line with daily requirements, the interior spaces of the houses are arranged by the inhabitants. Thus, privacy and social requirements usually determine the design of buildings in the country. Protection and privacy comprise the two elements that serve as the core pillars of conventional Arab house design philosophy (Ajaj and Pugnaloni 2014). Architectural details, spatial relations, and house layout are impacted by such elements. The significance of identity is improved via the colour, form, and geometry which make up some of the aspects that encapsulate architectural identity (Lynch cited in Hojjatollah 2012). Nonetheless, in the context of the changes in conventional Saudi

architecture, the inextricably connected nature of privacy and identity is notable, especially in terms of their apparent separateness in their definitions. The works of academics on local architecture and identity from distinct outlooks, conventional architecture's decreasing reliance on windows, and sustainability and conventional architecture highlight the attention placed on this area of changing identity (Akbar 2012; Al-Naim 2008). Nevertheless, the progressive loss of Saudi architectural identity is noted in each of the mentioned studies, representing a central deduction in their overall conclusions. As a result of this loss in a city, residents have ended up in distinct physical communities, leading to expressions of perplexity on their parts (Al-Naim 2008). The origins of this loss of identity in a city have provoked contradictory conclusions and perspectives in both academics and residents experiencing these shifts in community. Moreover, sustainability principles are ignored in favour of an affluent living style in many novel designs of homes in Saudi Arabia. As (Jamil et al. 2018) note, consistently operating air conditioning units in large residences characterises the Saudi home, upon comparison with other countries worldwide.

Resultantly, the alterations in social structure alongside the lifestyle and culture of distinct societies are transmitted via the informative and significant design of buildings, beyond their protective functionality. Hence, when equilibrium is achieved amongst economic, environmental, and social factors, optimal sustainability results can be produced.

2.3 THE EFFECT OF CLIMATE ON SAUDI BUILDINGS

CO2 emissions and energy consumption are significantly impacted by the extreme temperatures experienced in Saudi Arabia during the summer, with temperatures frequently exceeding 40°C, thereby highlighting the vital role of design in the construction process. Alshaikh et al. (2016) note that the status of being an air conditioning-reliant society is widely associated with Saudi Arabia. The adoption of energy retrofit strategies is hindered by various barriers such as the high costs and complexity involved and altering housing units to comply with the minimum energy efficacy guidelines. In addition, the benefits of climatic elements are ignored by novel building codes in the country that attempt to minimise energy consumption and enhance the sustainability and efficacy of buildings via only building envelopes. However, diminishing energy consumption can be enabled to a great extent via the adoption of energy-efficient measures.

Even though, the harnessing of renewable energy sources is an appealing proposition in Saudi Arabia as multiple unique climatic and geographic locations exist. This is exemplified, as. Yousef Etier et al. (2010) mentioned, that the country possesses one of the highest solar irradiation levels internationally, reaching annual values of 2080 kWh/m^2, and Sheikh et al. (2021) highlight that the most widespread source of clean energy is the sun for the production of electricity. This Saudi climate benefit within the context of low-carbon technology has not been taken into account by residential building projects despite the establishment of multiple renewable energy plants by the Ministry of Energy to produce power for the industrial sector, as per Vision 2030. Hence, energy in residential buildings can be provided by the core green solution of solar energy in the country.

On the other hand, the traditional architectural features of buildings in Saudi Arabia are characterised by the low number and small size of external openings, which usually start on the first floor to reduce the effect of the arid and hot climate on the house's internal spaces (Talib, 1984). Additionally, living spaces populate the periphery of several courtyards in other houses. Abdullah and Saleh (1998); and Al-Sayed (2011) note that the buildings are kept cool during the day from the cold air at night being maintained and the daytime shade that these courtyards provision, which also influences the interior temperature and offers natural ventilation and light. Furthermore, Mashrabiya exemplifies the shading devices still used in Arab countries that are found in conventional architecture and serve to diminish the influence of the dry and hot climate (Fathy, 1996). He adds safeguarding privacy, regulating the passage of light, heightening the humidity of the air current, and regulating the airflow are among the areas these devices enable. However, widespread adoption of such devices in new residential buildings regulating climatic conditions did not occur in the country. It is a reality that the climate is not considered enough in the contemporary design process of residential buildings in developing nations.

According to La Roche, (2017) the near uniform heat emission over the superficies of the earth and the distinct solar heat input generates variances in climate. The manner in which the design of a building interact with the external environment provokes the quantity of energy a building consumes. Minimal emissions and interior comfort in a building can be fulfilled by utilising the available energy and developing the capacity to manage exterior conditions. Hence, air movement, humidity, temperature, solar radiation, and how these features impact

energy consumption comprise the most significant climate variables in the design of buildings, given that they influence thermal comfort. The bioclimatic variables should determine the design process of a building in order to ensure suitability. Additionally, such suitability to the climate can be fomented by incorporating passive design methods which necessitate local climate knowledge. Investigating the following data elements enable the comprehension of a building's local climate (La Roche, 2017):

1. Dry-bulb temperature
2. Relative and absolute humidity
3. Air movement, measured in terms of wind direction and speed.
4. Precipitation, measured in terms of the overall quantity of rain, dew, snow, or hail in millimetres per unit time, such as year, month, or day.
5. Cloud cover, expressed as the fraction of the sky hemisphere covered by cloud (in tenths, or octas).
6. Sunshine duration, signified by the period of clear sunshine where a stark shadow is observed; expressed in terms of hours per month or day and measured via a sunshine recorder burning a trace on a paper strip.
7. Solar radiation, typically recorded as a continuously changing irradiance (W/m^2) and is measured via a pyranometer situated upon an unimpeded horizontal surface.

Graphs or tabular forms are often utilised to better represent the raw weather data from meteorological stations, facilitating comprehension of the data. For manual load and building design calculations, general climatic data is provisioned by certain design standards and handbooks like the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Therefore, Chapter 7 the modelling and simulation will discuss a comprehensive insight into these data utilising ASHRAE and Energy Plus raw data gathered from various Saudi weather stations and the Climate Consultant 6.0 software.

Chapter 3: Concept of Passive Architectural Design: Passive Thermal Controls

3.1 INTRODUCTION

Buildings should be conceived of as selective filters that permit the entrance of desirable conditions, such as natural ventilation, solar radiation in winter, and daylight and hinder the admittance of undesirable conditions, such as cold, wind, and rain. Moreover, the efficacy of such admitted conditions in reducing energy consumption is a significant factor in this conception of buildings superseding their embodiment as solely a shelter. Sociology, environmental physics, engineering, environmental graphic design, and cognitive science are among the plethora of academic disciplines that place attention on the topic of space—a critical domain in architectural research.

Buildings featuring minimal greenhouse gas (GHG) emissions and energy use while delivering thermal comfort are among the contemporary challenges of architectural design. However, a building environment that is unhealthy and delivers low levels of comfort in its achievement of diminishing emissions can be viewed as a failed project similar to how excessively high emissions in a building that delivers a quality thermal environment is a failure in ethics.

Hence, the achievement of developing environmentally friendly, healthy, and low-carbon buildings that are thermally comfortable depends upon a fundamental comprehension of human thermal comfort. Furthermore, as Ajaj and Pugnaloni (2014) observe, the climate needs of the present, within the context of climate change worldwide, are largely fulfilled by traditional buildings and their utilisation of materials and structure per their principles of thermal control that are found extensively in the domain of passive traditional architecture design. According to Ochedi and Taki (2022) thermal comfort and energy efficiency can both be improved by the appropriate building design, so it is important to achieve a balance between the two.

3.2 THERMAL COMFORT: COMFORT ZONE

When the physiological effort of thermal regulation is reduced and skin moisture is low due to body temperatures lying within particular limited ranges, the state of thermal comfort is reached (La Roche, 2017). Personal or environmental aspects are frequently used to describe the elements that impact the rate of heat dissipation from the body which influence thermal comfort.

Relative humidity, radiation, air temperature, and air motion comprise the environmental elements. Radiant exchanges between the surfaces that surround a body and the body itself lead to thermal comfort being impacted by radiation. The evaporation of moisture from the skin is impacted by air motion. The surface resistance of the body is diminished when there is a high air velocity which also serves to augment the evaporative cooling effect. The evaporation rate from the skin is influenced by the relative humidity. When the moisture content of the air is high, such as when relative humidity supersedes 70%, sweat does not evaporate with ease thereby complicating the process of the skin cooling such as occurs in lower relative humidity of the air. Given that the rate of convective heat dissipation is largely determined by air movement and air temperature, the significance of air temperature cannot be understated among the environmental aspects. (Lechner and Andrasik, 2022; and La Roche, 2017).

On the other hand, clothing and metabolic rate activity comprise the personal factors that influence thermal comfort. The heat produced by the body makes up the metabolic rate. With the exception of shivering, physical activity that is consciously controllable leads to the generation of muscular metabolism. Conversely, ongoing, and nonconscious biological processes which are in the range of roughly 60W/m^2 of body surface area—amounting to 100 W in a standard body—lead to basal metabolism. These two forms of metabolism cause heat generation in the human body.

Equivalent units of thermal transmittance (U-value) W/m^2K serve to evaluate the insulation around the body that clothing provides. It is worth mentioning the lack of definitive evidence regarding the impact of supposed psychological factors, such as aroma, light, texture, colour, movement, and sound that certain academics posit in their works (Hens, 2007; La Roche, 2017; and Foruzanmehr, 2018).

As per the ASHRAE Standard 55, the range of climatic conditions in which most people would obtain the sensation of thermal comfort embodies the concept of the comfort zone. The general conception and feeling of thermal comfort arise from specific amalgamations of radiation, relative humidity (RH), air temperature, and air motion. As Lechner and Andrasik (2022) emphasises, the comfort zone is achieved via specific comfortable mixes of RH and air temperature, as demonstrated in Figure (3.1). Nonetheless, Yun (2018) states that factors such as physical activity, an individual's level of fat, the time of year, the quantity of clothing worn, health, and culture impact thermal comfort, thereby highlighting that the borders of the comfort zone are not immutable.

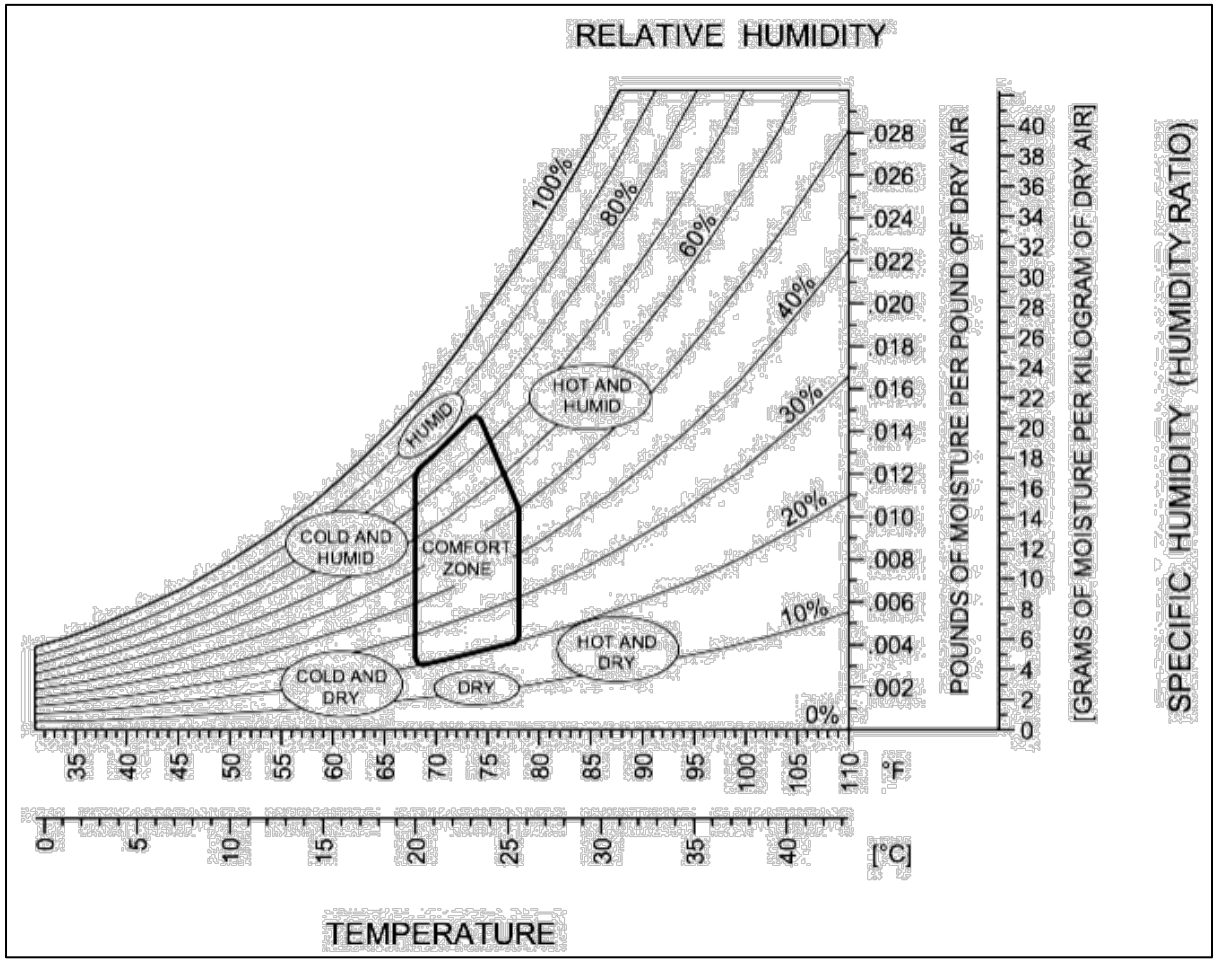


Figure 3.1. A Psychometric Chart Demonstrating Several Forms of Discomfort and The Comfort Zone. (Source: Lechner, Andrasik 2022)

According to the most up-to-date Saudi Building Code and Rating System "Mostadam" the conditions outlined in ASHRAE Standard 55 Sections 6.1 and 6.2 must be adhered to by new Saudi buildings. In the ASHRAE Standard Clothing is defined as (0.5 Clo - 1 Clo) and the

limits of humidity for sedentary activity (1 met - 1.3 met) and operative temperature are outlined in the accepted comfort zone displayed on a psychometric chart (Kumar et al. 2016). The utilisation of increased air velocities for comfort improvement is permitted in the Standard Effective Temperature method and the Graphical Elevated Air Speed technique while an airspeed of up to 0.2 m/s is the limit in the ASHRAE Standard 55 which uses the Predicted Mean Vote (PMV) model (Kumar et al. 2016). In comparison with the comfort zone set by ASHRAE 55, high comfort temperature bandwidths (25°C to 30°C) were observed in naturally ventilated buildings in North India, per an academic paper that was one of the first of its kind relating thermal comfort in hot arid climes (Sharma and Ali 1986). Nevertheless, thermal comfort can be recovered via alterations made to environmental factors that compensate for one or more factors lying outside the optimal comfort range. Additionally, the comfort ranges of environmental elements were determined in certain academic work (Lechner and Andrasik, 2022). An air temperature of 20 °C to 25 °C and Mean Radiant Temperature (MRT) proximal to air temperature were determined to be their ideal comfort ranges while 20 to 60 fpm (0.1 to 0.3 m/s) and 20% to 60% RH in the summer and 20% to 80% RH in the winter comprised the optimal air velocity and relative humidity ranges, respectively.

Thus, the efficacious design of thermally comfortable spaces is largely determined by the comprehension of how the mentioned factors interact with one another and influence thermal comfort. However, our connection with the external environment is evidenced by people adjusting their behaviour after noting or anticipating alterations in outdoor temperature which, in turn, demonstrates how the thermal comfort zone differs in passive and ventilated buildings in line with outdoor temperature. Notably, distinct factors that influence thermal comfort have not been quantified which reflects the complex nature of the mentioned adaptive procedure. It is probable that the presently acknowledged impact of cultural, social, and psychological elements understates their influence. This is exemplified by those inhabiting unconditioned spaces generally having a distinct comfort zone to those inhabiting air-conditioned spaces. Furthermore, thermal acceptability for most of the inhabitants of a space would provoke the attainment of indoor thermal conditions near to thermal neutrality which would be accomplished via distinct levels of energy consumption. Precisely calculated heating and cooling energy that are necessitated to maintain the thermal comfort within a low energy building depends upon an appropriate thermal comfort model. The accuracy of the thermal

comfort model is thought to be a favourable approach because it is cost-effective and reduces energy overconsumption (Albatayneh et al. 2019).

3.3 THERMAL BEHAVIOUR OF BUILDINGS

The manner in which the thermal environment of a building and its energy use are influenced by regulating the thermal behaviour of buildings highlights its significance (Andoni et al. 2019). The composition and kind of building materials used to establish the thermal behaviour of a building. While external conditions such as air velocity, humidity, and temperature differ each season, the capacity of the building to sustain comfortable internal conditions is determined by the thermal behaviour of the building. External conditions regulate the loss or gaining of the heat of a building to the environment via the process of convection upon solar radiation providing such heat to a building (Vijayalakshmi et al., 2006). The thermal conductance of the layers of the door, roof, wall, and window materials regulate the heat transfer that occurs between the internal and external surfaces of the wall. In addition, the convective heat transfer of the inner surface and the thermal radiation quantify the thermal balance between a room within the internal environment and the inner surface. A thermal system comprising a series of heat outputs and inputs is one conception of a building (Szokolay, 2014). The equation below outlines the mentioned system:

$$Qi + Qc + Qs + Qv + Qe = \Delta S \quad (1)$$

An alteration in heat stored in the building is signified by ΔS while evaporative heat loss, solar heat gain, internal heat gain, ventilation heat loss or gain, and conduction heat loss or gain are represented by Qe, Qs, Qj, Qv, and Qc, respectively.

When ΔS equals zero, which signifies the total of all heat flows being zero, thermal balance is present. The building is cooling when the total is less than zero and the building is gaining heat when the total is greater than zero.

Thus, convection, radiation, or conduction are the means by which heat transfer occurs in the enclosure. Diverse components constituting the building fabric serve as channels through which such flows take place. However, a crack or opening in the building accelerate

the process of convection, opaque and transparent materials are impacted by radiation, and solid components of a building control the process of conduction.

The ability of a material to transmit heat flow is a feature designated as thermal conductivity (La Roche, 2017). Greater energy flow is present in materials possessing high conductivity. Another definition of thermal conductivity is the rate at which heat flows through a homogeneous material per unit of thickness using the units of measurement Btu-in/h ft2 °F or W/m °C. A building will be directly heated or indirectly heated via conductive gains by radiation highlighting the requirement to diminish the quantity of solar radiation as building components are heated following their absorption of solar radiation within hot climes. Thus, Szokolay (2014) and La Roche (2017) highlight the need to elevate surface resistance with distinct surface treatments, utilise materials possessing low absorptivity, and generate shade. The procedure of heat transfer via mixing and flowing motions in fluids is known as convection. Air temperature is the prime determinant of convection. The absorption of heat from a warm surface by molecules of cool air which then rise and take it away defines the process of natural convection.

The units of measurement ft^2 °F hr/Btu or m^2 K/W are the expression for the more prevalently utilised resistance (R) value which represents the reciprocal of conductance. The insulating value is assessed by this measurement alongside the air spaces to the flow of heat by radiation, convection, and conduction as well as the resistance of materials. The high resistance of the material to the flow of heat is signified by a high R-value. As La Roche (2017) and Thorpe (2018) observe, an insulating material can be substantially thinner than a conductive material as the former will be substantially more resistant to the flow of heat compared to the latter, despite all materials providing some resistance to the flow of heat. The equation below demonstrates how the R-value is ascertained:

$$\mathrm{R} = \frac{K}{e} \qquad (2)$$

The thickness, conductivity, and resistance are denoted by e, K, and R, respectively.

Furthermore, the steady-state rate in which the heat flows through architectural skin aspects is signified by the numerical U-value which uses the units of measurement Btu/hr ft^2 °F or W/m^2 K. High U-values block less heat than low U-values and the quantity of heat that can be transmitted via a component of a building is best represented by the thermal transmittance value (La Roche, 2017).

However, the necessary conditions for one-dimensional heat flow are frequently not achieved within real building aspects (Szokolay, 2014). The development of two- or even three-dimensional heat flows takes place when the material is not homogeneous, or the edges are not plane-parallel surfaces. It is worth mentioning that thermal bridges are a term used to describe parts where elevated multidimensional heat flows take place. The amalgamation of materials of distinct conductivities alongside corner effects are possible causes of this due to their geometric structure.

Therefore, given that one of the most significant impacts on sustainability and energy use is exerted by the thermal behaviour of a building—an area for which the architect is entirely responsible—heat gain can be seen as the most influential aspect. Buildings in hot, arid climates should exploit the benefits of the philosophy of generating shade and compactness to diminish sun exposure in the summer. The general energy efficacy and thermal quality of a building can be enhanced by architects that prevent overcooling and overheating by determining and adopting building design strategies in line with their comprehension of such flows. Nonetheless, a decrement factor, a delay in the heat flow known as time lag, heat capacity, and other such elements can also influence the thermal behaviour of buildings.

3.4 CONTEMPORARY PASSIVE ARCHITECTURAL DESIGN

As outlined by Altan et al. (2016) passive design comprises the removal or decrease of dependence on mechanical systems for lighting, cooling, and heating while utilising natural climatic elements advantageously to sustain comfortable temperatures within buildings. Measures like ventilation, evaporation, and thermal mass work in tandem with the thermal conductivity of solar incidences, orientation, building façade, and geometrical parameters as component parts of passive design strategies (Rodriguez-Ubinas et al. 2014). Thus, within the operation stage, emissions and energy costs can be diminished while occupants of the building

can have their comfort guaranteed by the suitable adoption of passive design parameters in the design stage.

Two distinct yet intersecting methods regarding sustainable building are passive house and passive solar architecture (Thorpe, 2018). Maximising the utilisation of natural heat and light is the objective of passive solar architecture. In the case where cooling or heating is needed, hindering or facilitating the entry of heat is performed by absorbing and sustaining energy from the sun in the fabric of the building or preventing initial access respectively as per the design of the building formed in line with the geographical location and external conditions.

The objective varies marginally in passive house design in so far as the minimisation of the quantity of energy required to cool and heat the building is the goal, irrespective of the source of thermal energy loss or gain. The conduction of cold or heat via the external skin of the building is stopped by regulating the quantity of air changes per hour in this system.

Nonetheless, present-day passive solar design has developed significantly. Thorpe (2018) stated that standard passive solar design lacks the capability of widespread adoption in comparison to the passive house design given that it is more suitable in cases where buildings can be unshaded or face westwards. Hence, passive houses should be constructed and designed in line with five fundamental principles: airtight construction; ventilation with heat recovery; thermal bridge-free design; quality insulation; and superior windows (Passive House Institute, 2022). The construction of buildings with high levels of energy performance via passive house designs were first attempted and studied in northern Europe in the early 90s. Hopfe and McLeod (2015) outline the formation of the high energy efficacy building located in Darmstadt, Germany, that represented the first adoption of the Passivhaus standard of passive design in 1991, three years after this standard was formulated. Nevertheless, carbon emissions and building energy use can be diminished through the viable approach of incorporating advanced technologies such as net-zero energy buildings (NZEBs), passive design strategies, highly efficient mechanical systems, and renewable energy use (Lin and Chen 2022).

However, Attia (2018) perceives that the next step in the evolution of energy-efficient buildings is the construction of buildings capable of fulfilling their annual energy needs via its self-sufficient generation of energy via renewable sources, as is the case in NZEBs. Moreover, buildings that are capable of generating extra energy than what is required are a further progression of the NZEB model known as positive energy buildings or plus zero energy buildings

(PZEBs). As Magrini et al. (2020) and D'Agostino et al. (2022) observe, energy positivity and energy neutrality can be attained via the generation of the energy surplus to the requirement that can, in turn, contribute to providing energy to proximal consumers.

3.5 TRADITIONAL PASSIVE ARCHITECTURAL DESIGN

A direct link to the past is perceived in the cultural evidence embodied by passive traditional design that takes into account the alterations of local environments. Philokyprou and Michael (2021) note that the entrenched particular identity linked to the environs of vernacular buildings becomes sustainable due to the strong influences of the local environment. Furthermore, the reinterpretation, adoption, or conservation of passive design strategies within more recent projects enable hybrid and standard models for present-day architecture to be formed from heritage buildings possessing passive elements (Salameh et al. 2022). As demonstrated by La Roche (2017) and Figure (3.2), the aforementioned premise is exemplified by the presence of small windows that permit ventilation for night cooling while diminishing solar gains in the internal space within a compact heavy mass structure that regulates outdoor temperatures, in the case of a building requiring cooling in hot arid climes. Moreover, Chenvidyakarn (2007) emphasises that the interception of solar radiation prior to its passage through the building envelope into the internal space enabled by external shading devices makes these devices among the most efficacious see Figure (3.3). However, the angle of daylighting to clash with shading design is a significant problem that must be taken into account. Moreover, diminished heat gains due to energy saving are offset by elevated artificial lighting requirements that can arise as a result of unsuitable shading design decreasing daylight penetration.

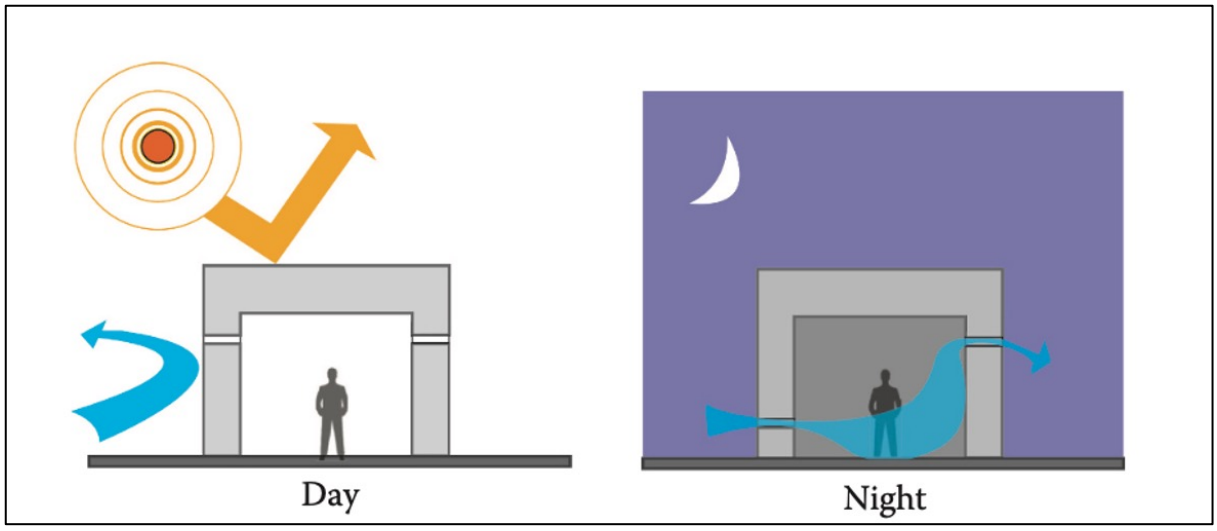


Figure 3.2. The Archetype of a Building Requiring Cooling in Hot, Arid Climates. (Source: La Roche, 2017).

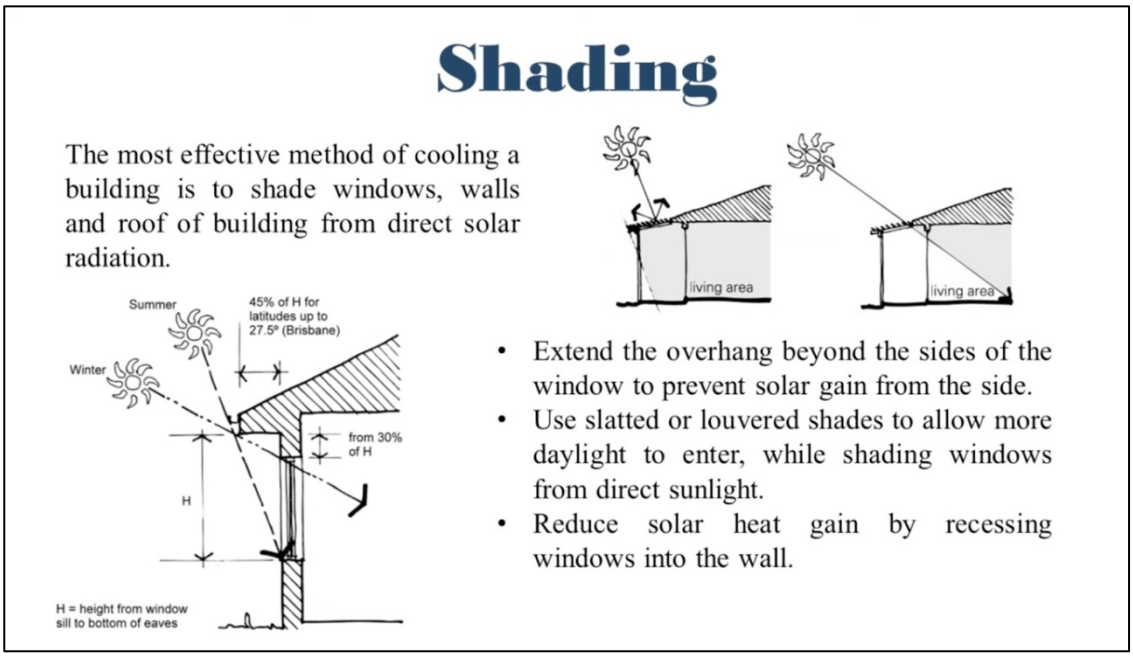


Figure 3.3. Shading Design (Chenvidyakarn 2007).

Therefore, designing effective shading devices requires understanding how the sun moves across the sky during the day and throughout the year. Several key solar angles help determine the appropriate size, shape, and position of shading elements to reduce heat gain and glare while allowing useful daylight (Szokolay, 2014; DeKay and Brown, 2014). These key angles are as follows:

Solar Altitude Angle: the vertical angle between the sun and the horizontal Earth's surface. It indicates how high the sun is in the sky and influences the depth of sunlight

penetration into indoor spaces. It is crucial for assessing the effectiveness of horizontal shading elements like overhangs.

Solar Azimuth Angle: the horizontal angle between the sun's projected position on the ground plane and true south, measured clockwise. It shows the sun's horizontal position at different times of day and helps identify which façades will receive sunlight and when. This information is useful for deciding where to place shading devices.

Profile Angle: the vertical angle between the sun's rays and a surface perpendicular to the façade, often used to size horizontal shading devices. It is typically derived from both the solar altitude and azimuth angles.

Shadow Angles: these include the Horizontal Shadow Angle (HSA) and the Vertical Shadow Angle (VSA). The VSA is the angle between the sun's rays and the horizontal surface, measured in a vertical section perpendicular to the façade. It is important for designing vertical shading elements such as louvers.

Nevertheless, these angles change throughout the day and year and are often calculated using sun path diagrams or digital simulation tools...Understanding them is essential for designing shading that improves comfort and reduces energy use. Hence, Figure (3.4) illustrates the principal solar angles and highlights their significance in achieving optimal shading performance. Specifically, Figure (3.4-A) shows three primary categories of external shading devices, outlining their architectural applications in regulating incident solar radiation and minimising heat gain. In parallel, Figure (3.4-B) demonstrates practical case applications, illustrating how these theoretical principles can be effectively adapted to different building facades.

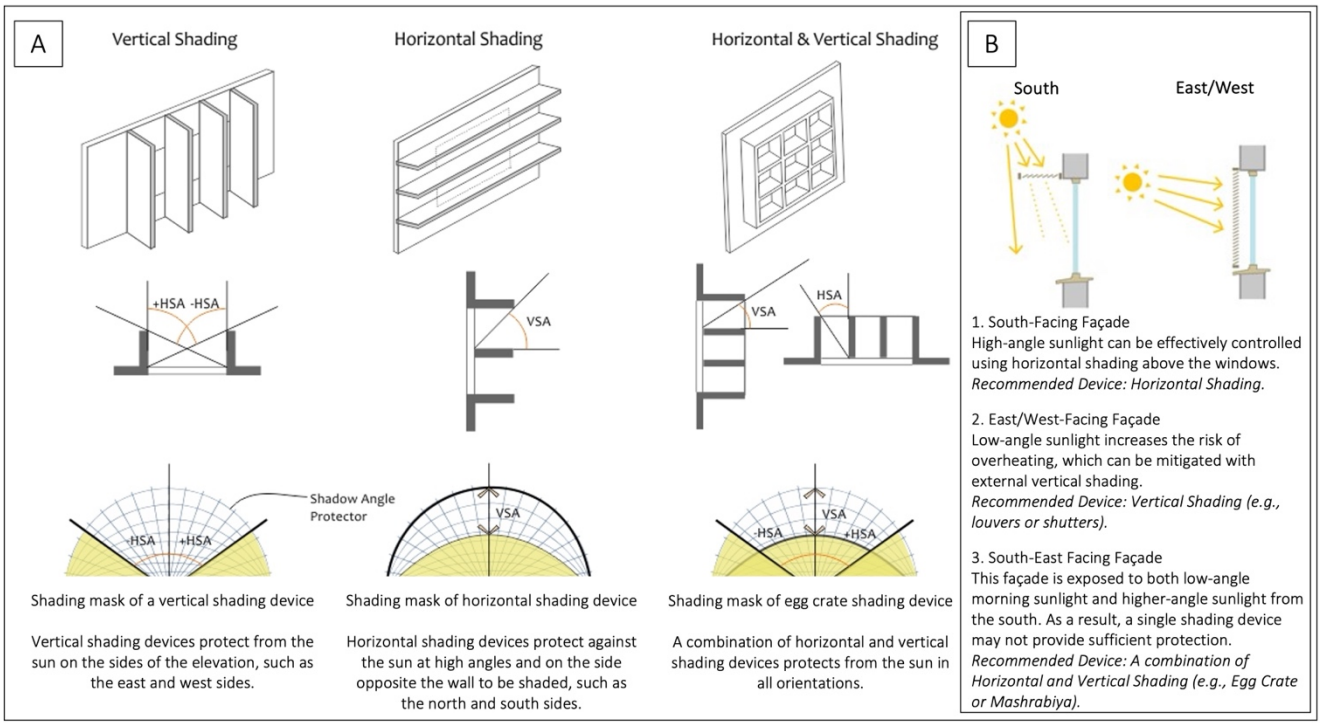


Figure 3.4. External Shading Strategies and Applications.

On the other hand, Hot dry climates worldwide were the first to implement courtyards within buildings (Edwards et al., 2006). The need for cooling in these areas is the reason behind this. Moreover, Akande (2010) stated that energy needs for cooling buildings were found to be minimised via the natural cooling provided by an appropriate courtyard and building orientation for a building within hot and arid climates. However, the thermal performance of courtyards is impacted by orientation and other such geometrical characteristics. The degree of openness to the sky depends upon the ratio between the average height of the surrounding walls and the area of the courtyard floor, known as the aspect ratio. Although wind entry is facilitated in high aspect ratio designs, as they allow a larger surface area of the floor to be exposed to the sky, thereby enhancing cooling, this configuration could also result in increased heating during the day, as a greater portion of the courtyard remains directly exposed to the sky.

Fernandes et al. (2015) note that the quality of being a highly sustainable building can be attributed to the adaptive reuse of vernacular architecture given that the social, economic, and environmental elements of sustainability are fulfilled in its design. However, Rapoport, A (1969) emphasised that tradition has ceased to function as a guiding force in modern architecture due to several factors. Firstly, the increasing complexity and variety of building

types make traditional construction methods impractical. Secondly, the erosion of a shared cultural value system and collective worldview has weakened the mutual understanding between designers and the public, resulting in diminished cooperation and respect for communal or neighbouring spaces. This breakdown has necessitated the implementation of formal controls such as zoning laws and building codes. Lastly, contemporary culture places a strong emphasis on originality, often valuing novelty over tradition. This pursuit of uniqueness, driven more by cultural trends than functional needs, undermines the vernacular process that once sustained traditional forms.

Therefore, adopting every possible passive traditional measure to safeguard against overheating in a building is considered to be a significant recommendation for hot dry climates locations. It is worth mentioning that natural ventilation and a wind tower or windcatcher are further measures of vernacular architecture that have been more prevalently investigated by academics in the field.

3.6 TRADITIONAL PASSIVE ARCHITECTURAL DESIGN IN SAUDI ARABIA

The ancient history of the Arabian Peninsula contrasts with the relative youth of the nation of Saudi Arabia founded in 1932. Every sphere of social life demonstrates unique traditions and culture. The climatic conditions, history, cultural heritage, and environment of the country have strongly impacted the traditional architecture found therein. Alrashed et al. (2017) note that the heritage of Saudi buildings typically possessed Mashrabiyas, courtyards, wind towers, fountains, and other such traditional architectural methods. Reflections upon privacy in Islamic ideology are stirred by the manifestation of Islamic social perceptions and culture in the form of Mashrabiyas and courtyards.

Moreover, further advantages were delivered by the traditional central courtyard beyond cultural, social, and ideological elements. This is exemplified by the three stages of courtyard functions in terms of building cooling in hot arid climes such as in central Saudi Arabia. The surrounding rooms are filled with cool night air after it descends into the courtyard in the first stage. Up until late afternoon, furniture and the building structure remain cool after their nighttime cooling. The clear night sky via radiation provokes the rapid loss of heat from the courtyard.

The courtyard surface is bathed in direct sunlight come midday in the second stage. A portion of the cool air commences to rise and escapes from surrounding rooms. Additional comfort can be provided via the convection currents caused by this change.

During the peak of outdoor temperatures, the courtyard becomes akin to a chimney. When late afternoon arrives, additional convection currents are formed while the internal spaces of the house and the courtyard surface gain heat in the third stage.

When sunset occurs, the majority of the cool air is released after being stuck in the rooms. Neighbouring structures and their shadows safeguard the building, courtyards, and street against the sunlight in the late afternoon. Upon the courtyard commencing to radiate quickly to the open night sky above, a rapid decrease in air temperature occurs in line with sunset. The cycle then repeats as cool air commences its falls into the courtyard once more.

The performance of distinct aspects of traditional passive architectural design is ascertained via the adoption of many diverse approaches by academics in the field. The use of simulation software analysis enabled the maximisation of natural ventilation systems in an office building following the energy consumption levels being forecasted, as per an investigation researching distinct courtyard designs by (Taleb et al. 2020). The real yearly energy consumption figures were then used to compare the forecasted levels. Measurements of 48.23 MWh to 29.38 MWh were attained denoting the energy savings produced from courtyards possessing a wind channel design, per the comparison with the benchmark. Each year 11.5% less energy was consumed by the external courtyard in comparison with the internal courtyard. Hence, energy consumption decreases of up to 39% can be achieved by the optimum courtyard design. Furthermore, a parametric comparison within an office building between the energy performances of atriums and courtyards with regard to factors such as their artificial lighting, heating, and cooling took place in another academic work (Asfour 2020). To control sunlight in hot climates, the use of shading devices, courtyards, and atriums is recommended. Moreover, in hot-climate areas, increasing the WWR to more than 50% will reduce glare and enhance the cooling demand. Window shading devices are considered to be the most efficient tools for improving daylighting and energy efficiency. However, this study did not take into account the effects of other variables, such as courtyard and atrium aspect ratios, building forms and other shading and glazing devices.

In the length of time where a building is at risk of overheating such as in Saudi Arabia, avoiding solar gain in the internal spaces of the building or shading the sunlight thereby blocking its access to the building comprise the two most effective ways of averting undesirable glare and overheating. Five functions are performed by the Mashrabiya which is considered by some to be the standout shading device in the Arab world (Ajaj and Pugnaloni 2014). Diverse conditions are met by the envelopment of distinct patterns that highlight the mentioned functions. As illustrated in Figure (3.5) below, safeguarding privacy, diminishing the air temperature, regulating the passage of light, elevating the air current humidity, and regulating the airflow comprise the functions of the Mashrabiya.

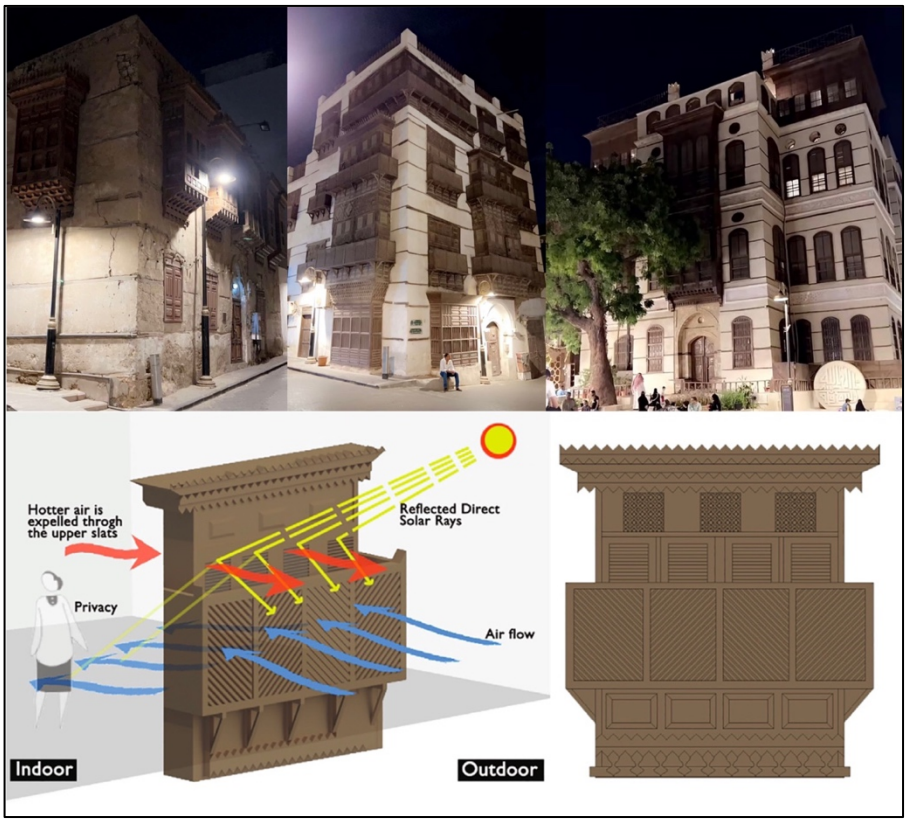


Figure 3.5. Mashrabiyas. (Source: By the author and Bagasi and Calautit 2022).

On the subject of the revival of vernacular architecture, the perspectives of influential figures and Saudi citizens were examined in a certain academic work (Alelwani et al. 2020). Moreover, interviews, questionnaires, and observations served to ascertain the impact on decreasing artificial light usage in residential buildings exerted by knowledge and awareness of shading devices like Mashrabiyas. The diminished energy consumption that a Mashrabiya

provides was found to be the second most significant aspect in the design of a Mashrabiya, reaching 75% in the results. While daylight was perceived to be the most significant aspect by the majority of respondents, it was in actuality ranked third of the five parameters, reaching a figure of 71%. Additionally, within arid desert regions of the country, traditional vernacular architecture techniques were analysed in a separate study (Alrashed et al. 2017). A computer simulation (IES-VE) served to determine the extent to which the energy performance of residences in the five climatic zones of Saudi Arabia was impacted by the multiple individual vernacular characteristics. The findings revealed that the implementation of a courtyard area could diminish annual electricity demand by -4% among all the regions examined. Similarly, this demand was found to drop between 1%–4% in each of the regions via the adoption of Mashrabiya. However, the most significant decrease in electricity consumption of 3%–6% was provoked by the adobe construction house.

The energy consumption of Saudi buildings was found to be impacted by multiple principal factors in passive design, as per the extant literature. The following section touches upon these elements such as cool roofs, glazing systems, window-to-wall (WWR), shading devices, building form and orientation, and building envelopes.

Multiple design variables in a standard villa were analysed in relation to their energy performance and daylight in a certain academic work (AL-Dossary and Kim 2020). Nonetheless, the findings that improved daylighting performance can be attained by elevating WWR by a quarter, a half, and 70% are unrevelatory. This similarly applies to the finding that energy consumption can be substantially diminished by the utilisation of external shading devices. In a humid and hot region of the nation, the self-shading envelope in a multi-storey building was analysed with regard to the impact on economics and energy-saving exerted by external shading devices (Alhuwayil et al. 2019). Enhancements to temperature control in tandem with diminished energy consumption were found to be enabled most economically and efficiently via the implementation of passive design solutions within the conceptual design phase. In addition, a reduction of up to 20.5% of annual energy consumption was found to be possible by fomenting shading and the cost related to the adoption of passive shading would be covered in two years, per the calculations in said paper. Nevertheless, annual energy reductions of only 5% were provided by the incorporation of improved glazing and insulation, such as roofs and

walls with polyurethane inside and triple-glazed windows. Furthermore, it was calculated that the investment in such an initiative would take roughly 84 years to break even once more.

The extent to which thermal comfort performances within the Boqri and Subra palaces situated in high-altitude desert regions of the country were impacted by orientation and thermal mass application is investigated in an academic work (Alwetaishi et al. 2020). The relative humidity was found to increase from 19% to 55% while the interior air temperature dropped by 2 °C following the occurrence of evaporative cooling that substantially improved thermal comfort. This effect took place in the field experiment for three-quarters of an hour. However, the findings of this paper did not make new ground in the field despite the computer-modelled outcomes and the qualitative investigation of results from other academics.

Utilising the case of a residential building in Al-Riyadh, the manner in which selected passive cooling influences multiple distinct kinds of building envelopes was ascertained in another paper (Al-Qahtani and Elgizawi 2020). Prior to the implementation of such passive techniques, the building consumed 124.760 KW and after it consumed 50.170 KW. The techniques adopted included green roofing, glazing, louvres, insulation, and shading. The most impactful passive technique was found to be implementing insulation while incorporating shading devices was found to be the second most impactful method. Nonetheless, passive measures such as atrium aspect ratio, courtyard, and building form were not taken into account by the mentioned paper. The extent to which hybrid and natural ventilation could be enhanced by building form was analysed in a separate study (Bayoumi 2018). A further research objective of the mentioned work was ascertaining how a building could generate the best conditions for ventilating semi-outdoor and outdoor spaces. Additionally, efficacious cooling systems that amalgamate energy savings with user comfort were enabled by the formulation of design improvement criteria. Wind velocities of up to 1.1 m/s occurred demonstrating the substantial rise in such velocities in the corridors, per the results of the mentioned paper. Simultaneously, air velocities of up to 2.0 m/s occurred in the semi-outdoor spaces. Occupants within humid and hot regions can experience substantially enhanced thermal comfort via the presence of higher air velocities. In comparison to the first standard case, the annual mean cooling energy need was 60% less given that the CO2 concentrations did not surpass 700 parts per million.

The distinct plant coverings for a residential building, such as trees, shrubs, and turfing, were stratified by Khabaz (2018) to enable the investigation of green roof efficacy in the Kingdom of Saudi Arabia (KSA). While certain areas of the country need increased cooling than what is shown by turfing, the covering achieved a 63% drop in heat transfer to the internal spaces of the building during peak hours. In the same time period, an 87% decrease in heat transfer to such internal spaces was observed via the implementation of shrubs on solid green roofs. Nonetheless, the mentioned paper did not examine energy performance.

Other residential buildings were examined in a certain study regarding the extent to which their energy performance was impacted by orientation and green roofs in the arid city of Dhahran and the humid and hot city of Riyadh (Khan and Asif 2017). A dynamic air-envelope system is generated by vegetation in a green roof which, in turn, served to diminish the heat intake into a building, per the findings of the mentioned study. In addition, a decrease in energy consumption of 6.8% and 6.7% in Riyadh and Dhahran respectively was observed via the implementation of green roofs. The energy consumption was found to be 141.3, 140.6, 140.3, and 141.6 KWh/m^2 for buildings orientated towards the south, west, east, and north, respectively. Another work examined the domain of diminished building energy consumption via incorporating green roofs through the lens of their possible economic and technical efficacy (Mahmoud et al. 2017). The energy consumption was found to be 110 KWh/m^2 and 169 KWh/m^2 following and prior to the incorporation of a green roof, respectively. Moreover, by the end of the 19th year, the green roofs possessed negative net present values (NPVs), per the results of the mentioned paper. At the close of the subsequent year, the NPV turns positive. Nevertheless, green roofs do not possess a positive outlook regarding their economic sustainability given the highly subsidised electricity tariff in the country.

In distinct Saudi climates, cool roofs and the linked hazard of mould growths and condensation were investigated in separate research by (Saber et al. 2019). The implementation of cool roofs instead of black roofs and the associated energy saving were calculated in this work. The cool roofs and black roofs possessed zero moisture aggregation after seven and six years respectively, per the results of the mentioned paper. Furthermore, zero risk of mould and condensation development was indicated as the peak relative humidity for both roof kinds fell significantly lower than 80%.

TAS EDL computer modelling software and measuring equipment were utilised in a study focused upon floor heat conduction in every classroom of prototype Saudi school building in both winter and summer with regard to their energy performance by (Alwetaishi and Gadi 2018). Natural ventilation was revealed to substantially impact the interior temperatures serving to dimmish the maximum and minimum temperature by 3 °C and 6 °C, respectively. Moreover, while the ceiling and roof are considerably influential regarding heat conduction, the floor exerts little influence. In comparison to the summer, heat conduction was impacted to a greater extent by solar radiation in the winter. Nonetheless, energy performance was not examined in the mentioned paper that focused primarily upon heat gain variables.

The most appropriate architectural design for a school building was identified in another work by implementing extant data regarding the microclimatic condition of two regions in the country (Alwetaishi and Balabel 2019). Natural ventilation was determined to be a vital component of the architectural design within hot climates given that the relative humidity and temperature of the internal air are enhanced by it. Thus, upon architecturally designing such a building, how to achieve a midpoint between relative humidity and temperature must be taken into account. Irrespective of the season, thermal comfort is delivered in all classes via the usage of cross natural ventilation in Abha.

A separate academic work analyses the compatibility to the climate of vernacular architecture in the building industry as well as the utilisation of passive design (Almatawa et al. 2012). In addition, manners of maximally improving modern Saudi buildings via the analysis of the most sustainable sources of renewable energy were explored. By implementing cutting-edge solar power technologies and passive designs, energy efficacy can be improved, per the findings of the mentioned work. Similarly, by studying vernacular design, the quality of interior environments can also be improved.

Resultantly, highly sustainable techniques of development are enabled by undertaking the construction of residential buildings in line with the three fundamental pillars of sustainability—social, economic, and environmental—through the integration of the optimal characteristics of traditional passive architecture design, which represent a side of green engineering solutions.

Chapter 4: Energy Conservation Measures

4.1 ENERGY EFFICIENCY MEASURES APPLICATIONS IN SAUDI ARABIA.

Efficient buildings can potentially boost economic growth, enhance social development, and promote the sustainability of the environment. Recent studies demonstrated that the applicability improvements of energy efficiency measures in buildings in Saudi Arabia were correlated with improvements in energy consumption. Since these studies represent a part of the critical review of this thesis, the following will critically discuss them in depth.

Alaboud and Gadi (2022) evaluated a residential building's indoor thermal performance and efficiency to examine how a building's cooling load is impacted by different materials used in the building envelope. They found that the combination model that optimised the relevant measures to reduce energy consumption had a cooling intensity of 79.7 kWh/m2/y. This is a 56.4% reduction in the cooling load in comparison to the base case. The study used physical measurements and (TAS) software for simulation. However, this research took the form of a case study that was built in 2008 without any consideration of energy efficiency aspects. Additionally, it focused on floors, walls, and roofs and only 1-2 rooms in the building were examined. Al-Tamimi (2021) determined the most effective way of using thermal insulation in building envelopes for residential buildings under different climate conditions. Additionally, four different insulation materials were used to perform economic modelling and lifecycle cost analysis. He stated that any of the four thermal insulation materials that were examined can be used to reduce the annual energy consumption, with the percentages of such reductions (in comparison to actual consumption) being 4.3% in Najran, and 5.6% in Gazan and 1.4% in Khamis Mushait. Additionally, energy cost savings differed based on the specific climatic conditions of each city. Thus, these savings varied between 5.6 $/m^2 to 9.7 $/m^2. The shortest payback period was found to be 4.7 years in Gazan (which has a hot, humid climate), whilst the longest payback period was identified in Khamis Mushait at 8.8 years (moderate climate). Notably, all the cities examined in this research were located in the same region within Saudi Arabia. Almushaikah and Almasri (2021) used eQUEST software to assess the effects of different factors on a building's envelope elements using a model-based design to examine the effectiveness of implementing solar energy systems in reducing energy consumption for two

cities in Saudi Arabia. They stated that the optimisation of energy efficiency (EE) measures reduced energy consumption by 27% for walls, 14% for roofs, and 6% for windows in Riyadh. On the other hand, these reductions were 29%,13%, and 6% for walls, roofs, and windows in Qassim, respectively. However, they indicated that the most effective (EE) option was to choose a high-energy efficiency rate heating, ventilation, and air conditioning (HVAC) system. This can reduce energy usage by 33% in Riyadh and 32% in Qassim.

Alayed et al. (2021) examined the building envelope including block-work, mortar joints and structural frame individual insulation blocks in order to investigate thermal bridging for one residential building as a case study. In comparison to the base case, their findings indicated that the effects of thermal bridging (caused by mortar joints and structural elements) increased the total annual energy consumption by 19MWh to 31MWh this is evident in the 78% increase in cooling load, which rose from the 14MWh to 25 MWh. In all three regions of Saudi Arabia, U-value was found to be higher for insulated concrete blocks than the regulatory U-value. However, the heat storage effects in the materials were neglected. However, the inconsistent and diverse methods of measuring energy consumption in this study potentially introduce significant misinterpretations or analytical ambiguities. Additionally, it did not validate the modelling results with measured in-situ energy performance data. Alyami and Omer (2021) focused on how to improve the energy efficiency of an existing building by simulating a case study of a residential building in Saudi Arabia using DesignBuilder software. They found that building insulation has the greatest impact on energy consumption reduction, decreasing annual consumption by 22.8% for walls and 18.4% for roofs. Moreover, they highlighted that to ensure that detached houses are energy-efficient, it is important that energy usage does not exceed 63 kWh/m^2. However, other parameters including traditional passive architectural design parameters were not considered in this study.

The thermal efficiency and comfort conditions of three mosques were investigated by Shohan et al. (2021), along with the impacts of solar radiation on energy consumption. The study utilised Thermal Analysis Software (TAS), physical measurements, and questionnaires to assess actual thermal sensation. In this study, the mosques were found to have high cooling energy levels, ranging from 37 to 55% form the total consumption. This is primarily because the envelope elements are of low quality. They emphasised that the first step in improving the thermal efficiency of the mosque should be to outline and improve the constructional details

of the roofs. However, the study was not evaluated advanced optimisation. Even though, Hamida et al. (2021) study was limited to scheduling the operation of the lighting system, controlling the operation of the HVAC System, replacing the envelope glazing type and sealing air leakages. He employed a BIM-based approach to evaluate the Energy Conservation Measures (ECMs) in a prototypical Government-built educational building located in Dammam city. Additionally, the ECMs were subjected to a techno-economic evaluation. The findings of their study showed that, by completely retrofitting the building examined in the case study, it is possible to reduce energy consumption by approximately 23%. Moreover, it will only take 2.7 years to pay back the initial money required to implement the four ECMs. Thus, investing in these ECMs can be considered a feasible option.

Ghabra et al. (2017) investigated which building envelope features were the most effective in improving energy efficiency in order to determine which parameter has the most significant impact on cooling energy loads for one residential building in Saudi Arabia. The most effective combination to use for a façade is thermal blocks for walls and a 32mm glazing possessing the lowest shading coefficient (0.23). However, the research did not consider the effects of other parameters (such as WWR) and the implementation of other glazing types or shading devices.

Alqaed (2022) explored the use of different facades in different climatic areas (namely, the cities of Jeddah, Abha and Tabuk). Furthermore, the effectiveness of a double-skin façade (DSF) with phase change materials PCM (Materials transmitting solid and liquid phases used in a glass) in reducing energy consumption was also explored for high-rise office buildings. In comparison to standard facades, the application of a DSF with PCM in Jeddah reduces energy consumption by 11.5% during the winter and 5.6% during the summer. Moreover, the use of a simple DSF in Abha reduces energy consumption by 20% in the winter but increases it by 14.5% during the summer. The use of a simple or double-skin DSF in Tabuk city can reduce heating energy demand by 18% and 40%, respectively. However, it might be beneficial to broaden the study's parameters by investigating innovative energy systems, such as active facades or solar skin facades. Alhefnawi (2021) compared the performances of terracotta and aluminium cladding for an educational building in Saudi Arabia and examined the thermal insulation capacities of both aluminium and terracotta cladding materials by using DesignBuilder software as a simulation tool. The study results show that the terracotta material

is much more effective in reducing cooling than heating loads (15.6% and 5.4%, respectively). Additionally, the thermal insulation performance of the aluminium cladding is much more efficient in the summertime. Terracotta was also found to be more efficient than aluminium in reducing total energy consumption (12% and 15.6%, respectively). However, the study did not assess the life cycle analysis (LCA) of the terracotta or aluminium cladding materials.

The effects of glazing on wall ratios in different microclimatic areas of KSA were explored by Alwetaishi (2019), in order to determine the best possible glazing ratio for a school building. Percentages of 5%, 10%, 20%, 30% and 40% for the external wall were employed using TAS EDSL computer modelling. The findings showed that the glazing systems in the cities of Riyadh and Jeddah were the worst in terms of overall heat gains. Furthermore, the use of a 20% glass to wall ratio in Riyadh and Jeddah will ensure that the indoor air temperature is maintained at 37-38 degrees in summer and 26-34 degrees in winter. It is recommended that a 10% glazing-to-wall ratio is recommended in both hot/dry and hot/humid regions.

Alaidroos et al. (2022), developed a new demand control ventilation (DCV) system for a mechanical ventilation (MV) system. Additionally, examined possible ways of maintaining adequate indoor air quality whilst simultaneously reducing cooling energy demands for a school building. The difference between (MV) and (DCV) ventilation rates resulted in a 17% reduction in cooling energy end-use. In comparison to traditional mechanical ventilation systems, the (DCV) can maintain acceptable IAQ while using less energy. However, the solution suggested is a near-optimal solution that is difficult to implement in real life.

The advantages and cost-effectiveness of advanced thermostat implementation for a residential building were examined by Krarti (2020). In addition, several different occupancy-based temperature controls were examined in terms of their suitability to the living styles of Saudi citizens. Even though the behaviour of occupancies was not considered in depth, he stated that occupancy-based thermostat settings can reduce the annual electricity consumption of houses in Riyadh by 38.7%. Moreover, spatially adapting the indoor temperature settings can reduce peak demand by 34.7% in most parts of Saudi Arabia and smart thermostats can cut the sum annual electricity consumption by 48 TWh/year.

Aldubyan and Krarti (2022) examined the effects that the COVID-19 stay-at-home period had on the energy consumption of residential buildings in Saudi Arabia. The study found that the average increase in electricity usage during the 2020 stay-at-home period (15th March-

15th June) was calculated to be 25.4% higher than the same period in 2019. They recommended that replacing the AC system seemed to have the greatest impact, saving 23.5% and 32.0% when Saudi Energy Efficiency Ratio 12 (EER-12) and (EER-13) units are installed, respectively. In addition, lighting and appliance retrofits can cut total electricity usage in Saudi homes by 13.3% and 9.2%, respectively. However, this study was limited to the evaluation of electrical device consumption such as lighting, air condition units and appliances.

Mohammed and Budaiwi (2013) evaluated the energy performance of a student canteen at King Fahd University in Saudi Arabia and its possible energy-saving benefits. They focused on the lighting system operation schedule, HVAC system operation schedule, glazing, insulation, and equipment efficiency. Found that if all relevant energy conservation measures are implemented, total energy consumption can be reduced by 27.4%. Meanwhile, the implementation of the HVAC system can save 10.6%, whilst standards can save around 16.7%, lighting saves 6.6%, equipment saves 2.6%, insulation saves 2.5% and glazing can save 1.4%.

Alshamrani et al. (2022) identify the factors impacting carbon costs and operational energy in 77 family houses. Additionally, the average monthly energy and carbon costs of these houses were estimated. The quantitative approach was used as a multiple-regression-based model to predict the monthly energy footage and associated carbon costs. They found that triple-glazing windows can generate a 36.2% cost reduction in comparison to single-glazed windows. Additionally, this cost can be further reduced by 4.1% if precast concrete panels are used instead of clay blocks, whilst the implementation of a split AC system can reduce the cost by 46.0% in comparison to a central AC system. A 30.7% cost reduction can also be achieved by implementing an LED lighting system rather than common systems. In general, the findings revealed that there are several factors that can impact the model's prediction of energy and operational carbon costs, including central air conditioning, building area, building age and number of users. However, this research only examined the relationship between parameters (predictors) and predicted monthly energy and carbon costs yet did not carry out simulations or implement advanced optimisation algorithms. What's more, the study did not take into account the Life Cycle Analysis (LCA) model for economic analysis.

Elnabawi (2021) assessed the effectiveness of Gulf Cooperation Council (GCC) energy consumption and carbon emission reduction measures for a typical Bahraini residential building. Additionally, the long-term economic viability of these measures was examined by

calculating the annual energy consumption savings, optimal cooling load reduction, payback time and building's life cycle. Energy consumption savings were found to be as high as 23.6% in Dubai, whilst it typically varies between 22.7% and 53% in Oman and between 22.7% and 39.5% in Saudi Arabia. However, this can only be achieved if building codes are accurately analysed and applied. Adds, (Abu Dhabi ESTIDAMA 1 code) offered a 29.35% reduction in annual cooling load and a 26.3% reduction in annual CO2emissions; this was followed by the Saudi building code, which recorded a 16.4% lower cooling load and 12.3% fewer carbon emissions.

Ahmed and Asif (2020) examined the techno-economic viability of retrofitting existing homes in Eastern Saudi Arabia and focused on two case studies in which BIM was applied as a retrofit model. They stated that in the Eastern Province of Saudi Arabia, there are eight energy efficiency measures (EEMs) (Cooling set point temperature, Efficient appliances, Efficient lights, Window shading, glazing type, Airtightness, Efficient air condition and Envelope insulation) that have shown great potential to lower energy consumption by 56.9% and 58.54% per year in villas and apartment complexes, respectively. It will take 0.92 years to pay off a level 1 retrofit, 8.37 years for a level 2 retrofit and 25.15 years for a level 3 retrofit. Meanwhile, the payback period for an apartment building was found to be 0.60, 11.28, and 24.60 years, for levels 1, 2 and 3, respectively. Nevertheless, Ahmed et al. (2019) conducted a professional interview and simulation utilising DesignBuilder plug-in Energy Plus to examine the scope of Building Performance Simulation (BPS) in Saudi Arabia's building industry and the potential energy and environmental savings that could be made in a typical home. However, some experts in their survey declined to participate in the study because they "had little knowledge of Building Performance Simulation (BPS). The study showed that at time of study, (BPS) has almost no application in Saudi Arabia's building industry. Nevertheless, altogether, 87.7% of practitioners believed that BPS-based design would generate significant energy savings, with the pre-design and schematic design stages being the most relevant Furthermore, the study indicated that the WWR ratio is important to be less than or equal to 10%, and horizontal shading devices between 0.5 and 1 m in length are recommended. Ultimately, a BPS-based design approach for a case study consumes in this paper 51.3% less electricity than a conventional residential villa.

There are other studies such as Besheer and El-Hamidi (2012) explored general and initial procedures and measures for building a medium-sized residential villa in Saudi Arabia using integrated green building concepts. However, this research did not investigate any energy conservation measures. Moreover, no simulation or advanced optimisation was performed. Additionally, the energy performance of residential buildings in KSA was examined by Al-Homoud and Krarti (2021). Their research examined measures implemented by the government to rationalise energy use across households, and existing studies on the topic have been explored systematically. Nevertheless, the conclusions made in this research about energy efficiency and performance have been around for a long time since it was based on only reviewing the literature.

4.2 CURRENT SAUDI BUILDING CODES AND REGULATIONS.

The Saudi Building Code (SBC) is a collection of legal, administrative, and technical rules and specifications that outline the minimum building construction standards. Alayed et al. (2021) claim that the majority of the existing building envelopes in Saudi Arabia are made from reinforced concrete frames containing insulated concrete blockwork and they fail to meet the U-value specifications outlined in the most recent national building regulations. Nonetheless, new regulations implemented at the start of July 2021 mandate that new residential buildings must adhere to the new Saudi building code.

The Saudi Building Code Energy's Saudi Energy Conservation section (SBC-602) outlines the minimum performance standards for constructing energy-efficient buildings in KSA as shown in Table (4.1) below. These standards focus specifically on designing energy-efficient building envelopes. The Building Code are established to be compatible for three different climate zones of Saudi Arabia as shown in Figure (4.1).

Table 4.1. Energy conservation requirements for Saudi residential buildings.

Item	REQUIREMENTS
Wall Overall heat transfer coefficient (U)	Wall: 0.454/0.511/0.591 for zones 1, 2,3
Roof U value	Roof: 0.272/0.340/0.397 for zones 1 ,2 ,3
Door U value	2.839 for all zones
Window Overall U value	2.668 for all zones
Window type	Aluminium frame with thermal breaks or PVC
Glass type	Double glazed with 12mm air space
External Colour	Light
solar heat gain coefficient (SHGC)	For all zones ≤ 0.25
surface reflectance index (SRI)	Light colour with SRI≥50
Water absorption for insulation materials	≤0.3%
Continuous insulation	Continuous across all building envelope
Ventilation	54.5L/s
Infiltration in fenestration	≤1.5L/s/m2
Infiltration in floors	≤2.5L/s/m2
Lighting power density	10W/m2 ground floor, 6 W/m2 first floor
Equipment power density	2.0kW ground floor,1.0kW first floor
Vertical fenestration area	≤25% of the wall area
minimum energy efficiency ratio,	≥11

(SORCE: Saudi Energy Efficiency Centre, SBC 602).

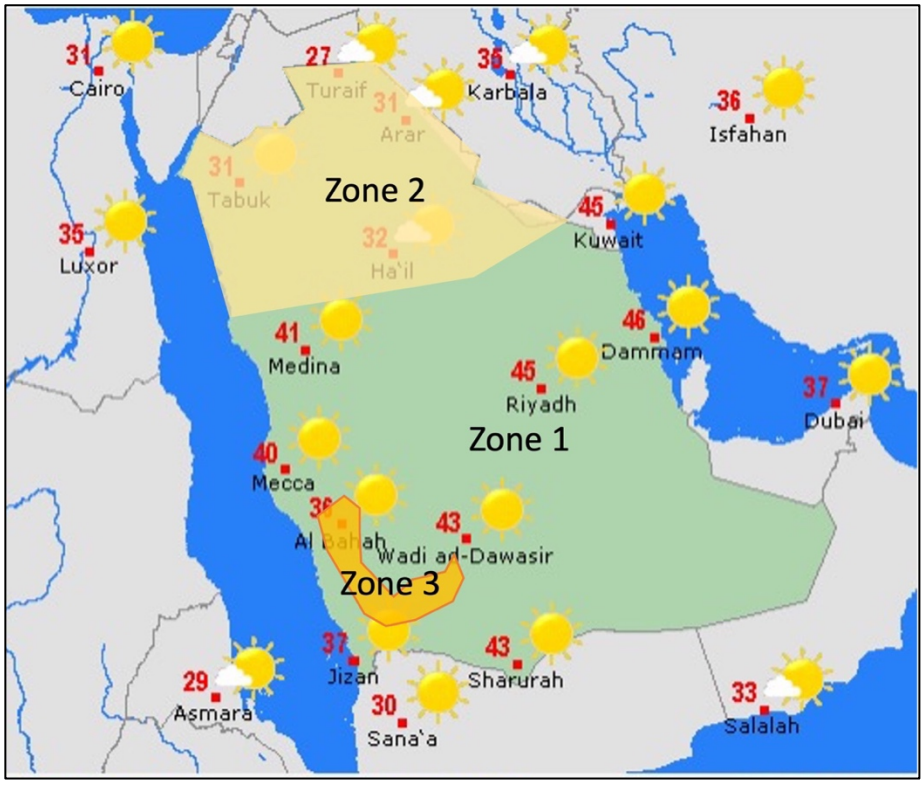


Figure 4.1. Climate Zone Map of the Saudi Building Code.

Furthermore, the Saudi Government established the "Mostadam" comprehensive sustainability rating and certification system to improve the long-term sustainability of residential buildings throughout Saudi Arabia (KSA). Mostadam is designed to achieve the goals of Vision 2030 and covers various sustainability issues relevant specifically to Saudi Arabia. Additionally, to ensure even greater sustainability for Saudi buildings, "Mostadam" is developed in alignment with the SBC and goes above and beyond the minimum SBC requirements. Alardhi et al. (2020) point out that adhering to the SBC-602 requirement for buildings in Riyadh (located in zone 1 of SBC-602) can save as much as 17% of total electrical energy consumption for an entire building when the air conditioner is set at 25 C instead of 18 C. Moreover, Almasri et al. (2021) strongly advised that the SBC-602 code be fully applied when constructing new buildings in zones 1 and 2.

Thus, one of the most effective and efficient methods of reducing total electrical energy consumption in Saudi buildings is adhering to the Up-To-date energy conservation requirements of the Saudi Building Code. However, integrating a number of traditional passive strategies aforementioned for minimising energy consumption with these energy conservation measures would also be highly beneficial.

4.3 IMPLEMENTATIONS OF THE LATEST GREEN INNOVATIVE SOLUTIONS.

Even though the building industry plays a critical role in the development of the wider economy, the use of innovations to conserve energy in this sector is a complicated process. All construction sites are different, and thus designers, architects, and engineers have to modify their processes to suit the needs of each individual project. Moreover, each site in itself is a singular prototype with a configuration that can change over time. For example, Agostinelli et al. (2022) used Renewable Energy Systems (RESs) to create a number of energy-saving processes and integrated production systems to promote sustainable mobility in Anzio port. In this project, they used LED lights to replace the older, energy-consuming floodlights located in light towers in order to minimise energy consumption. Additionally, they set up solar and wind energy sources. Despite the fact that the study's energy consumption load was restricted to lighting and charging systems, they still reduced lighting energy consumption by approximately 65% compared to the previous state. What's more, on-site wind and photovoltaic systems (PV)

provide all of the annual energy required in the port area. The Anzio port area uses a total optimising electrical load of 219,755 kWh per year. Although the yearly energy production by RESs (PV 186,254.63 kWh annually and wind turbine 36,300 kWh per year), the energy contribution made by wind turbines is much lower than solar energy sources.

Balabel et al. (2022) examined the different applications of Solatube daylight systems by referring to existing case studies in different countries. The findings revealed that Solatube technology can reduce energy consumption in Saudi Arabia by around 20–30%. Nonetheless, it is important to note that this investigation was limited to the description of Solatube technology as passive daylight and no simulation for energy performance was carried out.

Gassar and Cha (2022) carried out a study to investigate solar photovoltaic panel installations on the roofs of medium-sized multifamily resid in 17 different areas of Korea with different climates. They also examined the incorporation of bio-phase change materials (PCMs) in internal sections of the design envelopes in a low-energy, medium-sized multifamily building. Their findings indicated that roof-based solar photovoltaic panels generate 30–44% of the total annual electricity consumption needs for each medium-sized multifamily residential building in Korea. Moreover, the integration of BioPCMs into internal sections of the building envelopes was found to reduce household electricity consumption (for cooling and heating) by 5.81-6.71% in Korean medium-sized multifamily residential buildings (in order words, 8153.30 to 11110.66kWh). Thus, the energy-generation methods discussed above can contribute to approximately 35.03% to 49.78% of annual household electricity needs. Nonetheless, it is important to note that the annual energy in this work was based on estimated.

Kim and Im (2021) used a new building-integration photovoltaic (BIPV) curtain wall to achieve net-zero energy retrofitting, believing this to be a sustainable alternative to traditional windows in three different cities, the first of which is Miami, Florida (which is hot), the second is Charlotte, North Carolina (which varies between hot and cold), and Minneapolis, Minnesota (which is cold). Their findings indicated that, in buildings with a 3:1 ratio, the use of a BIPV curtain generally offsets between 20 and 30% of total energy consumption and intensity demand. Moreover, roof-installed PVs were found to reduce total energy use intensity from 10% to 150%, depending on the height of the building height. Meanwhile, in buildings that have a 2:1 ratio for the building to façade area, BIPV curtain walls contribute between 30 to

60% of the total energy use intensity demand, whilst roof-installed PVs can reduce total energy use intensity by <5% to 50%, according to the height of the building. Similarly, BIPV curtain walls generate between 40-65% of the total energy use intensity demand for buildings with a 1:1 ratio for building area to façade area and roof PVs can generate a <1% to 20% reduction in total energy use intensity, according to the building's height.

Hemaida et al. (2021) examined the relationship between energy loads/daylight performance of an office building and control transmittance in order to determine the efficacy of polymer dispersed liquid crystal (PDLC) windows in London and Riyadh (2021). They employed the Grasshopper tool plug in EnergyPlus and the 3D modelling programme Rhinoceros in their study. The findings indicated that operating the (PDLC) window in Riyadh at a minimum temperature of 4°C reduced the annual cooling load by 12.8%. The annual heating load was also reduced by 4.2% in London when the (PDLC) window temperature was set at 20°C. In addition, it was found that the application of solar radiation control in the (PDLC) window enhanced the building's daylight performance by 75.8% in Riyadh and 63.06% in London. In Riyadh, the (PDLC) window generated a 100 W/m^2 reduction in annual energy usage in response to solar radiation, whilst this reduction was 500 W/m^2 for the city of London.

Thus, there are many different forms of sustainable green engineering solutions depending on where and when they are examined. Moreover, technical innovations (such as type of glazing, solar panels, lighting systems, etc) enable the achievement of developing environmentally friendly, healthy, and low-carbon buildings that are thermally comfortable.

4.4 RENEWABLE ENERGY SOURCES

According to Clark (2018), the most common renewable energy sources at present are wind, sun, water systems, digestive processes that convert waste into biomass and waste recycling for fuel generation. Other examples of renewable energy sources include geothermal energy, "run of the river streams," and bacteria and algae. However, Medved et al. (2019) stated that "renewable energy sources are constantly generated in the environment by natural processes and contain different forms of energy as the results of the transformations of the following primary energy sources":

• The solar energy that reaches the surface of the earth through an electromagnetic radiant flux emitted by the sun's photosphere. In essence, solar energy is converted into environmental heat, waves, wind, biomass and hydro energy.

• Gravitational or planetary energy is produced through the interactions between gravitational and centrifugal forces of the earth, sun and moon, which generate periodical changes to kinetic energy in water reservoirs, thus producing tidal energy.

• Geothermal energy is an energy source that transfers heat from the earth's core. It is continually produced in the form of geothermal energy by the nuclear decay of radioactive chemical elements (e.g., thorium and uranium).

Nonetheless, even though these systems produce electricity, none of them can be considered to be as affordable as current fossil fuels (i.e., oil, coal, and natural gas). They also generate low-density energy. It is critical that renewable energy sources are incorporated as connected or bundled supply sources based on the local environment in order to maximise the efficiency of renewable energy sources. Even though, the sun does not shine at all times (particularly at night) and the wind is not always strong, these intermittent power generation resources can benefit significantly from the addition of storage devices (Clark 2018; Medved et al. 2019). The potential of renewable energy, as well as the global and domestic impacts of such energy sources, will be critically assessed in the next two sections.

4.4.1 Global Renewable Energy sources

In decarbonisation methods designed to reduce the negative impacts of climate change, renewable energy is essential (Bush 2019). Renewable energy reduces the environmental impact and avoids reliance on the supply of fossil fuels (Syahputra and Soesanti 2021). Thus, given their role in sustainable development, renewable resources (i.e., solar energy) are gaining increasing attention from academics and researchers (Zazoum 2022; Khan and Arsalan 2016). The International Energy Agency estimates that capacity additions for solar PV increased by 17% in 2021, despite the rise in manufacturing costs resulting from increasing commodity prices. Nonetheless, Solar PV is emerging as the most affordable solution for generating electricity around the world, and this is expected to spur investment in the upcoming years. Today, a number of countries (including China, the EU, the USA and Brazil) have established ambitious goals to further develop solar energy (Sun et al. 2022). The sheer amount of solar

radiation available will facilitate the application of photovoltaic panels and solar collectors for generating electricity and energy. This also helps to compensate for the shortage of traditional energy sources (i.e., oil, coal, and gas). Additionally, this will slow down the continuous rise in carbon dioxide levels, which contributes to global warming and other negative environmental effects (Kassem 2020). However, Sharma et al. (2020) state that, in addition to many other factors (i.e., the clearness index, surface direction, turbidity coefficients, and angle of inclination), the levels of solar energy that strikes a particular surface are also influenced by the climatic features of the local area. The ideal incline angles of solar collectors and panels must thus be determined separately for each location. A number of variables can impact how much electricity is produced by PV modules. Some of these factors (i.e., location, size, quantity, and effectiveness of the PV modules used) are design variables, whilst others (such as the day duration and climate), are site-specific variables that are uncontrollable (Vahdatikhaki et al. 2022).

The use of PV modules in buildings has thus been extensively researched. Researchers from all over the world have turned their attention toward investigating the renewable energy benefits of installing solar rooftop panels. Building-attached PVs (BAPVs) and building-integrated PVs (BIPVs) are the two main categories of PV systems used in building applications. BAPVs are an addition to a building structure; they have no immediate impact on its structural capabilities. A photovoltaic system that is integrated into the building envelope and is a part of the building structure is referred to as a BIPV (Ghosh 2020).

Nonetheless, solar rooftop panels can change the interaction that takes place between the roof surface and its surroundings, which it converts into energy to meet the requirements for heating, ventilation, and air conditioning (Albatayneh et al. 2022). Therefore, the incorporation of PV into building windows or glazed façades to generate aesthetically attractive building features is becoming more and more popular (Makrides et al. 2010). Additionally, the thermal performance of rooftop PV as a shading component on uninsulated roofs and the HVAC energy consumption of buildings located in moderate dry to warm areas have been examined by Albatayneh et al. (2022). The findings suggested that PV roof structures generated a 10.87% decrease in heat gain during the summer and a 3.8% increase in heat gain during the winter. During the summer, there was a reduction in the indoor electricity demand, whilst the demand for indoor heating during the winter increased.

The ability of the solar cooling system to meet the summer energy needs of a building situated in a Mediterranean region was examined by Bilardo et al. (2020). The latter researchers designed a dynamic calculation model, examined the energy performance and contrasted it with conventional systems. Subsequently, they performed an economic analysis of the solar cooling system's investment, energy, operation, and maintenance costs. This enabled them to come up with an ideal design that increased the renewable energy ratio to 83% whilst simultaneously reducing the initial non-renewable primary energy demand by 48%. The findings indicated that the suggested approach could help constructors to make important design decisions in this area and that solar cooling has the potential to help achieve the NZEB target in light of future climate change and the evolution of building energy requirements.

Huang et al. (2022) carried out an interesting academic study to examine how peer-to-peer solar PV energy trading was performed in a local community in Sweden under simulated future climate change situations. There are four contrasting scenarios with various PV ownerships and pricing plans. In this study, the energy trading performances of four comparative scenarios (i.e., PV power self-sufficiency, cost savings, revenues, and compound annual growth rate) are analysed and contrasted based on present and future climate conditions. The findings of this study indicated that future climate change will be more beneficial to large energy-use households, but not so advantageous for smaller households. The fairness of economic performances in the community can be enhanced by placing high prices on energy trading, particularly if the households do not own PVs. This study provides an insight into the future climate impacts on the energy-sharing performances of building communities. In turn, this can help those responsible to make decisions to install PV ownership and understand how future climate change will impact different households.

Consequently, the key benefit of solar energy is that it is a clean, renewable source of electricity. Additionally, solar energy can be scaled up, meaning that it could be used to power a single building or be implemented on a district scale. Extra electricity can then be fed back into the grid or stored in a battery when used on a smaller scale. In general, the sun produces far more energy than we will ever require. Thus, it is just our capacity to efficiently convert it into electricity that limits its potential at present.

4.4.2 Renewable Energy in Saudi Arabia

A number of different renewable energy solutions for residential buildings were examined for five locations in KSA by Al-Douri et al. (2019). They emphasised that solar energy is considered to be the most effective power generation method. It is also the cheapest and most readily available energy source for applying, converting, and investing in electric planning projects. However, Makki, Mosly (2020) determined the most important factors influencing individuals' willingness to embrace Renewable Energy Technologies (RET). The finding clustered all factors into five main components they are cost and government regulations and policies, public awareness and local market, environment and existing infrastructure, specification of residential buildings, and localisation of RET manufacturing.

Alyami et al. (2021) examined a number of different green building solutions. An auxiliary holistic framework was employed to explain how green practices (i.e., Zero Energy Buildings ZEBs) can be developed in Saudi Arabia without damaging the local environment. They stated that natural ventilation, thermal mass, daylight, cavity walls, double-glazing, and solar panels (PV) are important green-building concepts that can be employed when designing and operating buildings in hot, dry climates. In addition, the most efficient method for achieving ZEB in their case was the installation of PVs on 60 m^2 of the total roof area, which can reduce their energy consumption by as much as 75%. The employed simulation tool in this study was Integrated Environmental Solutions-Virtual Environment (IES-VE).

Therefore, since the literature has confirmed that solar energy is the most applicable renewable energy source in Saudi Arabia, the following will critically discuss the recent academic work within the field.

Alqahtani and Balta-Ozkan (2021) used HOMER Pro software to compute the Net Present Cost, Levelized Cost of Energy, orientation of PV panels, and optimum PV system size. To study a techno-economic framework for rooftop PV with battery storage facilities that were examined in terms of its effectiveness in existing building types that are most likely to be constructed in the city of Neom. Furthermore, the optimal PV size, optimal PV panel orientation and battery storage capacity were assessed. They found that the ideal size for PV systems in the villa is 14.0 kW, 11.1 kW for the conventional dwelling, and 10.3 kW for the apartment, each with a single 12 kWh battery. Additionally, a south-facing panel with a tilt angle of 28 was found to be the most effective PV orientation. However, at time of the study,

was not commercially feasible for the first 6000 kWh/month consumed because the tariff produced negative Net Present Cost (NPC) and a Discount payback period (DPBP) values that surpassed the project's lifespan. Asfour (2018) examined the employment of building-integrated photovoltaics (BIPVs) for an office building to serve as shading devices (vertical and horizontal) in hot climates as well as (BIPV) inclination angles of 0°, 30°, 45°, and 60°. He found that on the eastern, southern, and western facades, the BIPV horizontal shading device (H-SD-45) received the largest amount of annual total solar (104 kWh/m2). Moreover, horizontal shading devices can be applied to the eastern and western faces of buildings located in places with high solar altitudes (i.e., Saudi Arabia) to generate electricity and provide window shading.

Additionally, Zubair et al. (2018) examined the use and effectiveness of photovoltaic arrays in electrical power generation on the rooftop of the College of Engineering Building in Majmaah City. This research showed that the most effective PV arrays are tilted PV arrays that provide electrical energy at a high-capacity factor while simultaneously saving building cooling energy by shading the rooftop. This produces a 13.97% reduction in cooling load. With a capacity factor of 22.8% and diffuse shading of 1.47%, 1720 PV panels spaced 1 m apart will produce 1444.845 MWh of electrical energy from 4859 m² of roof space. The annual output of PV per panel is 394.7 kWh/m^2, which is increased to 430.8 kWh/m^2 by including the benefit of reducing the building's cooling demand.

Krarti and Aldubyan (2021) outlined the key features of prototypical housing units and examined the effectiveness of renewable power systems in achieving carbon neutrality. They found that by reducing the electrical loads for communities through the implementation of energy-efficient activities in individual housing units, the cost-effectiveness of carbon-neutral communities can be greatly enhanced. In fact, this can generate a reduction in construction costs of more than 50%. Moreover, annual energy demands can be reduced by 51%, the quantity of PV required to achieve carbon neutrality can be reduced by 66%, and the number of wind turbines can be reduced by 50%. Nonetheless, the costs associated with installing PV arrays must be at least 35% lower than the reference costs to ensure that they are cost-effective ways of creating energy-efficient communities in Riyadh.

Dehwah et al. (2022) evaluate the possibility that an old Saudi Arabian village can be converted into an efficient and high energy performing hotel. To redevelop the village, energy efficient systems for lighting, appliances and even HVAC systems must be installed. By utilising

DesignBuilder plug-in Energy Plus they found that the ancient village's total annual energy consumption was found to be reduced from 778 MWh to 356 MWh (54%). They add that by implementing a fixed PV system that operates at a capacity of 206 kW on-site, it is possible for the retrofitted village to achieve net-zero energy status. However, it is important to note that population sizes and energy generation were not sufficiently investigated in this study.

Aldabesh et al. (2021) study was aimed to investigate tailored optimisation solutions that address the specific climatic conditions of the case at hand in KSA. Moreover, it aimed to identify ways of maximising the energy efficiency of the problematic building envelope elements and translating the Saudi Building Code (SBC) requirements into an ideal building model. They stated that the only method that was found to be individually capable of meeting the energy target was the rooftop PV system. Nonetheless, this tool was considered to be highly effective because it has excellent energy-generation capacities and can enhance the general effectiveness and performance of the retrofit packages. Almasri et al. (2021) examined the effects of energy efficiency and renewable energy measures on Saudi Arabia's energy demand. Moreover, economic feasibility analysis was carried out on different types of thermal insulation, including connected solar PV. OpenStudio Software and RETscreen 6.1 software were used to design a PV system. They found that the proposed PV system should generate annual electricity of 30,348 kWh/year in Riyadh, 31,485 kWh/year in Hail, and 32,476 kWh/year in Abha. In addition, when the SBC-602 thermal insulation standard is applied, the capital cost of the PV system covering may drop by as much as 296% in Riyadh, 251% in Hail, and 142% in Abha. However, as all of the materials will be acquired in the first year, the LCC of thermal insulation will equal the capital cost. As opposed to the LCC of a PV system, no maintenance or operational costs are acquired during the project's lifetime.

Aldossary et al. (2014) carried out a case study in Jeddah to investigate energy consumption for three typical houses and three typical flats in hot and humid areas of Saudi Arabia by focusing on shading devices, domestic renewable energy sources and glazing using a computer simulation software (IES-VE). They stated that each property has a potential annual energy consumption reduction capacity of 21-37% by implementing the different types of mentioned energy conservations. However, PV has the potential to generate 8016 kWh of power per year for houses (A) and (B), whilst this is 20,842 kWh per year for house (C). In turn, this contributes to 12% of house A's electricity demand and 24% for houses (B) and (C). PV will

produce around 5344 kWh of energy for each apartment per year, which accounts for 21% of the apartments' total energy demand. Mesloub et al. (2020) evaluated the effects that energy performance and visual comfort have on the retrofitting of photovoltaic integrated shading devices (PVSDs) to the façade of a prototype office building in hot and humid, desert-like regions. Suggested that not only did the unfilled egg-crate PVSD show the greatest conversion efficiency (20%), but it also produced extra energy. This is a critical feature in Saudi Arabia's hot and dry desert areas. However, Life Cycle Costs and economic feasibility of the suggested device in this study were not considered.

In the study of Alrashed and Asif (2015) five zero-energy homes around the world developed in climates similar to those in the five main climatic regions of Saudi Arabia were compared. The Saudi locations examined in this work have greater potential for solar energy generation than their global counterpart areas. For instance, in Dhahran, Guriat, Riyadh, Jeddah, and Khamis Mushait, the annual energy consumption was found to be 135, 98, 119, 170, and 61 kWh/m^2, respectively. On the other hand, these values were found to be 50, 51, 53, 18, and 33 kWh/m^2 for the areas of Borrego Springs, Tucson, Phoenix, Lake Bennett and Cupertino, respectively. Notably, the design of the virtual house was on basis of a questionnaire survey and using Computer simulation (IES-VE). They concluded that, although energy consumption in Saudi cases was nearly double that of their international counterparts, the development of zero-energy homes (ZEH) in Saudi Arabia using solar photovoltaic (PV) technology is a feasible solution.

In light of this, solar energy is the most promising renewable energy source for Saudi Arabia. Solar energy can be a significant source of renewable energy in Saudi Arabia due to its high average annual solar irradiation more than (2000 kWh/m^2), as was already mentioned. In addition, in order to offset the energy use of a building in KSA, building rooftops have greater advantages for PV installations than building facades, taking into account the appropriate orientation and inclination angles.

4.5 SUMMARY AND IMPLICATIONS

As a result of the work carried out in relation to the literature review in chapters 2,3, and 4 and how that connects with the aim and objectives of this research project. It is evident that the three fundamental elements of the sustainable approach, with respect to the sphere of residential buildings within the Kingdom of Saudi Arabia (KSA), should be taken into account when designing a building while climate effects and energy consumption serve as the focal aspects. Furthermore, the field of traditional passive architectural design, together with the elementary understanding of the behaviour and thermal comfort of a building, provides an opportunity for notable characteristics which could contribute to making the designs work successfully in relation to a building that offers appropriate thermal comfort with the least possible energy usage and greenhouse gas (GHG) emissions.

Furthermore, diminishing energy consumption can be enabled to a great extent via the adoption of energy-efficient measures which should take into consideration the efficient building regulation codes and the newest innovations in the field of green engineering solutions. In addition, solar energy should be considered a renewable source of energy with the greatest potential for use in KSA, as the sun generates more energy than consumers are likely to need. The promise of solar energy is simply restricted by the technical ability to transform it into electrical energy.

Therefore, extremely sustainable techniques of building are enabled by undertaking the design in line with the three fundamental pillars of sustainability—social, economic, and environmental—through the integration of the optimal characteristics from traditional passive architecture design and low-carbon technologies while ensuring the utilisation of the latest energy efficiency measures. Hence, all the aforementioned aspects represent solutions from the field of green engineering. Consequently, in light of the aim, objectives, and literature review outcomes, Figure (4.2) below illustrates the guidelines of the current research project. Furthermore, the concept associated with the final layer in the schematic presented below would be thoroughly analysed in Chapter 7, which addresses modelling and simulation.

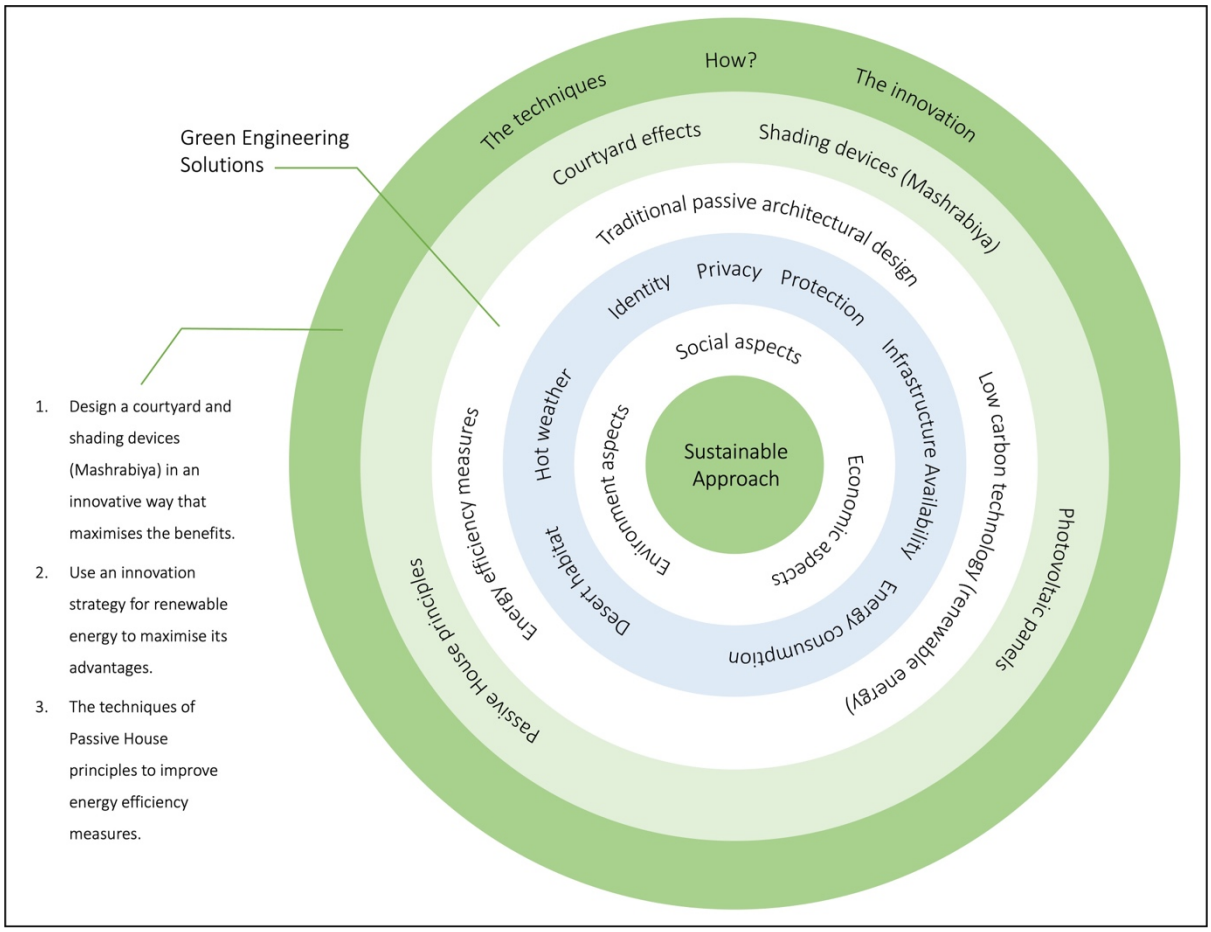


Figure 4.2. The Current Research Project Guidelines.

Chapter 5: Research Design

The present research topic is extremely unpredictable in nature, and thus the methods and processes available to researchers can be applied and combined to generate an overall methodology. Kumar (2007) explained that, before choosing a methodology, it is critical that researchers fully understand the strengths and weaknesses of different philosophies, strategies, and research approaches. Moreover, they must carefully plan the research methodology based on the needs and requirements of the research subject. This is critical because no two issues, phenomena, or contexts are ever the same (Echambadi et al. 2006). Glaser et al. (2005) also highlight the importance of researchers providing a comprehensive overview of the methodology that they have chosen, along with a detailed explanation for their choices. Ultimately, in order to ensure that the research project generates new, valid, and reliable information, intense engagement with the theory surrounding research methodologies must be combined with a rigorous consideration of the unique requirements of the research subject.

Therefore, this chapter discusses the philosophies and hypotheses guiding the research design to achieve the aim and objectives of this research that are outlined in Section 1.3. First, Section 5.1 discusses methodological frameworks and research within the field of architecture, as well as the evaluation and justification for selecting simulation software from the available options. Following this, Section 5.2 addresses the current research philosophy, while Section 5.3 presents the research approach. Furthermore, the justification for the chosen methodology is provided in Section 5.4, and the research strategy is illustrated in Section 5.5. The timeline for this research project is detailed in Section 5.6, and ethical considerations surrounding the research are highlighted in the Section 5.7. Finally, section 5.8 summarises the research design, outlining the methods, data collection, and analysis used in the study.

5.1 METHODOLOGY AND RESEARCH DESIGN

5.1.1 Methodology

Although there are many different methodological frameworks that can be applied to guide a study i.e., Crotty's (1998) research design elements (see Figure 5.1. a)., Kagioglou et al.'s (2000) nested research model (see Figure 5.1. b), and Saunders et al.'s Saunders et al. (2003-2019) Research Onion), the researcher has chosen to employ Saunders et al.'s (2019) Research Onion in this research project (see Figure 5.2). Based on key principles underpinning the research onion, the research philosophy, approach, time horizon, methodological choices and research methods will be presented below. Furthermore, the data collection procedures, analysis methods, and techniques adopted in this research were thoroughly discussed in the associated chapter where they are used.

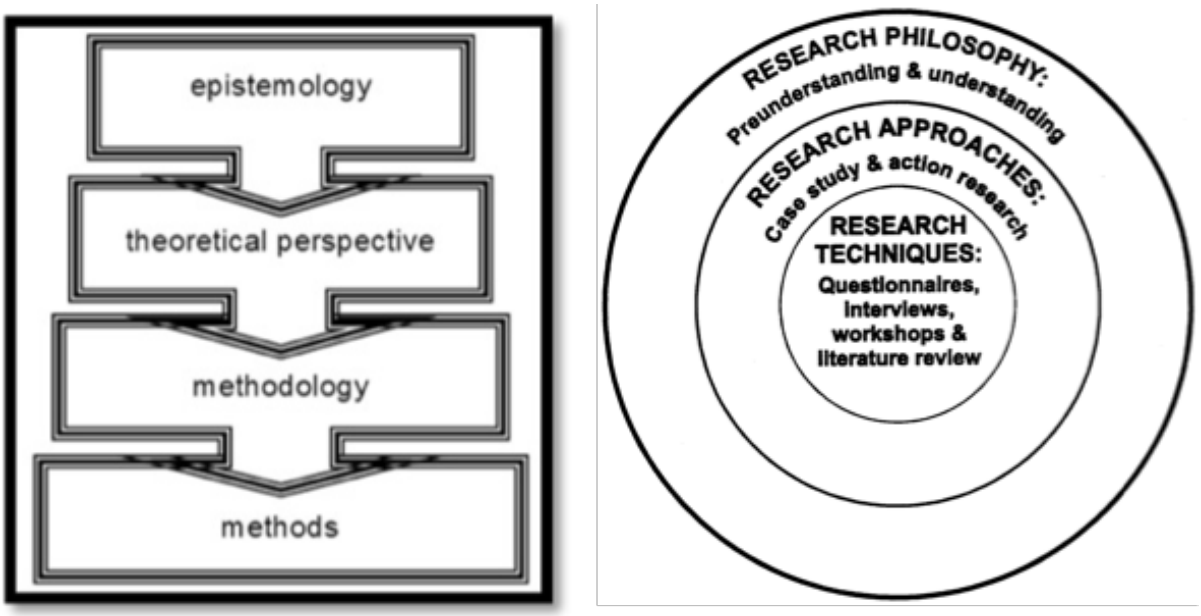


Figure 5.1. a Lift. The Four Elements of Crotty (1998) As Part of Research Elements. b Right. Kagioglou et al.'s (2000) Nested Research Model.

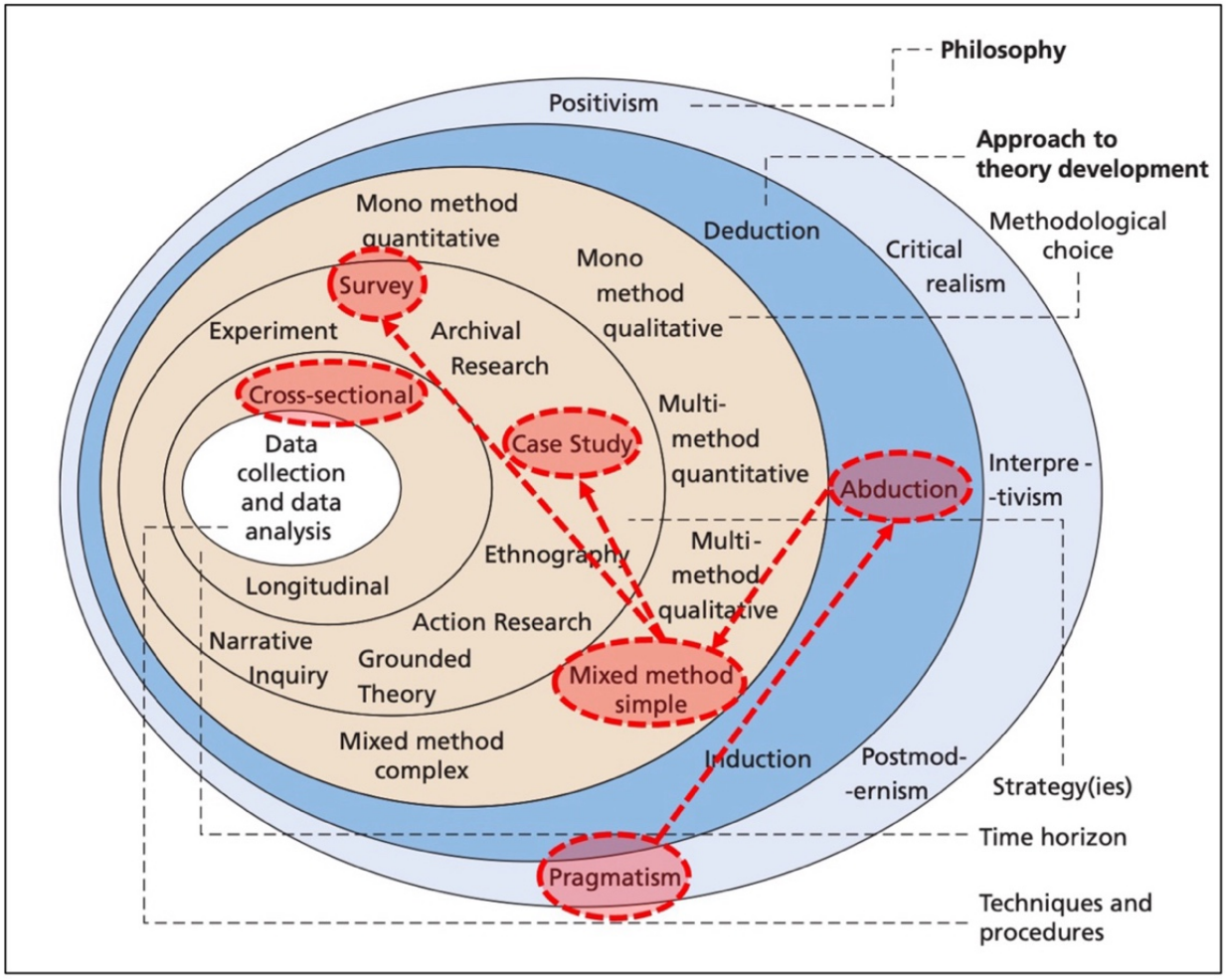


Figure 5.2. Saunders et al.'s (2019) Research Onion with A Mark-Up of the Present Methodology.

5.1.2 Research in the Field of Architectural Design

Architectural design research refers to processes and research findings involved in architectural projects and the wider contributions to design thinking, which is a key component of a process that also involves more generalised research activities such as writing, thinking, testing, verifying, debating, disseminating, performing, and validating (Fraser, 2013,). Additionally, Niezabitowska (2018) points out that social sciences, in addition to sustainable development concepts and information technologies have had a significant influence on the development of architectural design research (environmental sociology and psychology). Graff (2021) asserts that the primary objective of architectural design research is to determine how anticipation and experience interact during conception and perception, as well as to envision

the innate qualities and potential of the process and disseminate information. Over the last three decades, computer-aided simulative research has evolved as a research and design tool in the architectural field, according to Niezabitowska (2018). It is very effective and makes an architect's research easier. It also facilitates big, radical, and important design modifications and can also be used for quality assurance (e.g., energy saving, ergonomics, conformity with the rules).

Simulative research employs a variety of tools to assess variables and create measures that explain the reality of the phenomenon in question in quantitative terms. They also provide answers to the "what," "how much," and "when" questions. According to the aforementioned philosophical concepts, architectural design research is a thought process that combines the advantages of various disciplines.

5.1.3 Buildings Performance Simulation Tools

Globally, there is a current trend towards energy conservation and efficiency. Thus, key and fundamental tools used in the design include building performance simulation (BPS) software packages (Nadarajan and Kirubakaran 2016). These facilitate decision-making, design and engineering aspects thus increasing the comprehension of the likely performance and costs pertaining to a specific build. Sample parameters acquired from BPS analysis encompass thermal comfort, energy performance, carbon dioxide emissions, energy expenditure, energy assessments and the life cycle of the building. Although architects have to make an initial choice, additional difficulties pertain to the ability of the specialists to maximise the output of BPS, which is complicated to utilise and necessitates training and precision in the entered data in order to ensure that the output is close to real life contexts.

Computer-based tools exploited for the design of constructions can be classified as either computer-aided documentation, design and drafting, or computer-based simulation (Hong et al. 2000). The former is an application for individual computers and facilitates the development of technical plans and drawings; it is frequently employed by designers. Computer-based simulation frequently includes the application of engineering systems in order to calculate envelope and space heat increases and loads, respectively, to forecast the edifice’s energy

performance, and to offer a diagnostic process which facilitates automatic system regulation and plant operation.

Thus, in order to maximise the content of the output, the two application types should be used in concert; although the output of designers is assisted by the first, it has a minimal effect on the efficiency of building whereas the latter software application facilitates the enhancement of the building's efficient energy consumption. At present, there is no stand-alone BSP that can engage in all types of project simulation.

From the user's perspective, there is a triad of elements that should be taken into account, i.e. need or purpose, budget and facility availability. It is therefore key to comprehend the type of issue for which a solution is required from the software. There is a necessity to have sufficient financial resources for software procurement, maintenance and usage, and potentially for a digital platform on which the BSP tool can run, although it might be prudent to choose a package that can be uploaded to a current computer setup. Additionally, monies may be required for personnel training.

Twenty recognised BPS for constructions noted in one report included: EnergyPlus, IES <VE>, BLAST, Energy Express, BSim, DeST, DOE-2.1E, Ener-Win, Energy-10, PowerDomus, eQUEST, ESP-r, IDA ICE, HAP, TAS, HEED, SUNREL, TRACE, ECOTECTand TRNSYS (Crawley et al. 2005). A further publication (Al Ka'bi 2020) suggested that the most frequently utilised softwares were: EnergyPlus, DesignBuilder, eQUEST, IDA-ICE, IES-VE, TRNSYS, Autodesk Green Building Studio, RIUSKA, Ecotect and VIP-Energy. Absolute comparisons of the various BPS software packages are impossible as they all have their unique benefits and drawbacks. As stated above, the requisites of the project and the abilities of the software should be closely correlated. Four BPS software packages often applied within this context, together with some of their features, are shown in Table (5.1) below. More contemporary versions are likely to offer numerous identical capabilities.

Table 5.1. A Comparison of the Various BPS Software (2023).

Features Based on The Research Requirements		Energy Modelling Software			
		Design Builder	**IES-VE**	**eQUEST**	**TRNSYS**
General Overview	Primary Purpose	Integrated energy, CFD, daylighting, and cost analysis	Detailed building performance & compliance analysis	Building energy modelling	Energy system simulation (HVAC, renewables, thermal)
	Simulation Type	Transient (hourly/daily, EnergyPlus engine)	Transient (hourly, advanced physics-based models)	Steady-state (monthly/yearly analysis using DOE-2)	Transient (time-dependent)
	Software Engine	EnergyPlus	EnergyPlus	DOE-2	Modular (Component-based system)
	User Interface	Graphical 3D modeling	Graphical 3D modelling	Wizard-based (Easy input)	Modular programming based (Requires scripting)
	Software Cost	Paid (Subscription-based)	Paid (Subscription-based)	Free	Paid (Flexible licensing)
3D Building Modelling & Visualization	3D Geometry Support	Full 3D modelling	Full 3D modelling	Limited (Simplified 3D view)	Basic (via TRNBuild)
	CAD Import Support	✓ Yes (SketchUp, AutoCAD, Revit, DXF)	✓ Yes (Revit, SketchUp, DXF, IFC, gbXML)	✗ No	✓ Yes (with plugins)
	Custom Geometry	✓ Yes (Parametric modelling available)	✓ Yes (Full control over custom shapes and building layout)	✗ No (Fixed templates only)	✗ No (Basic box-based modelling)
	Visual Rendering	✓ Yes (Realistic 3D view, shading analysis)	✓ Yes (Real-time 3D building visualization)	✗ No	✗ No
Energy & Performance Analysis	Energy Consumption Modelling	Advanced (EnergyPlus-based)	✓ Advanced (EnergyPlus-based)	✓ Simplified (DOE-2 based)	✓ Highly detailed (Time-step based)
	Heating & Cooling Load Calculation	✓ Yes	✓ Yes	✓ Yes	✓ Yes
	Dynamic Thermal Simulation	✓ Yes	✓ Yes	✗ No (steady state only)	✓ Yes
	Hourly Simulation	✓ Yes	✓ Yes	✗ No (steady state only)	✓ Yes
	Multi-Objective Optimization	✓ Built-In	✓ Built-In	✓ External (MATLAB, Excel)	✓ External (MATLAB, Python)
	Weather Data Support	✓ Yes (EnergyPlus weather files)	✓ Yes (Detailed weather datasets available)	✓ Yes (Preloaded weather files)	✓ Yes (Customisable)
Renewable Energy & Sustainability	Solar PV & Solar Thermal	✓ Yes	✓ Yes	Limited	✓ Yes (Highly detailed)
	Building Integrated Renewables	✓ Yes	✓ Yes	✗ No	✓ Yes
	Shading Analysis	✓ Yes	✓ Yes	Limited	✗ No
Daylighting, Comfort & Indoor Environmental Quality	Thermal Comfort Analysis	✓ Yes	✓ Yes	Limited	✓ Yes
	Air Quality & Ventilation	✓ Yes	✓ Yes	Limited	✓ Yes
	Daylight Simulation	✓ Yes (Radiance-based)	✓ Yes (Highly advanced, integrated with lighting controls)	✗ No	Limited
Compliance & Certification Support	ASHRAE Compliance	✓ Yes	✓ Yes	✓ Yes	✗ No
	LEED Certification Support	✓ Yes	✓ Yes	✓ Yes	✗ No
	BREEAM Compliance	✓ Yes	✓ Yes	✗ No	✗ No

During the conceptualisation stage of this study, a choice had to be made with respect to which BPS software to use; the options were reduced to two packages. i.e. DesignBuilder and Integrated Environmental Solutions-Virtual Environment (IES-VE), The former could be amalgamated with EnergyPlus, which is valuable for 3-dimensional (3D) geometry modelling in construction and energy performance evaluations (DesignBuilder, 2022). A link is available from CAD into the 3D modeller; it additionally can produce reports. Design evaluations can therefore be facilitated through its 3D image rendering ability. A full version of the latter, IES-VE, is available in a less expensive student version. The package offers facilities for sustainable design and energy analysis of constructions (IES-VE, 2022), and includes integral analytical functions which promote ease of modelling and building performance assessment.

However, DesignBuilder was selected as: (i) it is the most frequently utilised BPS software in the United Kingdom (Jentsch et al. 2008); (ii) it is commonly used for research at the University of Nottingham; (iii) it includes swift modelling functionality for constructions and contemporary simulations of energy dynamics; (iv) it offers a broad template spectrum, e.g. localities, climate data, construction models and materials, schedule options, and HVAC and lighting systems; and (v) a user-friendly graphical interface (DesignBuilder, 2022). Overall, the package appeared to be all-inclusive from an environmental perspective and was deemed to have the potential to offer an ongoing and approachable platform for learning, facilitating online training, online and in-person training. There are numerous freely accessible or purchasable online tutorials, some of which can be requested. It appears perfect for the current research project owing to its straightforward interface and geometric modelling facilities, rapid data output and required model scaling for simulations.

5.2 RESEARCH PHILOSOPHY AND PARADIGM

When used in scientific and philosophical research, the term “paradigm” has been defined as a series of related concepts or thought processes. Thus, Munar and Jamal (2016) explain that a collection of theories (or research methods) can be considered a paradigm. Moreover, Burrell, Morgan (2005) point out that paradigms are based on a number of fundamental philosophical suppositions, the first of which is ontological assumptions. Such assumptions relate to a person’s attitudes towards reality and what constitutes it. The second

such assumptions are epistemological in nature, and this concerns an individual's attitude toward knowledge and what constitutes it. Thirdly, methodological assumptions related to individuals' attitudes towards knowledge pertaining to a specific reality can and should be obtained. It goes without saying that the nature of one's philosophical assumptions largely influences the way in which one perceives another paradigm (in other words, a person's opinions regarding methodology are influenced by what they consider to be justified knowledge or true belief).

The two key ontological stances a person can adopt are objectivism and subjectivism, according to Saunders et al. (2019). Under subjectivist ontology, it is claimed that there is no such thing as an independently existing reality, while objectivist ontology maintains that reality exists independently of humans. Therefore, subjectivists argue that reality is largely a product of human interpretation. On the other hand, objectivists surmise that some things in the world are not determined by a person's mental processes and social structures. Thus, positivism is the obvious counterpart to the objectivist ontological viewpoint, while interpretivism is the natural counterpoint to the subjectivist ontological position (Creswell and Creswell, 2018). However, it is interesting to note that there are significant epistemological and axiological implications for each ontological position and researchers must carefully consider these when planning to conduct a study. When a person adopts a subjectivist view, their interpretivist philosophical leanings (a) encourage them to consider knowledge to be related to multiple social realities and interpretations; and (b) determine their opinion regarding what is valuable to individuals based on the social landscape surrounding them.

Saunders et al. (2019) categorise research philosophies into the following groups in order to further explore this issue: Critical realism, interpretivism, postmodernism, pragmatism, and positivism. As mentioned earlier, interpretivism is the preferred philosophy among researchers who are inspired by the subjectivist ontological stance, whereas positivism is linked to the objectivist ontological viewpoint. These two philosophical perspectives are closely associated with quantitative and qualitative research designs.

Sarantakos (2013) explained that the mixed methods study design, which uses both qualitative and quantitative methodologies, is the natural equivalent to the realism philosophical viewpoint. There is no allegiance to one philosophy or reality in the pragmatic school of thought. As an alternative to positivism, Morgan (2007) supports pragmatism.

Pragmatists, in his words, believe that theories can be generalisable by examining them for transferability to different contexts and contextual (dependent on or connected to conditions). However, a practical researcher should uphold both objectivity and subjectivity (in their own perspectives on research) (in data collection and analysis).

The key benefit of using this pragmatic approach to carry out social science research is that it focuses heavily on the connection between epistemological concerns regarding the nature of the knowledge and technical concerns relating to the methods used to generate this knowledge. This moves beyond technical questions pertaining to combined methods and justifies a call for a properly integrated methodology that can be used in social sciences (Morgan 2007).

The aim of the present research project is to engage with knowledge that can be generalised contextually based on values, complexity, and social surroundings. Thus, to achieve this, pragmatism was selected as the research philosophy. Additionally, the philosophy and its underlying assumptions about ontology, epistemology, and axiology were considered to be most suitable for shedding light on the social world of the Saudi building industry's public and private sectors. This is because it enables in-depth data to be collected using a mixed-methods approach, which is common in the pragmatism philosophical approach. Moreover, relevant literature shows that pragmatist philosophy is the most effective approach to use to obtain profound insights into the strategies and components involved in developing green engineering solutions in the construction industry.

5.3 RESEARCH APPROACH

Deductive (top-down) research involves testing hypotheses through statistical analysis, whilst inductive (bottom-up) research involves using exploratory methods to generate theories. These are the two fundamental types of research approaches. Deductive procedures often work better with research topics for which there are large bodies of existing literature available (Pickard, 2012). Additionally, Morgan (2007) explains that the abduction approach alternates between induction and deduction by first turning observations into hypotheses and then evaluating those theories through practical application utilising the pragmatic philosophy.

Even though deductive and inductive procedures are connected in most research projects (see Figure 5.3), the abduction approach was chosen in this study, since it is the logical antithesis of the pragmatist approach.

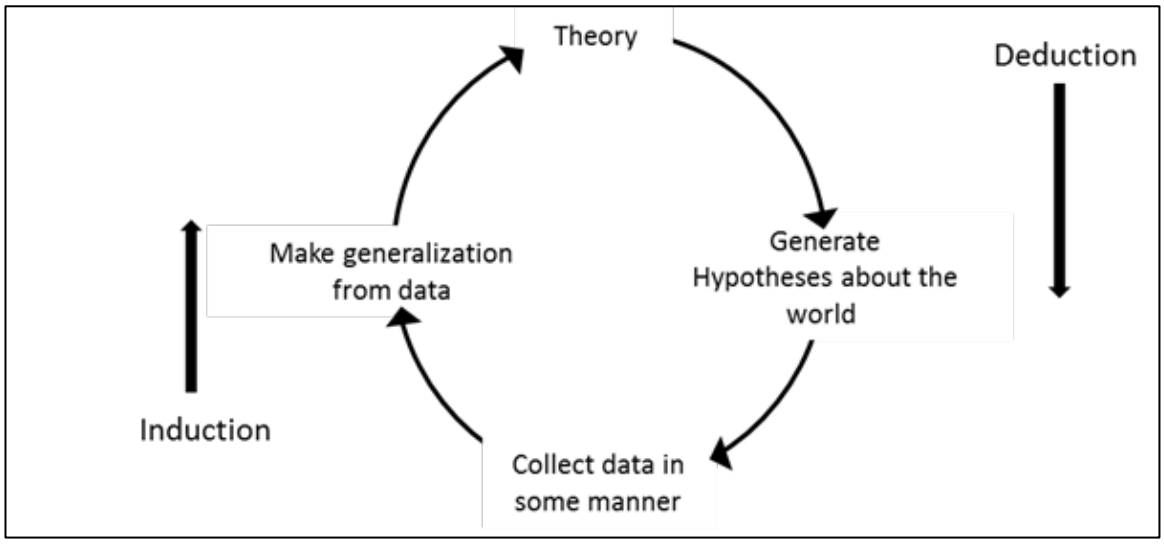


Figure 5.3. Deduction and Induction (Lee & Lings, 2008).

5.4 METHODOLOGICAL CHOICE

A researcher's methodological decision is influenced by their ontological and epistemological presumptions, as shown in Saunders et al.'s (2016) research onion. Researchers who adopt a positivist stance typically use quantitative methodologies, which involve structured, statistically informed methods for measuring, counting, and drawing descriptive conclusions (Creswell and Creswell, 2018). On the other hand, researchers who adhere to subjectivism typically adopt qualitative methodologies, as these are exploratory and attempt to generate insight into individuals' attitudes, perceptions, and motivations. The type of data that each methodology uses to draw conclusions differs significantly between the two approaches: the former utilises quantitative (i.e., statistical) data, whilst the latter utilises qualitative (i.e., non-statistical) data.

According to Viswambharan and Priya (2016), qualitative methodologies seek to produce in-depth descriptions and interpretations of the behavioural, affective, experiential, and attitude phenomena they engage with; because of this connection to the inductive approach, qualitative inquiry frequently results in the emergence of new theories. The findings from the

qualitative investigation can then be used to create a comprehensive, in-depth understanding of the target phenomenon, or these hypotheses can just be applied to perform prospective quantitative research (Creswell, 2014). As it focuses on vocally describing experiential phenomena, meanings, and interpretations, qualitative research tends to be subjective (Naoum, 2012). The different kinds of data gathered through qualitative research can be divided into two categories, namely exploratory data, and attitudinal data. On the other hand, quantitative research projects are grounded in theoretical frameworks to evaluate hypotheses, research questions, and objectives, and they are most helpful when investigating correlations, collecting data, or testing a hypothesis.

Another methodology that is commonly used under pragmatist philosophy is the mixed methods approach (Creswell and Creswell, 2018). Pragmatists prefer to be flexible when examining a research subject, and thus they use mixed methodologies that involve quantitative and qualitative data collection/analysis methods. Mixed-method studies can be extremely beneficial in testing hypotheses whilst also supplementing existing literature.

It is critical to understand that each research methodology has advantages and disadvantages. Quantitative designs are based on 'hard values' and rely heavily on the generation of generalisable, trustworthy, and valid results about correlations between variables. They also involve the testing of existing theories using numerical and deterministic measurements, experiments, and statistical analyses. On the other hand, the use of mixed-method approaches can enable researchers to produce disparate data sets, allowing for data triangulation.

Given the information presented above, it is evident that a mixed methodology is most suitable for achieving the aim and objectives of the present research project. Furthermore, the mixed methodology allows both contextual and situational factors to be considered when collecting and analysing data, and this is very much in line with the researcher's pragmatist philosophical standpoint. It is also important to note that the mixed methodology employed for this study demonstrates the importance of the participants' knowledge as well as testing the hypotheses and adding in-depth knowledge to a body of literature, supporting the trinity of ontology, epistemology, and axiology.

5.5 RESEARCH STRATEGIES

Creswell and Creswell (2018) explain that ontological and epistemological assumptions can largely influence the strategy adopted by a researcher when carrying out a study. Moreover, Gill and Johnson (2010) define a research strategy as an overarching plan detailing how the research will be carried out, and this is critical in avoiding false leads and improving clarity. Additionally, the content of the research strategy enables the research to orientate away from its focal point and towards the processes that should be involved. Researchers can select from a variety of research methodologies, including experiments, surveys, case studies, grounded theory, archival research, ethnography, and action research (Saunders et al., 2019).

These researchers also stress that a researcher's choice of study strategy should be guided by their objectives, philosophy, time, and financial resources, as well as the breadth of the existing body of literature on the subject. In light of these factors, the present researcher chose case study and experts survey research methodologies as a means of achieving the study's goal and objectives.

5.6 PROCEDURE AND TIMELINE

Saunders et al. (2019) proposed that the timeline for research projects can be split into two aspects, i.e., cross-sectional and longitudinal. The latter implies that the research is being conducted over a prolonged duration; the former suggests a snapshot approach at a particular stage. For PhD research projects, a cross-sectional strategy is deemed to be more apposite. Hence, since this particular research project is being submitted as part of the requisites for a PhD degree, the cross-sectional study design was applied.

5.7 ETHICAL CONSIDERATIONS

It is essential that the researcher take a responsible approach to research ethics in order to receive approval for the data collection required for the current research project prior to its initiation. Each part of the proposed methodology was conducted with apposite assiduousness in relation to the acquisition of voluntary informed consent, maintenance of anonymity and confidentiality, and in keeping with the ethical recommendations published by the University

of Nottingham. Each study participant was given transparent information regarding the objectives of the research project and how their confidentiality and anonymity were preserved. The normal practice of secure data storage of subjects' data was adhered to; any pertinent files and databases were password-protected by a strong password available to the researcher alone. The researcher's supervisor has screened all raw data, and the questions encompassed within the topic guide for the interviews, in line with the University's recommended ethical conduct. Furthermore, a submission requesting ethical approval was made on 01/08/2023 to the Faculty Research Ethics Committee at the University of Nottingham, and the decision was that the Approval was Awarded, with no changes required.

5.8 RESEARCH DESIGN OUTLINE

In summary, the research project ultimately adopted a mixed-methods approach, which involved both quantitative and qualitative methods to accomplish the research aims and answer the research questions. In light of this, the researcher chose case study and survey research methodologies as a means of reflecting the mixed methods. The case study method consists of computer-based modelling and simulations that shape the quantitative approach (objectives 3,4&5), while the expert survey represents the qualitative dimension of the mixed-methods research (objectives 2,3&5). Moreover, before commencing with the methods, the secondary data was gathered through a review of literature that relates to the sustainable building industry landscape within Saudi Arabia and worldwide (objectives 1,2&5). This should take place in order to build strong knowledge about the research context. However, each associated chapter systematically addressed the detailed discussion and justification of the processes involved in designing and implementing the mixed-methods research approach. Figure (5.4) exhibits a flowchart representation of the methodology that guides the research.

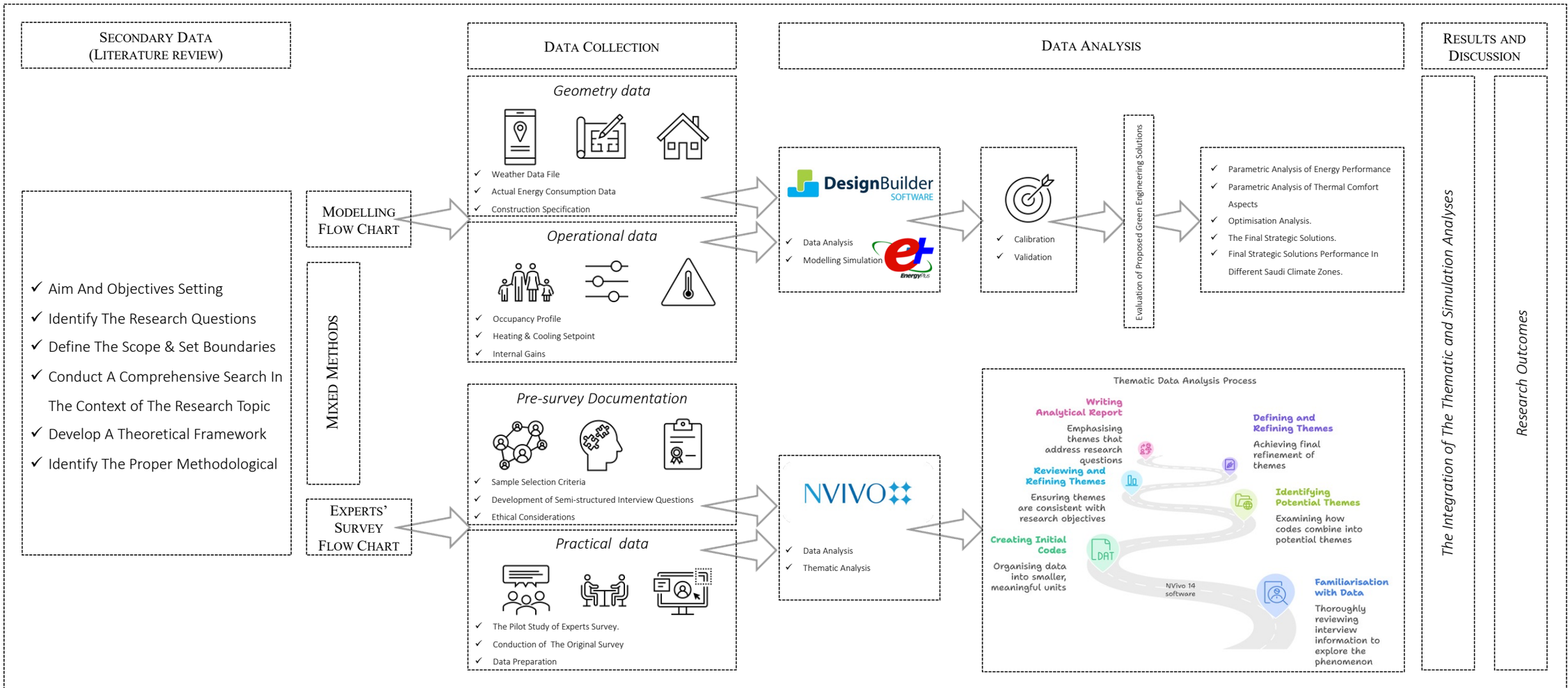


Figure 5.4. Research Methodology Outline.

Chapter 6: Experts' Interview Survey

The purpose of conducting an expert survey was to support achieving the research project's goals. The survey typically involves navigating through several sequential stages to ensure successful execution. This chapter discusses the various dimensions of conducting the experts' study in this research project. Consequently, Section 6.1 explores the sample selection criteria, while Sections 6.2 and 6.3 discuss the procedure for designing the interview questions survey. In Section 6.4, the analysis technique for survey outcomes is examined. Lastly, Section 8.5 provides a summary of the experts' interview survey outcomes.

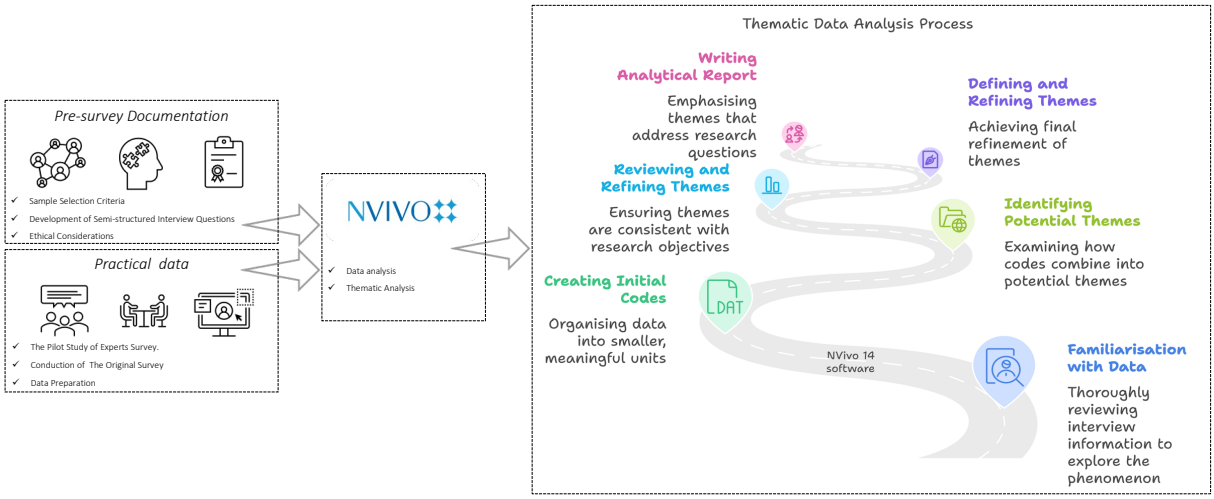


Figure 6.1. Experts Survey Flow Chart.

6.1 THE SAMPLE SELECTION CRITERIA

An understanding of the challenges and possibilities associated with integrating green engineering solutions into the design of Saudi residential buildings was essential to this study. Hence, engaging with key stakeholders who could have provided valuable insights would have been beneficial. The decision was therefore made to interview specific consultants and individuals with expertise in this area, e.g., those working in relevant firms and consulting offices who are responsible for the designs and construction of residences within KSA. An analysis of their perspectives would provide valuable support to the study. Thus, the sampling technique and the structure of the interviews were selected in an assiduous way to make sure

they were appropriate for the study's purpose. The 24 stakeholders identified for the interview are detailed in Table (6.1) below.

The decision to collect data from this group of interested parties stems from the need to gather critical information regarding the green engineering solutions described in the literature review and their potential applications in KSA residences. Since the previously mentioned stakeholders have an obligation to ensure that the buildings are constructed in keeping with their planned design, the researcher has presumed that these specialists would be well-situated to offer access to data relating to the research topic. In order to conduct the interview survey, several methods were utilised, such as face-to-face interviews or conversations via telephone or email, as well as through the Voiceform website, which offers the ability to distribute the questions and allow the participants to answer by either voice recording or text writing. Once data has been collected, the pivotal next step involves performing a comprehensive and impactful analysis to derive meaningful insights and draw informed conclusions.

Table 6.1. The Participants' Details for the Interview Survey.

Participant Code	Area of work	Organisation's Code	its main activity & Reasons of the Organisation choice	Position	The Participant's main role
P1-AB	Private sector	ACC	Designing & Consultancy Firm Specializing in Architecture, Fire Safety, Structural, And Interior Design. Designing several residential projects for special clients in different regions of KSA.	CEO	Designing & Consulting
P2-MA	Private sector	NHC	The real estate development and investment in the residential and real estate sector. One of the biggest companies that the Saudi Ministry of Housing recruited to design, construct, and sell residential projects for public clients in different regions of KSA. Has an authority to recruit other contractors for execution.	Senior Construction Manager	Constructing
P3- OB	Private sector	DWE	Designing & Constructing Residential Projects. One of the companies that the Saudi Ministry of Housing recruited to design, construct, and sell residential projects for public clients in different regions of KSA.	Civil Engineer	Constructing
P4-MD	Private sector	NHC	The real estate development and investment in the residential and real estate sector. One of the biggest companies that the Saudi Ministry of Housing recruited to design, construct, and sell residential projects for public clients in different regions of KSA. Has an authority to recruit other contractors for execution.	Projects Director	Constructing
P5-AA	Public sector	RSAF	Responsible Section for Housing Projects Supervision that provides the residential units for their employees. Has an authority to recruit other contractors for design and execution	Architecture Designer	Designing & Supervision
P6- WA	Private sector	RC	National real estate developer owned by the Saudi Public Investment Fund. Design, execution and sell the Residential Projects for public clients. Has an authority to recruit other contractors for execution.	Director, Sustainability	Designing & constructing
P7- FA	Private sector	ARE	Designing & Constructing Residential Projects. One of the companies that the Saudi Ministry of Housing recruited to design, construct, and sell residential projects for public clients in different regions of KSA.	Senior Projects Manager	Constructing

P8-BA	Private sector	KEO	Consultancy company that specialises in providing services related to planning, architecture, engineering, sustainability, project management, and construction management. Design, and supervision the mega Residential Projects in Saudi Arabia that powdered by the Saudi Public Investment Fund.	Senior Sustainability Associate	Design Consulting
P9-FS	Private sector	AAC	Develop Innovative And High-Quality Real Estate Residential Projects One of the companies that the Saudi Ministry of Housing recruited to design, construct, and sell residential projects for public clients in different regions of KSA.	Architecture Designer	Designing
P10- MM	Public sector	MH	The central governmental organization entrusted with the oversight and regulation of municipalities and housing across the country's cities, towns, and villages. Has an authority to recruit other contractors for design and execution.	Architecture Designer	Designing & Supervision
P11-AJ	Private sector	ZFP	More than four decades of professional expertise, the company has been active in the local, regional, and international markets since its establishment in 1975. Designing several residential projects for special clients in different regions of KSA.	Head of PMO	Designing & Consulting
P12-FG	Private sector	JRE	Designing & Constructing Residential Projects. One of the companies that the Saudi Ministry of Housing recruited to design, construct, and sell residential projects for public clients in different regions of KSA.	Planning Engineer	Designing & constructing
P13-HA	Private sector	APC	Designing & Constructing Residential Projects. One of the companies that the Saudi Ministry of Housing recruited to design, construct, and sell residential projects for public clients in different regions of KSA.	Architecture Designer	Designing & constructing
P14-MH	Private sector	TRE	The real estate development and investment in the residential and commercial. One of the companies that the Saudi Ministry of Housing recruited to design, construct, and sell residential projects for public clients in different regions of KSA.	Architecture Designer	Designing & constructing
P15-AR	Private sector	SRE	Designing & Constructing Residential Projects. One of the companies that the Saudi Ministry of Housing recruited to design, construct, and sell residential projects for public clients in different regions of KSA.	Civil Engineer	Constructing

P16-NA	Public sector	RCJ	Department of Design and Supervision that provide the housing units for their employees. Design and Supervision the construction projects. Has an authority to recruit other contractors for execution.	Project Manager	Designing & Supervision
P17-AH	Private sector	RC	National real estate developer owned by the Saudi Public Investment Fund. Design, execution and sell the Residential Projects for public clients. Has an authority to recruit other contractors for execution.	Senior Manager, project sustainability	Designing & constructing
P18-AM	Public sector	KFH	Responsible Section for Housing Projects Supervision that provides the residential units for their employees. Has an authority to recruit other contractors for design and execution	Civil Engineer	Designing & Supervision
P19-AB	Private sector	RUC	Designing & Constructing Urban Development Projects. One of the companies that the Saudi Ministry of Housing recruited to design, construct, and sell residential projects for public clients in different regions of KSA.	CEO	Designing & constructing
P20-HH	Private sector	TRE	Designing & Constructing Residential Projects. One of the companies that the Saudi Ministry of Housing recruited to design, construct, and sell residential projects for public clients in different regions of KSA.	CEO	Designing & constructing
P21-MH	Public sector	AFU	Responsible Section for Housing Projects Supervision that provides the residential units for their employees. Has an authority to recruit other contractors for design and execution	Civil Engineer	Designing & Supervision
P22-UN	Private sector	GC	Building a residential unit as a sub-contractor	Civil Engineer	constructing
P23-SK	Private sector	ARE	The real estate development and investment in the residential and commercial. One of the companies that the Saudi Ministry of Housing recruited to design, construct, and sell residential projects for public clients in different regions of KSA.	CEO	Constructing
P24-SH	Private sector	AEC	Multidisciplinary engineering services, the company provides an extensive range of offerings to clients in both the private and public sectors. Design of a large residential projects consisting of villas and residential units. Involved for designing Sidra community in Riyadh of ROSHN company.	CEO	Designing & Consulting

6.2 DEVELOPMENT OF SEMI-STRUCTURED INTERVIEW QUESTIONS

The way an interview is conducted can vary and the different approaches can be categorised; interviews can take either an unstructured, structured or semi-structured format. Additionally, either a flexible or inflexible approach may be utilised, or they may be set up to be standardised or non-standardised, controlled or uncontrolled, or formal or informal (Naoum, 2012). There are therefore three principal strategies that could be implemented when drafting interview questions: (i) an informal interview that is essentially conversationalist in nature; (ii) the use of a topic guide to lead the content; and (iii) a standardised interview which is open-ended (Gall and Borg, 2003). Questions that are open-ended provide the subject with the chance to express their perspectives, mindsets and experiences to their full extent (Creswell, 2007). However, despite its advantages, one of the main challenges arising from this approach is its impact on the coding process at the point of data analysis, making it extremely complicated. For the current study, an interview design encompassing a semi-structured format and open-ended questions has been chosen.

The predominant objective of carrying out these interviews is to collect as much data as possible relating to the feasibility of proposed green engineering solutions for residential buildings in KSA. Additionally, it is anticipated that information will be gathered relating to the factors that impede the application of such solutions with respect to thermal comfort and energy usage. In-depth and key questions will be posed; their wording will be influenced by the need to fulfil the aims and objectives of the research.

One way to conceive interviews which primarily exploit the use of open-ended questions is as an entity shaped like a funnel. This structural format therefore creates a straightforward and benign approach with which the investigator is able to start the conversation. The funnel-shaped sequence of subsequent questions is useful when managing emotional issues as the interviewees are provided with the space in which to describe their perspectives frankly. (See Figure 6.2).

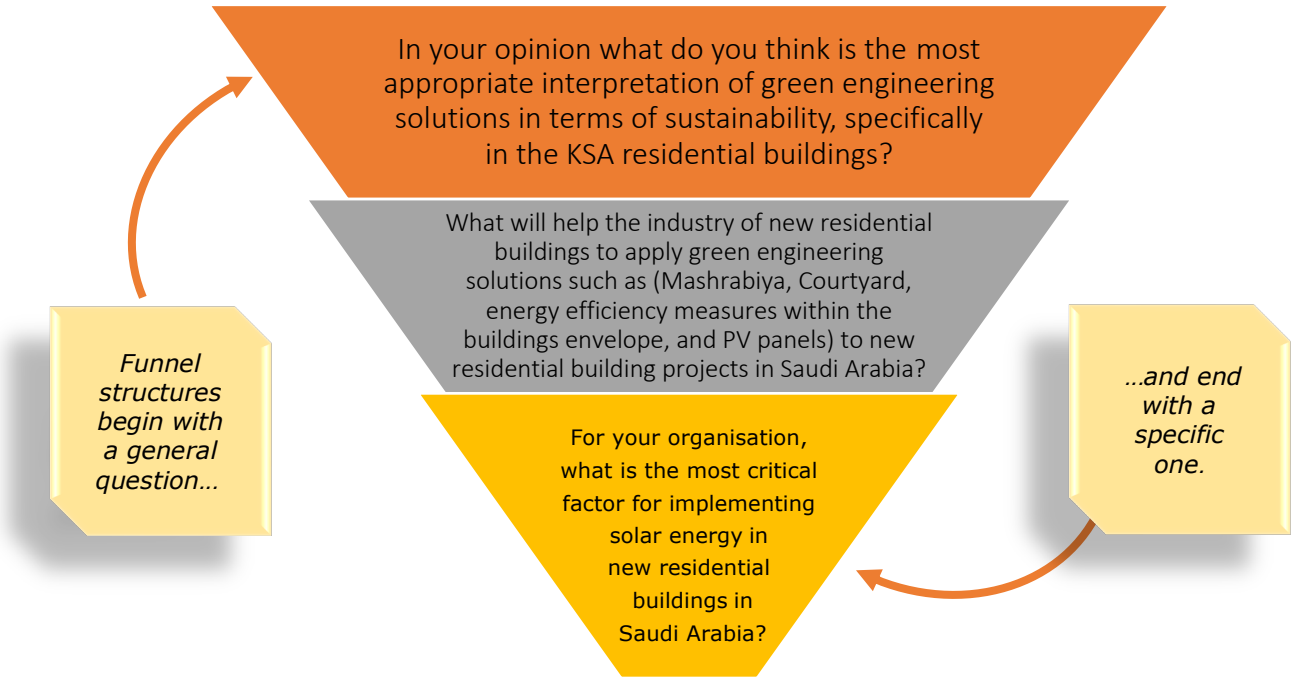


Figure 6.2. Example of Using the Funnel Structure Method For Interview Questions.

According to Magnusson and Marecek (2015), good interview questions have critical characteristics. To begin developing interview questions, review the literature to improve question ideas. Second, all of the interview questions are directly related to the topics. Third, some of the items are followed by others, and the interviewer is responsible for guiding the interview and constraining the content of the conversation. Fourth, each interview item focuses on a single aspect of a subject. In line with these, the expert survey questions were designed to response objectives 2&3 and the two main questions of the current research, which are as follows:

Research Question 2 (RQ2): How can new buildings apply energy efficiency measures, renewable energy, and traditional passive architectural design? Would it be possible to implement a complex retrofitting strategy without affecting a building's architectural values? (Possibility of Implementation)

Research Question 4 (RQ4): Even though the simulation results of the current research project and most of the previous studies evaluated through the literature review confirm that green engineering solutions (such as passive traditional architectural design, energy-efficient measures, and low-carbon technology) have a significant positive impact on cooling energy performance and thermal comfort aspects, why have there been no implementations of these

proposed green engineering solutions within the new residential building projects in KSA to exploit their benefits? (Barriers of Application)

6.3 THE PILOT STUDY OF EXPERTS SURVEY

In order to make the survey questions more valid and feasible. It was proposed that a pilot study to assess the survey questions be conducted before the original survey started. According to Gudmundsdottir and Brock-Utne (2010), conducting a pilot study holds significance in improving the reliability and validity of the survey. Additionally, Chenail (2011) highlighted additional crucial concerns that may surface when piloting qualitative interviewing approaches, he was emphasising challenges for researchers in terms of maintaining "instrumentation rigour" and addressing bias. A pilot study, often termed as a feasibility study, involves creating scaled-down versions of the intended research. These may include trial runs of planned methods or miniature renditions of the anticipated research. The purpose is to address methodological questions and provide guidance for the development of the research plan (Prescott and Soeken 1989). The objective of a pilot study extends beyond a simple acknowledgement of its completion or a justification of methods without providing explicit details. Instead, the emphasis should be on recognising the need to adjust questions or other procedures that hinder obtaining suitable responses or enable researchers to collect data comprehensively (Kim 2011).

In-depth focus group interviews are often used in the first stages of pilot studies to determine the central issues for a more extensive questionnaire survey. Following this, the questionnaire is subjected to a pilot phase, which involves testing elements such as wording, question order, and the choices presented for multiple-choice questions. Finally, a concluding pilot is carried out to evaluate the overall research process, encompassing diverse approaches to distributing and collecting questionnaires. The pilot study of the experts' survey for this PhD thesis spanned two weeks and involved in-depth, face-to-face, semi-structured interviews with a group of four professionals. Each interview lasted between 20 and 30 minutes. Table (6.2) illustrates an example of some changes in questions before and after conducting the pilot study. However, several participants' suggestions were taken into consideration and incorporated, such as adding some answers and clarifying unclear or ambiguous terms.

Table 6.2. Example of Enhancements in Questions After the Pilot Study.

Interview Question Before	Interview Question After	Comments
5. What are the critical barriers to applying green engineering solutions such as (Mashrabiya, Courtyard, and PV panels) to new residential buildings in Saudi Arabia? 6. What is the most important aspect to manage these success factors and/or barriers in terms of the sustainability triangle (among economic, environmental, and social factors), for example, within a new residential building project that you are involved in?	4. What are the barriers to applying green engineering solutions such as Mashrabiya, Courtyard, new innovations in energy efficiency measures for the building envelope, and PV panels to new residential buildings in KSA?	Question 5 & 6 was merged
7. Would it be possible for the design of the new residential buildings, for example, in the following phases of the new residential buildings project that you are involved in, to apply energy efficiency measures, renewable energy, and traditional passive architectural design? Would it be possible to do this without affecting a building's architectural values?	5. Would it be possible for the design of the new residential buildings, for example, in the following phases of the new residential buildings project that you are involved in, to retrofit to apply up-to-date innovations energy efficiency measures, renewable energy, and traditional passive architectural design? Would it be possible to do this without affecting a building's architectural values? (If Yes, please choose which option is most applicable.) (If No, please highlight the reasons.)	Reordered & reworded
10. In your opinion, what are the most potential and appropriate green engineering solutions that could apply to new residential buildings in KSA?	10. In your opinion, how would the following green engineering solutions on an applicability scale be ranked for new residential buildings in KSA?	Reworded

Thus, taking into consideration these aspects, the findings from the literature review, the concept of the funnel-shaped sequence of subsequent questions, and the outcomes of the pilot study mentioned previously were beneficial in structuring the interview questions presented in Table (6.3) below. Additionally, the table demonstrates how these findings were translated into domains, allowing the researcher to focus only on items relevant to the research project's questions.

Table 6.3 Designing of Interview Questions.

Description of Literature Review Findings	Domaine	The Question
The three fundamental elements of the sustainable approach, with respect to the sphere of residential buildings within KSA, should be taken into account when designing a building while climate effects and energy consumption serve as the focal aspects.	Sustainable approach Green engineering concept	In your opinion what do you think is the most appropriate interpretation of green engineering solutions in terms of sustainability, specifically in the KSA residential buildings?
Extremely sustainable techniques of building are enabled by undertaking the design in line with the three fundamental pillars of sustainability—social, economic, and environmental—through the integration of the optimal characteristics of traditional passive architecture design and low-carbon technologies while ensuring the utilisation of the latest energy efficiency measures.		How would you describe the current condition of new Saudi residential buildings in utilising green engineering solutions, such as the design of the residential building within the project that you are involved in?
Buildings featuring minimal greenhouse gas (GHG) emissions and energy use while delivering thermal comfort are among the contemporary challenges of architectural design. A building environment that is unhealthy and delivers low levels of comfort in its achievement of diminishing emissions can be viewed as a failed project similar to how excessively high emissions in a building that delivers a quality thermal environment is a failure in ethics.	Green engineering solutions implementation	What will help the industry of new residential buildings to apply green engineering solutions such as (Mashrabiya, Courtyard, energy efficiency measures within the buildings envelope, and PV panels) to new residential building projects in Saudi Arabia?
		What are the barriers to applying green engineering solutions such as (Mashrabiya, Courtyard, energy efficiency measures the of buildings envelope, and PV panels) to new residential buildings in KSA?
		Would it be possible for the design of the new residential buildings, for example, in the following phases of the new residential buildings project that you are involved in, to retrofit to apply energy efficiency measures, renewable energy, and traditional passive architectural design? Would it be possible to do this without affecting a building's

		architectural values? (If Yes, please choose which option is most applicable.) (If No, please highlight the reasons.)
Diminishing energy consumption can be enabled to a great extent via the adoption of energy-efficient measures which should take into consideration the efficient building regulation codes and the newest innovations in the field of green engineering solutions.	Green engineering solutions (energy-efficient measures) Building code	Would green engineering solutions impact positively the energy performance of the KSA's residential buildings, with full consideration of the Saudi climate, and do you think their impacts are valuable? If No, please choose the reasons.
		In your opinion, does the Saudi Building Code need to discuss or relate to traditional passive architectural design and low-carbon technology? If Yes or NO, please highlight the reasons.
The field of passive traditional architectural design, together with the elementary understanding of the behaviour and thermal comfort of a building, provides an opportunity for notable characteristics which could contribute to making the designs work successfully in relation to a building that offers appropriate thermal comfort with the least possible energy usage and greenhouse gas (GHG) emissions.	Green engineering solutions (Passive traditional architectural design)	In your opinion, why most new residential building projects in Saudi Arabia do not exploit the benefits of traditional passive architectural design to enhance energy performance?
Solar energy should be considered a renewable source of energy with the greatest potential for use in KSA, as the sun generates more energy than consumers are likely to need. The promise of solar energy is simply restricted by the technical ability to transform it into electrical energy.	Green engineering solutions (Low-carbon technology)	For your organisation, what is the most critical factor for implementing solar energy in new residential buildings in Saudi Arabia?
The selection of the most applicable green engineering solutions should take into account the three fundamental aspects of sustainability in line with climate effects in the sphere of designing new residential buildings in KSA.	Green engineering solutions applicability	In your opinion, how would the following green engineering solutions on an applicability scale be ranked for new residential buildings in KSA?

Once the interviews are completed, it is important to use an appropriate and efficacious method of data analysis. Typically, this comprises a number of steps in order to comprehend the data with clarity and in detail, including the need to recognise key information, contemporary working methods and pertinent factors to the topic; these are required in order to construct a framework. The data analysis will therefore comprise data preparation, analysis, and interpretation. The data are therefore initially confirmed as accurate and then imported into a computer database. There is no immediate shortcut between the analysis of the data and its interpretation, and so the data have to be managed in a way that facilitates the latter so that it can be accomplished in a logical fashion and with validity. Thematic analysis is a common method employed for qualitative data analysis, and this technique was used for this research project. Major benefits of this process include the opportunity for the investigator to interact with the data in a systematic way, to acquire a deeper understanding of the mindsets and opinions expressed by the study participants, and consequently, to meet the aim and objectives of the current research.

6.4 THEMATIC ANALYSIS OF THE SURVEY OUTCOMES.

Following the refinement of the interview questions based on insights from the pilot study, the main survey commenced by engaging pertinent participants over approximately two months. The thematic analysis abduction approach was chosen in this research as highlighted in the research design chapter. The abductive thematic analysis uses pre-determined tightly defined codes that were independently, and collaboratively, developed before analysing the data as well as the codes that arise from the collected data.

Braun and Clarke (2006) outlined a six-step process for thematic data analysis. Initially, be familiar with the data by thoroughly reviewing interview information to explore the studied phenomenon. The second step formulate creating initial codes, where the researcher organises the data in a meaningful and systematic manner to condense it into smaller, meaningful units. This involves coding each participant's transcript before transferring them to analysis software manually. The third phase involves identifying potential themes by examining how the codes combine into potential themes using patterns or clusters of the data. The fourth phase is to review and refine themes to ensure they are consistent with the research

objectives. Fifth step consists of defining the themes and achieving the final refinement. Writing up the report, emphasising themes that greatly aid in addressing the research questions, and creating an analytical report comprise the sixth and final step.

Therefore, the analysis of interview results adhered to the systematic approach outlined in the aforementioned scholarly work. NVivo 14 software, a computer-assisted qualitative data analysis tool, was employed to facilitate the systematic organisation and coding of the gathered data.

Hence, familiarisation with the data by diving deeply into the content and responses to distinguish initial themes and significant parts should take place first. Following a thorough understanding of the data, the transition to the next stage is required, which involves the creation of preliminary codes. Accordingly, Table (6.4) below displays the initial codes generated using NVivo 14. After that, these codes, which were based on different responses and quotes, as well as highlighting a variety of opinions, were carefully sorted. The goal was to organise these findings into clusters that directly related to the main research questions, helping to shed light on various aspects of the study, as Table (6.5) illustrates.

Table 6.4. The Initial Codes of the Thematic Analysis.

Initial codes
○ Having environmental awareness while designing, executing, and operating.
○ Integrating renewable natural resources.
○ Knowing the sustainability triangle that meets Saudi residential buildings' needs.
○ Only focusing on adherence to guidelines.
○ Contractors have already provided some improvements beyond the building code.
○ Green engineering solutions is driven by the client.
○ The industry has no sufficient knowledge.
○ There is a notable shift towards being greener.
○ Sustainable code evolution. Green engineering inclusion.
○ Financial support for green implementation.
○ Skilled workforce availability and training.
○ Certification and rating systems.
○ Collaboration and knowledge sharing
○ Government supportance.
○ Research and development.
○ Society's awareness of sustainability's future impacts.

- Profitability, expertise, and information gaps.
- Project parties' neglect and client apathy.
- The complexity of the implementation.
- Insufficient awareness.
- Limited availability of suitable technologies and materials.
- Resistance to change.
- Future regulations that obligate the application of green retrofits.
- It is possible by harmonise green design with management directives.
- It is easy upon client request without architectural compromise.
- Building design and structural constraints.
- Compatibility with existing systems.
- Cost-effectiveness.
- Long process for approval.
- Upon client requirements.
- Due to behavioural hindrances.
- Due to climate challenge. Cooling needs in Saudi’s arid climate.
- Due to the high implementation cost vs. Expected energy savings.
- The end-user financially.
- Agreeing on the positive and valuable impacts on energy performance.
- Saudi building code's lack of comprehensiveness.
- Due to the implementation complexity of unmeasurable solutions.
- Partial yes, inclusion with flexibility.
- Client's energy saving expectations.
- No enhancement in energy performance.
- Saudi code lacks enforcement for exploiting traditional design benefits.
- Designers are unaware of passive design principles.
- Saving in initial cost & modern design preference.
- Several parties are engaged for implementation.
- Solar implementation cost not appreciated.
- Solar energy insufficient for demands.
- Client unawareness.
- The organisation does not have prior experience.

Table 6.5. The Categorisation of Themes and Codes for Thematic Analysis.

RQ2. How can new buildings apply energy efficiency measures, renewable energy, and traditional passive architectural design? Would it be possible to implement a complex retrofitting strategy without affecting a building's architectural values? (Possibility of Implementation)				
Theme 1: Building Code Evolution & adherence	Theme 2: Having Sustainability awareness.	Theme 3: Considering Environmentally resources	Theme 4: Managing consumers requirements	Theme 5: Contractors Supportance
Sustainable code evolution. Green engineering inclusion. Only focusing on adherence to guidelines. Contractors have already provided some improvements beyond the building code. Certification and rating systems.	Knowing the sustainability triangle that meets Saudi residential buildings' needs. The industry has no sufficient knowledge. Society's awareness of sustainability's future impacts.	Having environmental awareness while designing, executing, and operating. Integrating renewable natural resources. There is a notable shift towards being greener.	Green engineering solutions is driven by the client. Collaboration and knowledge sharing.	Skilled workforce availability and training. Financial support for green implementation. Government supportance. Research and development.

RQ4. Even though the simulation results of the current research project and most of the previous studies evaluated through the literature review confirm that green engineering solutions (such as passive traditional architectural design, energy-efficient measures, and low-carbon technology) have a significant positive impact on energy performance and thermal comfort, why have these proposed green engineering solutions not been implemented in new residential building projects in KSA to exploit their benefits? (Barriers to application)					
Theme 1: Navigating implementation complexities within management.	Theme 2: Appreciating the needs and expectations of stakeholders.	Theme 3: Having comprehensive obliged Building Code.	Theme 4: Enhancing awareness and addressing undesirable behaviour.	Theme 5: Optimising returns, Minimising Initial Costs.	Theme 6: Supply chain and design constraints.
The complexity of the implementation. It is possible by harmonise green design with management directives. Long process for approval. Due to the implementation complexity of unmeasurable solutions. The organisation does not have prior experience.	It is easy upon client request without architectural compromise. Upon client requirements. No enhancement in energy performance. Due to climate challenge. Cooling needs in Saudi's arid climate. Solar energy insufficient for demands. Client's energy saving expectations. Several parties are engaged for implementation.	Future regulations that obligate the application of green retrofits. Saudi building code's lack of comprehensiveness . Partial yes, inclusion with flexibility. Saudi code lacks enforcement for exploiting traditional design benefits.	Project parties' neglect and client apathy. Insufficient awareness. Due to behavioural hindrances. Client unawareness. Resistance to change. Designers are unaware of passive design principles. Agreeing on the positive and valuable impacts on energy performance.	Profitability, expertise, and information gaps. Saving in initial cost & modern design preference. Due to the high implementation cost vs. Expected energy savings. The end-user financially. Solar implementation cost not appreciated. Cost-effectiveness.	Building design and structural constraints. Compatibility with existing systems. Limited availability of suitable technologies and materials.

Subsequently, the fourth step involved a critical evaluation of the mentioned themes, making sure that they were in line with the research questions. The fifth step comprised the formulation of the final titles for each theme, aligning them cohesively with both the research questions and objectives. The resultant final themes from the survey outcomes are presented in Table (6.6) below. Moreover, Table (6.7) provides a structured display of the ultimate compilation of final codes and themes. In the following sections, the sixth step provides a summary and interpretation of the analysis results. This phase shows how different codes emerge and are combined to form coherent themes that aim to answer the research questions posed in the study. This also includes a few quotes that highlight citations from a range of interviewees, providing further evidence for the themes and codes that have been established.

Table 6.6. The Final Main Themes of the Analysis.

Themes	Files (Case Count)	References (Code Count)
(RQ2 Themes)	**24**	**103**
Building Code Evolution & adherence	21	41
Having Sustainability awareness.	13	16
Considering Environmentally resources.	15	20
Managing consumers requirements.	7	8
Contractors Supportance.	11	18
(RQ4. Themes)	**24**	**187**
Navigating implementation complexities within management.	19	26
Appreciating the needs and expectations of stakeholders.	18	28
Having comprehensive obliged Building Code.	22	38
Enhancing awareness and addressing undesirable behaviour.	19	41
Optimising returns, Minimising Initial Costs.	22	51
Supply chain and design constraints.	1	3

Table 6.7. The Ultimate Compilation of Final Codes and Themes.

Themes & Codes	Case Count	Code Count
(RQ2. Themes) 103		
(Theme) Building Code Evolution & adherence	**21**	**41**
(Code) Sustainable code evolution. Green engineering inclusion.	19	19
(Code) Only focusing on adherence to guidelines.	11	11
(Code) Contractors have already provided some improvements beyond the building code.	10	10
(Code) Certification and rating systems.	1	1
(Theme) Having Sustainability awareness.	**13**	**16**
(Code) Knowing the sustainability triangle that meets Saudi residential buildings' needs.	13	13
(Code) The industry has no sufficient knowledge.	1	1
(Code) Society's awareness of sustainability's future impacts.	2	2
(Theme) Considering Environmentally resources.	**15**	**20**
(Code) Having environmental awareness while designing, executing, and operating.	8	8
(Code) Integrating renewable natural resources.	11	11
(Code) There is a notable shift towards being greener.	1	1
(Theme) Managing consumers requirements.	**7**	**8**
(Code) Green engineering solutions are driven by the client.	7	7
(Code) Collaboration and knowledge sharing.	1	1
(Theme) Contractors Supportance.	**11**	**18**
(Code) Skilled workforce availability and training.	7	7
(Code) Financial support for green implementation.	7	7
(Code) Government supportance.	3	3
(Code) Research and development.	1	1
(RQ4. Themes) 187		
(Theme) Navigating implementation complexities within management.	**19**	**26**
(Code) The complexity of the implementation.	7	8
(Code) It is possible by harmonise green design with management directives.	14	14
(Code) Long process for approval.	1	1
(Code) Due to the implementation complexity of unmeasurable solutions.	2	2
(Code) The organisation does not have prior experience.	1	1
(Theme) Appreciating the needs and expectations of stakeholders.	**18**	**28**
(Code) It is easy upon client request without architectural compromise.	7	7
(Code) Upon client requirements.	1	1
(Code) No enhancement in energy performance.	1	1
(Code) Due to climate challenge. Cooling needs in Saudi's arid climate.	4	4
(Code) Solar energy insufficient for demands.	4	4
(Code) Client's energy saving expectations.	10	10
(Code) Several parties are engaged for implementation.	1	1
(Theme) Having comprehensive obliged Building Code.	**22**	**38**
(Code) Future regulations that obligate the application of green retrofits.	3	3
(Code) Saudi building code's lack of comprehensiveness.	14	15

(Code) Partial yes, inclusion with flexibility.	9	9
(Code) Saudi code lacks enforcement for exploiting traditional design benefits.	11	11
(Theme) Enhancing awareness and addressing undesirable behaviour.	**19**	**41**
(Code) Project parties' neglect and client apathy.	9	9
(Code) Insufficient awareness.	4	4
(Code) Due to behavioural hindrances.	5	5
(Code) Client unawareness.	8	8
(Code) Resistance to change.	2	2
(Code) Designers are unaware of passive design principles.	3	3
(Code) Agreeing on the positive and valuable impacts on energy performance.	10	10
(Theme) Optimising returns, Minimising Initial Costs.	**22**	**51**
(Code) Profitability, expertise, and information gaps.	15	17
(Code) Saving in initial cost & modern design preference.	5	5
(Code) Due to the high implementation cost vs. Expected energy savings.	12	12
(Code) The end-user financially.	1	1
(Code) Solar implementation cost not appreciated.	15	15
(Code) Cost-effectiveness.	1	1
(Theme) Supply chain and design constraints.	**1**	**3**
(Code) Building design and structural constraints.	1	1
(Code) Compatibility with existing systems.	1	1
(Code) Limited availability of suitable technologies and materials.	1	1

Figures (6.3) and (6.4) display a breakdown of participants' responses based on their experience levels, categorised into “More than five years,” “More than ten years,” “Less than five years,” and “Less than two years,” in relation to Research Questions 2 and 4 (RQ2 & RQ4) themes. Each bar represents a specific theme, and the numbers within bars refer to the code count references that are associated with each theme based on participants' experience level. These figures provide an overview of how different themes are referenced across various experience levels in order to facilitate the analysis of themes within the context of the targeted research question.

The indication here is that participants with work experience of more than ten and five years covered most of the themes. However, participants with various experiences were all insistent on the significance of the “building code evolution & adherence”, and ‘considering environmental resources’ themes of RQ2. In addition, most of the themes in RQ4 were underlined by all participants with deference work experience lengths except the “supply chain & design constraints” theme which was mentioned by participants with work experience of

more than five years. In contrast, the “contractors’ supportance” in RQ2 themes was particularly highlighted by participants with work experience of more than ten and five years.

Figures (6.5) and (6.6) illustrate the coding frequency associated with themes of Research Questions 2 and 4 (RQ2 &4) within the context of participants' involvement in new residential projects. Participants are strategically categorised based on their project involvement into groups such as “More than five projects”, “More than ten projects,” “Less than five projects,” and “Less than two projects”. These bar charts offer an examination of coding patterns that contribute to accurately understanding how these themes are distributed across varying levels of project participation among the participants. It is clear that most of the participants have substantial involvement in new residential projects in KSA, that contributing to all the research questions’ themes accordingly as the charts show.

The numerical values in Figures (6.7) and (6.8) below indicate the count of repetitions of each theme being referred to in the code by participants in each job role. For example, in the "Building Code Evolution & Adherence" theme, participants in the CEO role have mentioned this theme 13 times, which refers to the code count, and so on. These graphs’ representation allows for analysis of the significance of each theme across different job roles. Also, they provide an insight into the specific coding patterns associated with distinct positions within the context of the themes presented.

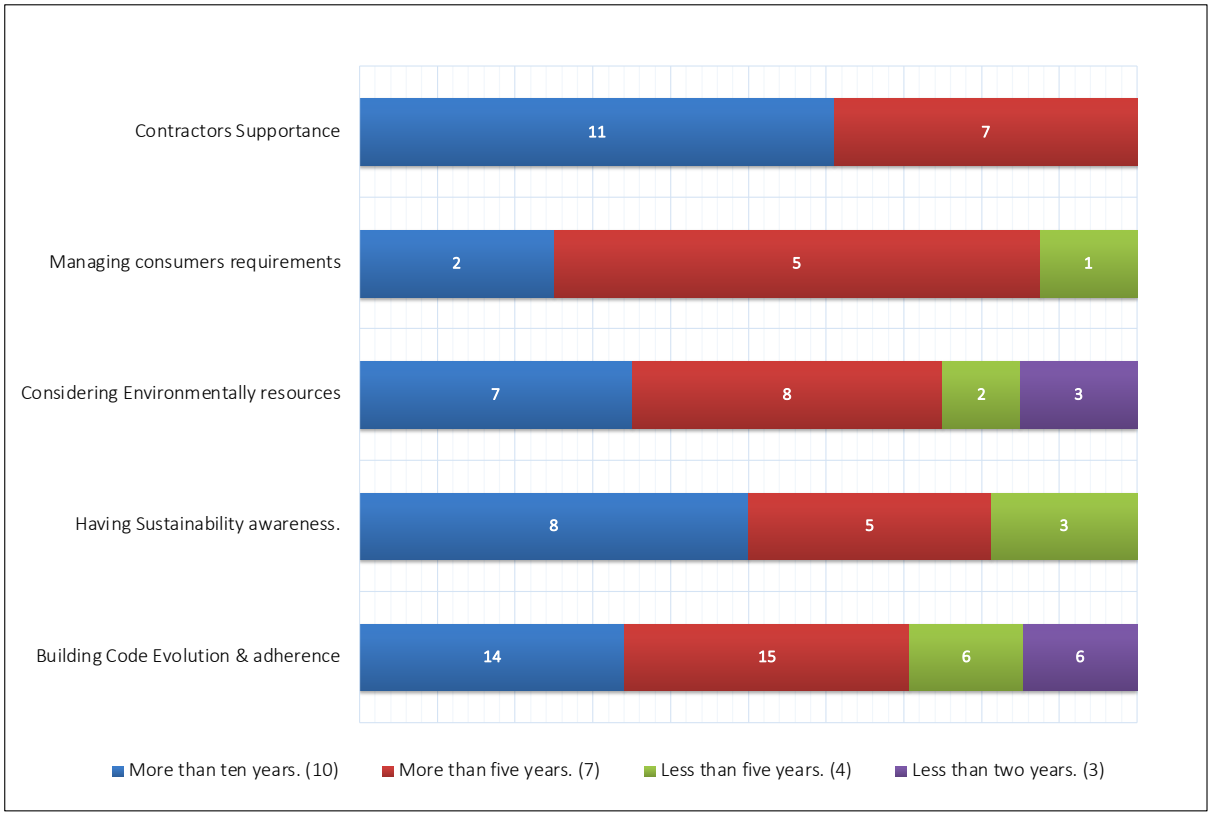


Figure 6.3. The Repetitiveness of RQ2 Themes Across Responses Based on Experience Level and Participant Count.

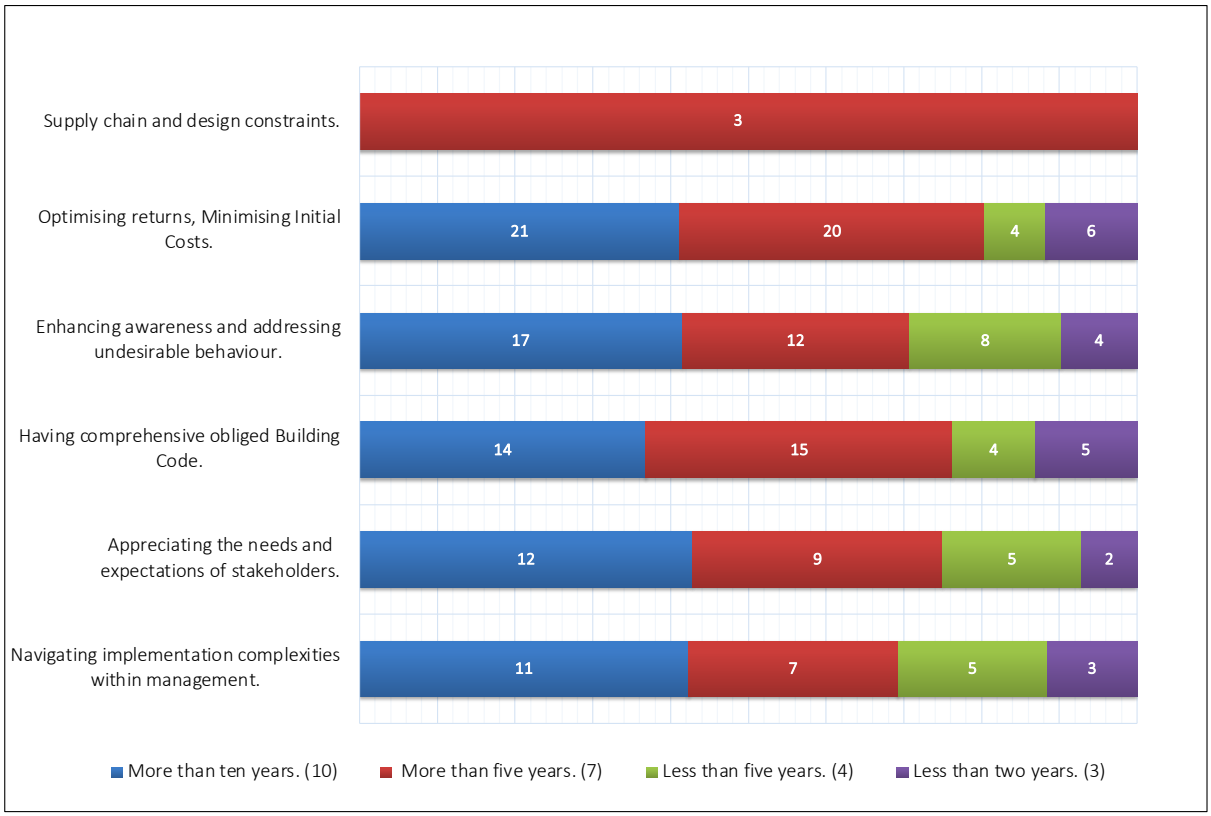


Figure 6.4. The Repetitiveness of RQ4 Themes Across Responses Based on Experience Level and Participant Count.

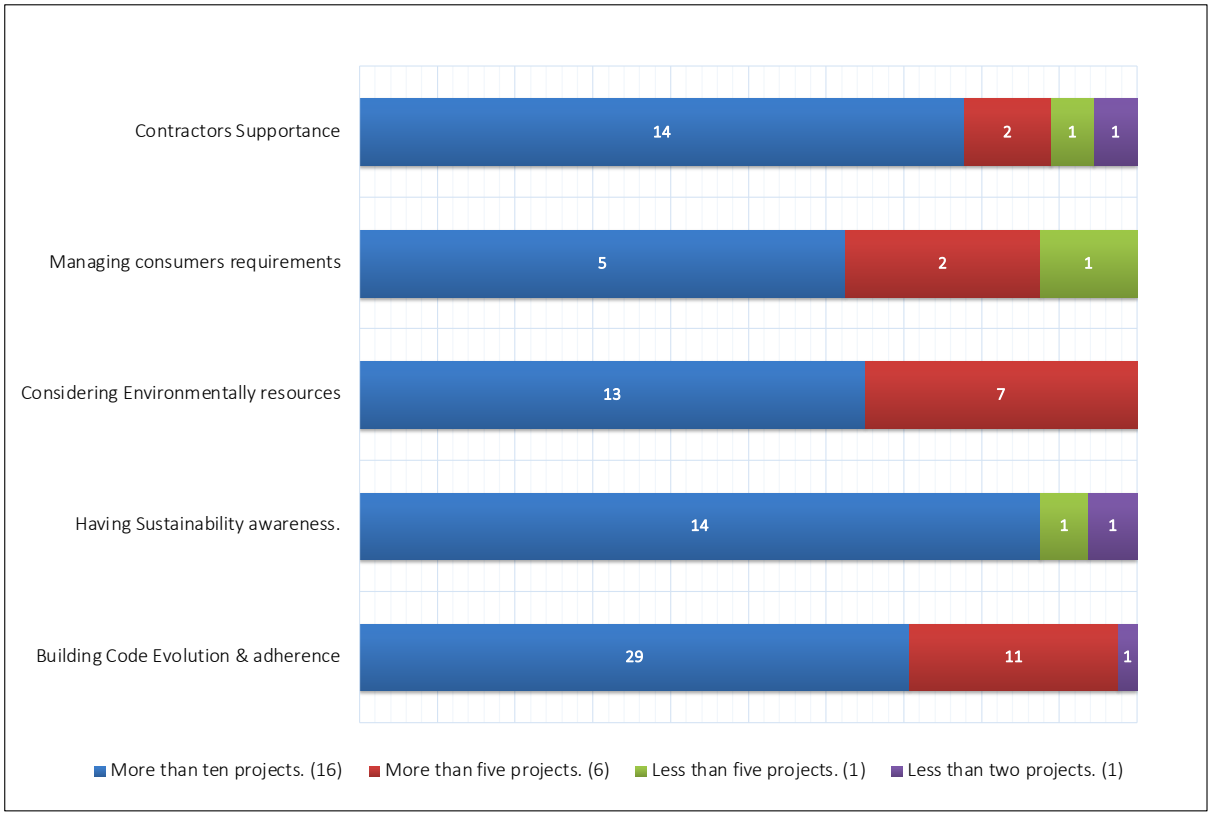


Figure 6.5. The Repetitiveness of RQ2 Themes Across Responses Based on Projects Involvement and Participant Count.

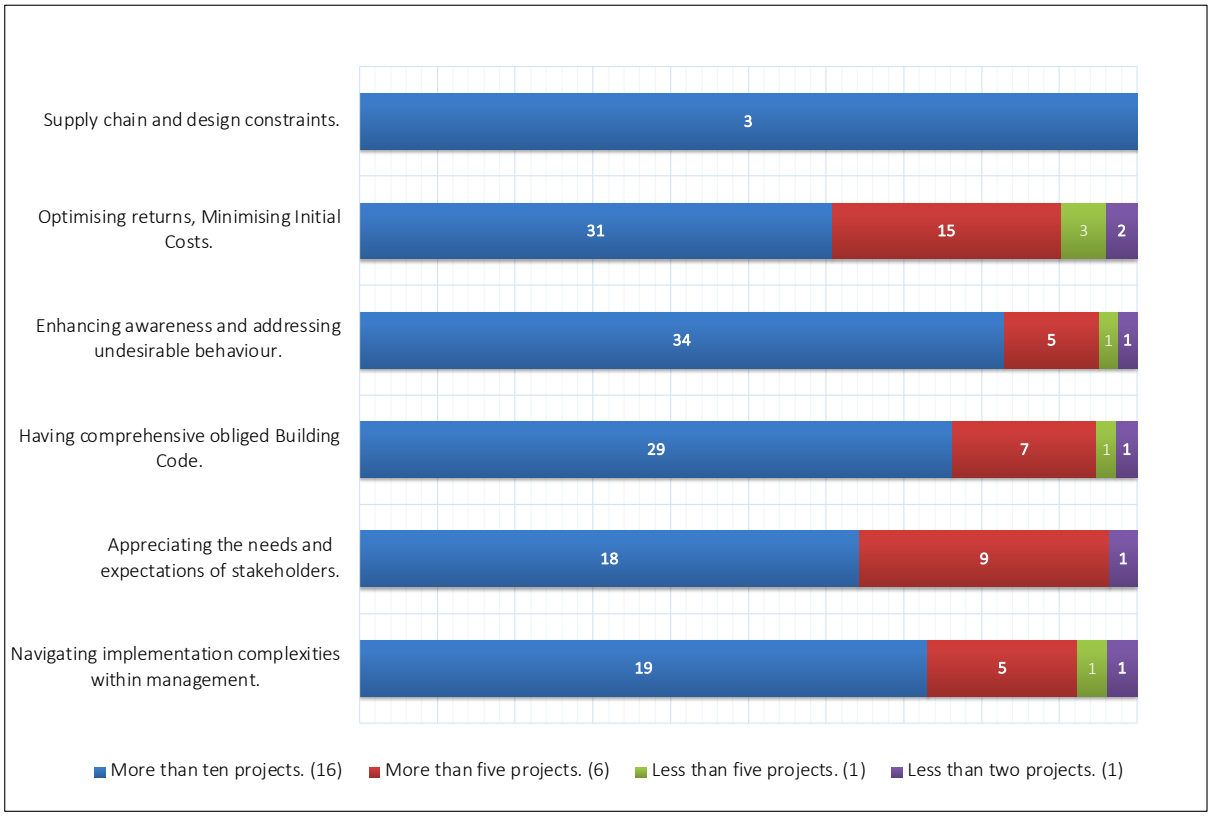


Figure 6.6. The Repetitiveness of RQ4 Themes Across Responses Based on Projects Involvement and Participant Count.

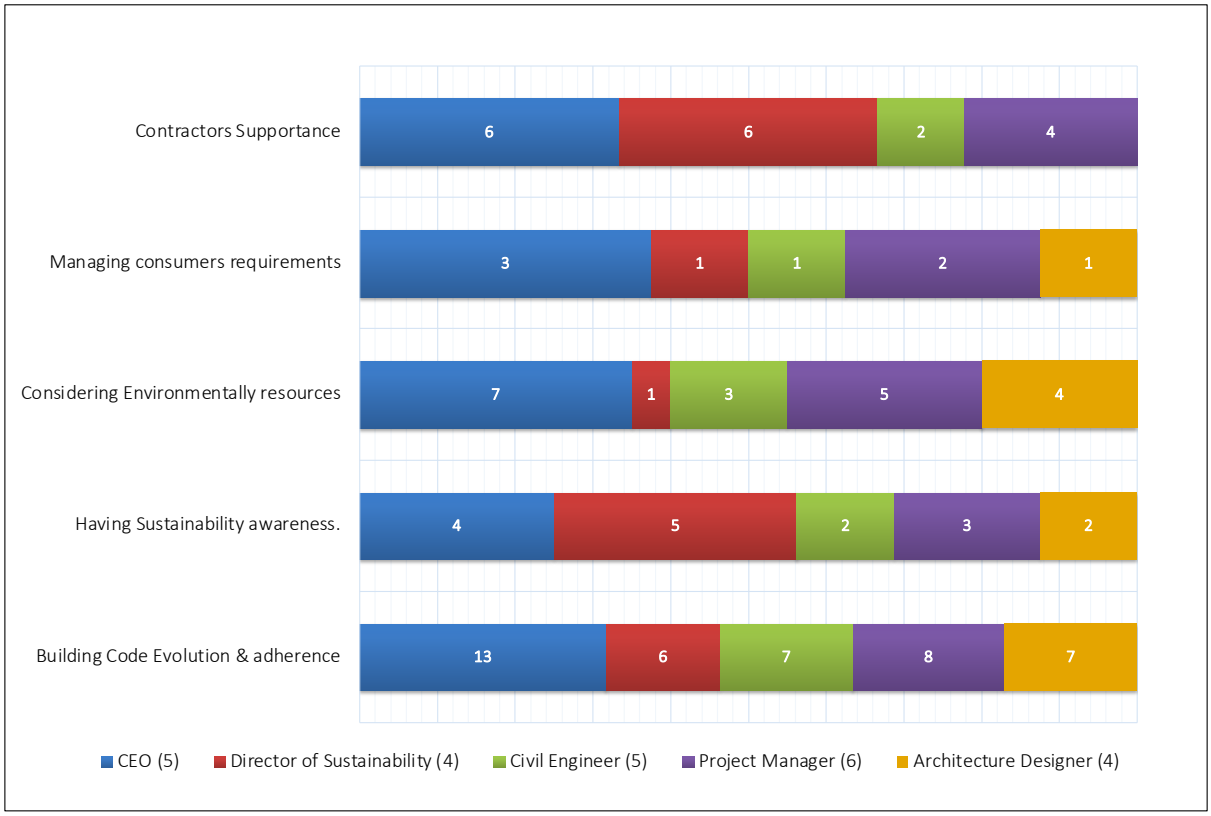


Figure 6.7. The Repetitiveness of RQ2 Themes Across Responses Based on Participants' Position and Count.

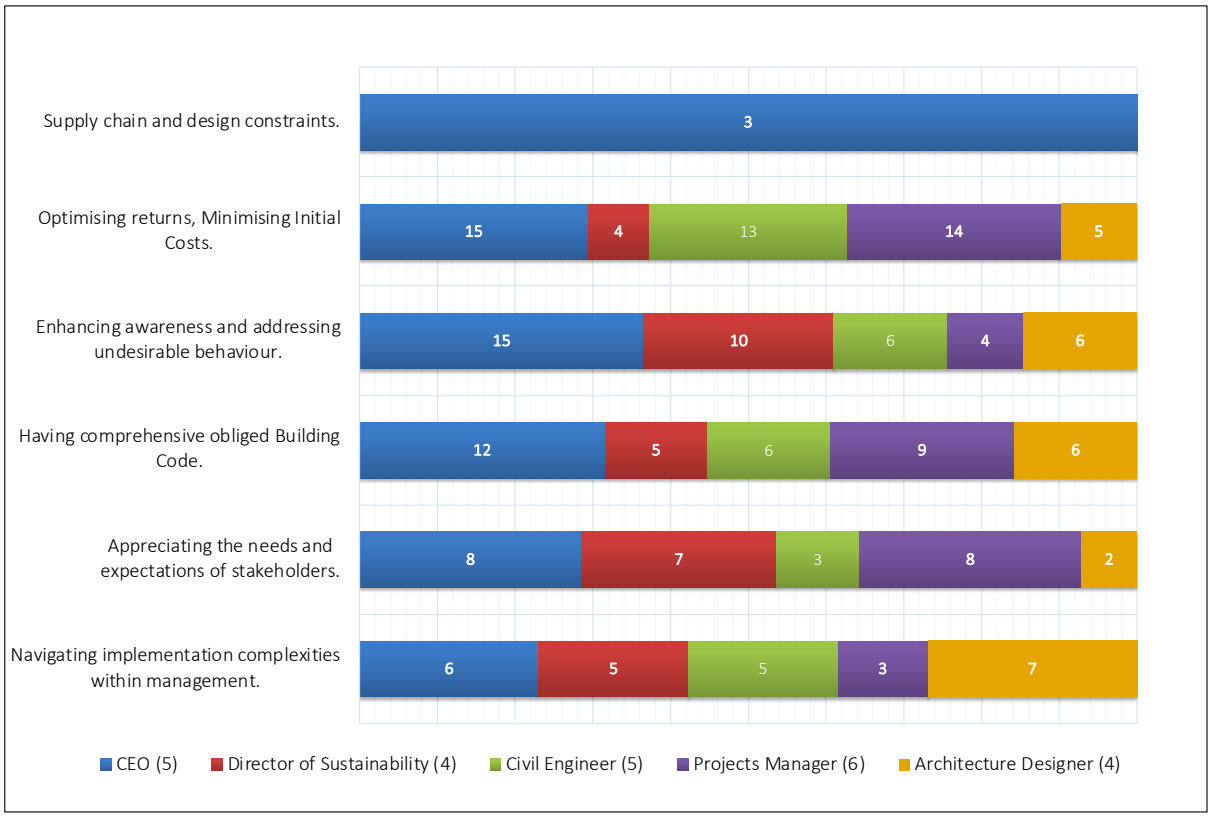


Figure 6.8. The Repetitiveness of RQ4 Themes Across Responses Based on Participants' Position and Count.

Figures (6.9) and (6.10) below present the patterns of consistency or variability of stating the themes across all 24 participants related to Research Questions 2 and 4 (RQ2&4). Each participant (P1 to P24) is associated with a specific percentage that indicates his alignment with each theme. This offers insights into the overall agreement or variability across the participants regarding the specified themes under investigation that are outlined in RQ2 and RQ4.

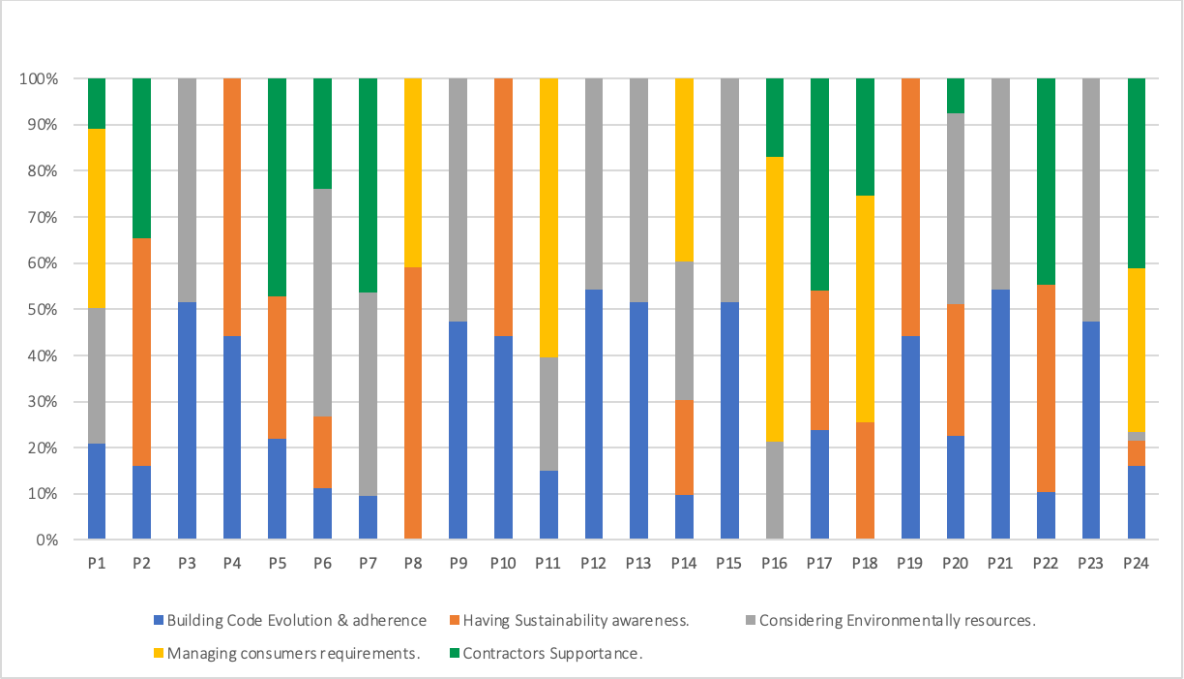


Figure 6.9. The Patterns of Consistency or Variability Across Participants For Each Theme In RQ2.

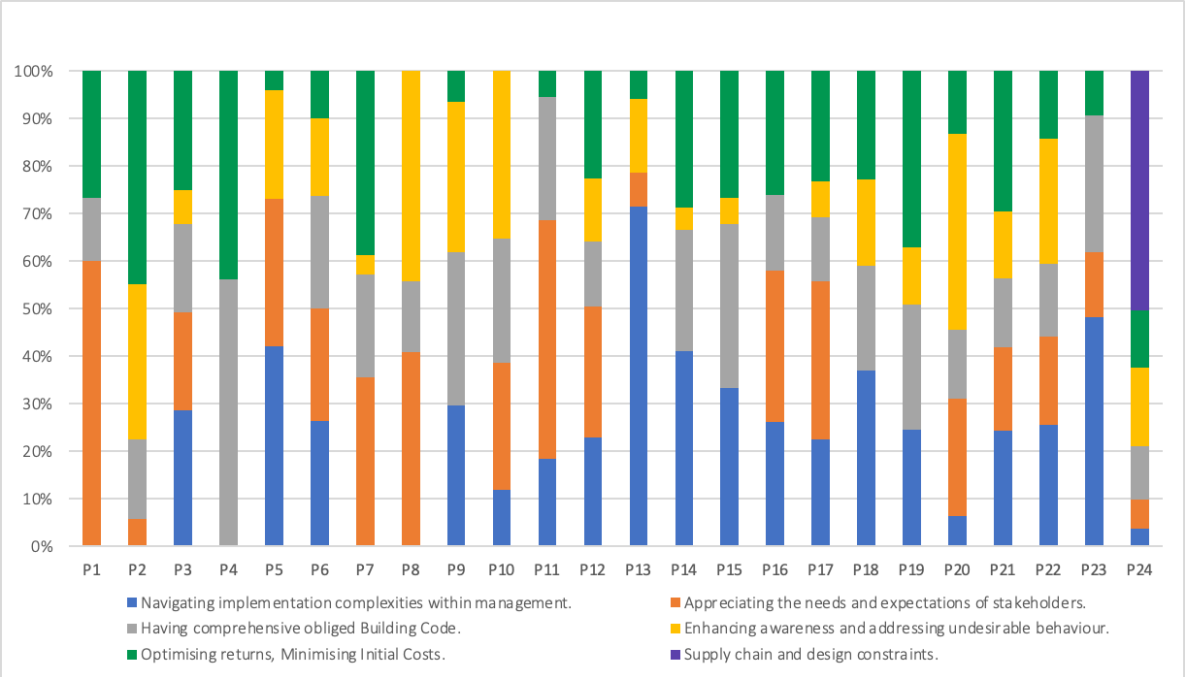


Figure 6.10. The Patterns of Consistency or Variability Across Participants For Each Theme In RQ4.

However, the thematic results analysis report is not just a description of the themes; it's an interpretation of the data. The results should provide a rich and meaningful understanding in order to answer the research questions. Therefore, in the context of addressing the research questions, the following will interpret these themes by discussing how they contribute to the overall understanding of the facts. Moreover, it will discuss the frequency or salience of each theme, mentioning how often a theme appeared in the data or how prominently participants discussed it. This analysis report will highlight any patterns of consistency or variability across participants, shedding light on whether certain themes were more dominant among specific participants or in particular contexts. Furthermore, it will illustrate examples and quotes from the participants' transcripts to support each theme. These quotes serve as evidence of the existence of each theme and help to understand the context.

Hence, in terms of RQ2, the exploration of the possibility of implementing green engineering solutions for new buildings in KSA without compromising architectural values was the focus. The analysis results indicated that the most significant factor aiding the residential industry in KSA for this was the theme of "building code evolution & adherence" with a total code count of 41 out of 103 references. Examples from participants, namely P6-WA and P19-AB, were quoted respectively.

> *"The lack of mandatory requirements or incentives within the Saudi Building Code to incorporate traditional passive architectural design elements may contribute to the underutilisation of these strategies in new residential building projects."*

> *"By adapting the building code to include a diverse set of sustainable options, it empowers project parties to choose the solutions that best fit the specific requirements of their residential building projects. This approach fosters flexibility and innovation, encouraging the adoption of a variety of green engineering solutions, including Mashrabiya, Courtyard designs, energy-efficient building envelopes, and PV panels, to create environmentally friendly and energy-efficient residential spaces in Saudi Arabia."*

The second theme contributing to the answer to research question (2) is the "considering environmentally resources" theme, followed by the "having sustainability awareness" theme. However, this could establish a debate about the sequence, as the sustainability aspect might have been more prioritised and covered some areas of the former theme. Nevertheless, P6-WG, P14-MH P19-AB, and P20-HH highlighted that respectively:

"The current scenario of residential buildings in Saudi Arabia, there is a notable shift towards incorporating green engineering solutions. Government initiatives, certifications, and heightened community awareness of sustainability are influencing development practices."

"I really think that day by day it will be more relevant to apply climatic and environmentally sustainable solutions to Saudi residential buildings."

"The integration of environmentally conscious materials, techniques, and innovations should be economically viable and socially beneficial, ensuring that sustainable practices contribute positively to the overall well-being of both the residents and the broader community.

Using sustainable and locally sourced materials, adopting effective waste management practices, incorporating green spaces and urban planning, implementing smart building technologies, and fostering community engagement in sustainability initiatives.

Furthermore, the theme "contractors' supportance" had an impact on the feasibility of implementing green engineering solutions for new buildings in KSA without compromising the architectural values, according to the participants' viewpoints as P16-NA and P24-SH indicated that:

"Whenever professional manpower is available to manufacture and operate renewable energy, there will be a bright future. Currently, we suffer from a scarcity of technicians."

"The government can play a crucial role in promoting the adoption of green engineering solutions by providing incentives such as tax breaks or subsidies for incorporating sustainable features like Mashrabiya, Courtyard, energy efficiency measures, and PV panels. This can help offset the upfront costs and encourage developers to invest in green technologies." "The availability of professionals trained in this specific design approach may be limited, making it challenging to incorporate these principles effectively into residential building projects."

On the other hand, in addressing research question (4), which seeks to investigate the fundamental reasons behind the underutilisation of advantageous engineering solutions that have demonstrated their effectiveness through evidence from literature and simulation results in new residential building projects in Saudi Arabia. The pivotal factor of addressing the 4th

question revolves around the "optimising returns, minimising initial costs" theme with a code count reference of 51 from most of the participants. Subsequently, there is the theme of "Enhancing awareness and addressing undesirable behaviour" with a total code count reference of 41. The majority of participants in this theme have over five and ten years of experience and have been involved in more than ten projects. Evidence of these themes is quoted for example from participants P4-MD, P6- WA, P17-AH, P19-AB, P20-HH, and P22-UN in the following respectively,

> *"The customer will not pay a huge amount due to lack of knowledge and regulations."*
>
> *"Contractors may be hesitant if there is uncertainty about financial returns."*
>
> *"It is important to focus on community awareness of sustainability first, and then it can be gradual."*
>
> *"The high implementation costs of green engineering solutions compared to the anticipated energy savings may be a barrier to their positive impact on the energy performance of residential buildings in Saudi Arabia."*
>
> *"Economic concerns, including the perception that incorporating passive design features might increase upfront costs, can also discourage their widespread adoption." "There might be a lack of awareness and understanding among architects, developers, and builders regarding the potential benefits."*
>
> "*If the cost of such technology is maintained, it will be all around KSA soon."*

However, P14-MH indicated that:

> *"It's hard to apply new technology and costly implications to maintain a healthy price for the unit. Although implementing solutions like mashrabiya shouldn't have a significant cost impact on the unit."*

Additionally, the "Having a comprehensive obliged Building Code" theme was one of the repetitive matters among the participants that also has been mentioned within RQ2 in various facets. In order to enforce regulations promoting green engineering solutions, a well-defined system of responsibility and authority is crucial. This involves assigning the responsibility for

implementing and enforcing these regulations to specific departments or organisations. However, it was observed that these regulations are not obligatory components of contracts. Even when included in contracts, enforcement is lacking. The green and sustainable government departments operate independently, with limited information-sharing among them. Consequently, there is a lack of clarity and enforcement regarding the specific responsibilities involved, as mentioned by P6- WA, P19-AB, and P24-SH respectively,

> *"A comprehensive strategy that addresses regulatory frameworks, financial considerations, and human resources development is key to the successful adoption of green engineering solutions in the industry." "If the code does not explicitly encourage or mandate the adoption of such design principles, developers and builders may prioritise other aspects, and the potential benefits of traditional passive architectural design for enhancing energy performance may not be fully realised." "A comprehensive code ensures that these aspects are considered, providing a guideline for architects, engineers, and builders to integrate environmentally friendly and innovative solutions into their projects, contributing to the overall sustainability goals in the construction industry."*

> *"The Building Code plays a crucial role in shaping construction practices, and if it does not explicitly encourage or require the incorporation of traditional passive architectural design, it may not be prioritised in projects".*

> *"The absence of comprehensive and supportive policies and regulations specifically addressing green engineering solutions can hamper their widespread adoption. Clear guidelines and incentives from regulatory bodies can encourage developers to prioritise sustainability in their projects."*

Moreover, the themes of "Appreciating the needs and expectations of stakeholders" and "Navigating implementation complexities within management" appeared multiple times in the responses of most participants, with code counts of 28 and 26 references, respectively. The former theme revolves around the importance of recognising and understanding the diverse requirements, interests, and expectations of stakeholders involved in a project. It emphasises the significance of engaging with various parties. The latter focuses on the challenges and complexities associated with the implementation phase of projects within a management framework. It acknowledges the multifaceted nature of executing plans and strategies, highlighting the need for adept navigation through various complexities. Here are some examples of other aspects highlighted as per the words of P6-WA, P5-AA, and P19-AB:

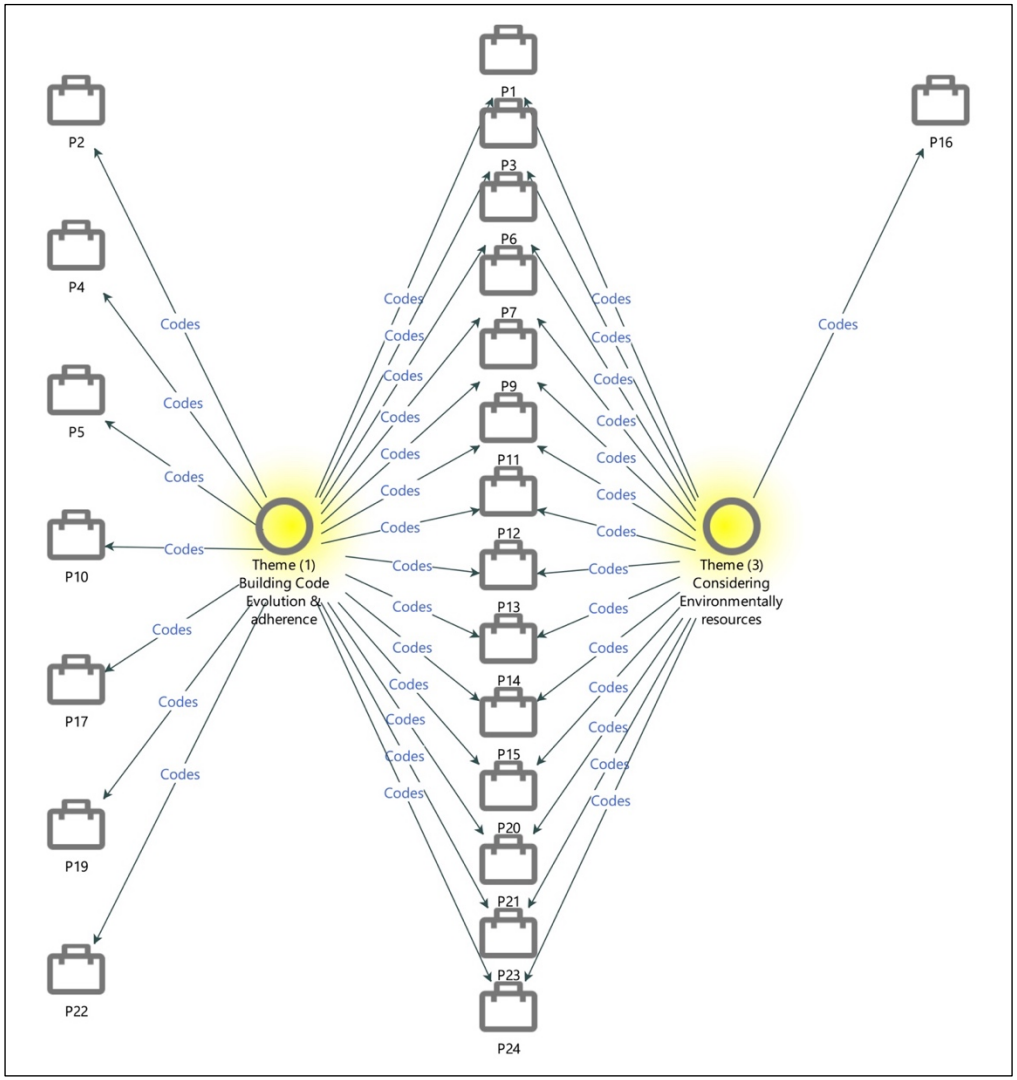
"Ensuring that the energy generated from solar sources aligns with the energy requirements of new residential buildings is a critical factor." "A lack of expertise or information could hinder successful implementation"." limited availability of specialised materials or technologies, resistance to change within the industry." "Successful implementation is feasible by clearly explaining the long-term benefits to superior management or when clients explicitly request such features".

"Retrofitting the following phases of the new residential buildings I supervise wouldn't be feasible due to the extended approval process for these additional aspects. This might cause a delay in project handover."

"A shortage of expertise in green building practices, and insufficient information about the technologies involved. These factors collectively hinder the widespread adoption of green engineering solutions in new residential buildings in Saudi Arabia".

Figures (6.11) and (6.12) present a comparison of the responses from participants in the research project as an example. The focus of this comparison is on the dominant two themes related to Research Questions 2 and 4. The figures illustrate how participants' responses vary or align concerning the specified themes in the context of the research questions. For example, in Research Question 2 (RQ2), it is clear that theme (1) "building code evolution & adherence" was addressed by all participants. However, one participant did not mention this particular theme. In contrast, only fifteen participants discussed theme (3) "considering environmental resources," while the remainder did not address it. However, within the findings of Research Question 4 (RQ4), it emerged that two participants ignored the most dominant theme, namely, theme (5) "Optimising Returns, Minimising Initial Costs", which recorded 51 code references. Instead, their attention was directed only towards theme (4) 'Enhancing awareness and addressing undesirable behaviour.

At the end of the survey's questions, participants were asked to rank the applicability of proposed green engineering solutions for new residential buildings in KSA. This question captures the most significant perspectives and thoughts of the experts. Figure (6.13) below illustrates the ranking of green engineering solutions based on participants' responses. The highest rank was assigned to 1st Passive architectural designs, such as Mashrabiya and Courtyard; 2nd Low-carbon technologies, such as solar energy and wind turbine energy; and 3rd Energy efficiency measures within the building envelope. In addition, Figure (6.14) shows the frequency word cloud of research interview survey analysis themes among the participants.



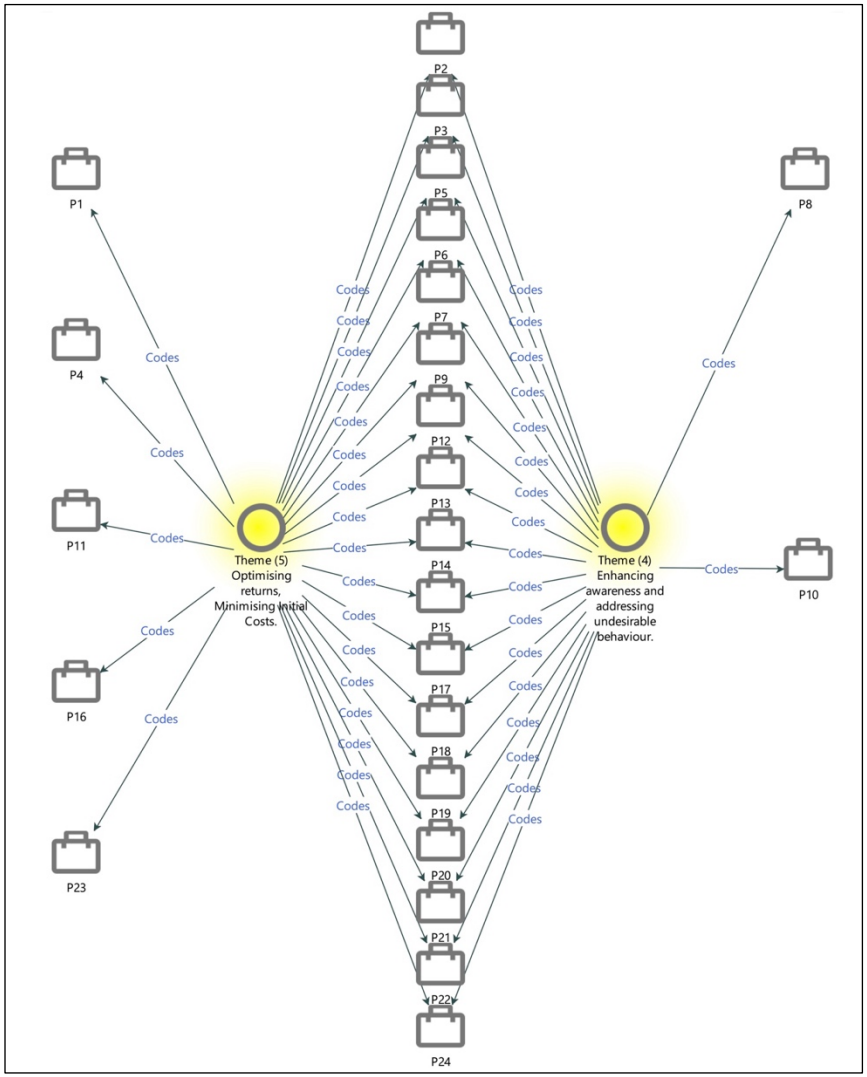


Figure 6.11 Left and 6.12 Rigit. Comparisons of Participants' Responses For The Two Dominant Themes of RQ2 Left and RQ4 Right.

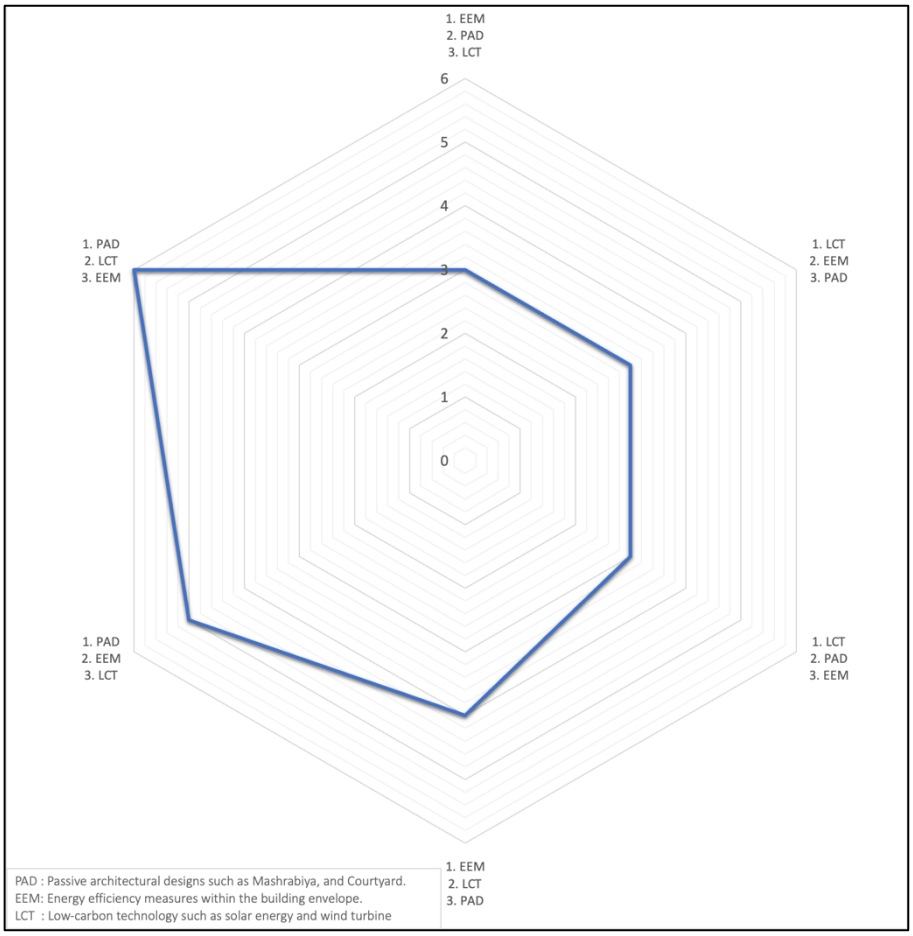


Figure 6.13. The Ranking of Green Engineering Solutions on an Applicability Scale For New Saudi Residential Buildings Based on Participants' Responses.



Figure 6.14. Word Frequency Cloud of Research Interviews Survey Analysis Themes.

6.5 THE SUMMARY

The following summarises the key findings from the presented data of the thematic analysis in order to address both Research Questions 2 and 4 (RQ2 and 4). Firstly, regarding Research Question (2), the theme "Building Code Evolution & Adherence" emerged as a central point. This shed light on the need for regulatory advancements to promote sustainability in new Saudi residential building projects. Participants expressed their concerns with respect to the current Saudi Building Code by stating that it lacks mandatory requirements and incentives to encourage the use of traditional passive architectural elements. This indicates a need for a more supportive regulatory framework that encourages the implementation of any methods that contribute to being sustainable. It is worth mentioning that participants emphasised the value of certification programs like Estidama or LEED, indicating a demand for defined frameworks for evaluating and identifying sustainable performance.

Secondly, a positive shift in the building industry towards adopting green engineering solutions was indicated by some participants, which was confirmed by the appearance of the theme "Considering Environmental Resources." However, government initiatives and increased community awareness were cited as driving forces behind this shift. Hence, the crucial factors for the successful implementation of sustainable practices stem from the availability of a comprehensive approach that involves both regulatory changes and community engagement. Moreover, the "Contractors Supportance" theme added another layer to the discussion by shedding light on the need for a skilled workforce to operate, for example, renewable energy solutions effectively. This draws attention to the practical aspects of implementation by emphasising that the availability of professionals trained in green design solutions is a potential limitation. Accordingly, addressing workforce shortages and providing incentives, such as tax breaks or subsidies, becomes fundamental aspects for facilitating the adoption of green technologies. Although retrofitting is not clearly discussed, the emphasis on flexibility and innovation indicates a willingness to embrace new technologies and design principles, provided they align with regulatory frameworks.

Turning to research question (4), the most prominent theme was "Optimising Returns, Minimising Initial Costs". This suggests that economic considerations are a major barrier to the widespread adoption of green engineering solutions. Participants expressed concerns about the high upfront costs of implementing these solutions compared to the perceived energy

savings. This economic obstacle is further exacerbated by a lack of awareness and understanding among architects, developers, and builders regarding the potential long-term benefits. The hesitancy of customers to pay higher prices due to a lack of knowledge and regulations further complicates the economic landscape. Unexpectedly, the theme of "Having Comprehensive Obliged Building Code" reappears here, emphasising that a comprehensive code is essential to guide architects, engineers, and builders toward incorporating green solutions. The absence of supportive policies and regulations is seen as a hindrance, and participants advocate for explicit encouragement or mandates within the building code to prioritise sustainable design principles. Nonetheless, the theme of "Enhancing Awareness and Addressing Undesirable Behaviour" indicated that user behaviour plays a significant role in the success of green engineering solutions. The lack of active engagement in energy-saving practices by users is considered a potential barrier. This underscores the importance of not only technological solutions but also behavioural change and community awareness programs.

Overall, the data suggested that a holistic approach involving regulatory changes, economic incentives, community engagement, and awareness programs is crucial for overcoming barriers to the implementation of green engineering solutions in new residential building projects in Saudi Arabia.

Chapter 7: Modelling and simulation

The accomplishment of the research's aim and objectives were supported by modelling and simulation techniques. This chapter provides comprehensive discussions with regard to the subject of the selected building case study. Therefore, the climate analysis and weather data files of Saudi Arabia, where case studies are located according to Saudi Building Code zones mentioned in section 4.2, are evaluated in the opening Section. Furthermore, the data and construction specifications related to the case study building are highlighted in section 7.2. Subsequently, Section 7.3 sheds light on the data input of the modelling, such as occupant user profiles, in order to construct an accurate model. While Sections 7.4 and 7.5 present the energy consumption and the free running simulation of the baseline model. Furthermore, in order to refine the baseline model data, Section 7.6 examines the validation and calibration criteria to emphasise the accuracy of the base case model compared to the actual building. Lastly, Section 7.7 provides an evaluation of the proposed green engineering solutions nominated from the critical appraisal in relation to the literature review.

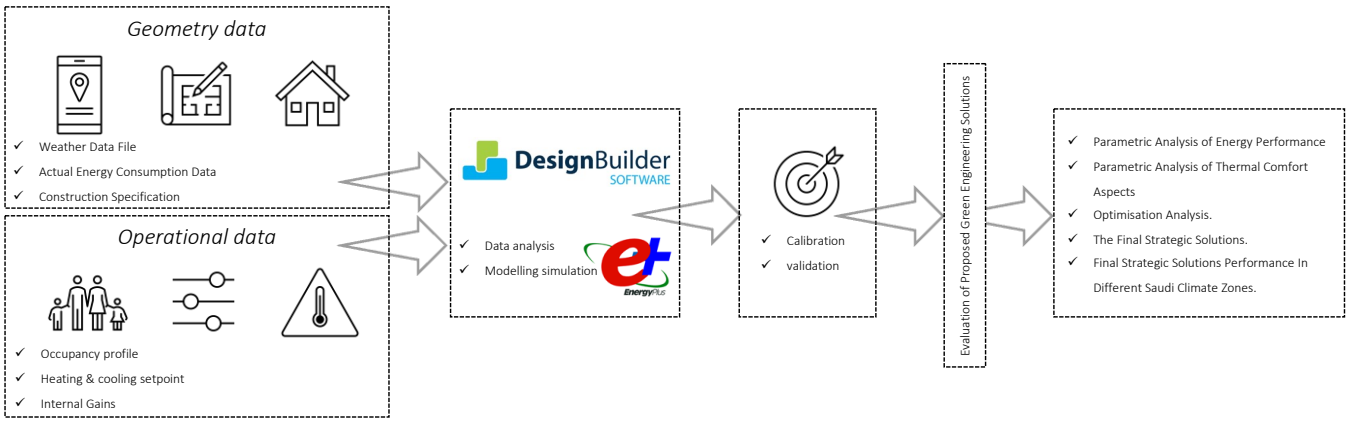


Figure 7.1. Modelling Flow Chart.

7.1 CLIMATE ANALYSIS AND WEATHER DATA FILE

The research project focuses on four Saudi cities that represent the conditions of various regions for the case study, given the differences between Saudi regions in terms of their cultural, topographic, and climatic features. The climate of the case study country can be classified as 'hot arid desert' according to the Köppen-Geiger Climate Classification. However, the selected cities from Saudi Arabia for the case studies are Riyadh, Tabuk, Abha, and Dammam. These cities showcase the desert climate that dominates Saudi Arabia, but with variations. Riyadh represents the central desert, Tabuk the northern cooler desert, and Dammam the hot and humid coastal desert. Abha, on the other hand, provides insight into the cooler, wetter, and more temperate conditions found in Saudi Arabia's mountainous regions, which is a significant contrast to the country's predominantly arid climate. Each of these cities is located in a different region of Saudi Arabia and experiences distinct climate characteristics. Riyadh: located in the central part of Saudi Arabia, Riyadh is in the heart of the desert and has an arid desert climate with extremely high temperatures and very low rainfall. Dammam: positioned on the eastern coast by the Arabian Gulf, Dammam has a hot desert climate but is influenced by coastal humidity. The combination of high temperatures and high humidity creates a unique climate compared to inland cities like Riyadh. Tabuk: situated in the northwestern part of the country, Tabuk has a slightly cooler desert climate, influenced by its proximity to the Mediterranean and occasional cold fronts that can bring snow to nearby mountainous areas. Abha: located in the Asir region in the southwest, Abha is at a higher altitude (around 2,200 meters) and has a temperate mountain climate. It experiences cooler temperatures, more rainfall, and higher humidity due to its elevation and its location near the Red Sea (Said et al. 2003; Alrashed and Asif 2015). Figure (7.2) illustrates the case study location, with the selected cities highlighted to ensure a comprehensive capture of the diverse weather conditions in Saudi Arabia.

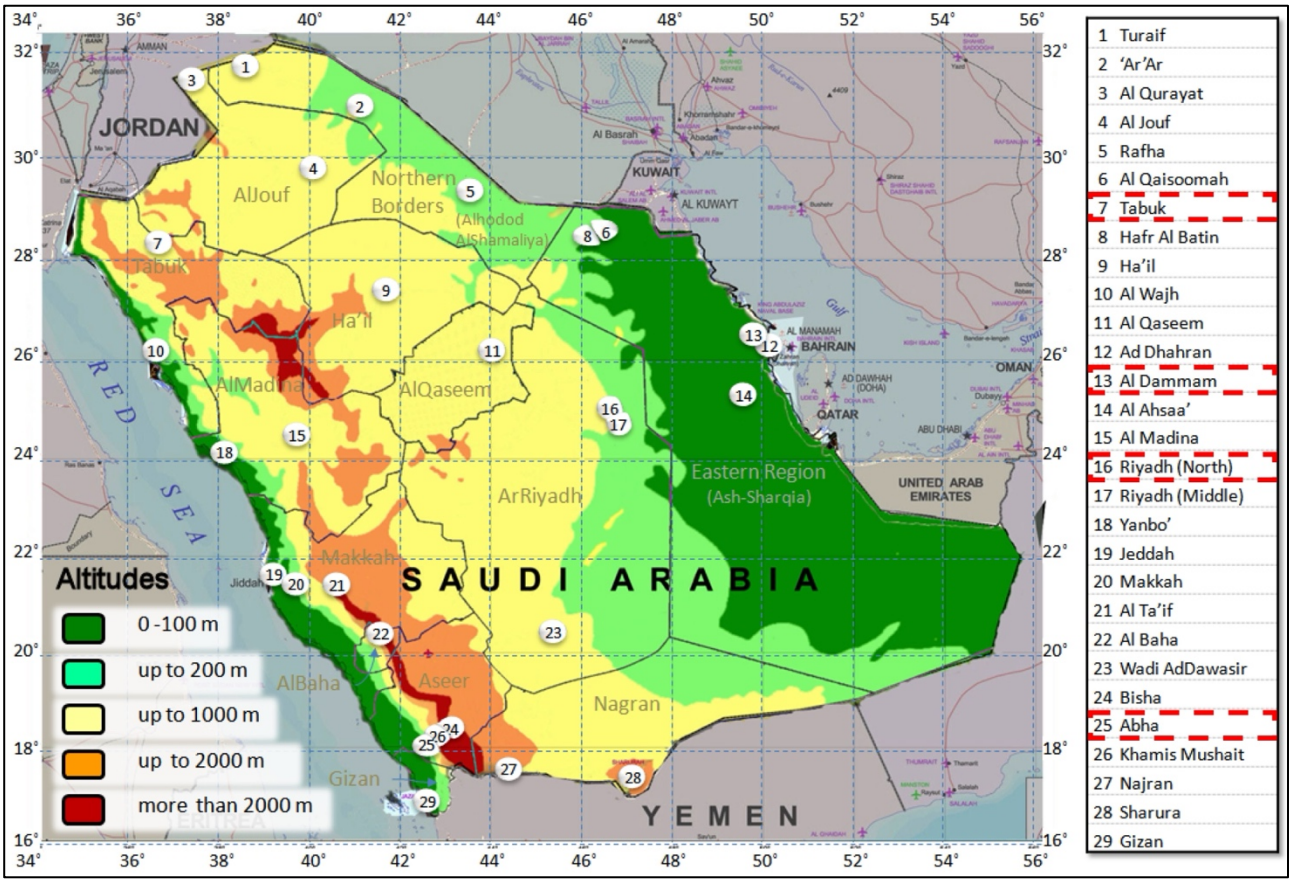


Figure 7.2. Saudi Arabia Map Showing the Selected Cities with Geographic and Topographic Profiles. (Source: Albakry et al., 2010 cited in Rafique et al., 2016).

Comprehension of the data analysis is facilitated by examining the local climate in which the case study building is situated. The ASHRAE served as the data sources for the raw weather data gather for the selected cities. Notably, the data gathered by ASHRAE utilised the proximal weather stations located at the King Salman Airbase and the Riyadh Airbase, Dammam King Fahd international airport, Tabuk airport, and Abha airport.

Table (7.1) below details an extensive collection of weather data for these cities in Saudi Arabia: Riyadh, Dammam, Tabuk, and Abha. The data include key parameters such as dry bulb temperature (°C), which represents the true ambient air temperature, and cooling degree-days (base 10.0°C and 18.3°C), which indicate the cooling demand by measuring how long temperatures exceed these limits. Heating degree-days (base 10.0°C and 18.3°C) reflect the need for heating during colder periods when temperatures fall below these values. The relative humidity ratio provides a measure of moisture in the air, while solar radiation (kWh/m²) quantifies the total solar energy received, crucial for solar energy assessments.

Additionally, average wind speed (m/s) offers insight into wind energy potential, and average precipitation (mm) highlights rainfall patterns, helping to understand each city's aridity or humidity and seasonal variations. These data capture the unique climate profiles of each city, offering a window into their climate patterns and providing a foundation for deeper exploration.

Table 7.1. Weather Datasets for The Four Selected Cities to Be Use with Modelling Analysis.

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Riyadh, WMO: 404380												
Dry bulb temperature, °C	27.9	31.8	35.6	40.1	43.8	45.2	46.1	45.8	43.3	39.0	33.6	28.8
Cooling degree-days base 10.0 °C, °C-day	157	221	362	520	712	772	827	829	704	569	344	203
Cooling degree-days base 18.3 °C, °C-day	8	34	113	271	454	522	568	571	454	311	104	19
Heating degree-days base 10.0 °C, °C-day	3	1	0	0	0	0	0	0	0	0	0	1
Heating degree-days base 18.3 °C, °C-day	112	48	9	1	0	0	0	0	0	0	10	74
Relative humidity %	41	30	24	20	14	10	11	12	14	18	35	44
Solar Radiation kWh/m²	4.31	5.16	5.93	6.45	7.19	7.83	7.48	7.12	6.55	5.71	4.42	4.08
Average wind speed, m/s	3.1	3.6	3.6	3.8	3.5	3.6	3.5	3.2	2.7	2.4	2.8	2.9
Average precipitation, mm	14	7	31	37	8	0	0	0	0	1	7	9
Dammam, WMO: 404150												
Dry bulb temperature, °C	28.1	31.0	37.7	41.0	45.2	47.2	48.0	47.1	45.2	41.2	35.1	29.0
Cooling degree-days base 10.0 °C, °C-day	178	212	367	514	708	773	844	829	711	601	376	231
Cooling degree-days base 18.3 °C, °C-day	11	24	114	264	450	523	586	571	461	343	130	24
Heating degree-days base 10.0 °C, °C-day	1	0	0	0	0	0	0	0	0	0	0	0
Heating degree-days base 18.3 °C, °C-day	92	47	5	0	0	0	0	0	0	0	4	52
Relative humidity %	66	62	54	50	43	38	43	53	53	58	60	66
Solar Radiation kWh/m²	3.80	4.55	5.45	6.06	7.01	7.57	7.20	6.86	6.26	5.22	3.91	3.57
Average wind speed, m/s	4.4	4.7	4.6	4.5	4.7	5.3	4.7	3.8	3.7	3.4	3.9	4.3
Average precipitation, mm	17	6	7	9	2	0	0	0	0	0	20	16
Tabuk, WMO: 403750												
Dry bulb temperature, °C	26.0	29.4	33.9	36.9	40.0	42.0	43.1	43.1	41.7	37.4	31.2	26.9
Cooling degree-days base 10.0 °C, °C-day	67	116	242	379	530	607	678	686	583	457	237	94
Cooling degree-days base 18.3 °C, °C-day	1	6	39	136	272	357	419	427	333	199	32	2
Heating degree-days base 10.0 °C, °C-day	16	4	0	0	0	0	0	0	0	0	0	6
Heating degree-days base 18.3 °C, °C-day	208	127	56	6	0	0	0	0	0	1	46	172
Relative humidity %	44	34	26	20	18	18	20	22	24	28	38	43
Solar Radiation kWh/m²	4.18	5.15	6.37	7.24	7.83	8.40	8.08	7.52	6.71	5.48	4.40	3.88
Average wind speed, m/s	2.3	2.8	3.1	3.3	3.4	3.3	3.3	3.2	2.8	2.5	2.1	2.0
Average precipitation, mm	10	1	5	1	3	0	0	0	0	3	3	3
Abha, WMO: 411120												
Dry bulb temperature, °C	24.0	25.1	26.9	28.7	31.8	33.1	33.2	32.2	31.9	28.2	25.2	23.8
Cooling degree-days base 10.0 °C, °C-day	129	165	236	288	379	431	446	433	384	291	193	141
Cooling degree-days base 18.3 °C, °C-day	0	1	12	46	122	181	188	174	134	39	2	0
Heating degree-days base 10.0 °C, °C-day	0	0	0	0	0	0	0	0	0	0	0	0
Heating degree-days base 18.3 °C, °C-day	130	70	35	8	1	0	0	0	0	6	58	117
Relative humidity %	64	57	52	52	51	43	50	65	56	51	62	63
Solar Radiation kWh/m²	5.06	5.81	6.57	6.89	7.19	7.23	6.58	6.34	6.56	6.34	5.36	4.96
Average wind speed, m/s	3.5	3.8	4.1	3.4	2.7	2.9	3.0	3.0	3.0	2.6	2.5	2.8
Average precipitation, mm	11	9	28	43	29	8	18	25	7	3	6	2

(Source: 2021 ASHRAE Handbook — Fundamentals (SI))

Figure (7.3) below illustrates the dry bulb temperatures (°C) for Riyadh, Dammam, Tabuk, and Abha throughout the year, highlighting climatic variations. All cities registered their highest temperatures during the summer months, with Dammam recording the peak temperature at 48°C in July, closely followed by Riyadh at 46.1°C. Tabuk reaches a maximum of 43.1°C in July, while Abha, due to its higher elevation, remains notably cooler, with a maximum temperature of 33.2°C in June. Conversely, January is the coldest month for all cities, with temperatures ranging from 24°C in Abha to 28.1°C in Dammam. This data emphasises the extreme heat characteristic of Saudi Arabia's desert climate, where temperatures frequently exceed 40°C during the summer, especially in lower-elevation cities, while Abha maintains relatively moderate temperatures throughout the year.

Figure (7.4) illustrates the relative humidity rates for Riyadh, Dammam, Tabuk, and Abha, highlighting significant seasonal variations in moisture levels across these cities. Dammam experiences the highest humidity throughout the year, peaking at 66% in January and December, and reaching a low of 38% in June. In contrast, Riyadh exhibits much lower humidity, particularly during the summer months, with a minimum of 10% in June and increasing to 44% by December. Tabuk follows a similar trend, with humidity decreasing to 18% in May and June and rising to 43% by December. Abha, on the other hand, maintains relatively stable humidity levels, ranging from 43% in June to a high of 65% in August, reflecting its more moderate climate. Overall, the data underscores the contrast between Dammam's consistently high humidity and the drier conditions in Riyadh and Tabuk, especially during the summer, while Abha experiences relatively stable humidity levels throughout the year.

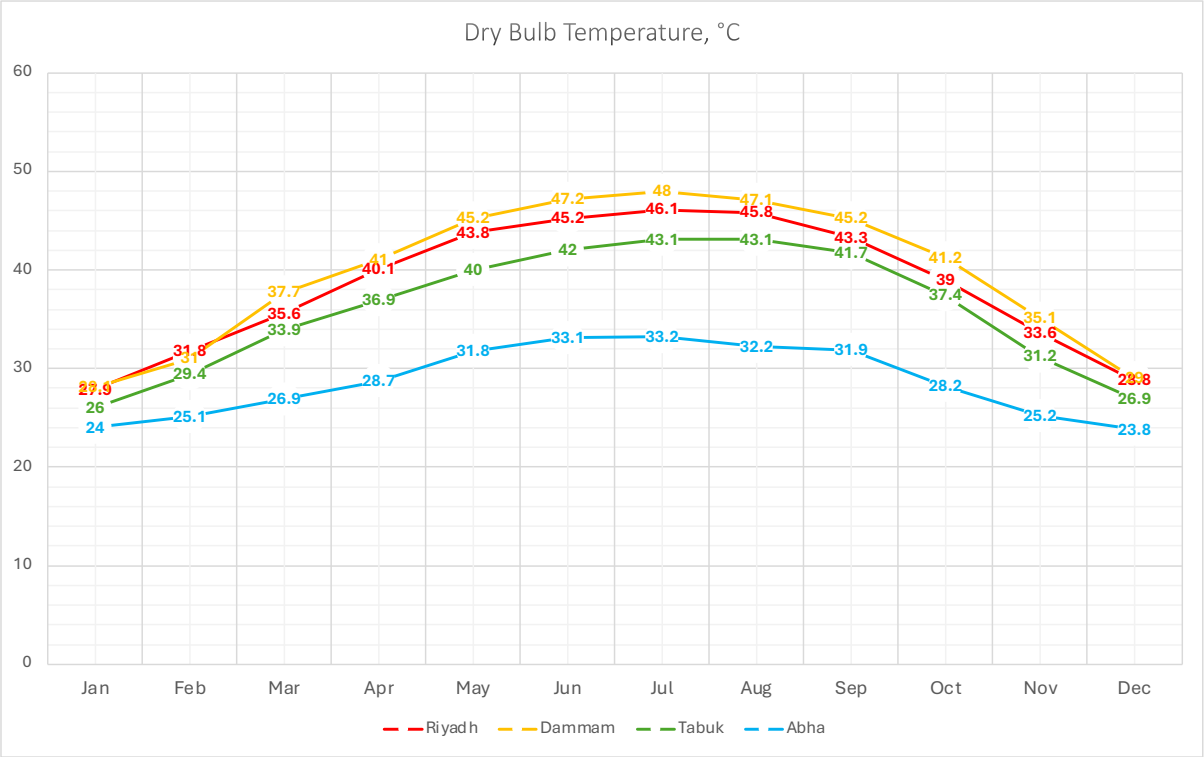


Figure 7.3. Monthly Variation in Dry Bulb Temperature (°C) Across Four Selected Cities.

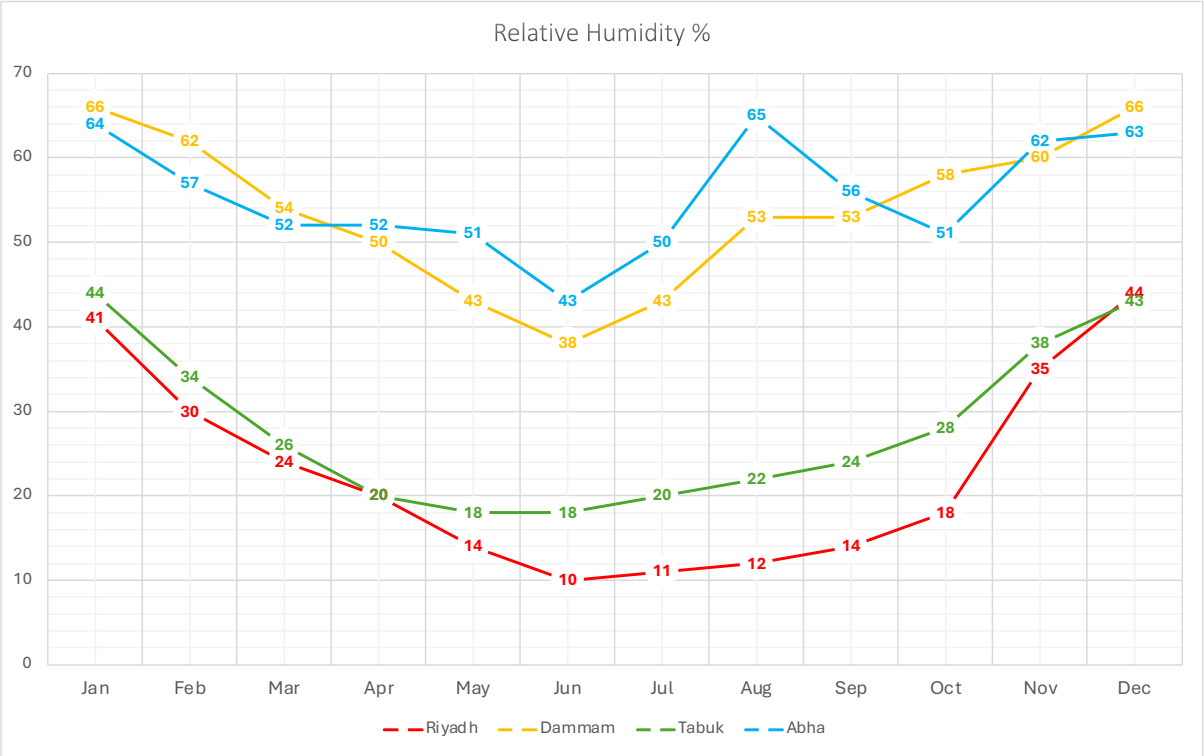


Figure 7.4. Monthly Variation in Relative Humidity (%) Across Four Selected Cities.

Figure (7.5) demonstrates the distribution of solar radiation (kWh/m²) across the selected cities, reflecting variations in solar energy throughout the year. Tabuk registers the highest solar radiation, peaking at 8.4 kWh/m² in June, followed closely by Riyadh with a maximum of 7.83 kWh/m² in the same month. Dammam and Abha show slightly lower levels, with their maximum solar radiation reaching 7.57 kWh/m² in June and 7.23 kWh/m² in May and June, respectively. Solar radiation is highest across all cities during the summer months and lowest in winter, particularly in December, when Dammam records the lowest value of 3.57 kWh/m². Abha exhibits relatively stable solar radiation throughout the year, ranging from 4.96 kWh/m² in December to 7.23 kWh/m² in June. This data emphasises the intense solar radiation experienced during the summer months in Saudi Arabia, with the highest values observed in Tabuk and Riyadh, while Abha maintains a more consistent solar energy profile year-round.

Figure (7.6) displays the average wind speed (m/s) for Riyadh, Dammam, Tabuk, and Abha, revealing variations in wind conditions throughout the year. Dammam consistently records the highest wind speeds, peaking at 5.3 m/s in June and maintaining speeds above 4 m/s for most of the year. In contrast, Riyadh exhibits moderate wind speeds, with the highest recorded value of 3.8 m/s in April and the lowest at 2.4 m/s in October. Tabuk generally witnesses the lowest wind speeds, ranging from 3.4 m/s in May to a minimum of 2 m/s in December. Abha shows relatively stable wind speeds, reaching a maximum of 4.1 m/s in March and a minimum of 2.5–2.6 m/s in the later months of the year. Generally, Dammam witnesses significantly higher wind activity, particularly during the summer months, while Tabuk and Abha maintain more moderate and consistent wind speeds throughout the year.

Figure (7.7) displays the average precipitation (mm) for Riyadh, Dammam, Tabuk, and Abha, illustrating the varying rainfall patterns across these cities throughout the year. Riyadh registers its highest precipitation in April (37 mm) and minimal rainfall during the summer months (June to September). In contrast, Dammam receives generally low precipitation year-round, peaking at 20 mm in November. Tabuk also has limited rainfall, with 10 mm recorded in January and a dry period from June to September. Abha, located in a more humid region, records the highest levels of precipitation, particularly in April (43 mm) and May (29 mm), with intermittent rainfall even during typically dry months. Overall, the data underlines the arid conditions prevalent in Riyadh, Dammam, and Tabuk, where rainfall is concentrated in the spring and winter, while Abha's more consistent precipitation is due to its geographical characteristics.

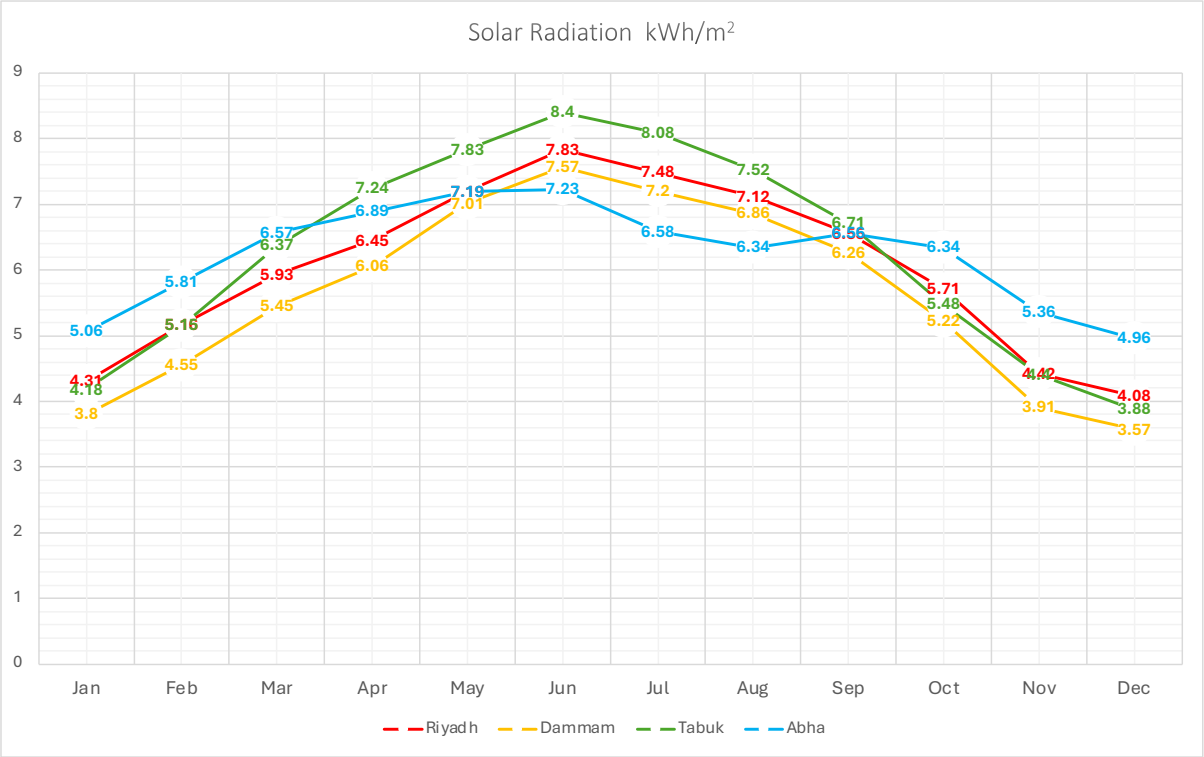


Figure 7.5. Average Daily All-Sky Solar Radiation (kWh/m²) Reaching the Ground Across Four Selected Cities.

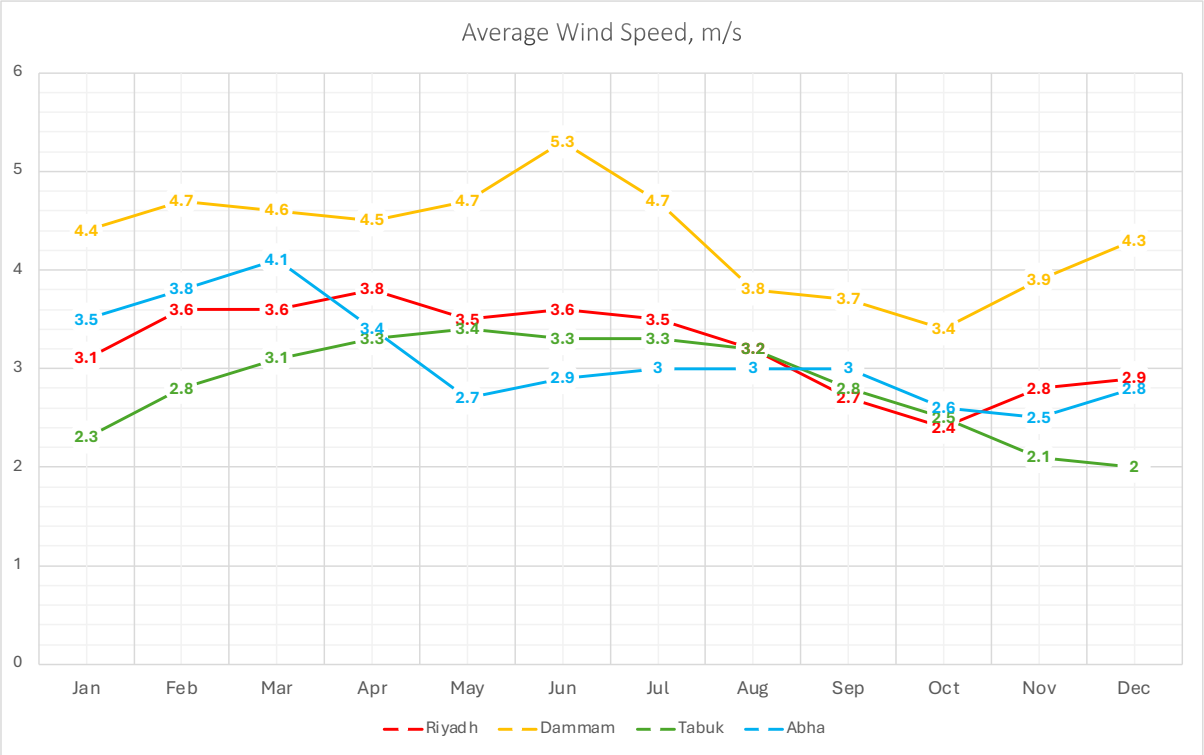


Figure 7.6. Average Monthly Mean Wind Speed (m/s) Across Four Selected Cities.

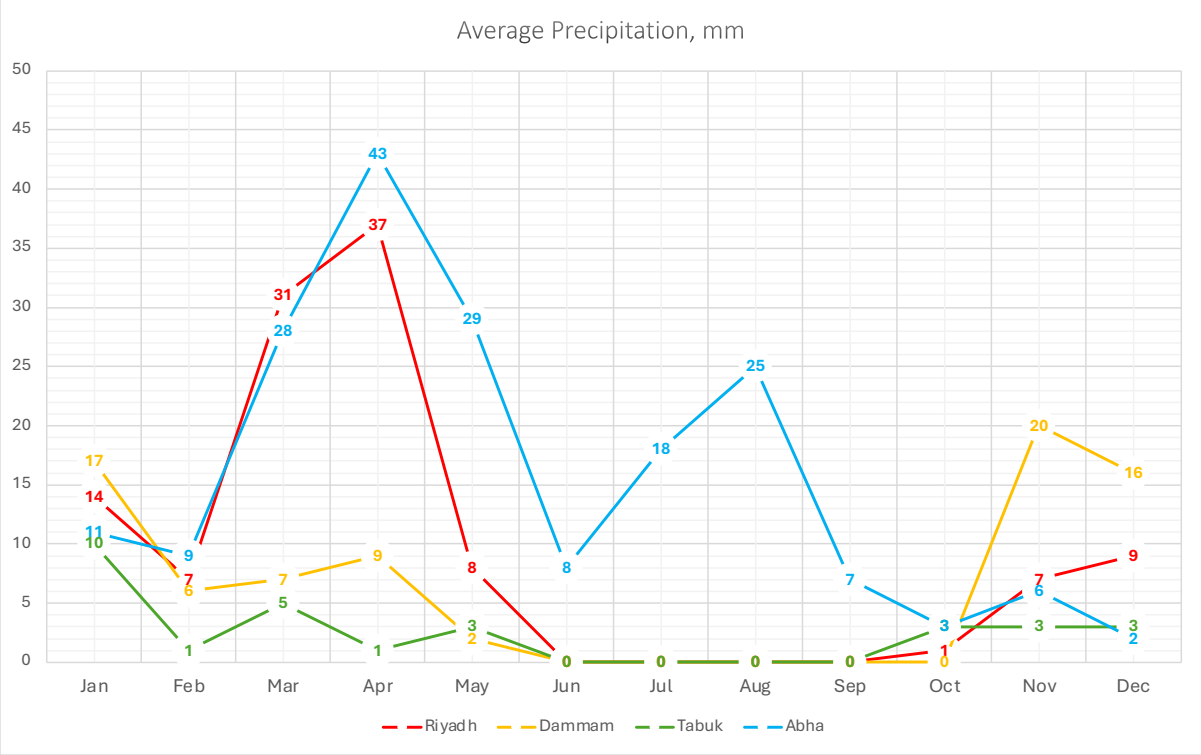


Figure 7.7. Average Monthly Precipitation (mm) Across Four Selected Cities.

In addition, the psychrometric charts in Figure (7.8) below illustrate the thermal comfort conditions in the four Saudi cities—Riyadh, Tabuk, Abha, and Dammam—during both winter and summer. Each chart depicts the relationship between temperature and humidity, with blue-shaded areas representing thermal comfort zones. The green and red dots on the psychrometric charts correspond to hourly data points, showing the combination of dry-bulb temperature and humidity levels throughout the seasons in each city. These charts are based on ASHRAE Standard 55 and the current handbook of fundamentals model, generated using Climate Consultant 6.0 software. A clothing insulation level of 0.5 Clo was used for the summer season and 1.0 Clo for winter, while the metabolic rate was set to 1.1 Met, representing activities such as sitting and reading.

For example, in Riyadh, in plot (7.8-B), the majority of data points initially fell outside the comfort zone (marked in red) prior to the implementation of any strategies. After the theoretical application of the proposed strategies, the thermal comfort zone expanded significantly, and most data points shifted into the comfort zone (marked in green), as shown in plot (7.8-A). In contrast, Abha exhibited a mix of data points both inside and outside the comfort zone, reflecting a combination of comfortable and cold conditions. Moderate improvements were observed after implementing the proposed strategies (see plots 7.8-E and 7.8-F). These charts provide valuable insights into the climate challenges of these regions and can inform building design and energy strategies aimed at ultimately enhancing occupant comfort.

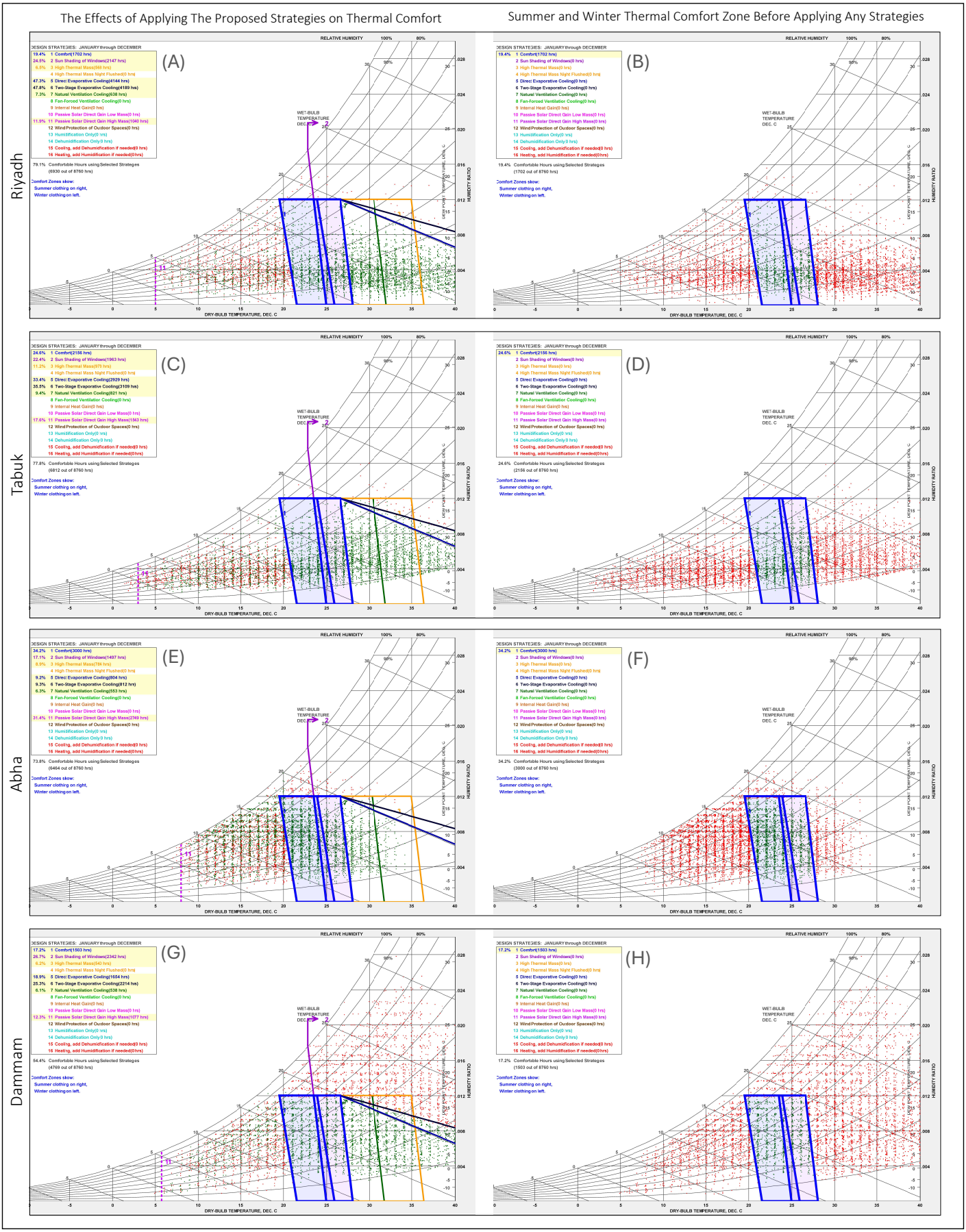


Figure 7.8. Thermal Comfort Levels in Four Selected Saudi Cities and the Impact of Proposed Strategies Using Climate Consultant 6.0 Software.

7.2 CASE STUDY BUILDING SELECTION

As mentioned previously in introduction chapter the ROSHN housing project consider to be one of the current "megaprojects" in Saudi Arabia. It being developed by the Saudi Public Investment Fund (PIF) and spans over 150 million square metres throughout nine major cities within four Saudi regions: Asir, Eastern, Riyadh, and Makkah. The initial stage of the project is Sedra district in Riyadh city that comprises eight-phase, which will eventually contain over 30,000 units spread over a 20 million square metre area. The first phase of it involved 4,500 buildings sharing the same construction specifications. In September 2021, some residential buildings that made up the first phase were completed and hand over to the clients.

Therefore, the baseline building is one of the residential buildings that were finished and handed over to the clients in September 2021. This building is part of the Sedra district within the ROSHN residential project (see Figure 7.9). The following aspects were taken into consideration when selecting the case study building:

1. The building should be central to the district and represent most of the other buildings since their design and materials are identical.
2. The building is fully operational and naturally occupied by the consumer.
3. Easy access to the energy consumption data from the Saudi Electrical Company.

It is worth mentioning that, while evaluating the selected case study, it has been taken into consideration that the research outcomes might allow the designers involved in the project to improve the building design by avoiding repeating the current drawbacks in the subsequent phases of such a megaproject. Additionally, the provision of free retrofit options for the researcher is possible since the subsequent phases are still under construction. Therefore, the building highlighted in the figure below was selected. Figure (7.10) and Table (7.2) illustrate the drawings, construction specifications, and data about the building collected from the ROSHN company.

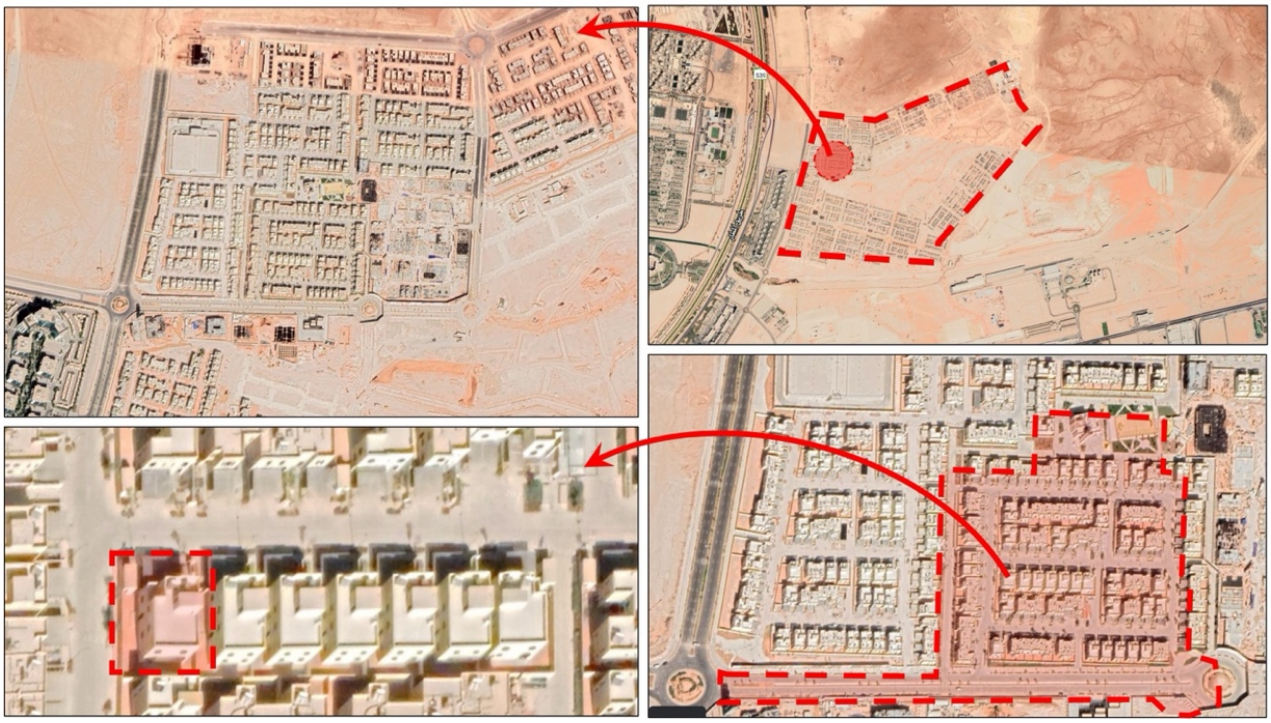


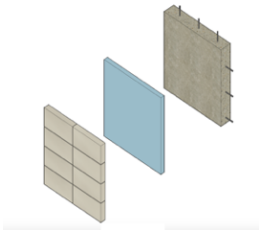
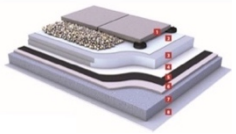
Figure 7.9. The Location of the Case Study Building in Riyadh City. [Source: www.maps.google.co]



Figure 7.10. Photographs and Configuration of The Case Study Building.

Table 7.2. Construction Specifications and Data About the Building Selected.

Description	Building Specifications			
Site Data				
Land area	16 × 25 = 400 m^2			
Net Floors Area	303.9 m^2			
Number of Stories	2			
Floor Height	3 m			
Orientation	North			
Longitude	46°44′23.5″ E			
Latitude	24°51′34.8″ N			
Glazing Details				
Window Area/Window Diminutions/	Mark	Dimensions	Quantity	Location
	W1	(1.6 × 2)	2	Reception Hall and master bedroom
	W2	(1.6 × 1.6)	7	Dining room and Reception Hall and kitchen and living room 1st floor and bedrooms 1, 2, 3
	W3	(1.2 × 0.8)	2	Others
	W4	(0.8 × 0.8)	5	Toilets
Window-to-Wall Ratio	Window-to-Wall Ratio 13%			
Frame Window Type	Aluminium			
Type of glazing	Double-glazed with 12 mm air space. U Value glazing including frames: 2.668 W/(m^2K). SHGC glazing: 0.25			

Construction Data					
External Walls details	U value 0. 34 W/(m^{2}K) (120 mm Precast Structural Wall + 120 mm EPS Insulation + 60 mm Precast Architectural Wall) 				
Roof details	U value 0. 202 W/(m^{2}K) (150 mm Precast Hollow Slab + 60 mm Structural Topping + 130 mm Screed + Waterproofing membrane + 145 mm XPS insulation + Geo-Textile sheet + Concrete Pavers) 				
Interior Walls details	Prefabricated walls concrete and cement block (10 cm)				
Outdoor Doors details	Mark	Dimensions	Quantity	Location	Materials
	D1	1.2 × 2.3	3	Main entrance and family entrance	Steel
	D2	2 × 2.3	1	Backyard door	Glass with Aluminium frame
	D3	1 × 2.2	1	Master room door	Glass with Aluminium frame
	D4	1 × 2.2	2	Roof door and driver	Steel
Facade Material	Paint				
Floor details	Hollow Core Ribbed Slab and Porcelain tiles				

Operational data	
Number of Occupants	7
Lighting Type	LED
Cooling System	Split AC units with roof-mounted compressor The HVAC system, with a COP of 3.2.
Heating System Type Capacity	Central heating unit
Thermostat Type	Each room has its thermostat

7.3 OCCUPANT PROFILES

7.3.1 Occupancy times

It is acknowledged that a building's energy consumption is usually influenced by the behaviour of the occupants. To determine the exact uses of a building that contribute to its annual energy consumption, it's crucial to have knowledge of how the occupants use the rooms within the building. This information is essential for accurately calculating the annual energy consumption.

Aldossary (2015) conducted intensive interviews with each householder of the selected eighteen residential buildings in his study in Saudi Arabian. The purpose of the interview was to learn how often each room in the homes was used, if cooling systems were being used, and whether any other electrical equipment was present. The interviews indicated a range in the duration and equipment of the rooms' uses. The activity of the house members and their living styles are reflected in occupants' profiles. He stated that all residential buildings typically have bedrooms that are occupied at night and left unoccupied during the day when residents are at work or school. There are also some regular usages for other rooms, for example, the sitting area. In addition, Aldubyan and Krarti (2022) performed a survey to identify the occupants' behaviour patterns in the sample housing units through surveys and questionnaires. They found that the typical schedule of occupancy is 100% for the buildings from 22 p.m. to 8 a.m., while the lighting operation hours in the same period are 5%. Table (7.3) below summarises the typical schedules of occupancy behaviour, lighting, and appliances for the year 2019 that were audited by the researchers for Saudi housing units.

Table 7.3. The Occupant's Behaviour Patterns in Saudi Buildings.

Building model		MHD (Villa)	
Typical schedules	Hours	WD (Sun.-Thu.)	WEH (Fri-sat)
Occupancy	1-8	100%	100%
	8-14	50%	60%
	14-22	80%	70%
	22-24	100%	100%
Lighting	1-8	5%	
	8—14	20%	
	14—22	60%	
	22-24	5%	
Appliances	1-8	20%	20%
	8-14	30%	30%
	14-22	60%	70%
	22—24	10%	10%

(Source: Aldubyan and Krarti (2022)).

7.3.2 Internal Gains and Operational Profiles

The number of occupants in the building case study for the present research project is 7, as shown in Table (7.2) above. This data will be used in simulations and cooling design calculations along with the metabolic heat output of the occupants and holidays for the calculation of the heat input to the building and how that affects the energy performance through DesignBuilder software. Therefore, the daily occupancy profiles would be assumed to follow a typical Saudi style of living based on the literature and the Design-Builder software method as illustrated in Figure (7.11). Moreover, KEO International Consultants, the consultant office for the ROSHN project, specified that the baseline lighting power density is 11.8 W/m^2 for each building in the project. In terms of appliance operating profiles for kitchen, laundry, and other occupied spaces, the consultant office of the ROSHAN project emphasised that all internal appliances installed in each building are compatible with energy-efficient units considering EnergyStar and/or SASO (Saudi Standard Organisation).

	Total	Bedroom	Lounges	Guest Room	Dining Room	Kitchen	Other Spaces
12:00:00 AM	100%	95%	0%	0%	0%	0%	5%
01:00:00 AM	100%	100%	0%	0%	0%	0%	0%
02:00:00 AM	100%	100%	0%	0%	0%	0%	0%
03:00:00 AM	100%	100%	0%	0%	0%	0%	0%
04:00:00 AM	100%	100%	0%	0%	0%	0%	0%
05:00:00 AM	100%	100%	0%	0%	0%	0%	0%
06:00:00 AM	100%	100%	0%	0%	0%	0%	0%
07:00:00 AM	100%	30%	20%	0%	20%	20%	10%
08:00:00 AM	50%	10%	15%	0%	10%	10%	5%
09:00:00 AM	50%	10%	15%	0%	10%	10%	5%
10:00:00 AM	50%	10%	15%	0%	10%	10%	5%
11:00:00 AM	60%	10%	15%	0%	10%	20%	5%
12:00:00 PM	60%	10%	15%	0%	10%	20%	5%
01:00:00 PM	60%	10%	15%	0%	10%	20%	5%
02:00:00 PM	60%	10%	15%	0%	10%	20%	5%
03:00:00 PM	80%	10%	30%	40%	30%	5%	5%
04:00:00 PM	80%	30%	40%	50%	0%	5%	5%
05:00:00 PM	80%	30%	40%	40%	0%	5%	5%
06:00:00 PM	80%	15%	30%	40%	0%	30%	5%
07:00:00 PM	80%	15%	30%	40%	0%	30%	5%
08:00:00 PM	80%	10%	20%	80%	30%	15%	5%
09:00:00 PM	80%	10%	20%	70%	30%	15%	5%
10:00:00 PM	100%	50%	35%	40%	0%	10%	5%
11:00:00 PM	100%	75%	20%	30%	0%	0%	5%

Figure 7.11. Anticipated Typical Weekdays Occupancy Profile of the Case Study. * The Guest room Occupancy is an additional Occupancy that is only during the weekend.

7.3.3 Heating And Cooling Temperature Setpoints

According to Kharseh and Al-Khawaja (2016) adjusting the setpoint of the indoor temperature in the air condition from 22 °C to 24 °C could reduce the cooling load by around –14% of buildings in hot climates such as Qatar. Andric et al. (2020) emphasised that in extremely hot and dry climates an average of –7% could be saved from the building energy consumption by increasing the cooling set point for the indoor temperature by just 1°C, Souayfane et al. (2022) focused on an indoor cooling approach for Saudi Arabia regions using weather clustering and energy-thermal comfort optimisation. They indicated that the optimal cooling setpoint for indoor air temperatures during occupied hours on the 15th of August, considering different values of occupants, ranged from 21 to 26 with clothing factors of 0.4 Clo, 0.6 Clo, and 0.8 Clo. The set-point for indoor air temperature has a notable impact, influencing not just the thermal cooling loads but also the portion of this load that hybrid systems utilising evaporative cooling can address. Raising the cooling temperature setpoints is beneficial in decreasing both thermal loads and the associated cooling operations. In a residence situated in Saudi Arabia, raising the cooling setpoint from 21 °C to 26 °C results in an enhanced reduction of total annual energy consumption, ranging from 30% to 40% (Krarti et al. 2023). Fasiuddin and Budaiwi (2011) stated that despite the rise in the indoor setpoint by 3 °C, by modifying the indoor temperature setpoint from 20 °C to 23 °C throughout the entire year during occupancy, they indicated thermal acceptance in this case. However, by increasing the setpoint from 20 °C to 25 °C, the indoor temperature exceeded the defined comfort limits. Additionally, by replacing the unitary air-conditioning systems with Ideal Systems, the VAV system and TPFC system can achieve energy savings of 17.4% and 17.1%, respectively. Worth mentioning that they were focusing on different HVAC strategies for energy efficiency in Saudi commercial buildings. Taking into account these scholarly proposals, as well as the cooling system of the baseline building highlighted in Table (10) above, which was served by split air conditioning systems with an efficiency coefficient of performance (COP) of circa 3.2. Therefore, the cooling indoor temperature set point was set at 21°C. For heating, the setpoint was set at 23°C. The AC units supply a constant airflow at 13°C in cooling mode and 35°C in heating mode.

7.4 BASE CASE ENERGY CONSUMPTION

DesignBuilder software was used to build the baseline of the case study for this study. However, before the DesignBuilder (DB) software can simulate a building's energy consumption, the model parameters were set by using the construction specifications in Table (7.2) above. Additionally, other inputs are employed, including the site location and climate, site geometry and design, equipment appliances installed, building purpose and occupancy profile, and nature of the immediate environment, etc. In order to provide accurate, measurable modelling, the DB tool requires these inputs to be precise. Therefore, the DB software employed all the above case study data to accurately validate the base case's energy consumption. Figure (7.12) shows the blueprint model of the baseline for the case study. Furthermore, Table (7.4) details the comparison of energy performance between the actual energy consumption of the case study, as collected from the bills provided by the Saudi Electrical Company for the year 2022, and the simulated energy consumption of the baseline model using DB software.

Table 7.4. The Details of the Actual and Simulated Energy Consumption for the Case Study.

Months	Actual Consumption (SAR) 2022	Electricity Tariff in KSA (SAR/kWh)	Actual consumption (kWh)	Simulated consumption (kWh)	Diff (Actual-Simulated)
Jan-22	296.3	0.18	1645.9	1597.9	2.9%
Feb-22	280.9	0.18	1560.8	1600.9	-2.6%
Mar-22	348.2	0.18	1934.2	2102.4	-8.7%
Apr-22	551.6	0.18	3064.3	2825.3	7.8%
May-22	743.8	0.18	4132.3	4028.1	2.5%
Jun-22	828.7	0.18	4604.1	4508.2	2.1%
Jul-22	866.8	0.18	4815.7	4768.0	1.0%
Aug-22	717.6	0.18	3986.7	4888.9	-22.6%
Sep-22	797.0	0.18	4427.5	4313.7	2.6%
Oct-22	681.1	0.18	3783.8	3670.8	3.0%
Nov-22	482.1	0.18	2678.5	2553.7	4.7%
Dec-22	277.8	0.18	1543.1	1694.3	-9.8%
Total	**6871.8**	--------	**38176.8**	**38552.3**	**-1.0%**

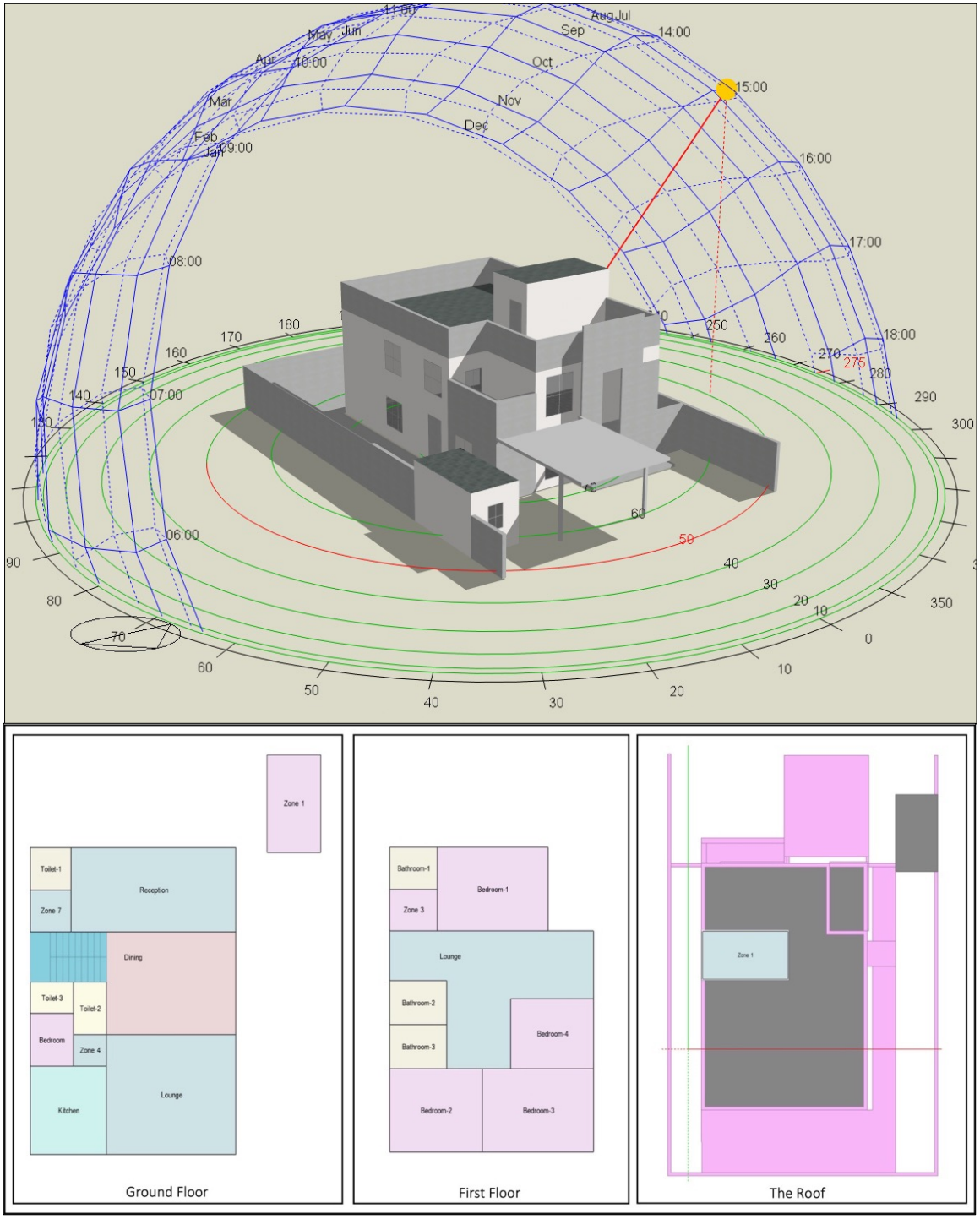


Figure 7.12. Designbuilder Model and Floor Plans.

Additionally, Figure (7.13) illustrates a comparison between the actual and simulated energy consumption of the case study. On the other hand, according to the simulation report of the annual energy performance for the case study, which is based on extensive energy modelling, the main contributor to energy use is space cooling, which accounts for 67% of total energy use, as illustrated in Figure (7.14).

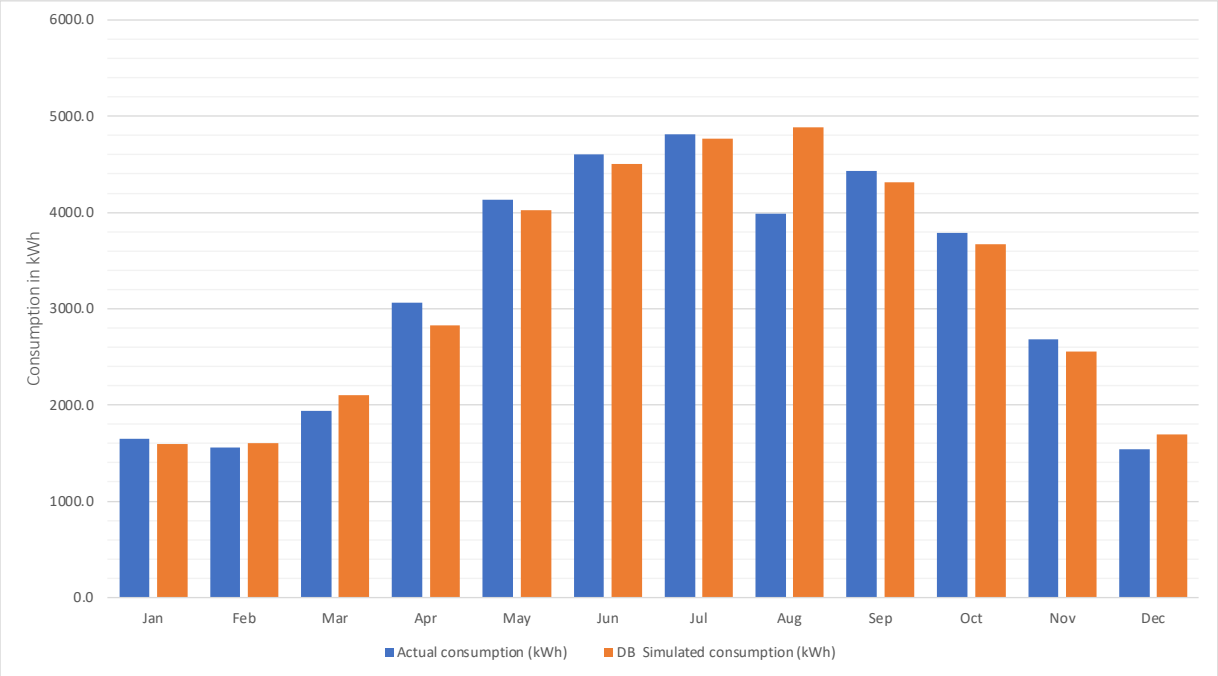


Figure 7.13. The Comparison of The Actual and Simulated Energy Consumption For The Case Study.

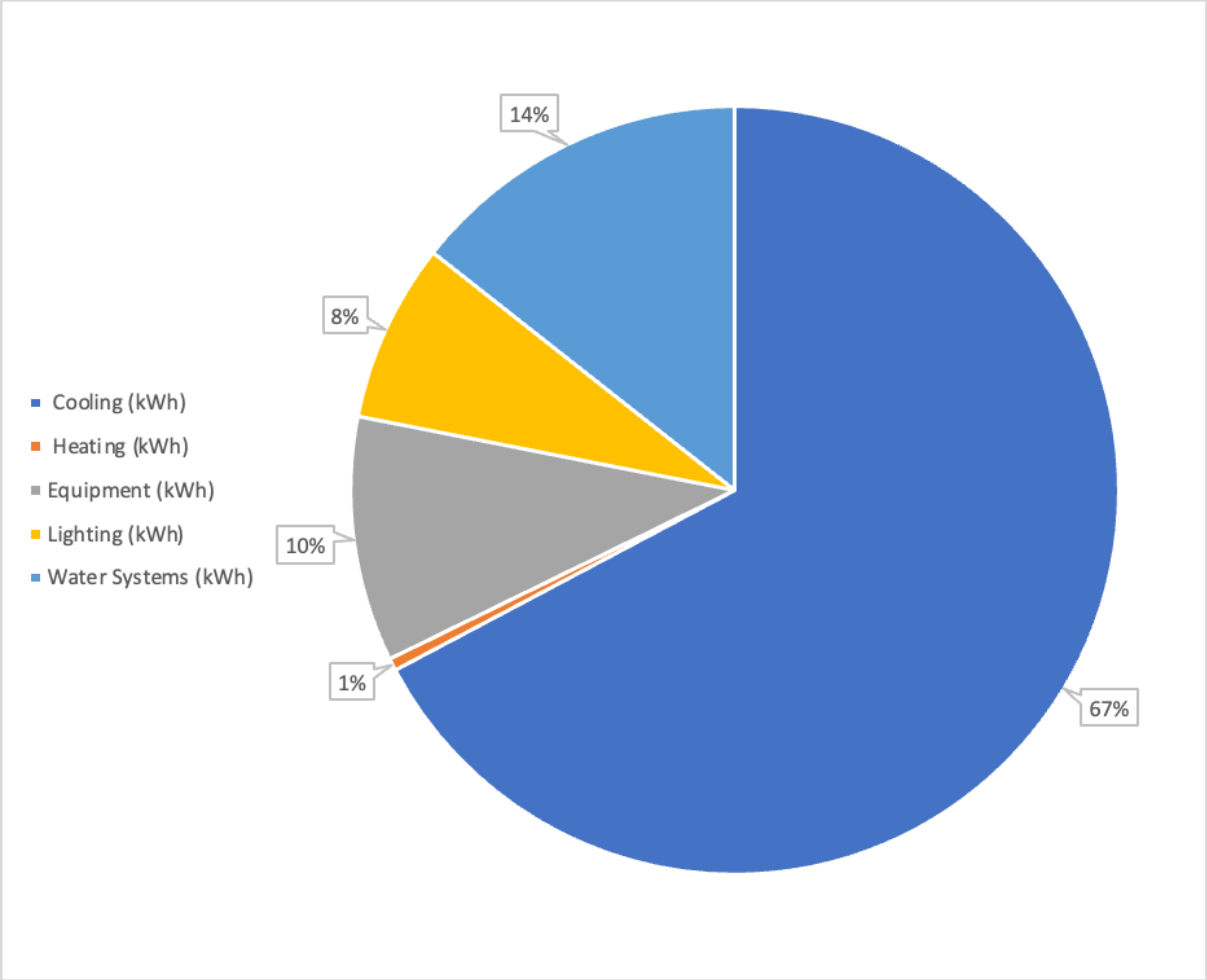


Figure 7.14. The Energy Consumption Breakdown For The Base Case.

7.5 FREE-RUNNING SIMULATIONS OF THE BASE CASE.

A free-running building simulation does not use any mechanical or electrical energy. The focus here is on how the building acts towards the outdoor environment in terms of the thermal comfort aspects. The thermal comfort aspects are impacted by both the outside temperature and the overall heat gains. The building's thermal behaviour should be taken into account in relation to examine thermal comfort. Moreover, when a building behaves positively towards the outside environment to achieve thermal balance, it contributes to enhancing its energy performance. For example, the energy consumption of the cooling system differs when it is required to transfer the indoor air temperature from 40 °C to 20 °C compared to when it is from 30 °C to 20 °C.

Therefore, the indoor air temperature (IAT), radiant temperature (RT), operative temperature (OP), and relative humidity (RH) values of the base case building for each zone during the 24 hours on the hottest day based on the climate analysis in the previous sections were identified as indicated in Figures (7.15), (7.16), (7.17), and (7.18), respectively. It is clear that zones that have surfaces that are directly exposed to solar radiation i.e. first floor zones have higher values due to the heat gain of the roof system.

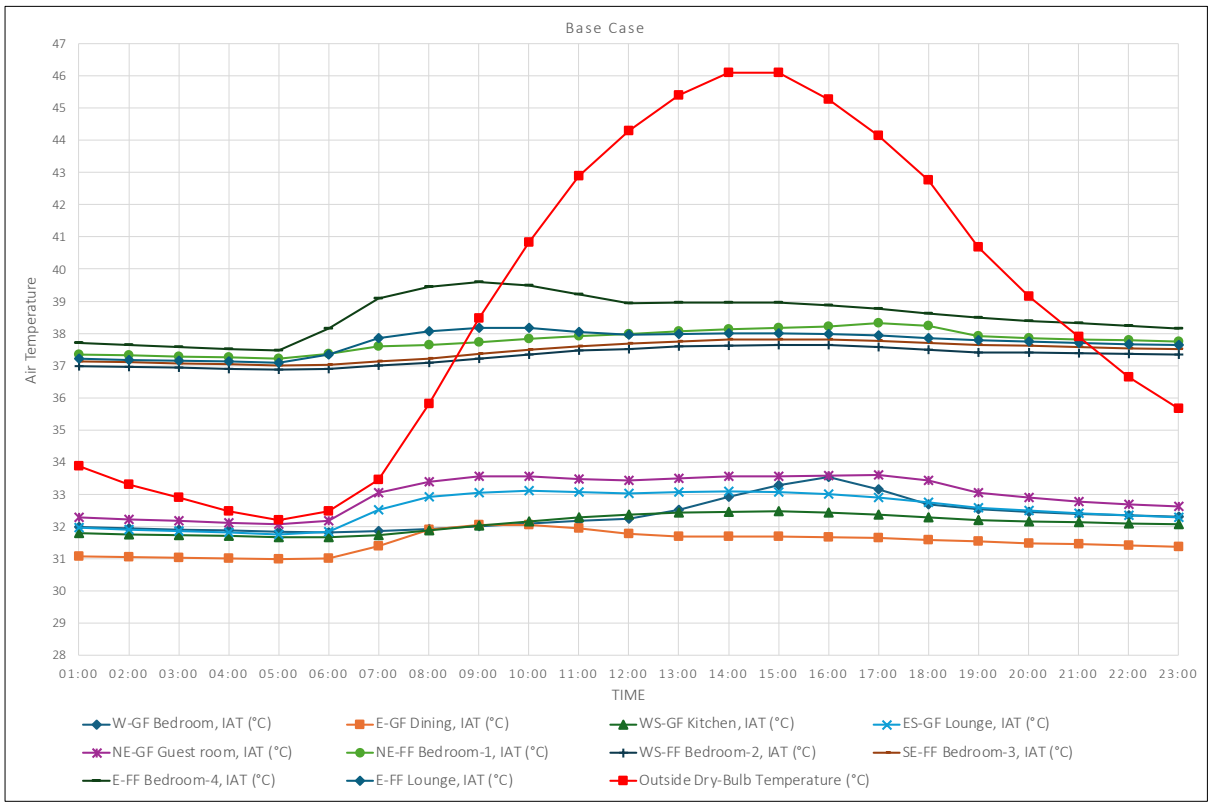


Figure 7.15. The Free-Running Simulation of Hourly Indoor Air Temperature in The Base Case Building Zones. (15th July).

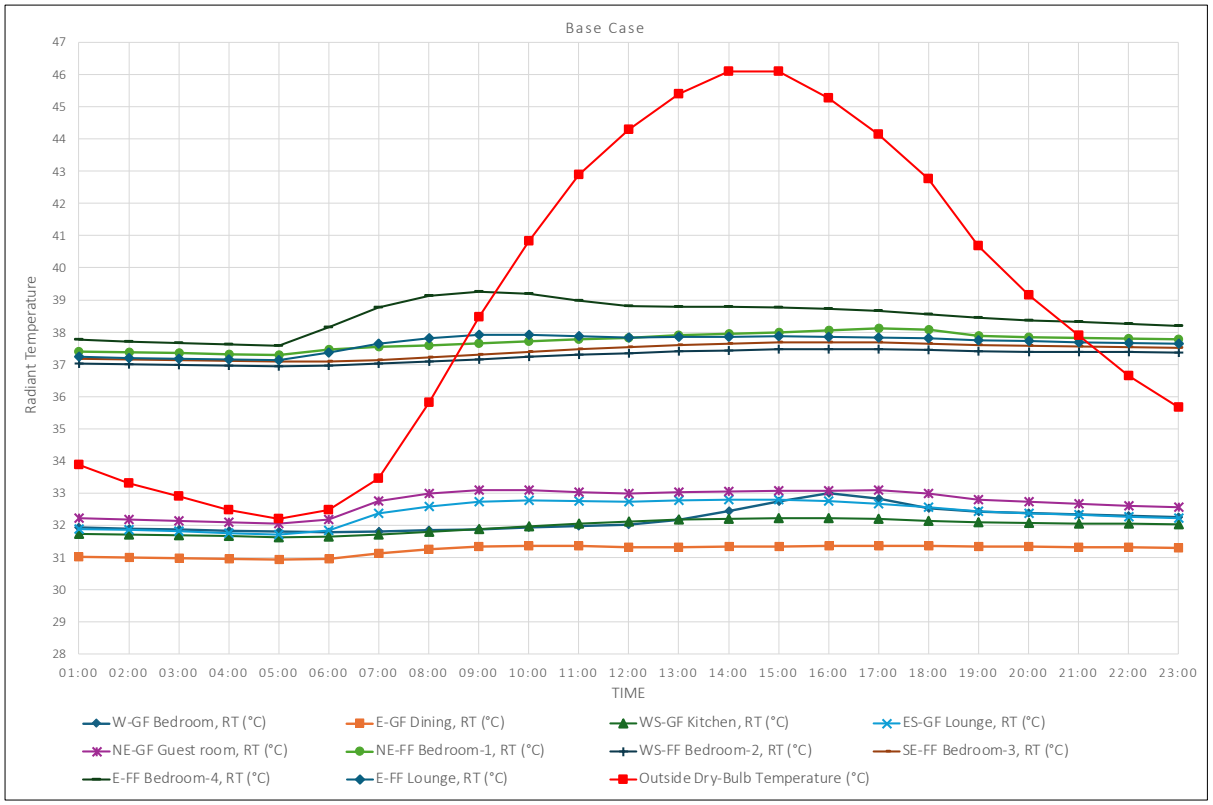


Figure 7.16. The Free-Running Simulation of Hourly Radiant Temperature in The Base Case Building Zones. (15th July).

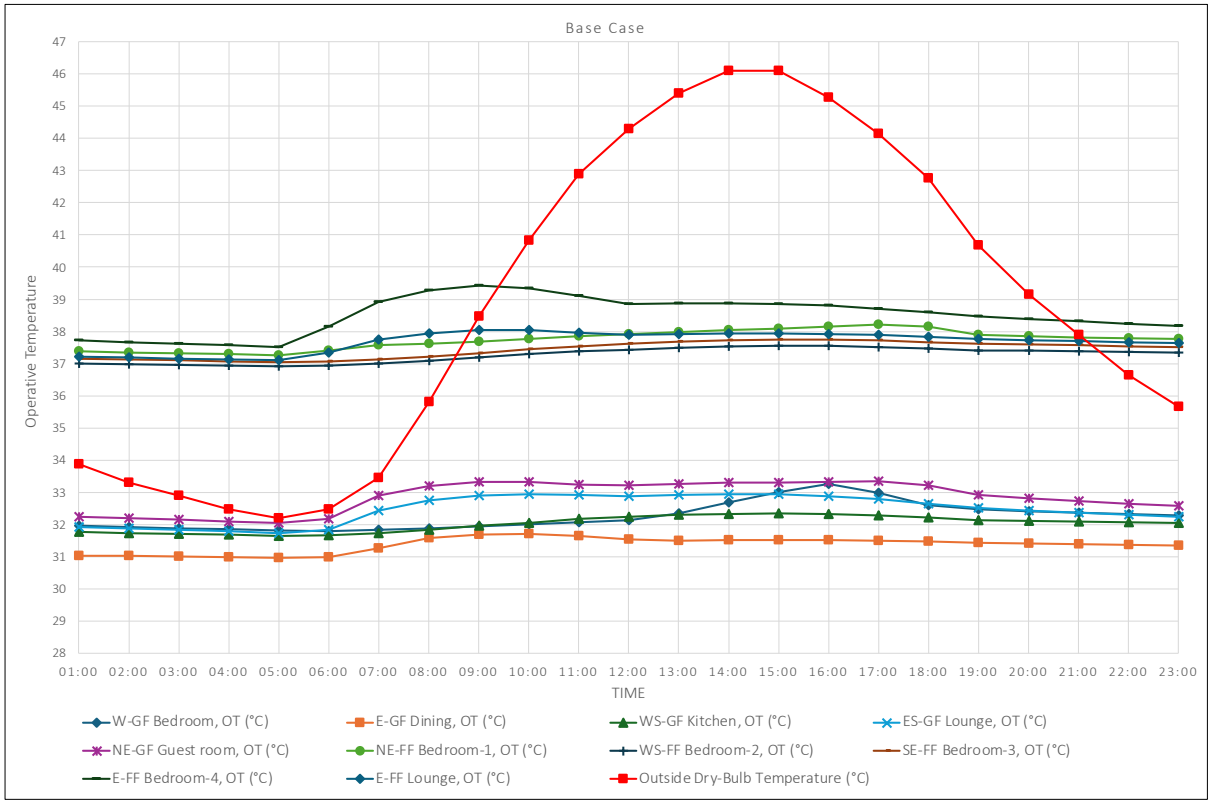


Figure 7.17. The Free-Running Simulation of Hourly Operative Temperature in The Base Case Building Zones. (15th July).

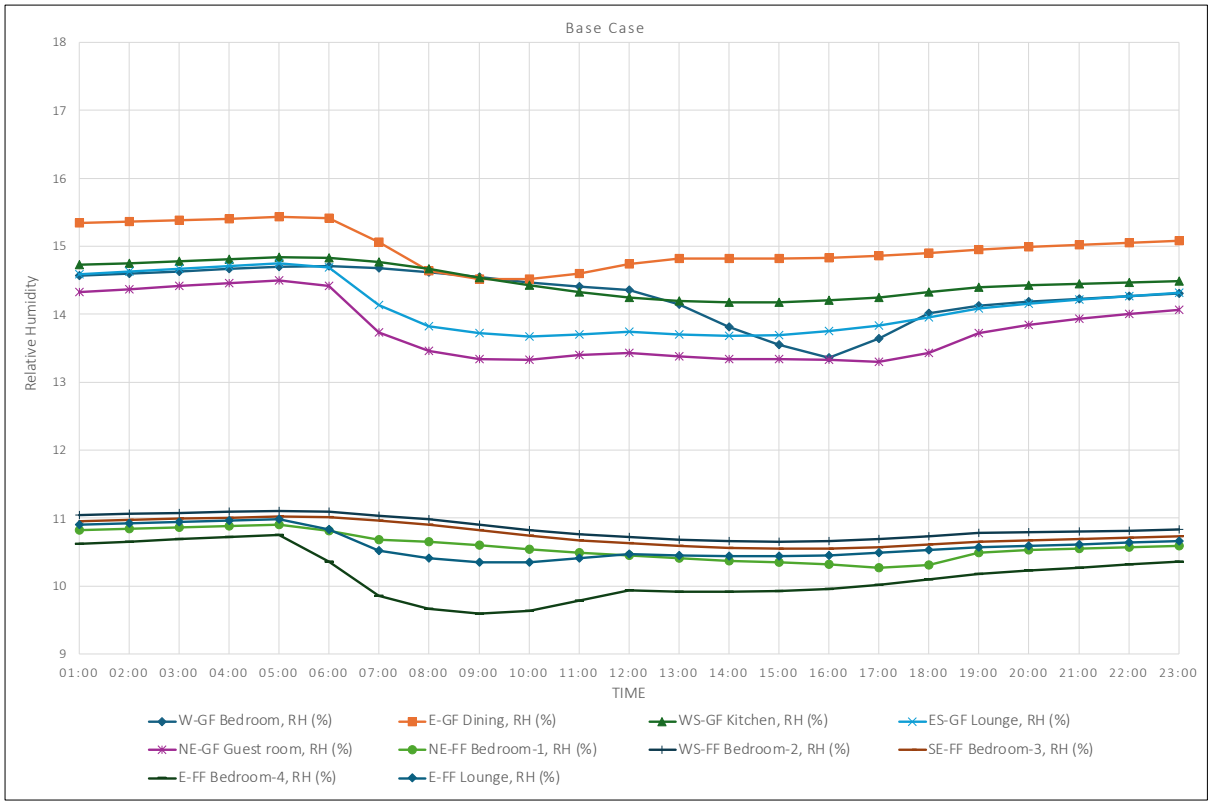


Figure 7.18. The Free-Running Simulation of Hourly Relative Humidity in The Base Case Building Zones. (15th July).

7.6 VALIDATION AND CALIBRATION

The ASHRAE 14-2014 guidelines describe calibration as diminishing any ambiguity within a model through the comparison of the model's forecast output within a defined group of conditions with the observed data parameters obtained during identical conditions. Ryan and Wheatcraft (2017) defined validation as the need to make sure that the performance of research is objective and without bias, and that the proposed objective is achieved within the desired setting. Calibration can therefore be viewed as confirming the precision of a design's performance, whereas validation is academic evidence that affirms that the study design, methodology or system yields an output that is reproducible. Thus, the former is conducted to establish accuracy; the latter is met by the maintenance of appropriate records. In keeping with these parameters, and to confirm that the findings of the research will reflect real life and the selected case study, data acquired from true energy usage will be compared with data obtained from simulations. The validation of the building model was utilised in order to achieve the best simulation model fit as possible to the true scenario. This was carried out in

accordance with the data gathered in the previous sections, such as the occupant user profiles, and the actual energy consumption of the base case.

The main uncertainty indices, as described by Ruiz, Bandera (2017) encompass normalised mean bias error (NMBE), the coefficient of variation of the root mean square error (CV(RMSE)) and the coefficient of determination (R2). The computation of these parameters can be achieved using the following equations.

$$MBE = \frac{\sum_{i=1}^{n}(m_i - s_i)}{n} \tag{3}$$

$$NMBE = \frac{1}{\widetilde{m}} \cdot \frac{\sum_{i=1}^{n}(m_i - s_i)}{n - p} \times 100(\%) \tag{4}$$

$$CV(RMSE) = \frac{1}{\widetilde{m}} \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^{2}}{n - p}} \times 100(\%) \tag{5}$$

$$R^{2} = \left(\frac{n \cdot \sum_{i=1}^{n} m_i \cdot s_i - \sum_{i=1}^{n} m_i \cdot \sum_{i=1}^{n} s_i}{\sqrt{(n \cdot \sum_{i=1}^{n} m_i^2 - \sum_{i=1}^{n} m_i)^2) \cdot (n \cdot \sum_{i=1}^{n} s_i^2 - (\sum_{i=1}^{n} s_i)^2)}} \right)^2 \tag{6}$$

Where MBE (Mean Bias Error) is the average of the errors of a sample space, $NMBE$ (Normalised Mean Bias Error) is a normalisation of the MBE index that is used to scale the results of MBE, making them comparable, $CV(RMSE)$ is the coefficient of variation of the root mean square error, commonly used to evaluate the accuracy of a model's predictions relative to the mean of observed data. R^2 is the coefficient of determination that indicates how close simulated values are to the regression line of the measured values.

m_i is the actual value.

s_i is the simulated one.

n is the number of actual data points.

p is the number of adjustable model parameters, which for calibration purposes, is suggested to be one.

$\widetilde{m}$ is the mean of measured values.

A comparison could be made between the results of these formulae and the three main guidelines outlined in Table (7.5) below, which detail the way in which to establish the confidence level and its uncertainty. These guidelines comprise the Federal Energy Management Program (FEMP), ASHRAE guideline 14, and the International Performance Measurement and Verification Protocol (IPVMP).

Table 7.5. Calibration Criteria of (FEMP), ASHRAE Guideline 14 and IPMVP.

Data	indicator	FEMP	ASHRAE	IPMVP
Calibration criteria				
Monthly criteria %	Normalized mean bias error. (NMBE)	±5	±5	±20
	Coefficient of variation of the root mean square error CV (RMSE)	15	15	-
Hourly criteria %	Normalized mean bias error. (NMBE)	±10	±10	±1 to ±5
	Coefficient of variation of the root mean square error CV (RMSE)	30	30	±10 to ±20
Model recommendation				
	Coefficient of determination (R2)	-	>0.75	>0.75

7.6.1 Validation Of the Base Case Model

The validation was carried out in accordance with the data acquired in the preceding sections by utilising the equations (3), (4), (5) and (6) and then comparing the equations' findings and guideline ranges to determine how the model is valid. According to the above validation criteria in Table (7.5), the results of these equations for the current baseline model are shown in Table (7.6) and Figure (7.19). As a result of that, the model has met these guidelines' criteria and proven to be valid, indicating that the simulation's predictions matched the actual data closely.

Table 7.6. Results of Validation Using NMBE & CV(RMSE) Equations.

Validation using NMBE EQUATION	
sum (mi−si)	−375.5
MBE= sum (mi−si)/n	−31.3
Mean (measured) m~	3181.4
p for NMBE (should be 0)	0
1/m~	0.000314327
NMBE	−0.98%
Validation using CV(RMSE) EQUATION	
$(\text{sum (misi)})^2$	140,988
Mean (measured) m~	3181.40203
p for RMSE (should be 1)	1
n-p	11
Sq root($(\text{sum}(mi-si)^2/(n-p))$)	113.2125957
CV(RMSE)	3.559%

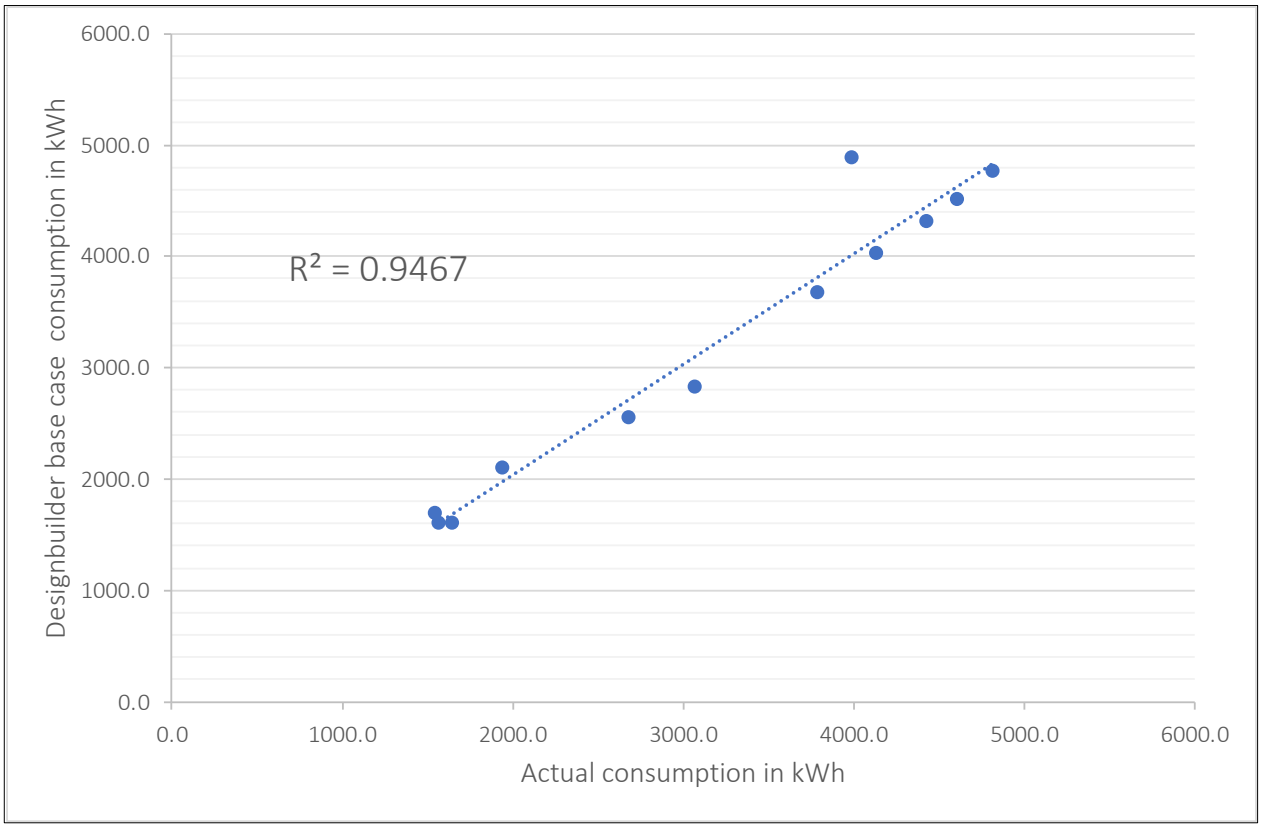


Figure 7.19. The Coefficient of Determination Between Actual and Simulated Values (R2).

7.7 EVALUATION OF PROPOSED GREEN ENGINEERING SOLUTIONS

The findings from the critical appraisal in relation to the literature review have led to the development of the initial concept of the research project, which is shown in Figure (7.20). According to this concept, as the KSA Public Investment Fund (PIF) asserted that there is greater compliance with sustainability principles and the new Saudi Building Code by the ROSHN project, a residential building from the latter has been chosen as the case study for this research project since the approach to energy efficiency should be optimal. Accordingly, this would bring challenges to this research project in terms of base case improvements. Thus, proposing different green engineering solutions for the enhancements in the context of sustainability to achieve a reasonable balance between cooling energy consumption and thermal comfort aspects was a critical objective, as shown in (7.21).

First, in the local context of applying knowledge from traditional Saudi passive architectural design solutions and bioclimatic design principles, the courtyard and shading devices (Mashrabiya) were selected as the most remarkable and effective components. This decision stems from the literature review and the fact that these elements were overlooked in the ROSHN project buildings. However, in order to optimise the advantages of these components in this research project, their design will feature with various additional parameters. For example, sunshade control above the courtyard would be exploited in order to minimise the direct sunlight on Saudi cities to cool the air prior to its introduction into the enclosed spaces of the building, as Table (7.7) details in addition to other variables.

Second, the research proposed as much as possible advanced green solutions for energy efficiency measures within the building envelope, which could be a system or materials, with full consideration of the climate analysis of the base case location (see Table 7.8). Furthermore, the key benefit of solar energy is that it is a clean, renewable source of electricity. Additionally, solar energy can be scaled up, meaning that it could be used to power a single building or be implemented on a district scale. Extra electricity can then be fed back into the grid or stored in a battery when used on a smaller scale. Hence, the peer-to-peer (P2P) renewable energy concept, which involves sharing energy among the buildings of the ROSHN housing project, was the proposed solution for generating power for each building using solar photovoltaics (PV), as shown in Table (7.9), taking into account the range of solar radiation in Saudi Arabia.

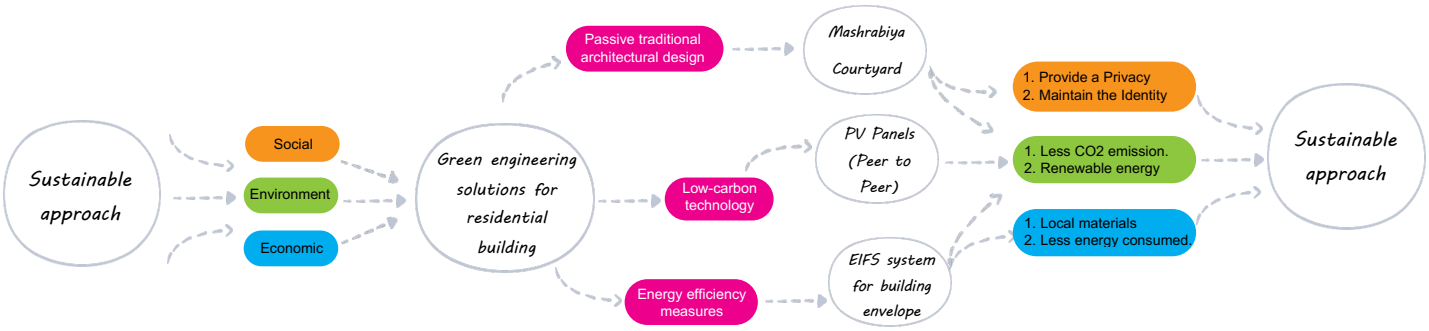


Figure 7.20. The General Concept of the Research Project.

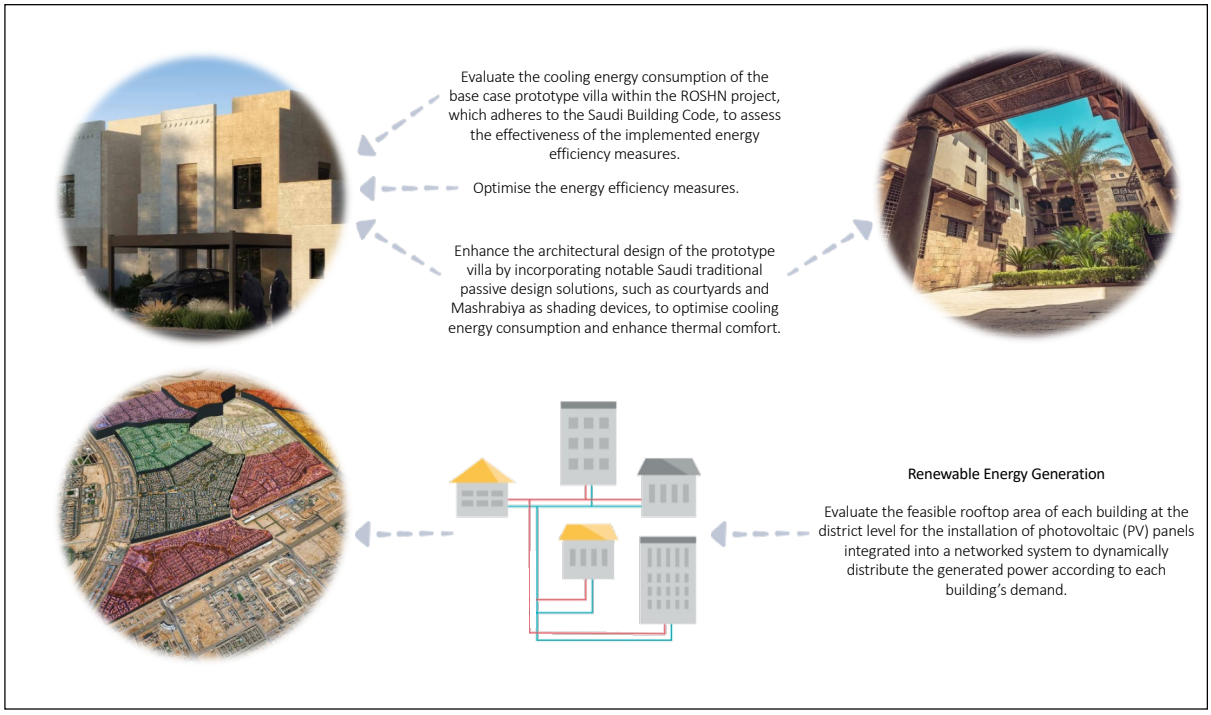
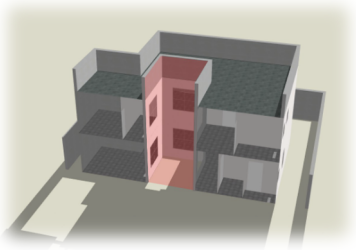
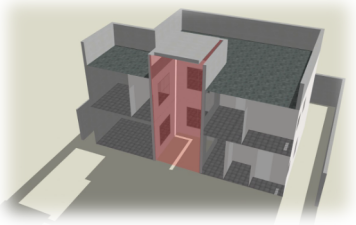
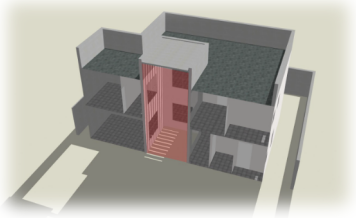


Figure 7.21. The Research Project Concept of Integrated Multi-Green Solutions Principals.

Overall, to target the research goal of evaluating the potential of the traditional passive architectural design, energy efficiency measures and low-carbon technology (renewable energy) in one integrated model within the context of the sustainability concept. The most (theoretically) effective green engineering solutions for the case of Saudi Arabia were selected based on the literature review (around 3–6 parameters for each component), varying from simplification, material alternatives, capacity, and cost variation including other proposed superior materials form the commercial market (see Tables below). Primary, these were analysed individually to assess their capacity to reduce cooling energy loads and evaluate their effectiveness regarding thermal comfort aspects. Subsequently, a holistic analysis was conducted using DB optimisation simulations to suggest the optimal integrated model.

Table 7.7. The Proposed Green Engineering Solutions for The Improvement in Terms of Traditional Passive Architectural Design.

The Parameter	The Justification	The Parameter Variables	Graphic	Design Guidelines
Traditional Passive Architectural Design				
The Courtyard	1. Given the hot/dry climate, heat mitigation strategies are most effective. These include promoting natural ventilation or self-shading provided by courtyards. 2. Since the case study building is energy-intensive for cooling. This can be reduced by promoting natural ventilation for the building. For example, when designed properly, courtyards can act as a natural ventilation system, allowing cool air to enter the building through openings and warm air to exit through vents or other openings. This can reduce the need for mechanical ventilation systems. 3. Courtyards have symbolic meanings in Islamic and Saudi architecture that can maintain the Saudi building's identity, which could be reflected in promoting the social aspect of sustainability.	Standard		Open roof courtyard surrounded by four walls with various wall-to-window ratios.
		Semi-open/shaded		Courtyard covered by semi-open roofs takes advantage of indoor and outdoor ventilation and thermal regulation, which can block the heat and direct solar radiation from the top and take into account air movement.
		Top sunshade		Courtyard contains shading measures (such as louvres and grilles) that can allow natural wind into the courtyard and increase ventilation of internal space.

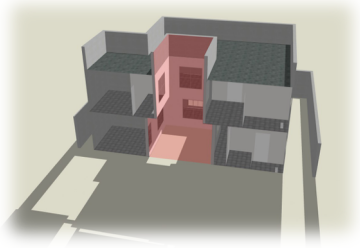
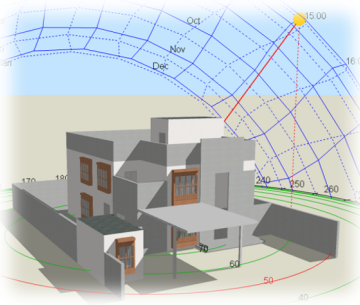
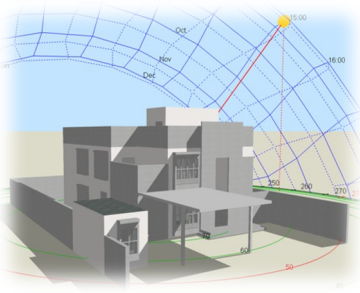
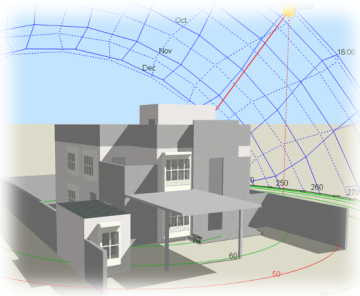
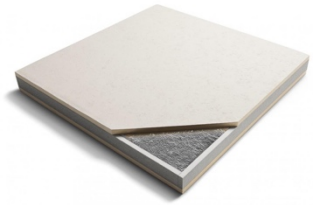
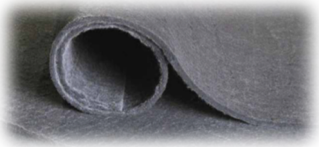
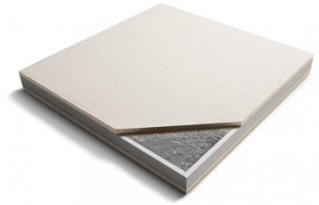
		Narrow upper and wide lower/upward contracted		The contracted shape of a courtyard sectional is narrower at the top and wider at the bottom, making it more conducive to creating additional shading.
The Mashrabiya	1. Given the hot/dry climate, heat mitigation strategies are most effective. These also include promoting natural ventilation and shading provided by Mashrabiya. 2. Since the case study building does not include any shading devices for the openings. Mashrabiya as shading devices can provide significant sustainability benefits in buildings. 3. Mashrabiya can help improve the sustainability of buildings by reducing the amount of energy required for cooling and ventilation. By blocking direct sunlight and allowing air to circulate, these screens can help reduce the need for air conditioning and other mechanical systems. 4. In terms of the social aspect of sustainability, Mashrabiya has cultural and religious significance in the Islamic world, where they are seen as a symbol of privacy and modesty to provide privacy for women and to create a sense of separation between public and private spaces.	Wood Oak Conductivity (W/m-K)0.190 Specific heat (J/kg-K) 2390 Density (kg-m^3) 700		The pattern of the Mashrabiya should be carefully designed to provide privacy while still allowing light and air to pass through. The pattern can be geometric, floral, or abstract but should be consistent with the local architectural style. The scale of the Mashrabiya should be appropriate for the building it is attached to. A Mashrabiya on a small building should be smaller in scale than one on a larger building. The placement of the Mashrabiya should be carefully considered to provide the desired level of privacy and shade. It should also be placed in a way that complements the overall design of the building.
		Metal Aluminium Conductivity (W/m-K)160 Specific heat (J/kg-K) 880 Density (kg-m^3) 2800		
		GRC (Glass Reinforced Concrete) Conductivity (W/m-K)22.7 Specific heat (J/kg-K) 450 Density (kg-m^3) 1900		

Table 7.8. The Proposed Green Engineering Solutions for The Improvement in Terms of Energy Efficiency Measures in Building Envelope.

The Parameter	The Justification	The Parameter Variables	Graphic	Design Guidelines
Energy Efficiency Measures Considering the hot/dry climate, implementing heat mitigation strategies is essential for optimising energy efficiency and ensuring occupant comfort. Key strategies include improving the insulation of the building envelope and enhancing glazing to reduce heat gain and enhance thermal performance.				
External wall	Since precast concrete was utilised in the building envelope of the case study, it can cause several thermal bridges where the precast concrete elements are connected, as well as at other surface components of the building that allow heat to escape or enter. To address this, the Exterior Insulation and Finish System (EIFS) was proposed. EIFS provides excellent insulation, which can help reduce heating and cooling consumption for a building. The insulation panels or boards used in EIFS systems typically have high R-values, meaning they have a high resistance to heat transfer.	Exterior insulation and finish system (EIFS) using XPS boards insulation 100mm (150mm Precast Structural Wall + 100mm XPS insulation. Total Wall Thickness = 250mm) U-value: 0.232 W/(m^{2}K)	 Dow Blue XPS Insulation Board Available at: [88]. (Accessed: 6 July 2023).	EIFS can be designed with enhanced thermal performance to meet the specific needs of the building and the climate of Riyadh. This may include the use of thicker insulation, higher R-values, or other insulation materials that provide better thermal performance. The insulation should be installed in a continuous layer to ensure maximum performance and energy efficiency. Proper moisture management is critical for the performance of the EIFS system. This includes the use of a moisture barrier, such as a vapour retarder, to prevent moisture from entering the substrate.
		Exterior insulation and finish system (EIFS) using XPS boards insulation 150mm (150mm Precast Structural Wall + 150mm XPS insulation. Total Wall Thickness = 300mm) U-value: 0.167 W/(m^{2}K)		
		Exterior insulation and finish system (EIFS) using XPS boards insulation 200mm (150mm Precast Structural Wall + 200mm XPS insulation. Total Wall Thickness = 350mm) U-value: 0.131 W/(m^{2}K)		
		Exterior insulation and finish system (EIFS) using Vacuum insulation panels (VIP) 50mm (150mm Precast Structural Wall + 50mm (VIP). Total Wall Thickness = 200mm) U Value = 0.123 W/(m²K)		
		Exterior insulation and finish system (EIFS) using Vacuum insulation panels (VIP) 60mm (150mm		

	EIFS can help reduce the occurrence of thermal bridges in buildings because it is installed on the exterior of the building's envelope and provides continuous insulation across the entire surface, which can help to reduce thermal bridging.	Precast Structural Wall + 60mm (VIP). Total Wall Thickness = 210mm) U Value = 0.105 W/(m²K)	Deck-VQ® | Recticel Insulation (2023). Available at: [86](Accessed: 30 June 2024).	Joints between different sections of the EIFS system should be treated with a joint sealant to prevent moisture penetration and ensure a continuous air barrier.
		Exterior insulation and finish system (EIFS) using Vacuum insulation panels (VIP) 70mm (150mm Precast Structural Wall + 70mm (VIP). Total Wall Thickness = 220mm) U Value = 0.091 W/(m²K)		
		Exterior insulation and finish system (EIFS) using Aerogel Blanket Insulation 10mm (150mm Precast Structural Wall + 60mm Multi Aerogel Blanket Insulation. Total Wall Thickness = 160mm) U Value = 0.201 W/(m²K)	 Spacetherm® Aerogel Insulation | A. Proctor Group Ltd. (2023). Available at: [203](Accessed: 30 August 2024).	
		Exterior insulation and finish system (EIFS) using Duplicate Aerogel Blanket Insulation 10mm (150mm Precast Structural Wall + 70mm Multi Aerogel Blanket Insulation. Total Wall Thickness = 170mm) U Value = 0.177 W/(m²K)		
Roofing	Roofing using superior insulation (Vacuum Insulation panels (Deck VQ))	150mm Precast Hollow Slab + 60mm Structural Topping + 130mm Screed + Water proofing membrane + 70 mm Vacuum Insulation panels + Geo-Textile sheet + Concrete Pavers U-value: 0.091 W/(m²K)	 Deck-VQ® | Recticel Insulation (2023). Available at: [86] (Accessed: 30 June 2024).	Since the zones in the base case building that are directly exposed to solar radiation, such as the first-floor areas, experience higher temperatures due to heat gain from the roof system, as confirmed by the free-running simulation, the proposal was to improve the roof system
		150mm Precast Hollow Slab + 60mm Structural Topping + 130mm Screed + Water proofing membrane + 140 mm Vacuum Insulation panels + Geo-Textile sheet + Concrete Pavers U-value: 0.048 W/(m²K)		

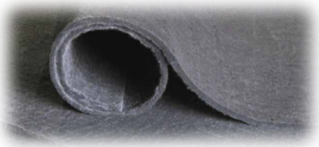
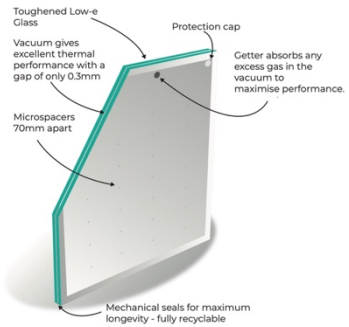
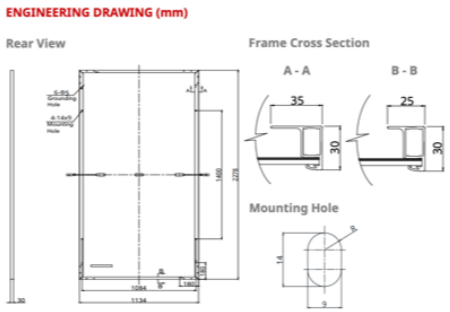
	Roofing using superior insulation (Aerogel carpet Insulation)	150mm Precast Hollow Slab + 60mm Structural Topping + 130mm Screed + Water proofing membrane + Multi Aerogel Blanket Insulation 70mm + Geo-Textile sheet + Concrete Pavers U-value: 0.176 W/(m²K)	 Spacetherm® Aerogel Insulation | A. Proctor Group Ltd. (2023). Available at: [203](Accessed: 30 August 2024).	using superior insulation to mitigate this effect and enhance overall thermal performance.	
		150mm Precast Hollow Slab + 60mm Structural Topping + 130mm Screed + Water proofing membrane + Duplicate Aerogel Blanket Insulation 140mm + Geo-Textile sheet + Concrete Pavers U-value: 0.097 W/(m²K)			
Glazing	Vacuum Insulated Glass Product series	U value= 0.5 W/m2K Transmittance%= 78 SHGC(g)= 0.58	 LANDVAC VIG SCIENCE & TECHNOLOGY CO., LTD (2023). Available at: [140](Accessed: 30 September 2024).	4T+0.3V+4TL (S1.16) series	T: Tempered Glass ; L: Low-E Glass ; V : Vacuum ; TL: Tempered Laminated ; P: Polyvinyl Butyral.
		U value= 0.5 W/m2K Transmittance%= 77 SHGC(g)= 0.53		4T+0.3V+4TL (S1.10) series	
		U value= 0.45 W/m2K Transmittance%= 68 SHGC(g)= 0.4		4T+0.3V+4TL(D80) series	
		U value= 0.45 W/m2K Transmittance%= 53 SHGC(g)= 0.33		4T+0.3V+5TL(XDTB0159) series	
		U value= 0.49 W/m2K Transmittance%= 77 SHGC(g)= 0.58		4T+12Ar+4TL (S1.10) +0.3V+4T series	
		U value= 0.44 W/m2K Transmittance%= 71 SHGC(g)= 0.5		3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	

Table 7.9. The Proposed Green Engineering Solutions for The Improvement in Terms of Low Carbon Technology.

The Parameter	The Justification	The Parameter Variables	Graphic	Design Guidelines
Low Carbon Technology				
PV Panel (Peer to Peer)	P2P PV panel systems can promote the use of renewable energy and reduce greenhouse gas emissions by enabling more widespread adoption of solar PV panels. The system can reduce energy costs for users by allowing them to generate and share their own electricity. It can promote community building and social interaction by allowing users to share resources and collaborate on energy generation and distribution. The system can be scaled up or down to meet the needs of different communities or regions. This scalability allows for greater flexibility and adaptability in the design and implementation of these systems.	One block Number of buildings: 7 Total roofs Area: (154.5 × 7 = 1081.5 m2) Net available area for installation: 368 m^2 A group of blocks Number of buildings: 111Total roofs Area: (154.5 × 111 = 17,149.5 m2) Net available area for installation: 5831 m^2 District scale Number of buildings: 4500 Total roofs Area: (154.5 × 4500 = 695,250 m2) Net available area for installation: 236,385 m^2	PV Panels Model: TOPHiKu6 (CS6W 570T) Cell Type: Mono-Crystalline Cells. Dimensions: 2278 × 1134 × 30 mm. Maximum power output: 570 W. Module Efficiency: 22.1%. Performance: (Vmp = 42.7 V, Imp = 13.35 A, VOC = 51.8 V, ISC = 13.81 A). Operating Temperature: −40 °C~+85 °C.  Available at: [211](Accessed: 17 July 2023).	The system provides a decentralised alternative to traditional electricity generation and distribution, which is typically controlled by centralised utilities. This can increase energy security and resilience and reduce the risk of power outages or disruptions. The system can be combined with energy storage technologies, such as batteries, to enable greater energy independence and resilience. Energy storage can also help balance energy supply and demand, ensuring that users have access to electricity when they need it. The system must be integrated with other energy systems and grids and may require the use of advanced technologies such as grid management software and energy storage systems.

Chapter 8: Improvements to the Modelling and Simulation Outcomes

Relying on the complexity of the research project goal and objectives, modelling improvements should be undertaken to address this complexity, which may involve several steps to accomplish. The process usually includes understanding the case, determining initial conditions, identifying the analysis requirements, selecting a standardisation technique, testing the overall performance of the analysis technique. As mentioned previously in Chapter 7, the base case model was simulated and analysed using the DesignBuilder simulation software, highlighting the evaluation of the proposed green engineering solutions for the enhancements that could aid in targeting the research goal.

Therefore, this chapter presents the improvements to the modelling and simulation by conducting a parametric analysis of the proposed traditional passive architectural designs, energy efficiency measures, and low-carbon technologies (renewable energy), (refer to Tables 7.7, 7.8, and 7.9). The aim was to assess their potential impact on energy cooling performance and thermal comfort aspects within the base case building. Accordingly, Section 8.1 discusses the results of implementing these green solutions in terms of energy cooling performance. Meanwhile, Section 8.2 concentrates on thermal comfort aspects. Subsequently, Section 8.3 evaluates the potential energy generation of the base case.

8.1 PARAMETRIC ANALYSIS IN TERMS OF THE BUILDING COOLING ENERGY.

The purpose of this parametric simulation analysis was to assess the impact of implementing the proposed green engineering solutions within the base case in terms of cooling energy performance. Hence, the following sections explored these impacts by examining cooling consumption within the base case building and analysing the potential contributions of applying traditional passive architectural design and the enhancements in energy efficiency measures.

8.1.1 Traditional Passive Architectural Designs (Courtyard & Mashrabiya as shading devices)

The total area of each courtyard option is 12 m^2 in the centre of the building, as well as an additional 13.2 m^2 for only the ground floor of the upwardly contracted courtyard. The dimensions of the courtyards are 3m by 4m, with a height of 7.50m, while the ground floor of the upwardly contracted courtyard dimensions is 4.20m by 6m as Figure (8.1 - A) below illustrated. The net floor area has been maintained to be the same as the values of the base case building by adding an additional room to offset the room that has been replaced by the courtyard. Since the courtyards are surrounded by living and dining rooms and bedrooms, windows overlooking the courtyard of the same size as base case windows have been added. Furthermore, the basic windows of these rooms overlooking the neighbouring buildings have been removed to maintain the window-to-wall ratio of the base case building. As mentioned earlier, this configuration enables cool air to circulate through the building and into each area. Figure (8.2) below illustrates the effects of different designs of courtyards on annual cooling load. It is obvious that the different designs of courtyards can reduce the cooling energy consumption from 25924.97 kWh/year to 24295.31, 23870.81, 23960.05, and 24796.32 kWh/year for Standard, Semi-open, Top Sunshade, and Upward Contracted Courtyards, respectively. Therefore, the Semi-open and Top Sunshade courtyard were considered the optimal solutions for the courtyard in this case, with up to a 7.92% reduction in cooling energy consumption. This because the Semi-open and Top Sunshade courtyards enhanced thermal performance by incorporating shading elements that effectively reduced direct solar radiation, thereby lowering surface temperatures and minimising solar heat gain. Additionally, both designs promoted stack ventilation, a natural process where warm air rises and exits through upper openings, pulling in cooler air from lower levels. This airflow improved convective cooling, reduced indoor air temperatures, and ultimately decreased the building's cooling energy demand.

On the other hand, while designing Mashrabiya as shading devices for the base case building, the three fundamental components of its heritage structure have been considered: the head "crown", the body, and the base as mentioned by Baik et al. (2014) regardless of other variables. The dimensions of all Mashrabiya components consisted of a protrusion of 35cm and a width of 2m, except for the small windows, which are 1m. The height of Mashrabiya is 2.15 m, while its height on the south facade is 2.5m since the openings there are larger (see Figure

(8.1 - B)). As mentioned in the Table (7.7) above, different materials can offer a wider variation in conductivity, specific heat, and density. In light of this, the study has compared the use of various materials for designing Mashrabiya and how that can affect cooling energy performance. Figure (8.2) shows that there is no significant impact from utilising different materials for Mashrabiya in the base case building. However, a reduction in cooling energy consumption of 11.45%, 11.48%, and 11.25% by implementing Mashrabiya as a shading device in itself was achieved. It was clear that the thermal conductivity of materials was not important. Although timber, metal, and GRC had different thermal properties, these differences were minimised because the Mashrabiya's surface area consisted mostly of open space due to the perforations. Furthermore, heat conduction through the thin framing elements was insignificant compared to the radiative and convective heat gains or losses occurring through the openings. The main thermal exchanges in a Mashrabiya were radiative gain—how much sunlight penetrated through the perforations—and convective flow—how air moved through and around the screen. These two processes were largely independent of the material used. Instead, they depended on the size, pattern, orientation, and depth of the design, as well as the solar angle and wind direction.

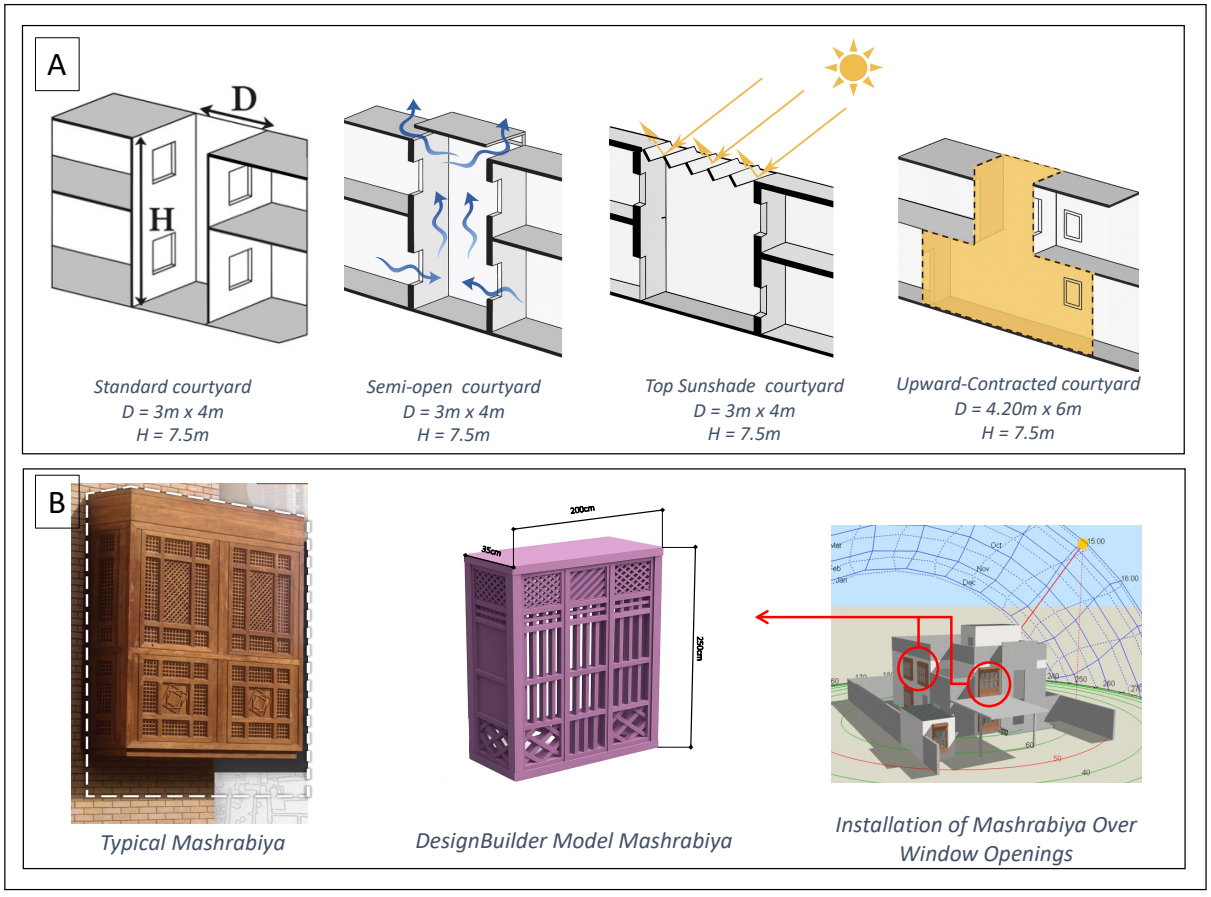


Figure 8.1. Design and Layout of Courtyards and Mashrabiya.

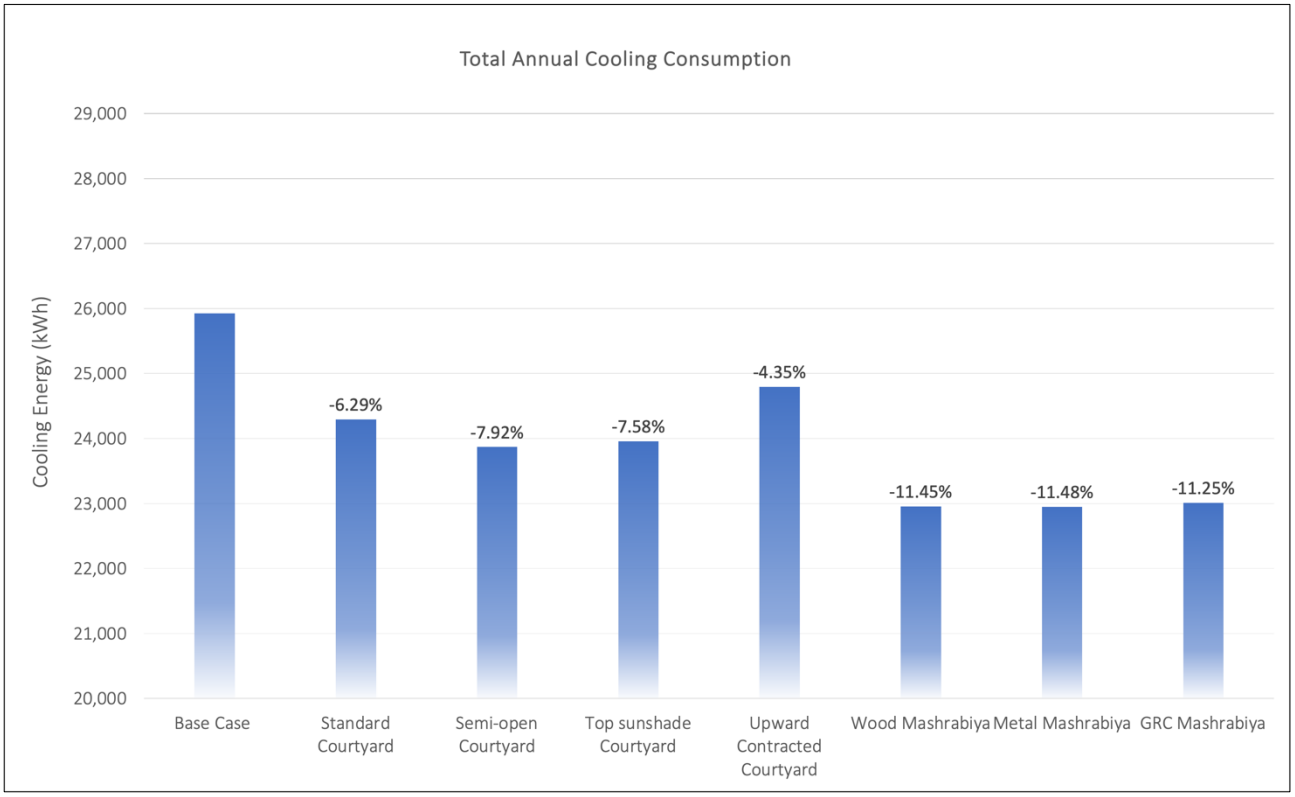


Figure 8.2. The Cooling Energy Consumption Applying Different Courtyard Designs and Mashrabiya Materials.

8.1.2 Energy Efficiency Measures (Exterior insulation and finish system (EIFS))

Even though the exterior insulation and finish system (EIFS) has several advantages as stated in Table (7.8) above, using this technique is not common in hot and arid countries such as Riyadh, KSA. However, the implementation of this system within the building walls of the base case building has indicated a reduction in cooling energy consumption of -4.22%, -6.40%, and -7.67% by using standard XPS insulation board materials of 100mm, 150mm, and 200mm, respectively. This could provide wall thicknesses of 250cm, 300cm, and 350cm, as Figure (8.3) below shows.

Nevertheless, the utilisation of advanced insulation materials, specifically Vacuum Insulation Panels (Deck VQ) (VIP) and an Aerogel Blanket in exterior insulation and finish system (EIFS) for the base case, has revealed noteworthy fluctuations in annual cooling energy performance outcomes as similar Figure shows. Despite this, the integration of the aerogel blanket into the external walls of the base case resulted in a reduction in wall thickness. This enhancement was accompanied by a reduction in annual cooling energy consumption,

registering at only -5.24% and -6.05% for varying Aerogel blanket thicknesses of 60mm and 70mm, respectively. However, the Vacuum Insulation Panels (VIP) provided both a decrease in the wall thicknesses and annual cooling energy consumption by up to -7.94%, -8.56%, and -9% for different (VIP) 50mm, 60mm, and 70mm, respectively.

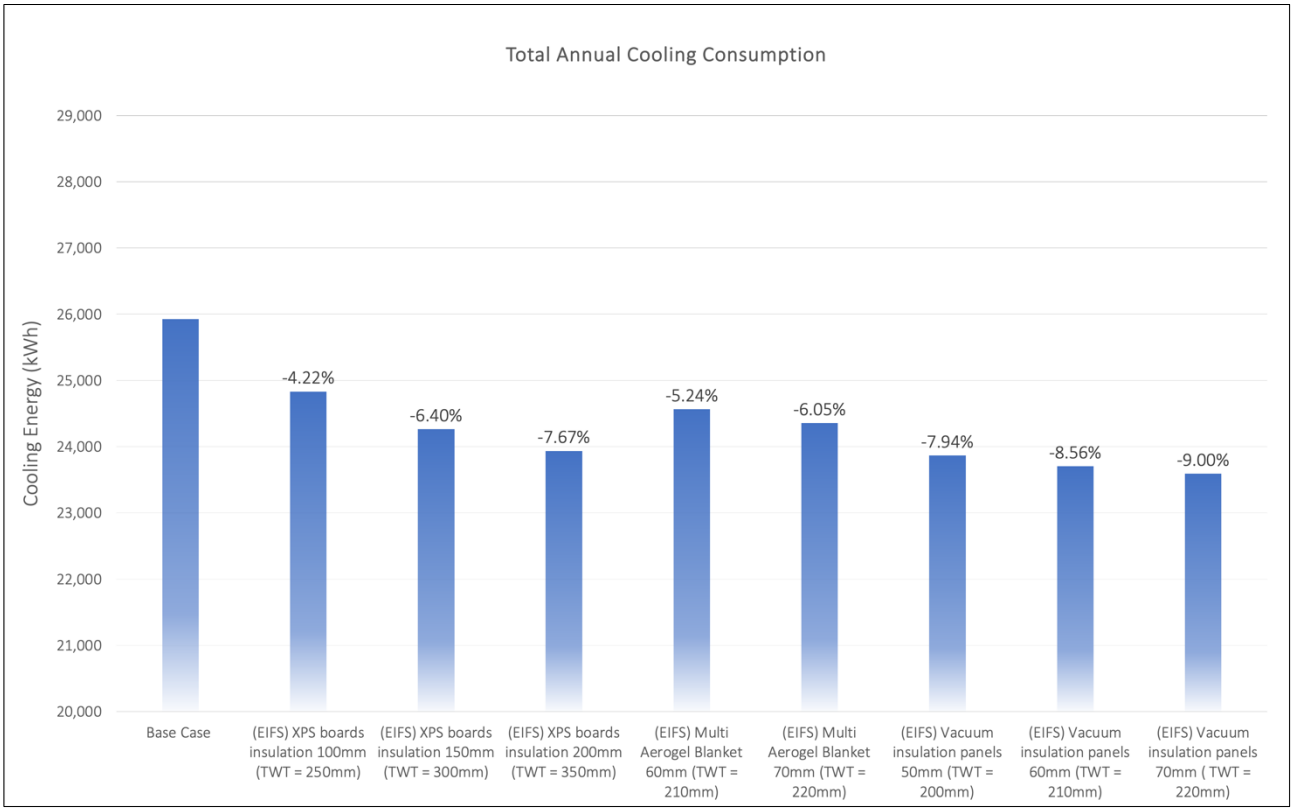


Figure 8.3. The Annual Cooling Energy Performance of Utilising Different (EIFS) Thicknesses for Walls.

8.1.3 Energy Efficiency Measures (Roofing by advanced insulation).

The roofing advanced insulation options against a base case that used a standard or commonly used insulation method were evaluated in order to optimise the cooling energy. The alternative insulation options include 70 mm Vacuum Insulation panels, 140 mm Vacuum Insulation panels, multi–Aerogel Blanket Insulation up to 70mm, and 140mm. Figure (8.4) shows that the maximum reduction in cooling energy consumption by up to -3.12% can be achieved by implementing the 140mm Vacuum Insulation panels for roofing. Following this a reduction of -1.96% is lower than that of the base case associated with the roofing by the 145mm XPS insulation. Unexpectedly, there were no notable decreases in cooling energy

consumption by applying 70mm or 140mm aerogel blanket insulation options for roofing. The decreases were ranging between -0.28% and -1.93% for the 70mm and 140mm, respectively. This underscores the importance of selecting appropriate insulation options for roofing to optimise energy performance and reduce environmental impact, regardless of its commercial advertisements.

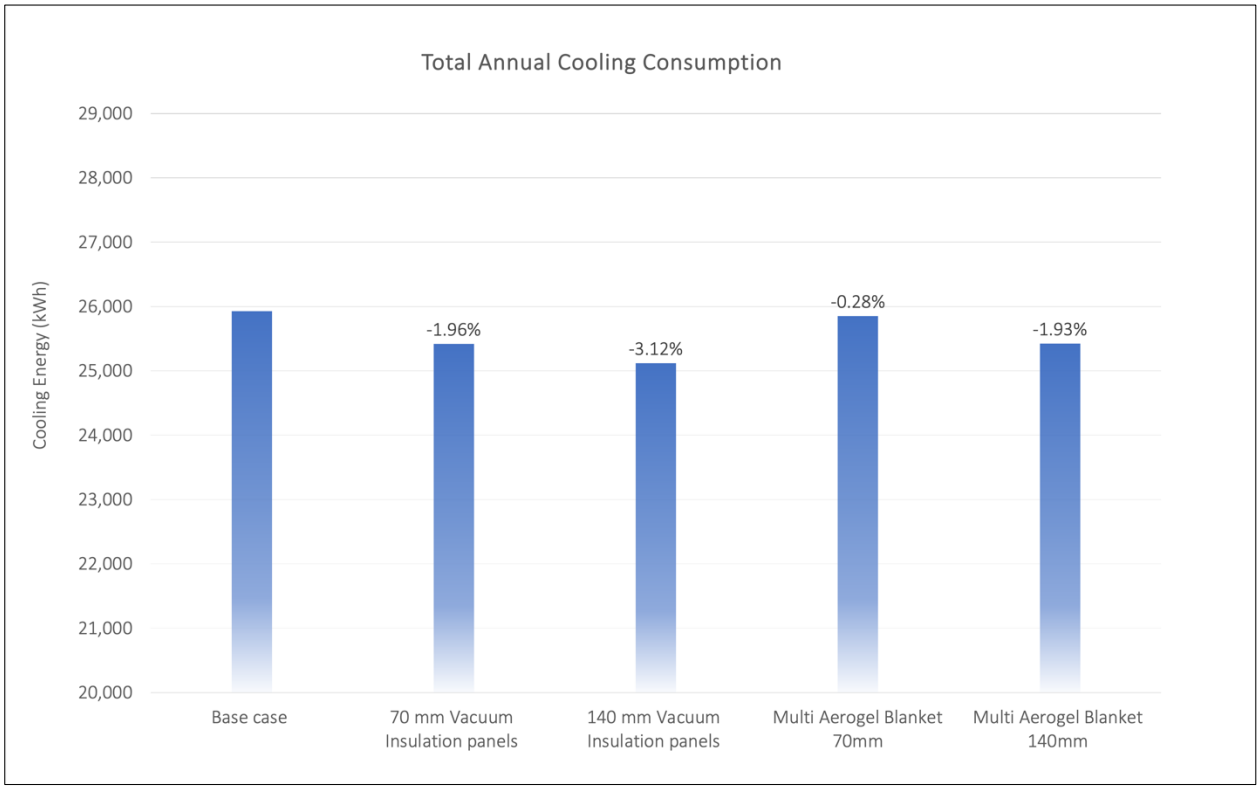


Figure 8.4. The Annual Cooling Energy Performance of Applying Advanced Insulation Options for Roofing.

8.1.4 Energy Efficiency Measures (Vacuum Insulated Glass Product series).

In order to evaluate the latest insulated glazing products in different configurations, the cooling annual consumption by implementing vacuum-insulated glass compared to a base case (Double-glazed with 12mm air space), was simulated. The configuration details of the glazing parameters comprised U value, transmittance percentage, and solar heat gain coefficient (SHGC), highlighted in Table (7.8) above. Notably, the glazing types "4T+0.3V+4TL(D80)" and "4T+0.3V+5TL(XDTB0159)" recorded a reduction, with the former showcasing a reduction of -8.71% and the latter displaying a reduction of -13.50% in the cooling energy consumption compared to the base case (Double-glazed with 12mm air space), as figure (8.5) shows.

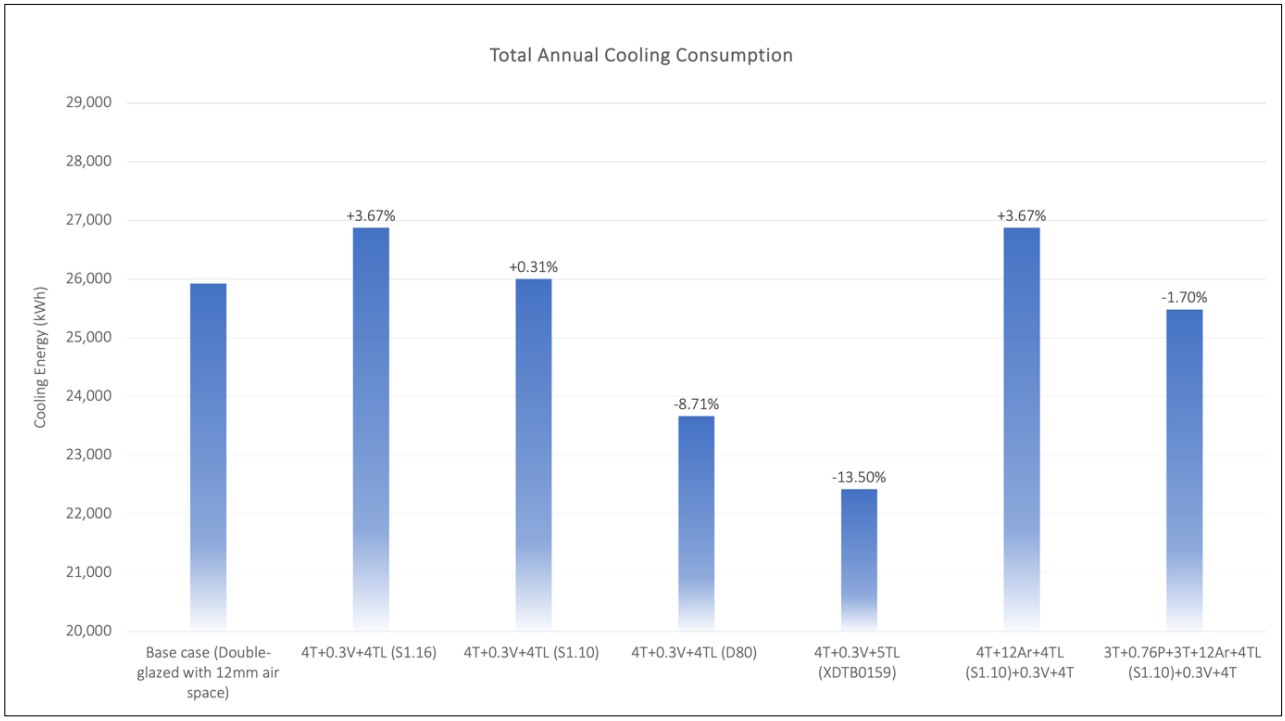


Figure 8.5. The Annual Cooling Energy Performance by Applying Different Configurations of Insulated Glass Products.

8.2 PARAMETRIC ANALYSIS IN TERMS OF THE BUILDING THERMAL COMFORT ASPECTS.

Utilising the concept of free-running simulation outlined in Section 7.6, an investigation into the performance of thermal comfort aspects (indoor air temperature (IAT), radiant temperature (RT), operative temperature (OT), and relative humidity (RH)) through the implementation of proposed green engineering solutions was conducted. This examination aims to assess how the integration of traditional passive architectural design and enhancements in energy efficiency measures within the base case building can improve thermal comfort aspects. Therefore, the following sections analyse these changes across each zone within the base case building in order to support the cooling system, minimise its energy consumption, and maintain an acceptable level of thermal comfort. However, the comprehensive evaluation of thermal performance in this section focused on selected zones from the base-case building to enable a more targeted and critical assessment. The tested spaces comprised the East–Ground Floor (E-GF) Dining, East–South–Ground Floor (ES-GF) Lounge, and East–First Floor (E-FF) Lounge, as illustrated in Figure 7.12 above. Furthermore, Appendices A1 to A3 present a more extensive analysis covering all zones of the base-case building, including all parameters and alternative plot styles for enhanced interpretation.

8.2.1 Traditional Passive Architectural Design (The Courtyard & Mashrabiya as shading devices)

The thermal comfort aspects of the base case building, after incorporating various courtyards and Mashrabiya as shading devices (using the same design principles specified in (Section 8.1.1), were assessed.

Firstly, Figure (8.6) below presents the free-running simulation results for the E-GF Dining zone on 15 July, showing hourly variations in indoor air temperature (IAT) for the Base Case and the evaluated traditional passive strategies. It was obvious that the Base Case exhibited the warmest conditions across the day, starting at 31.08 °C at 01:00, rising steadily to a morning peak of 32.05 °C at 09:00, and then gradually declining to 31.38 °C by 23:00. This pattern reflected the combined effects of early solar gains and the heat retention characteristics of the ground-floor space. However, Courtyard-based strategies improvements achieved substantial reductions in IATs compared to the Base Case. The Narrow Upper & Wide Lower Courtyard recorded the lowest and most stable temperatures, ranging from 29.06 °C at 01:00 to 29.32 °C at 23:00. The Standard Courtyard followed closely, peaking at only 29.35 °C late in the day. Meanwhile, the Sunshade Courtyard and Semi-Open Courtyard also performed effectively, showing only slight midday rises, with peaks between 29.55 °C and 29.57 °C, thereby limiting diurnal fluctuations.

On the other hand, Mashrabiya-based strategies (Wood, Metal, and GRC) displayed comparatively higher IATs to Courtyard cases. For instance, all three peaked above 30.40 °C in the late morning, with the Wood Mashrabiya reaching 30.40 °C at 10:00 before gradually cooling in the evening. This indicates that, within this context, façade-mounted shading had a lower cooling capacity compared to the microclimatic moderation provided by courtyard designs.

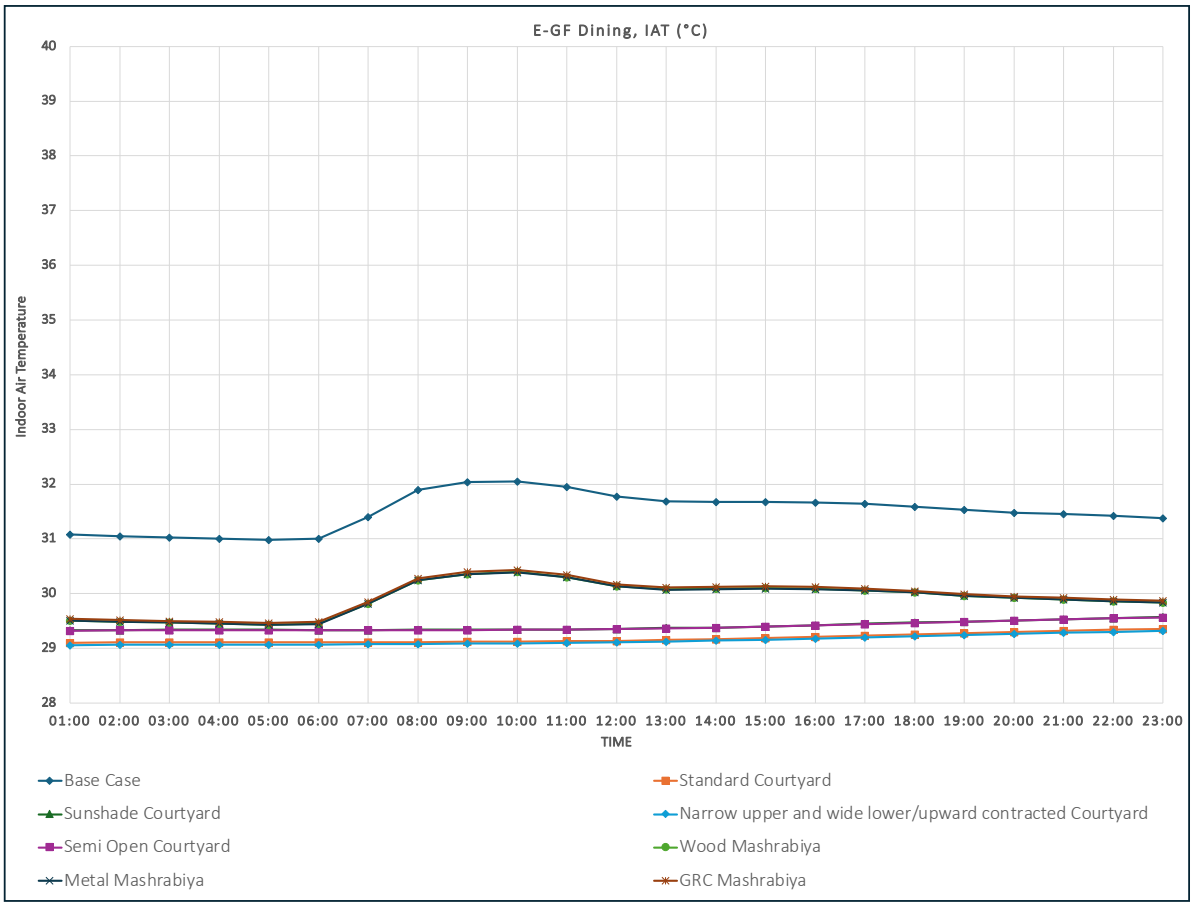


Figure 8.6. The Free-Running Simulation Results Comparing Hourly IATs in the Base Case Building (E-GF Dining Zone) and After Application of Traditional Passive Architectural Strategies (15 July)

Additionally, Figure (8.7) shows the free-running simulation results for the ES-GF Lounge zone on 15 July, illustrating the hourly variation in indoor air temperature (IAT) for the Base Case and the applied passive design strategies. To begin with, the Base Case consistently exhibited the highest indoor air temperatures, starting at 31.96 °C at 01:00, rising to a late-morning peak of 33.11 °C at 10:00, and then gradually decreasing to 32.29 °C by 23:00. This steady morning warming reflected the strong East–South solar exposure of the space, combined with minimal thermal buffering in the absence of shading.

In contrast, Courtyard-based strategies delivered noticeable, though varied, thermal moderation. The Standard Courtyard, for example, began at 30.90 °C and peaked at 32.45 °C by 11:00 before cooling through the afternoon, while the Sunshade Courtyard and Semi-Open Courtyard followed comparable profiles, reaching their highest values of 32.46 °C and 32.43 °C respectively—both about 0.6–0.7 °C cooler than the Base Case during peak hours. However,

the Narrow Upper & Wide Lower Courtyard performed less effectively in this zone, beginning at 31.91 °C and increasing to 33.62 °C at 14:00, closely shadowing the Base Case curve, likely due to reduced air circulation and greater heat retention.

On the other hand, Mashrabiya, as a shading device strategy, achieved the coolest overall indoor air temperature. For example, the Wood and Metal Mashrabiya both started at 30.39 °C, peaked modestly at 31.45 °C, and then steadily declined into the evening. The GRC Mashrabiya followed a similar pattern, peaking slightly higher at 31.50 °C.

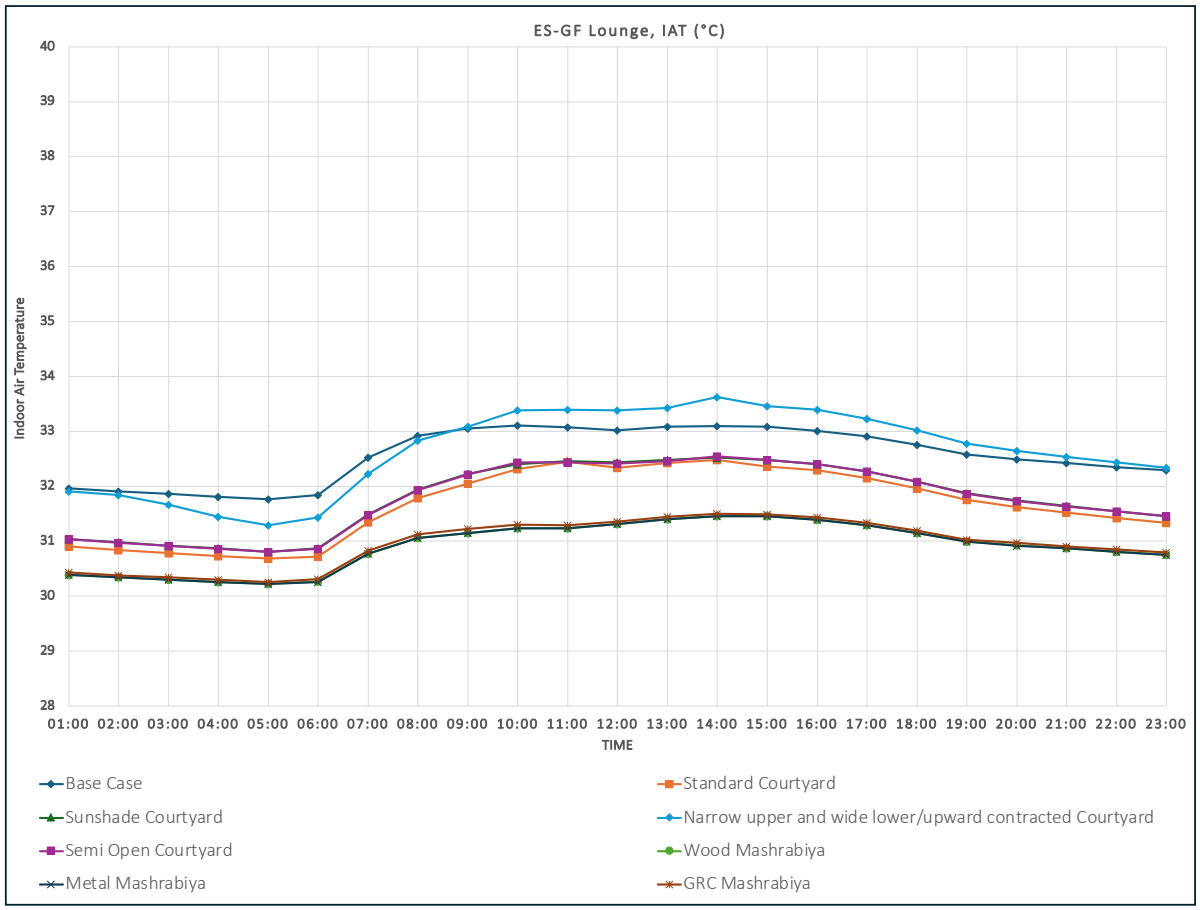


Figure 8.7. The Free-Running Simulation Results Comparing Hourly IATs in the Base Case Building (ES-GF Lounge Zone) and After Application of Traditional Passive Architectural Strategies (15 July)

Furthermore, Figure (8.8) illustrates the free-running simulation results for the E-FF Lounge zone on 15 July, showing the hourly indoor air temperature (IAT) patterns for the Base Case and various passive design strategies. Initially, the Base Case recorded the highest IATs

levels throughout the day, starting at 37.22 °C at 01:00, rising steadily to its peak of 38.18 °C by 09:00, and then showing only a marginal decline to 37.63 °C by 23:00. This sustained high temperature profile reflected the significant heat gain typical of upper floors with high solar exposure. However, the integration of Courtyard-based strategies provided varying degrees of improvement, with the Standard Courtyard reducing peak temperatures to 37.40 °C—almost 0.8 °C cooler than the Base Case—while maintaining lower values through the early morning. The Sunshade Courtyard displayed a similar performance, peaking at 37.13 °C, whereas the Semi-Open Courtyard reached 37.29 °C. On the other hand, the Narrow Upper & Wide Lower Courtyard was less effective, with temperatures nearing those of the Base Case, peaking at 38.03 °C. This indicates that although courtyards can reduce heat gain, their effectiveness on upper floors may be more limited due to less shading depth and exposure to direct sunlight.

In contrast, Mashrabiya-based shading devices delivered the most notable cooling benefits. The Wood and Metal Mashrabiya followed identical temperature trends, starting at 34.25 °C, peaking modestly at around 35.28 °C in the early afternoon, and then remaining relatively stable. The GRC Mashrabiya performed similarly, with only marginal temperature differences. These results highlight the capacity of façade-integrated shading to intercept solar gains directly on upper façades, where courtyards have less influence.

Notably, the first-floor zones exhibited greater variations in indoor air temperature (IAT) despite the improvements from various strategies, ranging from 33.86°C to 38.03°C, with maximum temperatures reaching 38.03°C in the E-FF lounge at 15:00, as shown in Figure (8.8). Similarly, other zones such as WS-FF Bedroom-2, SE-FF Bedroom-3, and E-FF Bedroom-4, frequently recorded temperatures above 35°C, highlighting the notable thermal load differences between the two floors as shown in Figures A3-3 in the appendices.

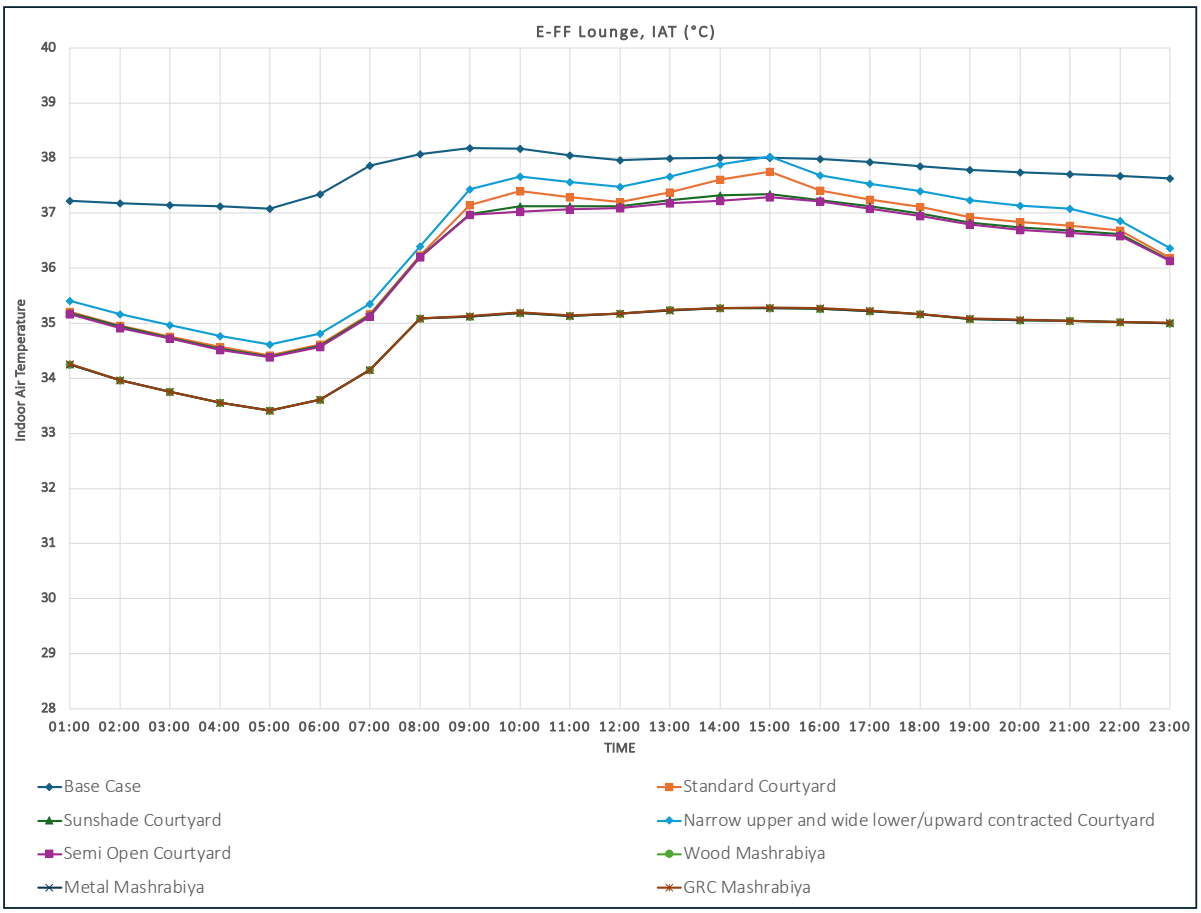


Figure 8.8. The Free-Running Simulation Results Comparing Hourly IATs in the Base Case Building (E-FF Lounge Zone) and After Application of Traditional Passive Architectural Strategies (15 July)

Secondly, Figure (8.9) presents the hourly radiant temperature (RT) profiles for the E-GF Dining zone under the Base Case and various passive design strategies on 15 July. In the Base Case, RTs remained relatively high and stable, beginning at 31.01 °C at 01:00, showing a slight midday increase, and ending the day at 31.29 °C. Nevertheless, Courtyard-based strategies demonstrated a marked improvement in reducing radiant heat exposure. The Standard Courtyard consistently maintained RT around 29.1–29.34 °C throughout the day, offering a reduction of nearly 2 °C compared with the Base Case. The Narrow Upper & Wide Lower Courtyard followed closely, with similar reductions but marginally higher readings than the Standard Courtyard in the later hours. The Sunshade Courtyard and Semi-Open Courtyard achieved intermediate performance, stabilising RT at approximately 29.32–29.55 °C, which reflects the additional benefit of controlled daylight penetration.

Mashrabiya-based shading devices, while still improving upon the Base Case, provided slightly less reduction in RT than courtyards for this ground-floor zone. The Wood and Metal Mashrabiya followed nearly identical patterns, starting near 29.4 °C, peaking modestly around 29.74–29.75 °C, and remaining stable into the evening. The GRC Mashrabiya recorded the highest RT among Mashrabiya systems, peaking at 29.79 °C, though still substantially cooler than the Base Case.

Overall, courtyards were more effective than Mashrabiya shading in lowering radiant heat on the ground floor. This can be attributed to the courtyard's ability to promote cooler surrounding air surfaces, reducing radiant load, whereas Mashrabiya systems primarily targeted direct glare and solar penetration through façades rather than altering the surrounding radiant environment.

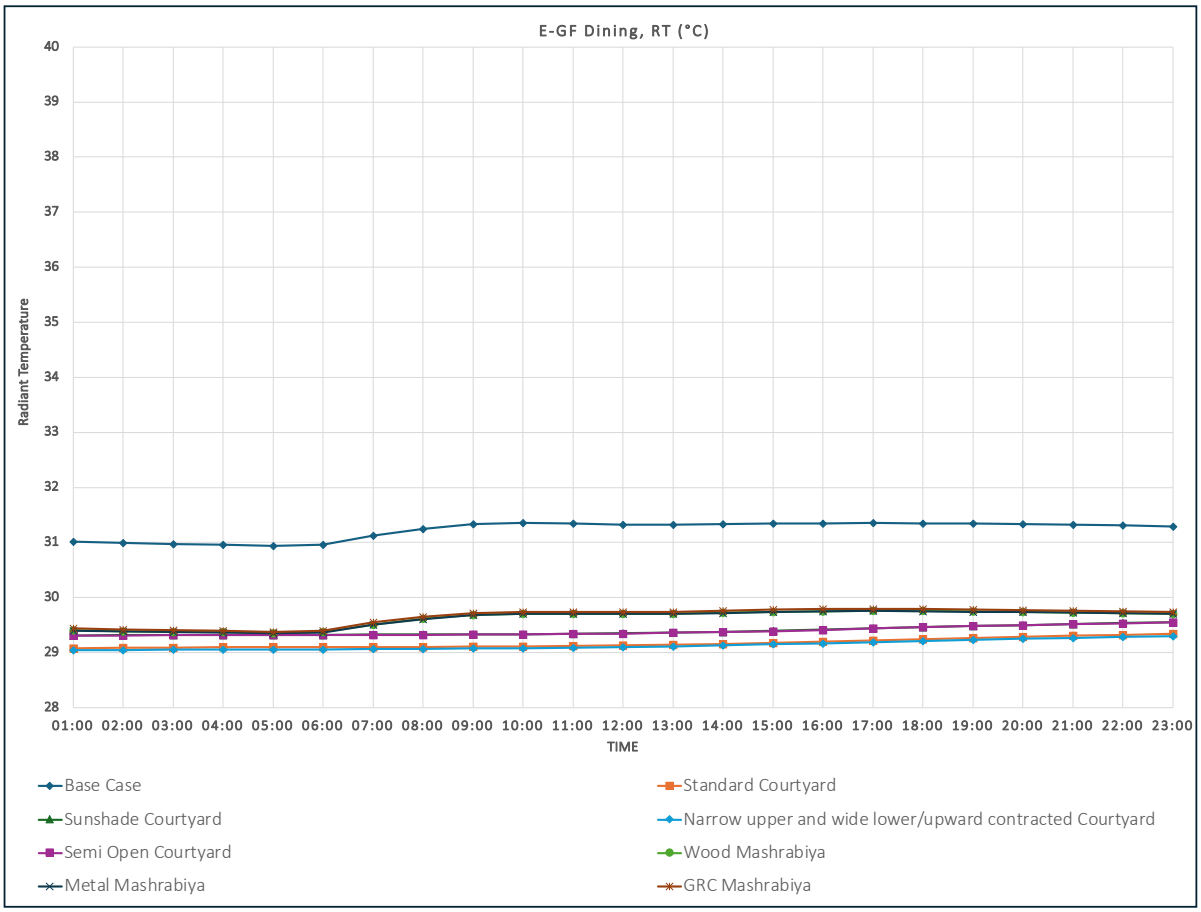


Figure 8.9. The Free-Running Simulation Results Comparing Hourly RTs in the Base Case Building (E-GF Dining Zone) and After Application of Traditional Passive Architectural Strategies (15 July)

In addition, Figure (8.10) illustrates the hourly radiant temperature (RT) variations in the ES-GF lounge zone for the Base Case and various passive architectural strategies on 15 July. In the Base Case, RT started at 31.89 °C during the early morning hours, gradually rose to a midday level around 32.78–32.80 °C, and then declined slightly towards 32.22 °C by late evening.

However, the incorporation of Courtyard-based strategies achieved notable reductions in RT. For example, the Standard Courtyard consistently maintained lower values, ranging from 30.63 °C at night to around 31.93 °C during the warmest periods, offering a reduction of nearly 0.9–1.0 °C compared with the Base Case at peak hours. The Sunshade Courtyard and Semi-Open Courtyard followed a similar pattern, slightly warmer than the Standard Courtyard but still outperforming the Base Case by reducing midday RT by about 0.8–0.9 °C. The Narrow Upper & Wide Lower Courtyard, however, delivered the minimum improvement among courtyard types, with readings approaching the Base Case in peak hours and even reaching 33.10 °C at 14:00.

Furthermore, Mashrabiya-based shading systems offered even greater RT reductions in this zone compared with courtyards. The Wood and Metal Mashrabiya displayed almost as usual identical patterns, starting around 30.3 °C, peaking modestly at 31.15 °C, and maintaining a stable profile throughout the afternoon, achieving reductions of about 1.6 °C at midday compared with the Base Case. The GRC Mashrabiya also followed a similar trend, though it recorded marginally higher peaks of around 31.19 °C.

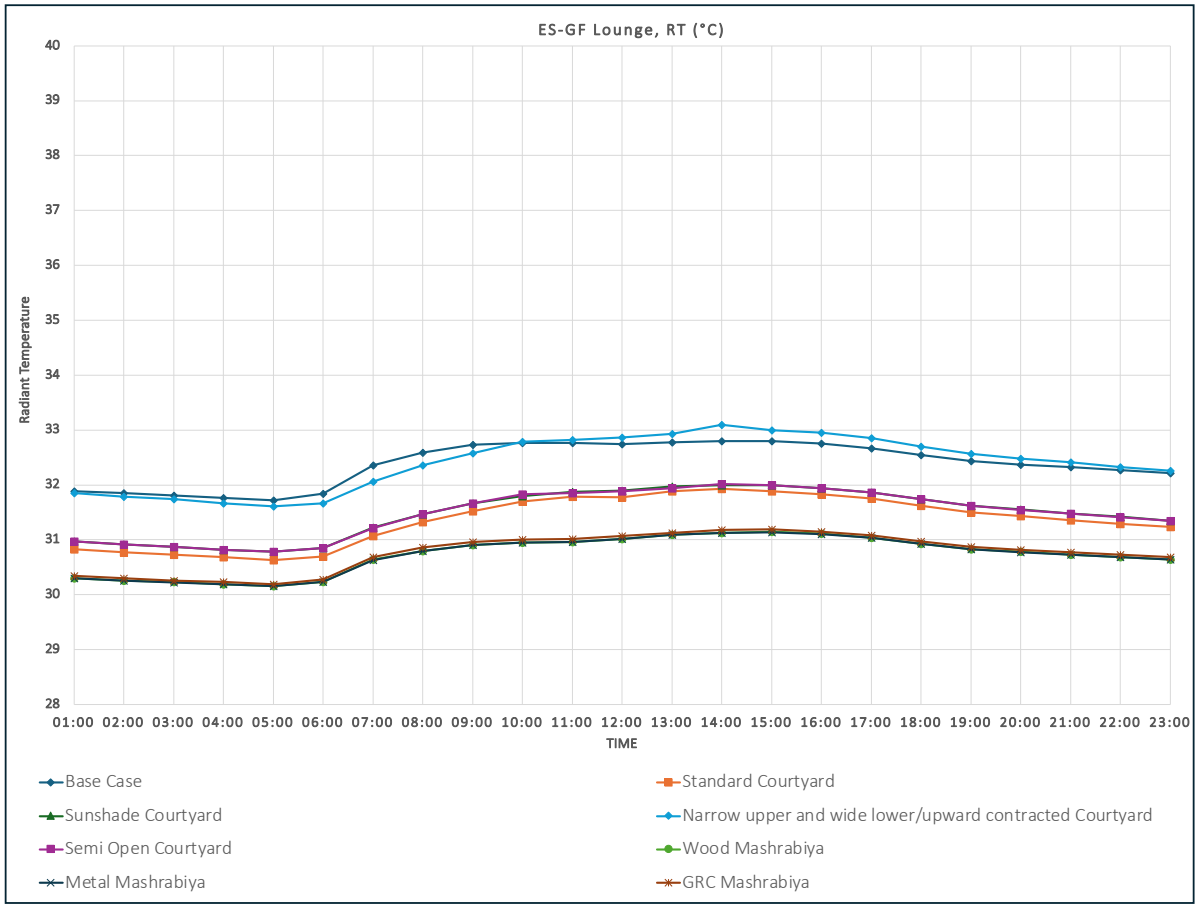


Figure 8.10. The Free-Running Simulation Results Comparing Hourly RTs in the Base Case Building (ES-GF Lounge Zone) and After Application of Traditional Passive Architectural Strategies (15 July)

However, the E-FF lounge zone in Figure (8.11) exhibited consistently higher radiant temperatures (RT) compared to the ES-GF lounge zone across all design strategies, with values remaining above 35°C throughout the 24-hour period. For example, early morning RTs (01:00–06:00) ranged from approximately 34.8°C for the Wood Mashrabiya to around 37.3°C for the Base Case, already exceeding the peak afternoon RTs recorded in the ES-GF lounge. A moderate rise in RT occurred after 06:00, reaching maximum values between 13:00 and 15:00, where the Base Case approached 38°C, while the most effective configuration (Wood Mashrabiya) maintained values near 35°C. In contrast, the ES-GF lounge demonstrated a wider dynamic range, with early morning minima near 30.3°C in the best-performing cases and afternoon peaks around 33.4°C in the Base Case. The smaller diurnal fluctuation in the E-FF lounge suggests a more persistent heat load, likely due to increased solar exposure and reduced thermal mass buffering on the first floor. While passive strategies in both zones achieved relative reductions of 2–3°C compared to the Base Case, their absolute performance was less effective in the E-FF lounge, where even the best design could not reduce RT to below 35°C, indicating a more severe overheating problem at the upper level. Furthermore, all the

first-floor zones witnessed consistently high RTs following the passive strategies improvements, with NE-FF Bedroom-1 reaching a peak of 35.50°C, while WS-FF Bedroom-2 and SE-FF Bedroom-3 reached peak around 35.28°C. E-FF Bedroom-4 reached up to 35.87°C, and the E-FF Lounge peaked at 35.11°C. This highlights a significant difference in thermal loads between the ground and first floors, as Plots (A3-2) in the appendices indicate as well.

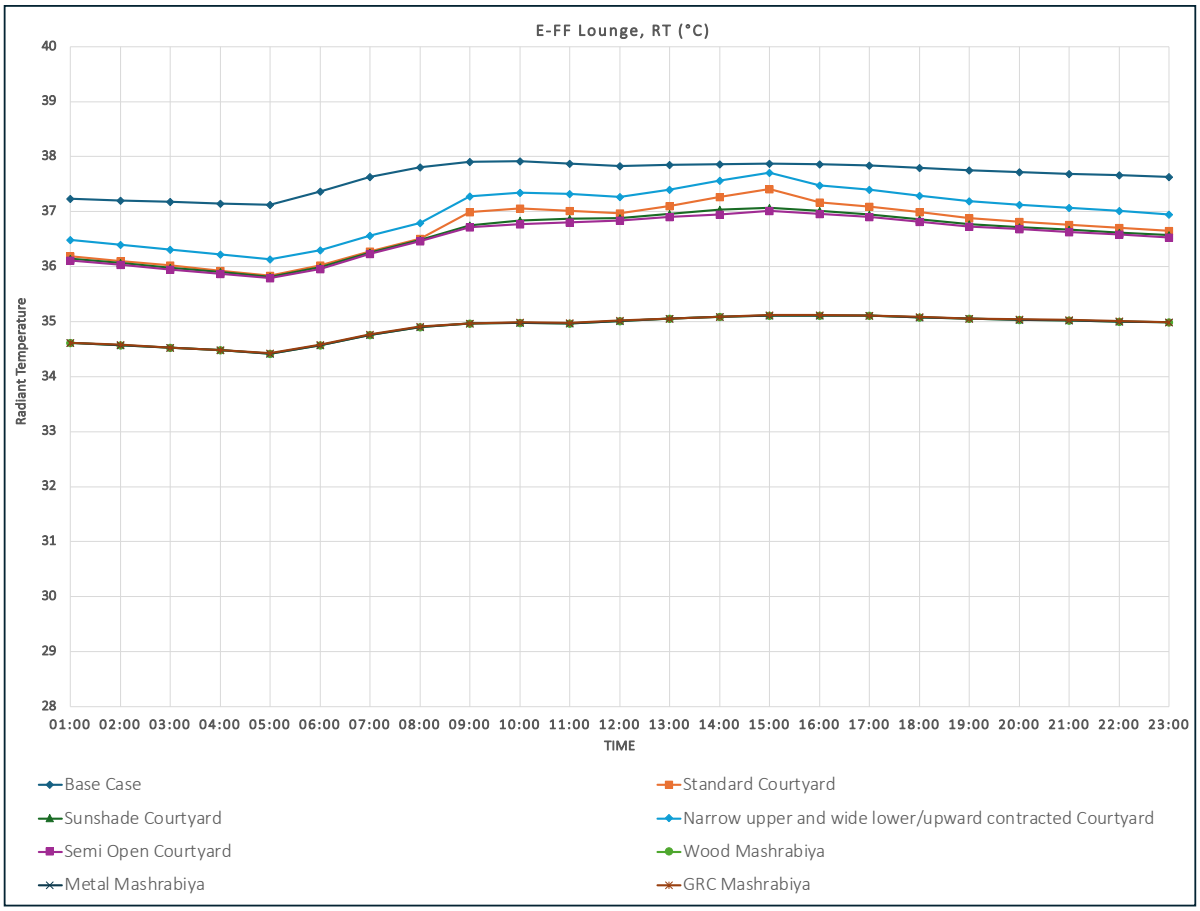


Figure 8.11. The Free-Running Simulation Results Comparing Hourly RTs in the Base Case Building (E-FF Lounge Zone) and After Application of Traditional Passive Architectural Strategies (15 July)

Figure (8.12) presents the hourly operative temperature (OT) profiles for the E-GF Dining zone under the Base Case and after implementing a range of traditional passive architectural strategies on 15 July. Clearly, the Base Case recorded the highest operative temperatures throughout the day, starting at 31.04 °C at 01:00 and rising to a peak of 31.70 °C at 10:00, before remaining above 31.5 °C for much of the afternoon. In contrast, all passive strategies delivered substantial cooling benefits, maintaining peak values at least 1.6 °C below the Base Case. Among them, courtyard-based configurations achieved the lowest OTs overall. The Narrow Upper & Wide Lower Courtyard recorded the lowest peak temperature (29.31 °C),

closely followed by the Standard Courtyard (29.35 °C), while the Sunshade Courtyard and Semi-Open Courtyard reached slightly higher peaks (29.56 °C).

The Mashrabiya -based shading systems—Wood Mashrabiya and Metal Mashrabiya—both peaked at 30.05 °C, with the GRC Mashrabiya marginally higher at 30.09 °C. These values are still considerably cooler than the Base Case but consistently warmer than the courtyard options. This performance pattern suggests that, in the E-GF Dining zone, courtyards are more effective in maintaining lower OTs across the day, likely due to their ability to enhance night-time radiative cooling, promote air movement, and limit cumulative heat storage within the enclosed zone. By contrast, mashrabiyas primarily target direct solar gain reduction at façades, which appears less critical for this ground-floor space, where solar exposure is more limited and internal heat dissipation plays a larger role.

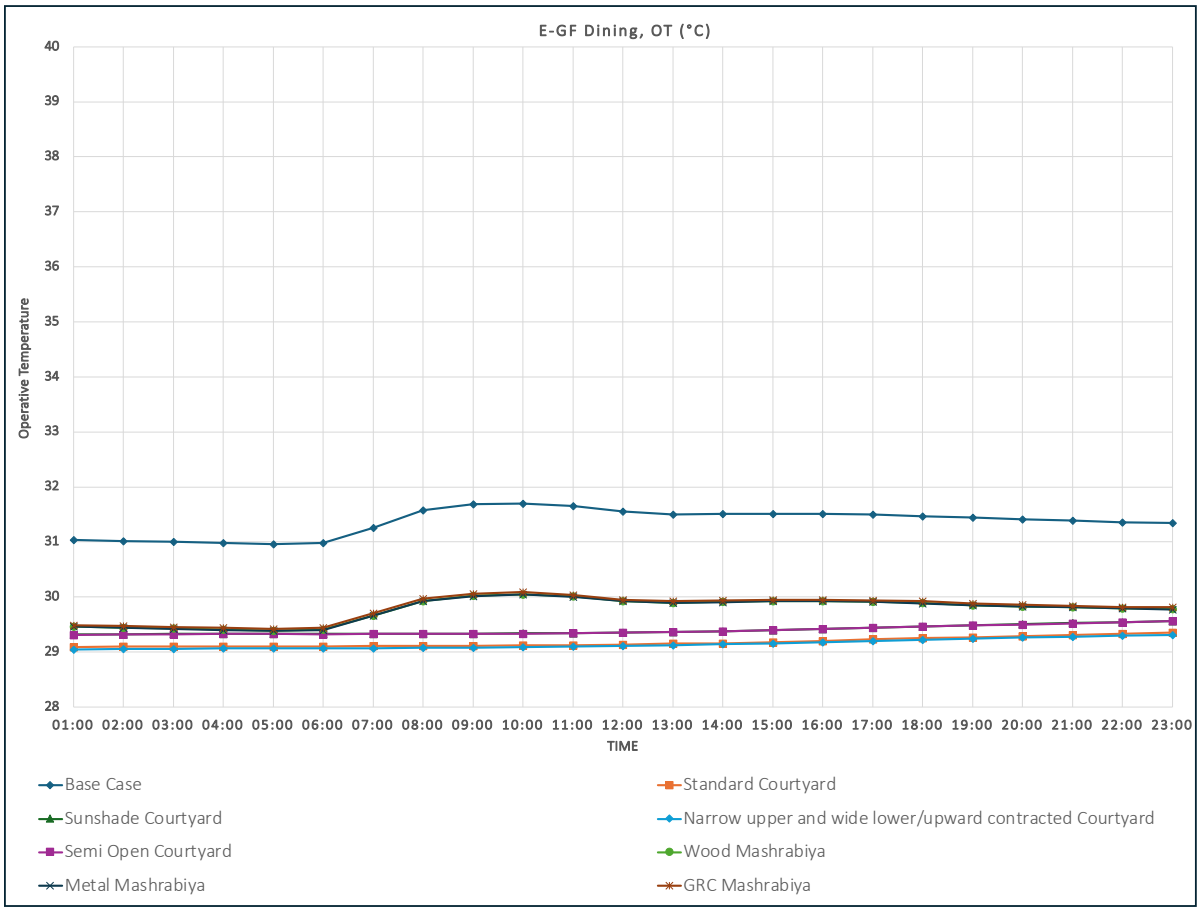


Figure 8.12. The Free-Running Simulation Results Comparing Hourly OTs in the Base Case Building (E-GF Dining Zone) and After Application of Traditional Passive Architectural Strategies (15 July)

Figure (8.13) shows the hourly operative temperature (OT) profiles for the ES-GF Lounge zone on 15 July, comparing the Base Case with various traditional passive architectural strategies under free-running conditions. Obviously, the Base Case recorded the highest OTs

across the day, beginning at 31.92 °C at 01:00 and reaching a peak of 32.95 °C at 14:00, remaining above 32.7 °C for much of the afternoon. Due to its east–south orientation, the lounge receives direct low-angle solar gains from the east in the morning and sustained high-angle exposure from the south at midday, intensifying heat loads throughout the day.

Among the improved designs, Mashrabiya-based shading systems achieved the most significant cooling effect. The Wood Mashrabiya and Metal Mashrabiya both peaked at 31.30 °C, while the GRC Mashrabiya reached 31.34 °C—representing reductions of around 1.6 °C compared to the Base Case peak. Their superior performance can be attributed to continuous façade-level shading, which intercepts solar radiation before it enters the space, particularly critical for the ES-GF lounge's orientation, where glazing is exposed to strong morning and midday sun. Courtyard-based strategies provided more modest improvements. The Standard Courtyard, Sunshade Courtyard, and Semi-Open Courtyard peaked between 32.20 °C and 32.28 °C, yielding only 0.7–0.8 °C reductions relative to the Base Case. The Narrow Upper & Wide Lower Courtyard performed worst, with a peak OT of 33.36 °C—exceeding the Base Case—likely due to restricted sky exposure and limited airflow, which can trap heat within the courtyard and reduce its cooling potential.

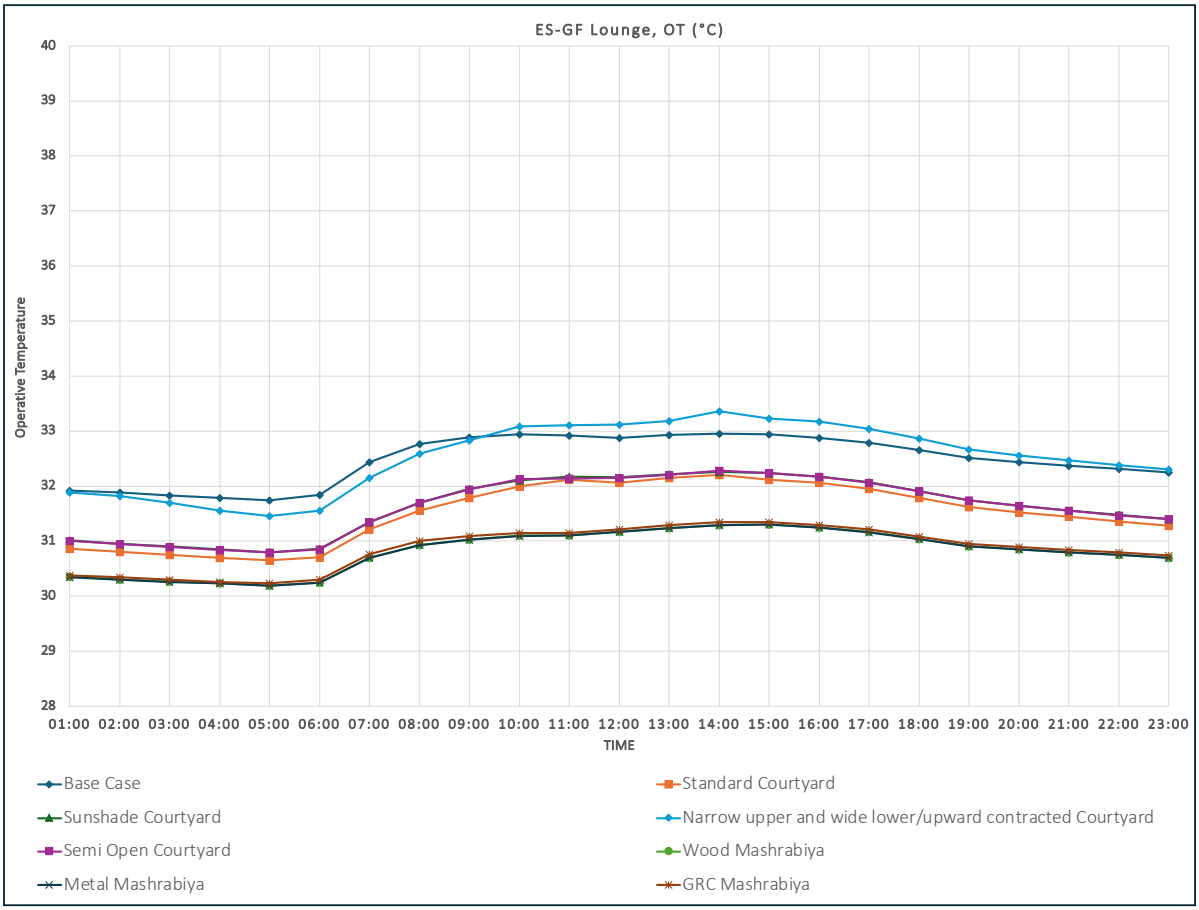


Figure 8.13. The Free-Running Simulation Results Comparing Hourly OTs in the Base Case Building (ES-GF lounge Zone) and After Application of Traditional Passive Architectural Strategies (15 July)

Figure (8.14) shows the hourly operative temperature (OT) profiles for the E-FF Lounge on 15 July, comparing the Base Case with various traditional passive architectural strategies under free-running conditions. Such high baseline values reflect the severe thermal load associated with the first floor's east-facing exposure, which receives intense low-angle morning sun followed by sustained solar heating into the midday period. However, among the improved designs, all Mashrabiya-based shading systems delivered the most substantial reductions, all peaking at 35.20 °C. This represented a decrease of approximately 2.8–2.9 °C compared with the Base Case peak. These devices were effective because they provide continuous façade-level shading, intercepting direct solar radiation during the morning and early afternoon, which are critical overheating periods for east-oriented upper-level spaces.

In contrast, courtyard-based strategies offered far less benefit in this zone. The Semi-Open Courtyard and Sunshade Courtyard peaked at 37.16 °C and 37.21 °C respectively, reducing peak temperatures by only about 0.8–0.9 °C relative to the Base Case. The Standard Courtyard performed even less effectively, peaking at 37.58 °C, while the Narrow Upper & Wide Lower Courtyard reached 37.87 °C—very close to the Base Case and indicating minimal mitigation. These results suggest that in high solar-exposure first-floor zones, courtyard cooling effects are limited because their benefits rely on night-time radiative heat loss and air circulation, which are less effective at countering intense direct solar penetration through façades.

In comparison between both zones (ES-GF Lounge and E-FF Lounge), Mashrabiya-based shading systems (Wood, Metal, and GRC) outperformed courtyard-based strategies. However, the cooling effect was more pronounced in the first-floor lounge, with Mashrabiya reducing peak OT by about 2.8–2.9 °C compared to the Base Case, versus 1.6 °C in the ground-floor lounge. Courtyard strategies showed limited benefit in both contexts, but their relative underperformance was especially evident in the E-FF lounge, where high-intensity solar gains outweighed their indirect cooling potential.

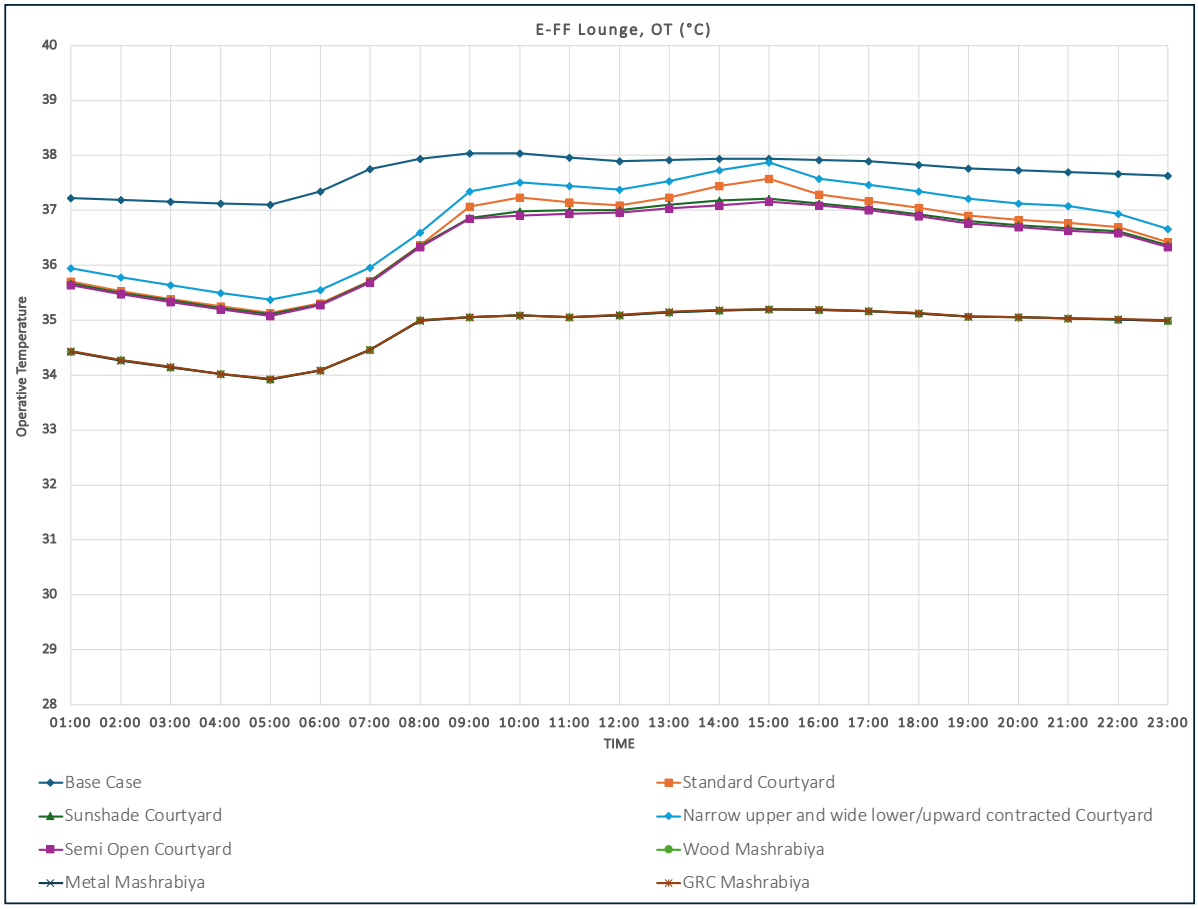


Figure 8.14. The Free-Running Simulation Results Comparing Hourly OTs in the Base Case Building (E-FF Lounge Zone) and After Application of Traditional Passive Architectural Strategies (15 July)

Figure (8.15) illustrates the free-running simulation results for the E-GF Dining zone (15 July), showing the variation in relative humidity (RH) across the Base Case and the tested passive strategies. The Base Case consistently maintains the lowest RH levels, starting at 15.34% at 01:00, dropping to a minimum of 14.52% between 09:00 and 10:00, and then gradually recovering to 15.08% by 23:00. This pattern reflects the impact of elevated operative temperatures in the Base Case, which reduces the air's capacity to retain moisture.

Courtyard-based strategies demonstrated the highest RH levels throughout the day. The Narrow Upper & Wide Lower Courtyard peaked at 17.22% during the early morning hours, closely followed by the Standard Courtyard (17.18%). The Sunshade Courtyard and Semi-Open Courtyard also maintained elevated RH values, ranging between 16.73% and 16.96% at the lowest points of the diurnal cycle. These consistently higher RH values were likely due to lower operative temperatures under courtyard configurations, which increased relative humidity by reducing the saturation deficit of the air.

Mashrabiya-based strategies (Wood, Metal, and GRC) showed intermediate RH levels between the Base Case and courtyard configurations. For instance, the Wood Mashrabiya maintained early morning values around 16.78% and reached a midday minimum near 15.95% before recovering to 16.47% by the end of the day.

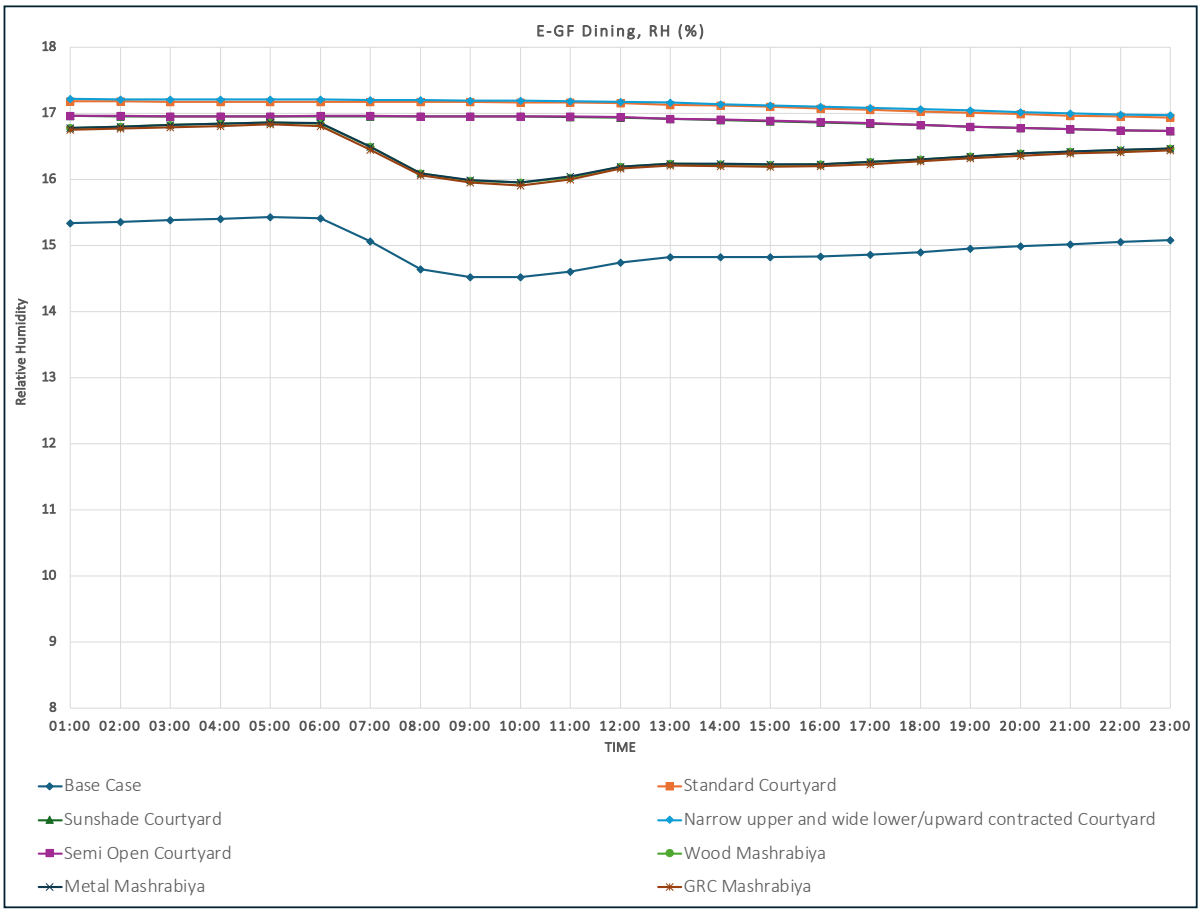


Figure 8.15. The Free-Running Simulation Results Comparing Hourly RH in the Base Case Building (E-GF Dining Zone) and After Application of Traditional Passive Architectural Strategies (15 July)

Figure (8.16) presents the free-running simulation results for the ES-GF lounge (15 July), showing the variation in relative humidity (RH) across the Base Case and the tested passive strategies. The Base Case consistently maintained the lowest RH levels, starting at 14.59% at 01:00, reaching an early morning peak of 14.75% at 05:00, before falling to a minimum of 13.67% at 10:00, and then gradually recovering to 14.32% by 23:00. This trend reflected the zone's east–south orientation, which exposed it to early and intense solar gains, raising operative temperatures and reducing RH during the late morning and midday periods.

Courtyard-based strategies showed moderate improvements over the Base Case. The Standard Courtyard recorded the highest early morning RH of 15.90% at 05:00, while the Sunshade Courtyard and Semi-Open Courtyard both peaked at 15.78%. However, during the late morning and midday period, RH values for these strategies declined to between 14.45% and 14.68%. The Narrow Upper & Wide Lower Courtyard performed less effectively, with RH dropping to 13.69% at 14:00—only slightly above the Base Case minimum—indicating limited humidity retention under this orientation.

Mashrabiya-based strategies (Wood, Metal, and GRC) consistently achieved the highest RH levels throughout the day. Both the Wood and Metal Mashrabiyas peaked at 16.11% at 05:00 and maintained midday RH above 15.0%, recovering to 15.63% by 23:00. The GRC Mashrabiya followed closely, with a peak of 16.07% at 05:00 and a midday low of 14.98%.

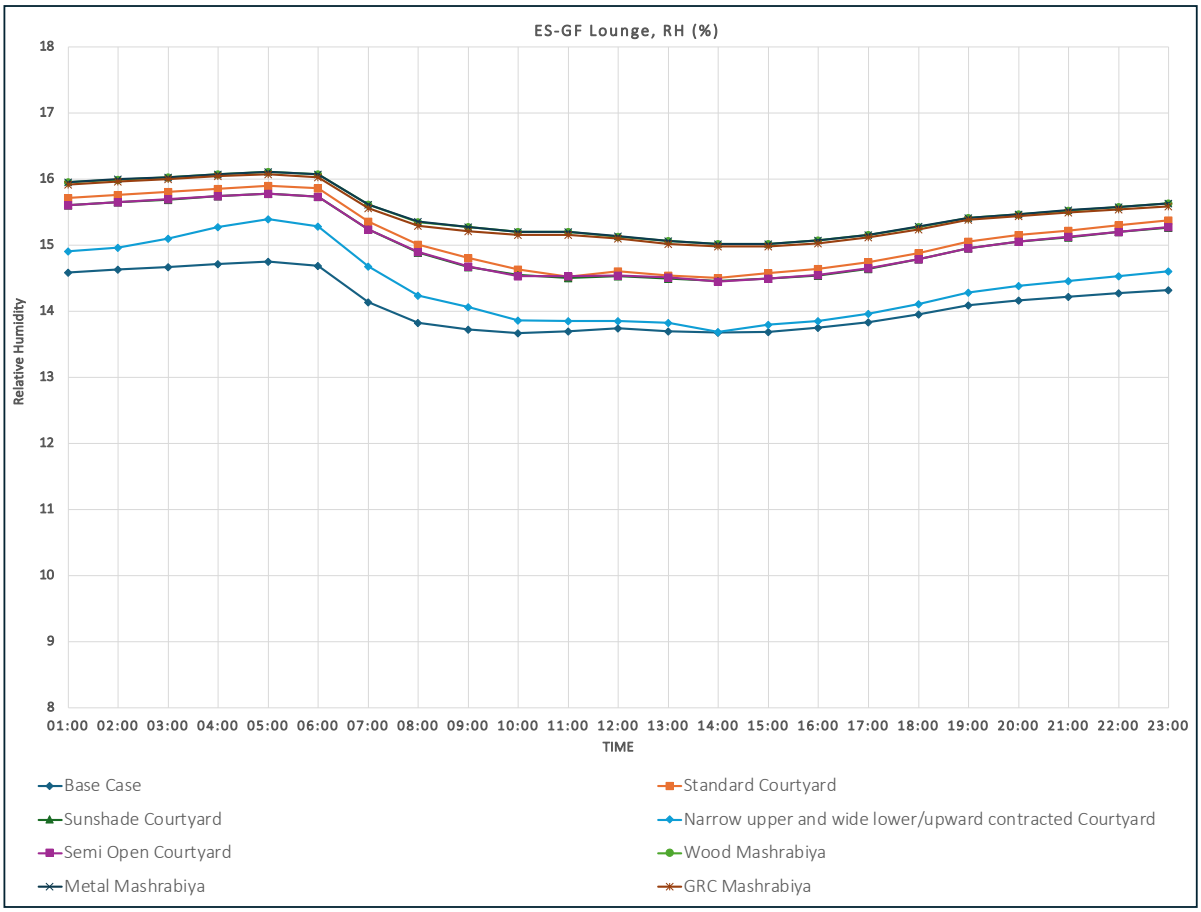


Figure 8.16. The Free-Running Simulation Results Comparing Hourly RH in the Base Case Building (ES-GF lounge Zone) and After Application of Traditional Passive Architectural Strategies (15 July)

Figure (8.17) presents below the free-running simulation results for the E-FF lounge (15 July), showing the variation in relative humidity (RH) across the Base Case and the tested

passive strategies. As in other zones, the Base Case consistently maintained the lowest RH levels, starting at 10.90% at 01:00, peaking slightly at 10.98% at 05:00, before declining to a minimum of 10.35% between 09:00 and 10:00, and then recovering marginally to 10.66% by 23:00. However, Courtyard-based strategies achieved modest improvements over the Base Case. The Standard Courtyard reached an early morning peak of 12.71% at 05:00 but dropped to a midday minimum of 10.59% at 14:00, closely followed by a recovery in the late afternoon. The Sunshade Courtyard and Semi-Open Courtyard showed similar trends, with early peaks of 12.72% and 12.73%, respectively, and midday lows near 10.86%–10.92%. The Narrow Upper & Wide Lower Courtyard recorded slightly lower morning RH at 12.56% and also experienced the sharpest drop, falling to 10.43% at 14:00—indicating that its temperature mitigation effect was insufficient to sustain RH during peak solar hours.

Furthermore, Mashrabiya-based strategies clearly outperformed courtyards in maintaining higher RH levels. The Wood and Metal Mashrabiyas shared identical readings, peaking at 13.43% at 05:00 and sustaining midday RH above 12.11%, before ending the day at 12.31%. The GRC Mashrabiya followed almost the same pattern, with only a negligible difference in midday values. These results reflected the Mashrabiyas' strong capacity for direct solar control on upper-level façades, limiting temperature rise and preserving indoor moisture during the most thermally stressful hours.

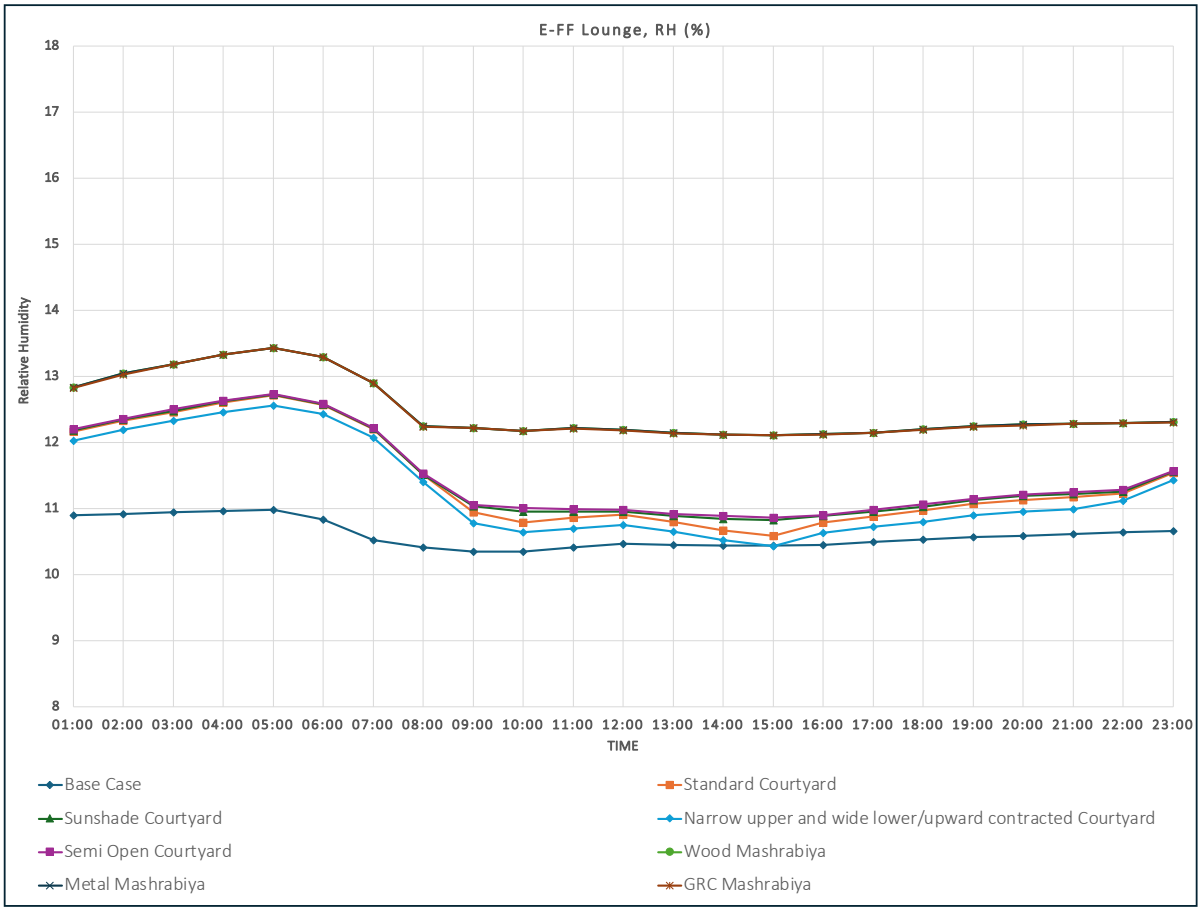


Figure 8.17. The Free-Running Simulation Results Comparing Hourly RH in the Base Case Building (E-FF lounge Zone) and After Application of Traditional Passive Architectural Strategies (15 July)

Across all examined strategies—covering indoor air temperature (IAT), radiant temperature (RT), and relative humidity (RH) for the E-GF Dining, ES-GF Lounge, and E-FF Lounge zones—the results consistently revealed that passive design strategies varied greatly in their thermal performance depending on both building zone and environmental parameter. Mashrabiya-based shading systems (Wood, Metal, and GRC) repeatedly emerged as the most effective in reducing both IAT and RT, particularly in upper-floor spaces where direct solar exposure is more intense. They maintained notably lower peak temperatures, often 2–3 °C cooler than the Base Case, while also delivering slightly higher RH levels, improving indoor comfort in arid summer conditions. Courtyard-based strategies, although beneficial in reducing heat gains, showed more modest impacts; their cooling effect was stronger at the ground-floor dining and lounge zones—where their spatial configuration better channelled ventilation and shading—but diminished at the first-floor level, where solar radiation bypassed courtyard walls. Among them, the Sunshade Courtyard and Semi-Open Courtyard consistently outperformed the Standard and Narrow Upper/Wide Lower configurations by achieving marginally lower peaks. The RH patterns confirmed these trends, with Mashrabiya solutions delivering the highest readings and narrow courtyard types the lowest.

8.2.2 Energy Efficiency Measures (Exterior insulation and finish system (EIFS))

The thermal comfort aspects of the base case building, employing various thicknesses and types of insulation boards within the building walls over 24 hours on the hottest day in Riyadh, Saudi Arabia (15th July), were assessed. The following sections examine in depth, with the aid of line charts, how the parameters interacted with each other and how they were influenced by factors such as insulation variety. These visual representations helped to better understand the trends and variations in indoor air temperature, radiant temperature, operative temperature, and relative humidity across the base case building zones throughout the day following the improvements.

Figure (8.18) demonstrates the results of the free-running simulation of indoor air temperature for each zone in the base-case building after employing various thicknesses and types of insulation boards within the building envelope.

The Base Case recorded the highest IAT values, with early morning minima around 30.9–31.0 °C and daytime peaks reaching 32.0–32.1 °C, particularly between 09:00 and 11:00. However, when insulation was upgraded, the results showed a consistent reduction in IAT across all strategies. The use of XPS insulation was effective, with reductions proportional to thickness. At 100 mm XPS, IAT dropped by approximately 0.6 °C compared to the Base Case, while 150 mm XPS achieved a further reduction to around 30.3 °C at peak. The 200 mm XPS case provided the greatest impact among XPS options, lowering midday peaks to 30.7–30.8 °C, representing nearly a 1.3 °C improvement compared to the Base Case.

More advanced materials offered even stronger performance. Vacuum Insulated Panels (VIPs) at 50 mm already outperformed 150 mm XPS, with IAT stabilising around 30.6–30.7 °C during midday. Increasing the VIP thickness further to 60 mm and 70 mm resulted in additional cooling, maintaining peaks close to 30.5 °C. This highlights the superior thermal resistance of VIP compared to conventional XPS. Similarly, Aerogel insulation demonstrated considerable effectiveness. At 60 mm thickness, IAT values remained near 31.2 °C at peak, while increasing to 70 mm reduced midday conditions to 31.0 °C, thus approaching the performance of XPS at 150 mm but with significantly reduced thickness requirements.

Interestingly, the Vacuum Insulated Panels (VIPs) at 60 mm performed slightly better than those at 70 mm. This can be explained by the fact that thicker insulation does not always reduce heat transfer; instead, it can sometimes delay it. In hot climates, this delay may result

in a thermal lag, where stored heat within the wall is released later in the day, coinciding with peak indoor loads and thereby leading to marginally higher indoor temperatures.

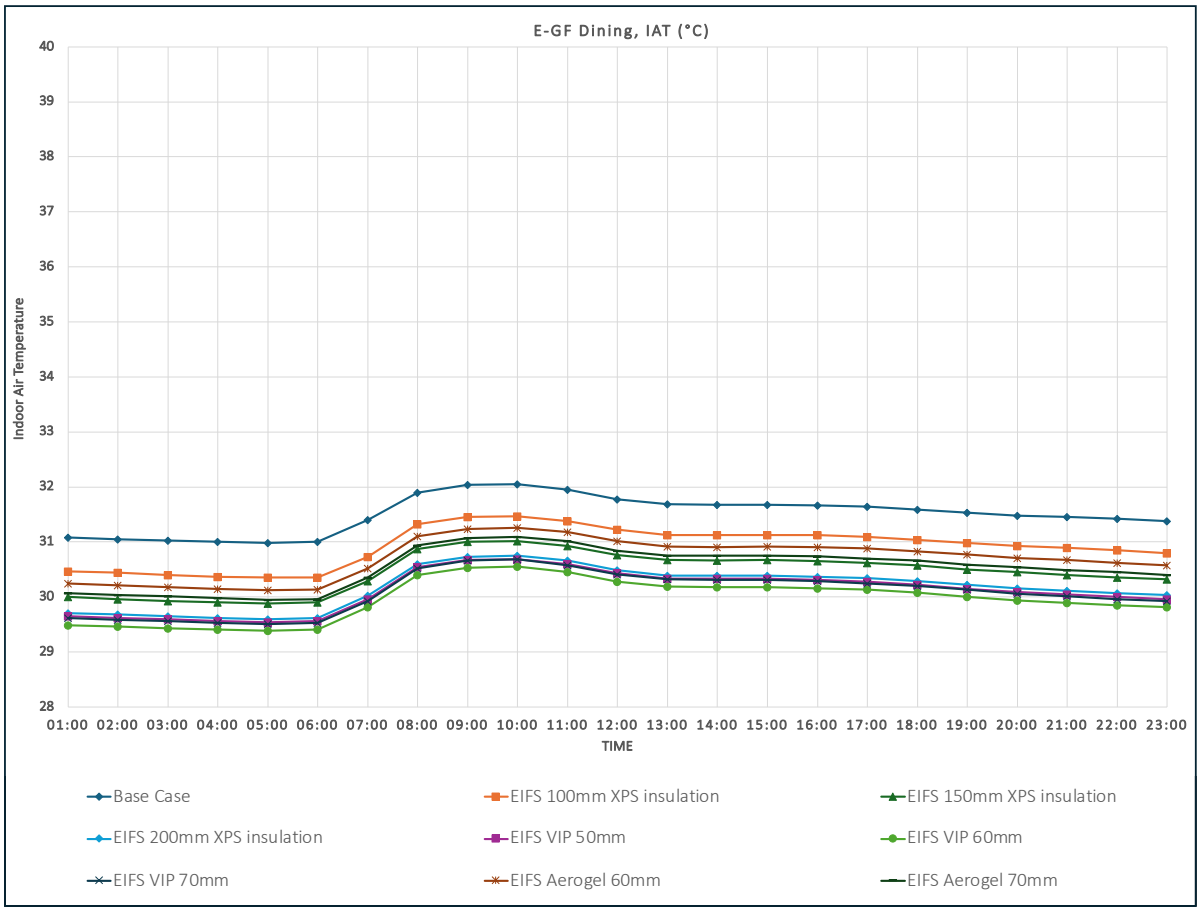


Figure 8.18. Free-Running Simulation Results Comparing Hourly IATs in the E-GF Dining Zone: Base Case vs. Improvements Using Exterior Insulation and Finish System (EIFS) with Different Insulation Types and Thicknesses (15 July).

Figure (8.19) illustrates the outcomes of the free-running simulation of indoor air temperature in the ES-GF Lounge, comparing the Base Case with different insulation strategies that employed varying thicknesses and types of EIFS boards within the building envelope. The Base Case displayed the highest IAT values, with early morning levels around 31.7–31.9 °C and midday peaks rising to 33.0–33.1 °C, especially between 10:00 and 14:00. This reflects the significant solar heat gain and the poor thermal resistance of the base scenario. However, the addition of XPS insulation led to clear improvements, with performance directly related to thickness. At 100 mm XPS, peak IAT dropped by nearly 0.5 °C, while 150 mm XPS decreased the values further, with maxima near 32.1 °C. The 200 mm XPS configuration provided the

greatest effect among this category, lowering midday peaks to approximately 31.9–32.0 °C, which represented a total improvement of more than 1.1 °C compared to the Base Case.

Moreover, the use of Vacuum Insulated Panels (VIPs) achieved even greater reductions. At 50 mm, peak IAT decreased to 31.8–31.9 °C, already outperforming 150 mm XPS. Similar to the E-GF Dining Zone, the 60 mm VIP option performed marginally better than the 70 mm case, maintaining peaks at approximately 31.7 °C, compared to 31.8 °C for the thicker variant. In comparison, Aerogel insulation achieved meaningful reductions, though not as effective as VIP. At 60 mm thickness, IAT was lowered to about 32.4 °C at peak, while 70 mm Aerogel reduced this further to 32.2–32.3 °C. Although these values were higher than VIP, they still represented a notable improvement over the Base Case, with much smaller material thickness compared to XPS.

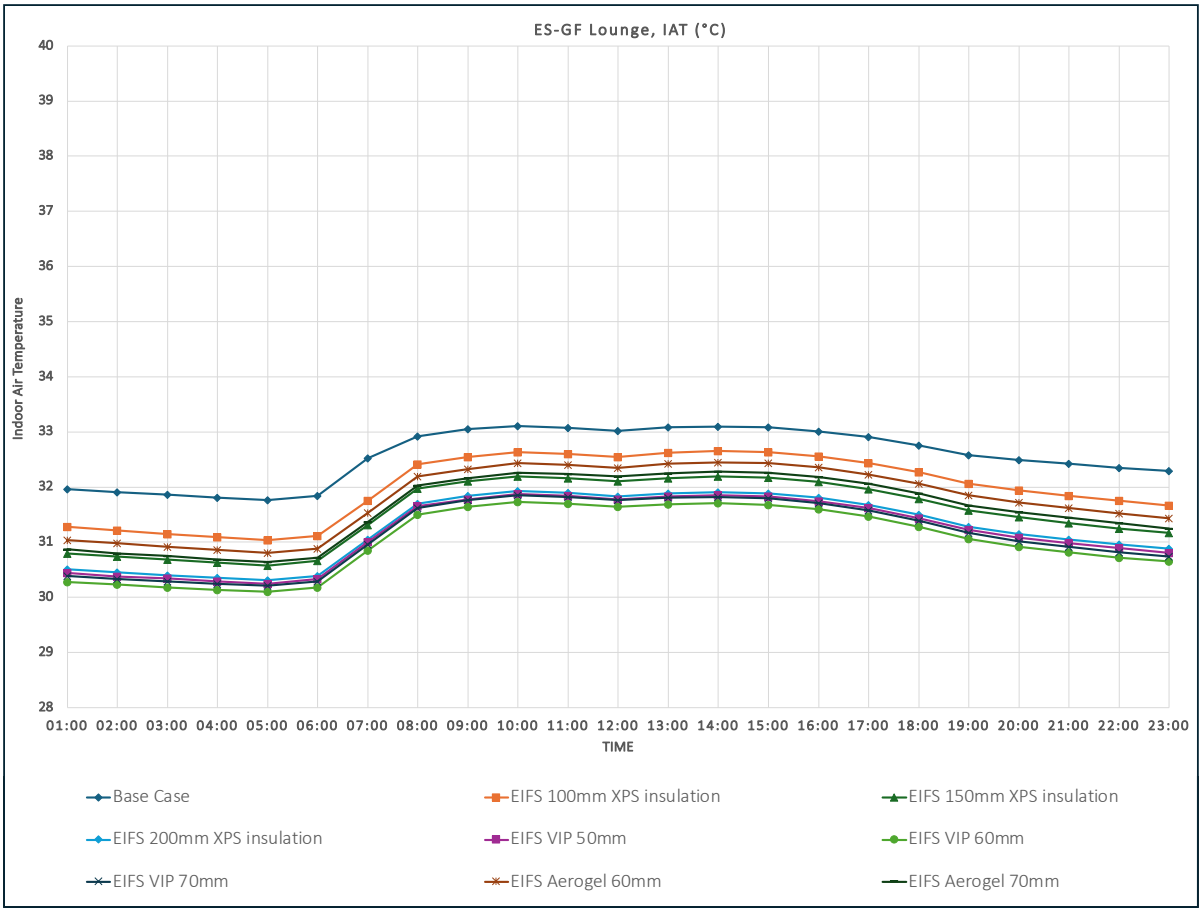


Figure 8.19. Free-Running Simulation Results Comparing Hourly IATs in the ES-GF lounge Zone: Base Case vs. Improvements Using Exterior Insulation and Finish System (EIFS) with Different Insulation Types and Thicknesses (15 July).

Moving to the first floor, Figure (8.20) presents the free-running simulation of indoor air temperature for the E–FF Lounge under the base case and subsequent application of various insulation systems. The base case scenario recorded the highest indoor temperatures among the tested zones, with values ranging from 37.1 °C in the early morning to peaks of 38.0–38.2 °C around midday, before gradually declining towards 37.6 °C in the evening. This high thermal load resulted from increased solar exposure and less thermal buffering on the first floor compared to ground-floor zones.

The addition of XPS insulation caused a gradual decrease in indoor air temperatures. For example, 100 mm of XPS layer reduced the daily peak to 37.8 °C, while increasing the thickness to 150 mm and 200 mm resulted in further decreases to 37.3 °C and 37.0 °C, respectively. Notably, the 200 mm XPS configuration maintained indoor conditions consistently lower by approximately 1.0–1.2 °C compared to the base case throughout the day.

Among the advanced insulation systems, Vacuum Insulated Panels (VIPs) once again outperformed normal insulation at lower thicknesses. The 60 mm VIPs lowered peak temperatures to 36.7–36.8 °C, while 70 mm VIPs were slightly less effective, at 36.9–37.0 °C. This trend was also observed in the ES–GF Lounge and is attributed to the thermal lag effect, where thicker insulation layers delay heat dissipation, releasing stored heat during late afternoon hours and coinciding with indoor thermal loads in hot climates.

On the other hand, Aerogel insulation provided moderate improvements but was less effective than VIPs. The 60 mm Aerogel reached peak values of 37.5–37.6 °C, while 70 mm performed slightly better at 37.3–37.4 °C, though still warmer than XPS at greater thicknesses or VIPs at thinner layers.

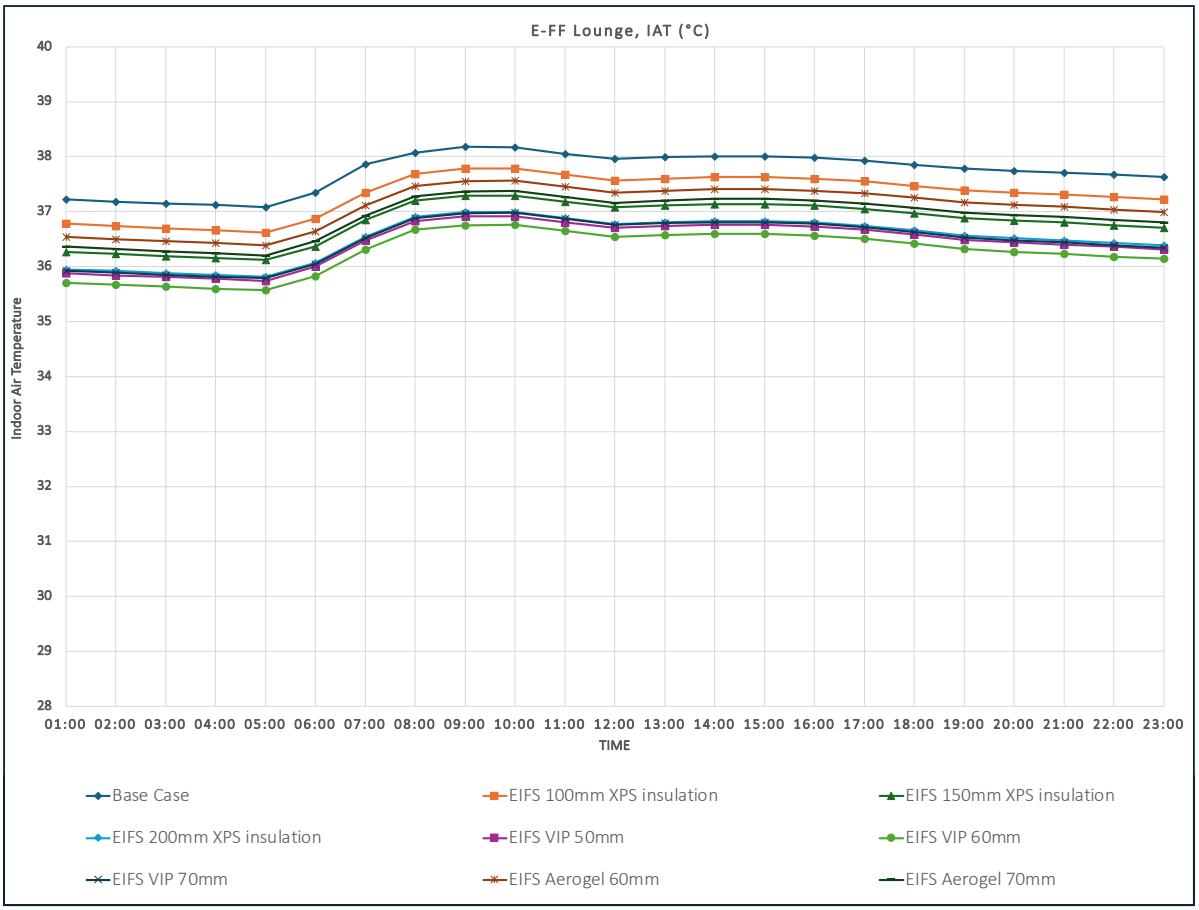


Figure 8.20. Free-Running Simulation Results Comparing Hourly IATs in the E-FF lounge Zone: Base Case vs. Improvements Using Exterior Insulation and Finish System (EIFS) with Different Insulation Types and Thicknesses (15 July)

Figure (8.21) demonstrates the free-running simulation of radiant temperature for the E–GF Dining zone under the base case and various insulation strategies. The base case recorded radiant temperatures fluctuating between 30.9–31.4 °C, with peaks around midday to late afternoon, following a similar trend to the IATs observed across the building zones.

The application of XPS insulation clearly reduced radiant temperatures. With 100 mm of XPS, peak values declined to approximately 30.8 °C, while increasing the thickness to 150 mm and 200 mm further lowered peaks to 30.3 °C and 30.0 °C, respectively.

The Vacuum Insulated Panels (VIPs) once again outperformed conventional XPS at significantly lower thicknesses. At 50 mm thicknesses, VIPs reduced midday peaks to about 29.9 °C, while the 60 mm option achieved the most obvious reduction, stabilising values at 29.8–29.9 °C. Meanwhile, the 70 mm VIP registered slightly higher midday values (29.9–30.0 °C).

On the other hand, Aerogel insulation provided moderate yet consistent reductions. The 60 mm Aerogel thicknesses stabilised radiant temperatures around 30.5–30.6 °C, whereas the 70 mm thickness achieved slightly lower peaks of 30.3–30.4 °C. Although effective, Aerogel remained less impactful compared with thick XPS or thinner VIPs.

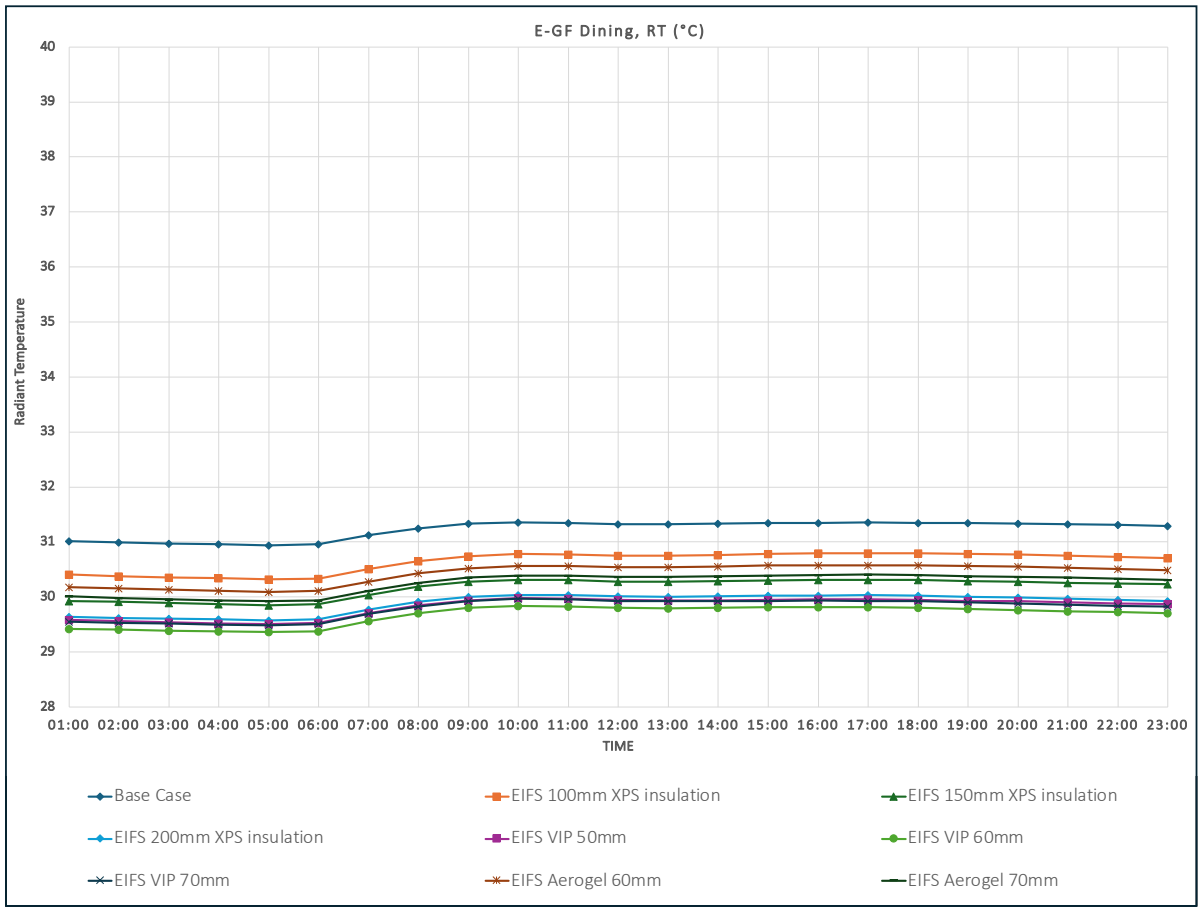


Figure 8.21. Free-Running Simulation Results Comparing Hourly RTs in the E-GF Dining Zone: Base Case vs. Improvements Using Exterior Insulation and Finish System (EIFS) with Different Insulation Types and Thicknesses (15 July)

Figure (8.22) illustrates the free-running simulation of radiant temperature for the ES–GF Lounge under the base case and alternative insulation strategies. In the base case, radiant temperatures ranged between 31.7–32.8 °C, with the highest values observed during midday and early afternoon periods. However, the incorporation of 100 mm XPS reduced the peak values to approximately 32.3–32.4 °C, while further increasing the thickness to 150 mm and 200 mm lowered the maxima to 31.8–31.9 °C and 31.5–31.6 °C, respectively. This progressive reduction underscores the cumulative effect of enhanced thermal resistance in mitigating heat transfer through the envelope.

Moreover, Vacuum Insulated Panels (VIPs) demonstrated superior performance at substantially reduced thicknesses. A thickness of 50 mm decreased midday peaks to around 31.5 °C, whereas the 60 mm configuration yielded the most significant reduction, stabilising values at 31.3–31.4 °C. The 70 mm VIPs, however, exhibited slightly diminished performance, recording peaks closer to 31.5 °C.

Aerogel insulation offered moderate but consistent improvements. The 60 mm Aerogel option stabilised radiant temperatures around 32.1–32.2 °C, while the 70 mm thickness achieved slightly greater reductions, with peaks of 31.9–32.0 °C. Nevertheless, Aerogel remained less effective than either thicker XPS or thinner VIPs, thereby reinforcing the relative efficiency of these systems for thermal performance optimisation.

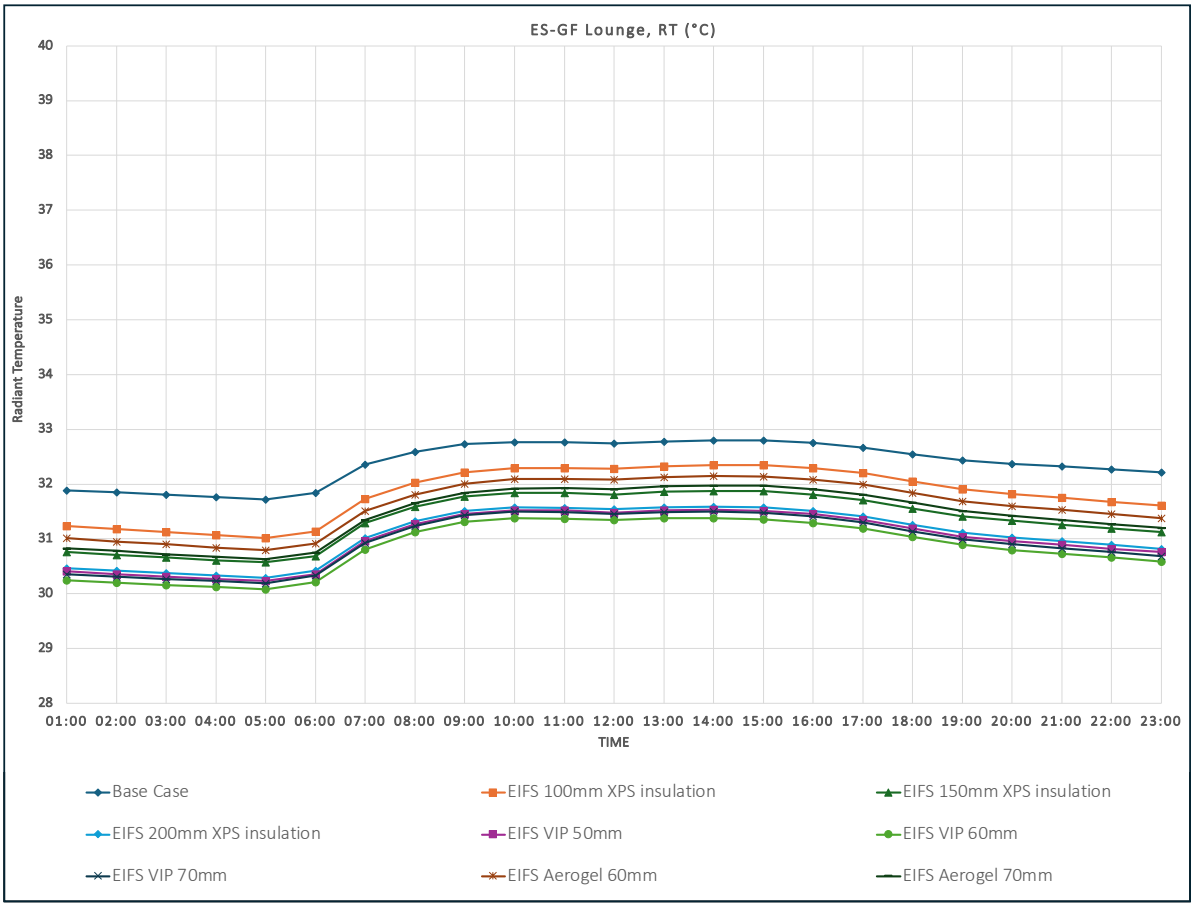


Figure 8.22. Free-Running Simulation Results Comparing Hourly RTs in the ES–GF Lounge: Base Case vs. Improvements Using Exterior Insulation and Finish System (EIFS) with Different Insulation Types and Thicknesses (15 July)

Figure (8.23) shows the outcomes of the free-running simulation of radiant temperature for the E–FF Lounge in the base case and following the application of different insulation types

using EIFS. The base case scenario consistently exhibited high radiant temperatures, fluctuating between 37.1 and 37.9 °C, with the most pronounced peaks occurring during the late morning and early afternoon hours. Consequently, the application of XPS insulation resulted in a noticeable reduction in radiant temperatures. For example, at 100 mm thickness, peak values declined to approximately 37.5 °C, while thicker layers of 150 mm and 200 mm further reduced the maxima to around 37.0 °C and 36.7–36.8 °C, respectively, highlighting the cumulative effect of increased thermal resistance.

In addition, the use of advanced insulation materials such as Vacuum Insulated Panels (VIPs) demonstrated superior thermal performance at substantially reduced thicknesses. At 50 mm thickness, VIPs reduced peak radiant temperatures to approximately 36.9–37.0 °C, which was comparable to or better than much thicker XPS layers. At 60 mm, the VIPs provided the most substantial reduction, stabilising values at 36.4–36.5 °C. Interestingly, increasing the thickness to 70 mm yielded slightly higher peaks of 36.7–36.8 °C in the 60 mm case. Meanwhile, Aerogel insulation, though less effective than VIPs or thicker XPS layers, still delivered measurable improvements. At 60 mm, radiant temperatures stabilised at around 37.2–37.3 °C, whereas increasing the thickness to 70 mm achieved slightly lower values of 37.0–37.1 °C.

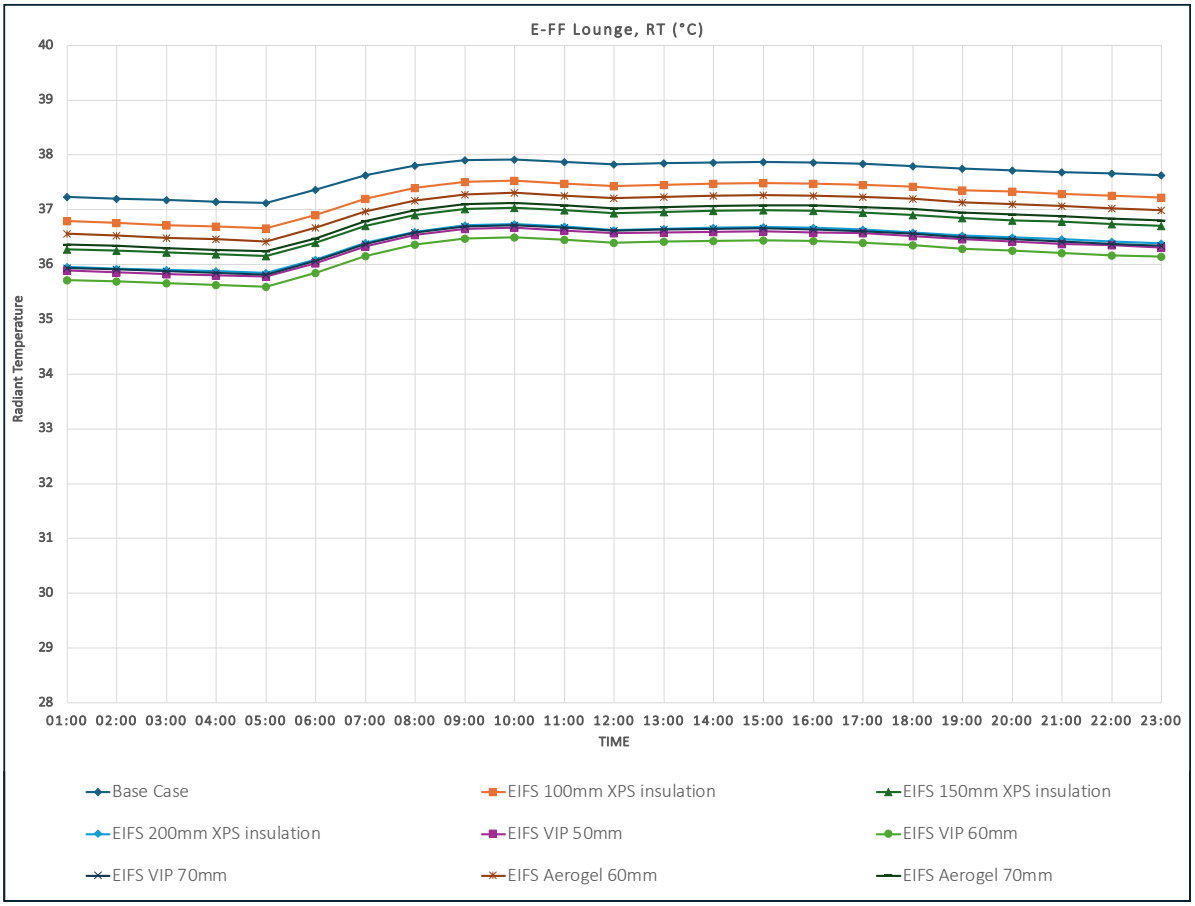


Figure 8.23. Free-Running Simulation Results Comparing Hourly RTs in the E–FF Lounge: Base Case vs. Improvements Using Exterior Insulation and Finish System (EIFS) with Different Insulation Types and Thicknesses (15 July)

Figure (8.24) illustrates the free-running simulation of operative temperature (OT) for the E–GF Dining zone under the base case and a range of insulation strategies using EIFS. In the base case, the operative temperatures fluctuated between 30.9–31.7 °C, with the highest peaks occurring in the late morning to early afternoon, closely mirroring the patterns observed in the indoor air and radiant temperatures. Nevertheless, when XPS insulation was introduced, a clear gap of reduction in operative temperatures was observed. For example, at 100 mm thickness, peak values declined to about 31.1–31.2 °C, representing a noticeable improvement compared to the base case. Further increasing the thickness to 150 mm and 200 mm resulted in progressively greater reductions, with peaks dropping to approximately 30.6–30.7 °C and 30.3–30.4 °C, respectively. These results underline the effectiveness of thicker exterior XPS in enhancing thermal resistance and reducing heat gains in hot conditions.

In contrast, Vacuum Insulated Panels (VIPs) showed superior performance at significantly thinner thicknesses. For instance, at 50 mm, operational temperatures were already reduced to around 30.3–30.4 °C, essentially matching the results of much thicker XPS layers. Moreover,

increasing the thickness to 60 mm provided the greatest benefit, with peaks stabilising at 30.1–30.2 °C—the lowest values among all insulation types. The trend was observed again with the 70 mm VIP setup, which showed slightly higher peak values (30.3–30.4 °C), indicating that additional thickness may not necessarily lead to proportional improvements. Furthermore, Aerogel insulation was less effective than VIPs or thicker XPS but still achieved measurable reductions in peak operative temperatures. At 60 mm, temperatures stabilised at about 30.8–30.9 °C, and increased thickness to 70 mm reduced them slightly further to 30.7–30.8 °C.

Overall, the findings confirm that VIPs achieved the greatest thermal improvement per unit thickness, primarily due to their ultra-low thermal conductivity derived from vacuum technology. However, XPS boards at increased thicknesses also produced substantial reductions, whereas Aerogel blankets functioned as a mediate option.

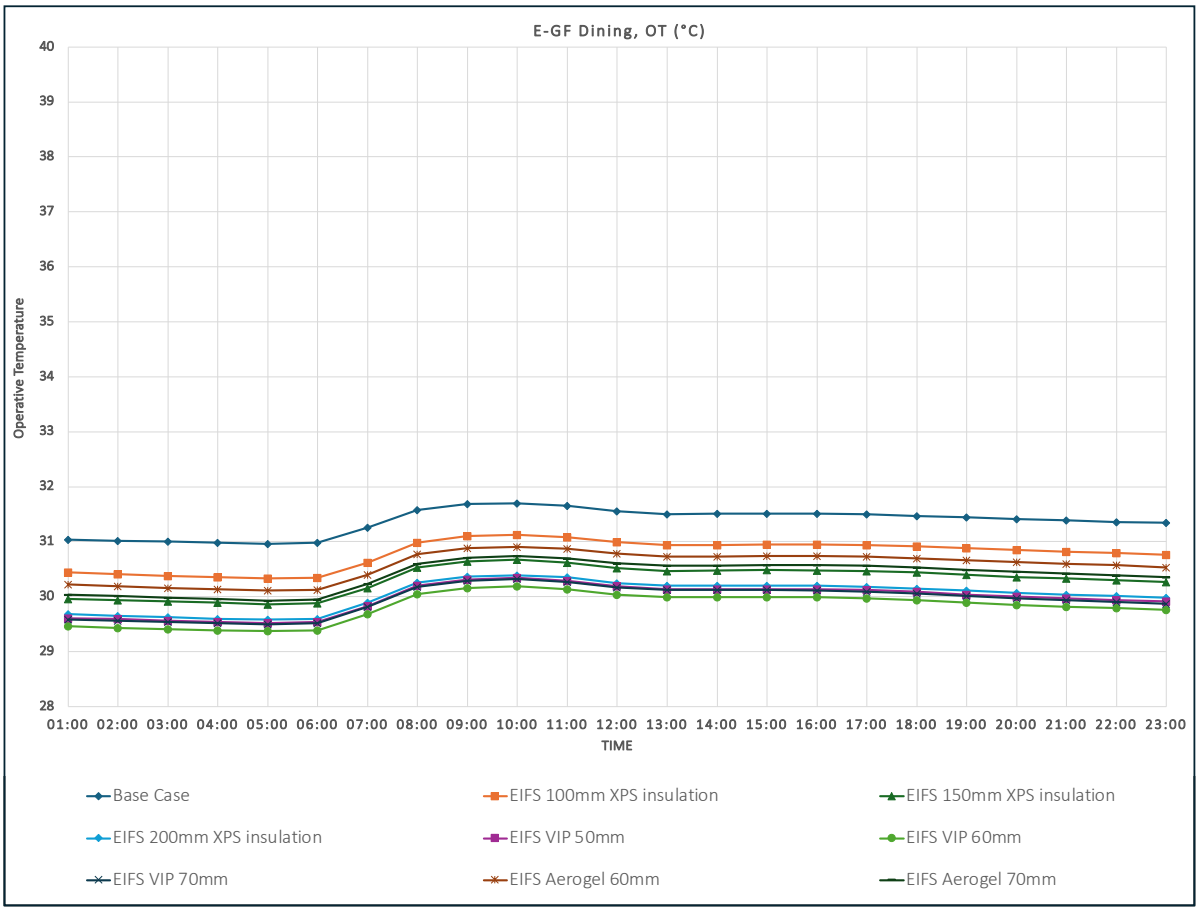


Figure 8.24. Free-Running Simulation Results Comparing Hourly OTs in the E-GF Dining Zone: Base Case vs. Improvements Using Exterior Insulation and Finish System (EIFS) with Different Insulation Types and Thicknesses (15 July)

Figure (8.25) presents the free-running simulation of operative temperature (OT) for the E–GF Lounge across the base case and a range of insulation strategies using EIFS. The base case consistently exhibited high operative temperatures, fluctuating between 31.7 and 32.9 °C, with pronounced peaks recorded between late morning and early afternoon.

After the implementation of the EIFS with XPS insulation, a gradual yet noticeable reduction in operative temperatures was observed. At 100 mm thickness, peaks declined to approximately 32.4–32.5 °C, marking a modest improvement. Increasing the thickness to 150 mm achieved further reductions, lowering peaks to 32.0–32.1 °C, while 200 mm XPS reduced them even more significantly to around 31.7–31.8 °C. This progression highlights the cumulative benefit of increasing thermal resistance in conventional insulation materials.

A more noticeable performance was delivered by Vacuum Insulated Panels (VIPs), which exceeded the XPS at considerably smaller thicknesses, similar to other zones. For example, at 50 mm, VIPs reduced peak operative temperatures to about 31.6–31.7 °C, nearly matching the performance of 200 mm XPS. The 60 mm VIP configuration proved even more effective, lowering midday peaks to around 31.5–31.6 °C, the lowest values across the dataset. The 70 mm VIPs recorded slightly higher peaks of 31.6–31.7 °C. On the other hand, Aerogel blankets showed a more moderate yet consistent improvement. At 60 mm, operative temperatures stabilised around 32.2–32.3 °C. Moreover, when the thickness was increased to 70 mm, reductions improved slightly, bringing peaks down to approximately 32.0–32.1 °C.

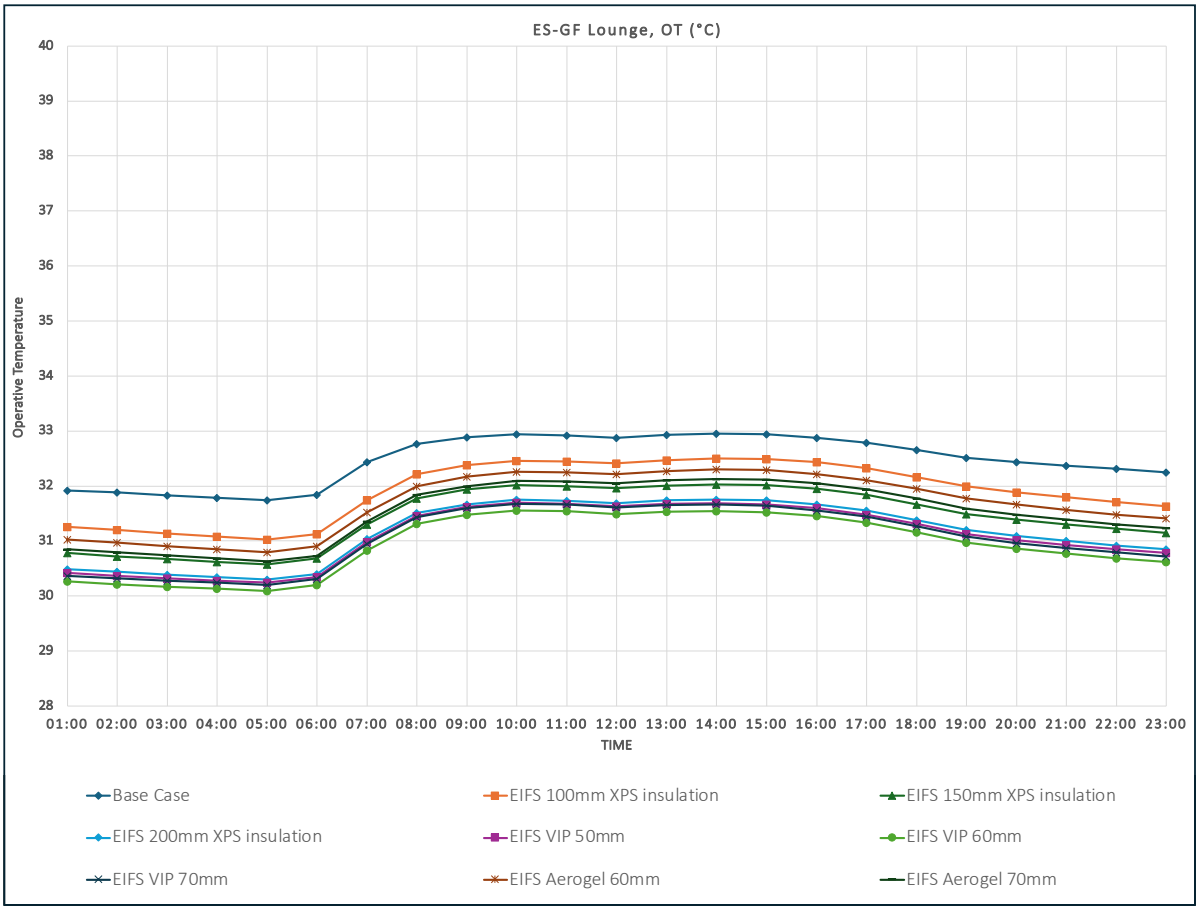


Figure 8.25. Free-Running Simulation Results Comparing Hourly OTs in the ES–GF Lounge: Base Case vs. Improvements Using Exterior Insulation and Finish System (EIFS) with Different Insulation Types and Thicknesses (15 July)

Figure (8.26) illustrates the free-running simulation results of operative temperature for the E–FF Lounge under the base case and after applying various EIFS insulation strategies. The base case recorded consistently high values, ranging from 37.1–38.0 °C, with peaks observed during late morning at 38.04 °C. However, the application of XPS insulation demonstrated a reduction in operative temperatures. With 100 mm thickness, peak values dropped to around 37.6 °C, while 150 mm achieved further reductions to 37.0–37.1 °C. The thickest option, 200 mm XPS, offered the most notable reduction among conventional insulation, lowering peak values to 36.7–36.8 °C.

Vacuum Insulated Panels (VIPs) achieved comparable or superior reductions at much smaller thicknesses. For instance, at 50 mm, peak temperatures dropped to 37.64 °C, while the use of 60 mm and 70 mm panels achieved even greater moderation, with maximum values of approximately 36.62 °C and 36.84 °C, respectively. Meanwhile, Aerogel blankets showed

moderate improvements compared to the base case, though it was less effective than XPS or VIPs. At 60 mm thickness, peak operative temperatures dropped to about 37.42 °C, while increasing the thickness to 70 mm reduced them further to around 37.24 °C.

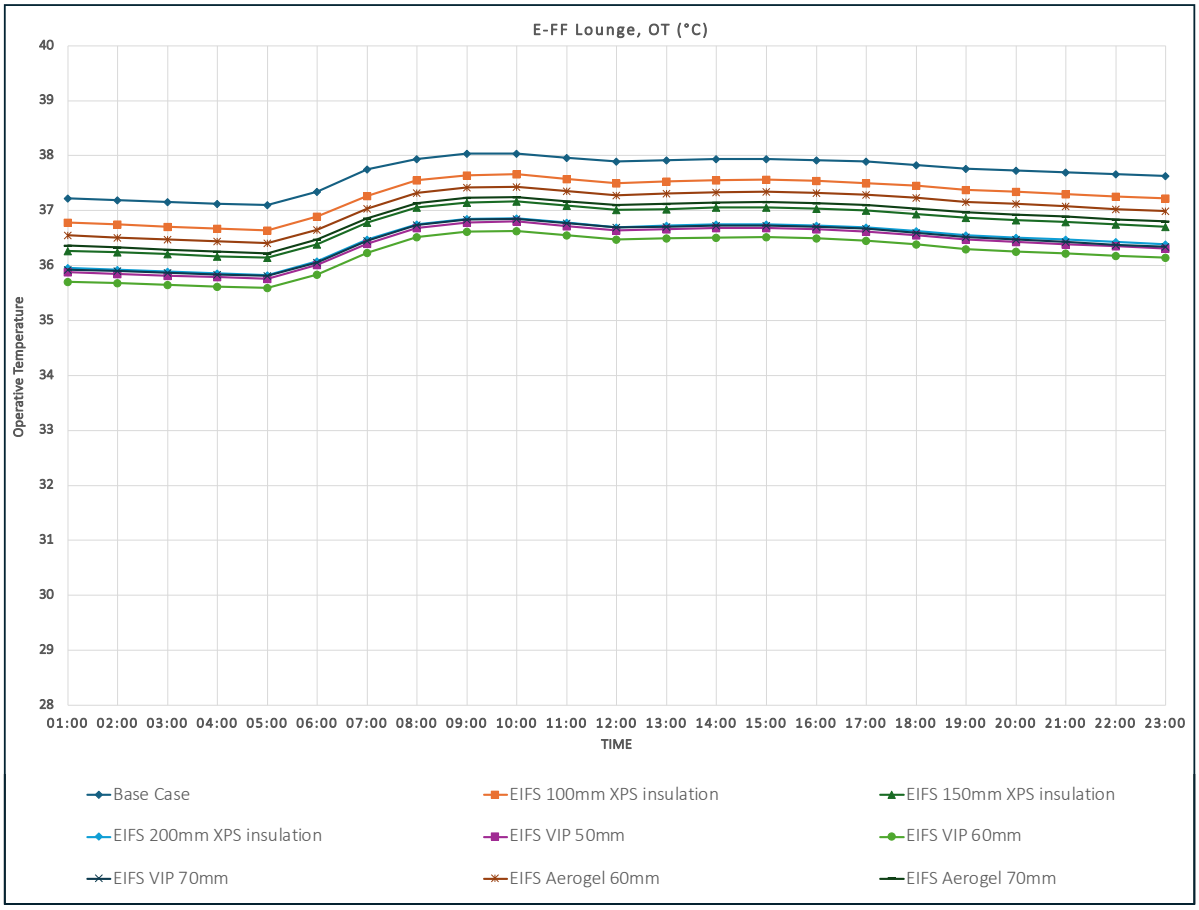


Figure 8.26. Free-Running Simulation Results Comparing Hourly OTs in the E–FF Lounge: Base Case vs. Improvements Using Exterior Insulation and Finish System (EIFS) with Different Insulation Types and Thicknesses (15 July)

Figure (8.27) demonstrates the results of the free-running simulation of relative humidity for the E-GF Dining Zone in the base-case building after employing various thicknesses and types of insulation boards within the building walls. It was obvious that with the application of XPS insulation, RH levels increased moderately across all thicknesses. For instance, at 100 mm, early morning values rose to 15.88%–15.99%, with daytime values stabilising around 15.0%–15.3%, and evening levels reaching approximately 15.58%. Increasing the thickness to 150 mm further improved RH, with peaks reaching 16.43% in the early hours and evening recovery at 16.02%. Furthermore, at 200 mm, the effect was more pronounced, with RH values ranging between 15.63% and 16.70%, clearly indicating the capacity of thicker insulation to enhance indoor humidity retention.

On the other hand, VIPs demonstrated superior performance at reduced thicknesses. For example, at 50 mm, RH levels ranged from 15.70%–16.75%, with evening values peaking at 16.35%. The 60 mm VIP configuration provided slightly higher stability, maintaining values between 15.83% and 16.90%, while the 70 mm VIPs showed a similar but slightly lower performance, ranging between 15.71% and 16.78%. In contrast, Aerogel insulation offered only moderate improvements. At 60 mm thickness, relative humidity increased to about 16.1%, while 70 mm achieved a slight rise to around 16.3%. Although better than the base case, its effect was less significant than that of VIPs or thicker XPS insulation.

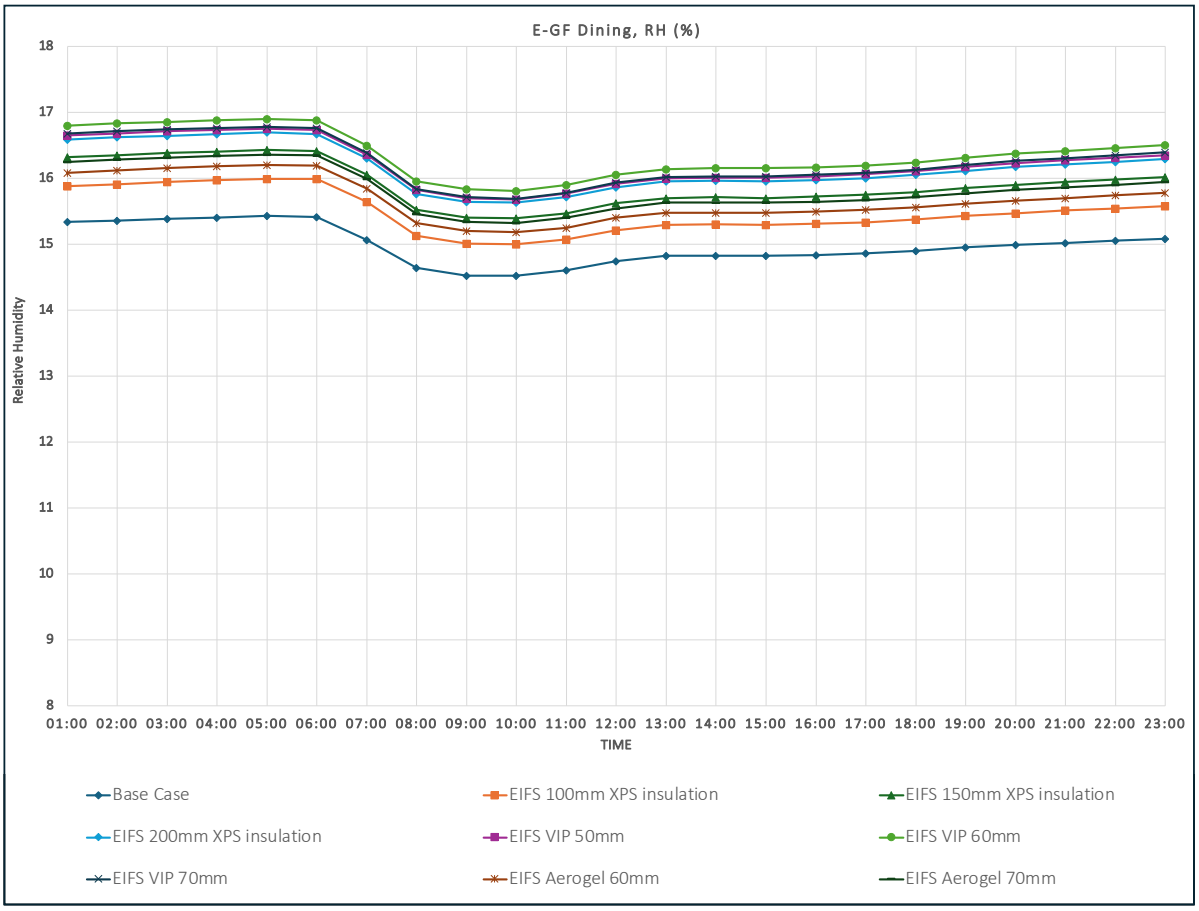


Figure 8.27. Free-Running Simulation Results Comparing Hourly RH in the E-GF Dining Zone: Base Case vs. Improvements Using Exterior Insulation and Finish System (EIFS) with Different Insulation Types and Thicknesses (15 July)

Figure (8.28) illustrates the hourly variation of relative humidity (RH%) in the ES–GF Lounge under different insulation scenarios. In the Base Case, RH values remained the lowest, ranging between approximately 13.7% and 14.8%.

However, when exterior insulation and finish systems (EIFS) were applied, RH consistently increased, reflecting reduced moisture exchange and enhanced indoor humidity stability. For example, the application of XPS insulation demonstrated clear improvements. At 100 mm thickness, RH increased to nearly 15.4%, while 150 mm and 200 mm further elevated peak values to 15.8% and 16.0%, respectively.

Moreover, the use of Vacuum Insulated Panels (VIPs) proved most efficient at relatively low thicknesses. For example, at 50 mm, RH rose to 16.1%, while 60 mm achieved the maximum of about 16.2%. A further increase to 70 mm did not yield additional gains, with RH stabilising at 16.1%. Finally, Aerogel blankets had more moderate effects. At 60 mm, the peak RH reached 15.6%, and at 70 mm it increased slightly further to 15.7%.

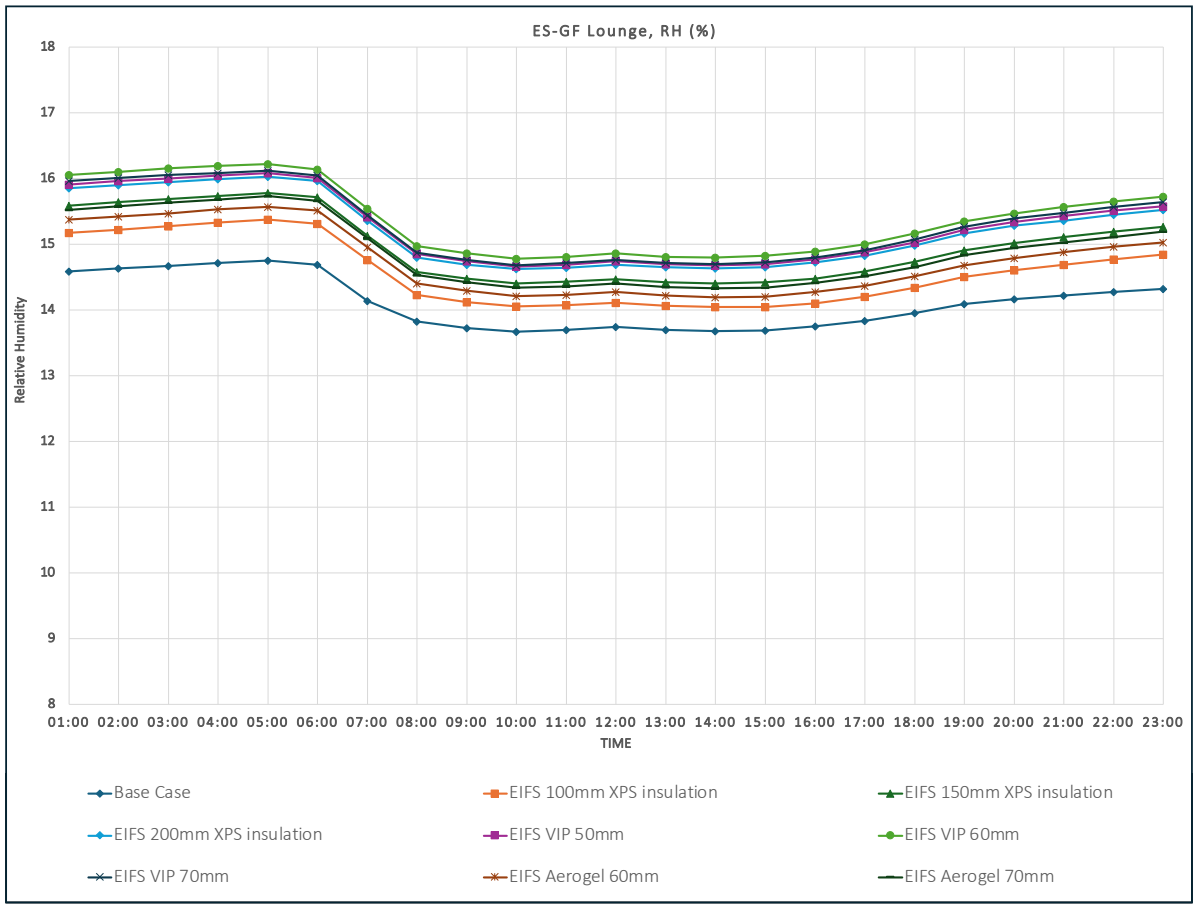


Figure 8.28. Free-Running Simulation Results Comparing Hourly RH in the ES–GF Lounge: Base Case vs. Improvements Using Exterior Insulation and Finish System (EIFS) with Different Insulation Types and Thicknesses (15 July)

Figure (8.29) presents the hourly distribution of relative humidity (RH%) in the E–FF Lounge under various insulation conditions. In the Base Case, the values were the lowest overall, fluctuating between 10.3% and 11.0%, which reflects a persistently dry indoor environment. Once insulation was implemented, RH levels improved gradually. For example, in the case of XPS insulation, a clear upward trend was observed as thickness increased. Specifically, 100 mm insulation elevated peak values to around 11.3%, while 150 mm and 200 mm achieved higher levels of 11.6% and 11.8%, respectively. This demonstrates a direct correlation between insulation thickness and enhanced humidity stability.

On the other hand, for Vacuum Insulated Panels (VIPs), the RH reached about 11.8% at 50 mm, while 60 mm recorded the highest value of approximately 11.92%. However, increasing the thickness to 70 mm did not provide additional benefits, as RH remained close to 11.8%. In contrast, with Aerogel insulation, RH improved to 11.4% at 60 mm and increased slightly further to 11.5% with 70 mm.

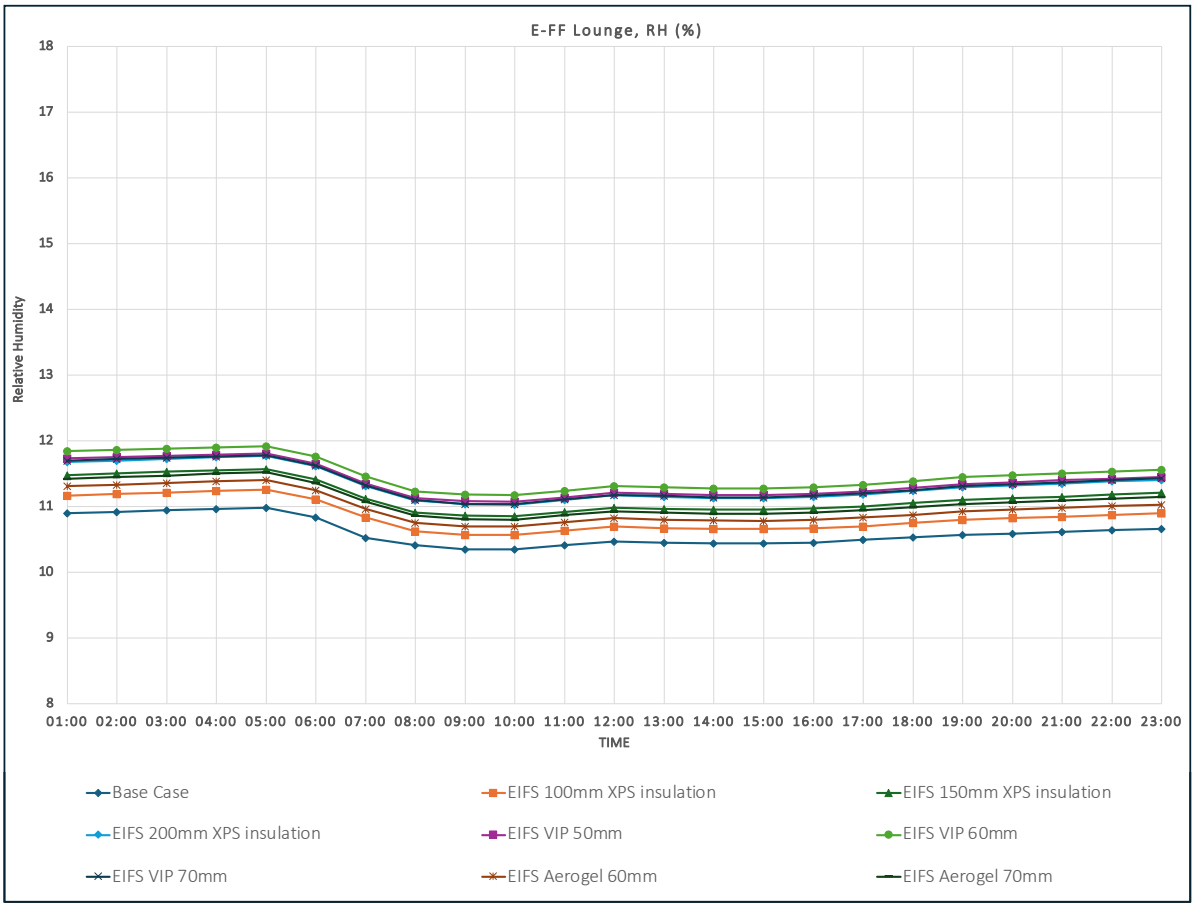


Figure 8.29. Free-Running Simulation Results Comparing Hourly RH in the E–FF Lounge: Base Case vs. Improvements Using Exterior Insulation and Finish System (EIFS) with Different Insulation Types and Thicknesses (15 July)

8.2.3 Energy Efficiency Measures (Roofing by advanced insulation).

It was clear that, despite the proposed green engineering improvements, significant gaps in thermal comfort values remained between zones with surfaces directly exposed to solar radiation and those at on the ground floor. This discrepancy was due to the heat gain from the roof system. Therefore, the following sections examine in depth how upgrading the base case roof insulation with advanced materials influences thermal comfort aspects within the base case zones over 24 hours on the hottest day in Riyadh, Saudi Arabia (15th July). The goal was to provide an optimal solution for surfaces directly exposed to solar radiation.

First, the free-running simulation results of indoor air temperature (IAT) for the E-GF Dining Zone in the base case building, after upgrading the roof insulation with 70 mm–140 mm Vacuum Insulation Panels (VIP) and 70 mm–140 mm multi-Aerogel blankets, are illustrated in Figure (8.30). In the Base Case, where the roof was insulated with XPS, IAT remained high, fluctuating between 30.98°C and 32.05°C. The lowest values occurred in the early morning (around 30.98°C at 05:00), while the peak was reached in the mid-morning at 32.05°C around 09:00–10:00. After this, the temperature gradually declined, reaching 31.38°C by 23:00. This scenario highlights the performance of conventional XPS insulation: although it moderates extremes compared to an uninsulated condition, the space still experiences overheating, with IAT consistently above 31°C for most of the day.

When VIP insulation was applied, the IAT dropped consistently compared to the Base Case. At 01:00, values fell to 30.85°C (70 mm) and 30.75°C (140 mm), compared with 31.08°C in the Base Case. The morning peak was also reduced: instead of 32.05°C, the maximum was 31.81°C (70 mm) and 31.70°C (140 mm) around 09:00–10:00. By the evening, IAT stabilised at 31.15°C (70 mm) and 31.04°C (140 mm), about 0.2–0.3°C lower than the Base Case.

Similarly, Aerogel roof insulation improved thermal performance relative to XPS, though not as strongly as VIP. For example, at 01:00, the IAT was 31.05°C (70 mm) and 30.87°C (140 mm), slightly cooler than the Base Case but consistently higher than the corresponding VIP cases.

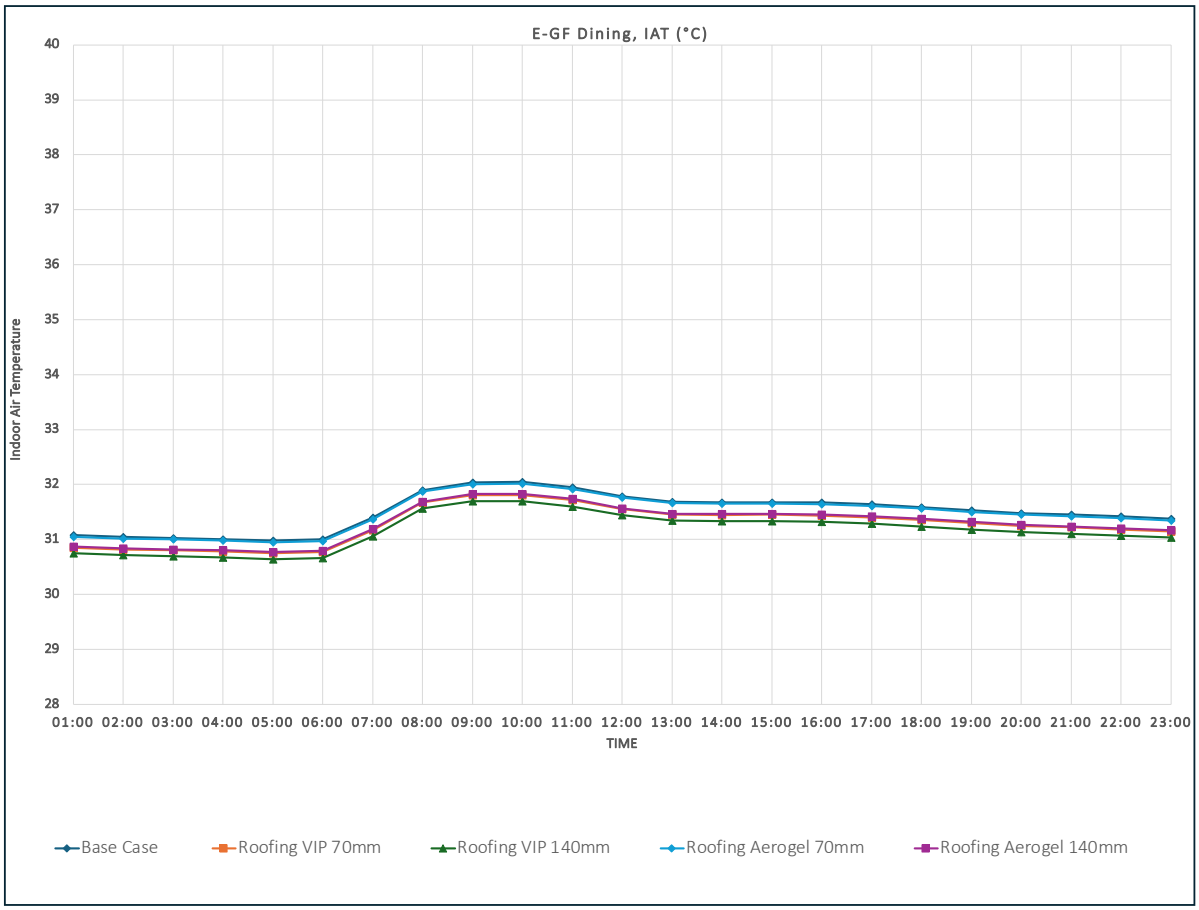


Figure 8.30. Free-Running Simulation Results Comparing Hourly IATs in the E-GF Dining Zone: Base Case vs. Improvements Using Various Energy Efficiency Measures for Roofing by Advanced Insulation (15 July)

Second, the free-running simulation results for indoor air temperature (IAT) in the ES-GF Lounge Zone are shown in Figure (8.31), comparing the performance of the base case roof with upgraded insulation using 70 mm–140 mm Vacuum Insulation Panels (VIPs) and 70 mm–140 mm multi-Aerogel blankets. In the Base Case, where the roof incorporates XPS insulation, IAT values remained higher, ranging between 31.76°C and 33.11°C. The lowest temperature occurred in the early morning at 31.76°C (05:00), while the highest point was observed in the mid-morning, reaching 33.11°C at 10:00.! Thereafter, the temperature gradually declined, finishing the day at approximately 32.29°C (23:00).

The implementation of VIPs in roofing led to an improvement in indoor air temperature conditions for this zone. For example, at 01:00, IAT dropped to 31.76°C with 70 mm VIP and 31.67°C with 140 mm VIP, compared to 31.96°C in the Base Case. Likewise, the daily maximum was reduced from 33.11°C down to 32.91°C (70 mm) and 32.81°C (140 mm) at around 10:00. By the evening, temperatures stabilised at 32.09°C (70 mm) and 31.99°C (140 mm),

confirming that VIPs provide a consistent reduction of 0.2–0.3°C throughout the day, with thicker panels performing best. Similarly, Aerogel-based insulation also contributed to lowering indoor air temperatures, though its impact was less obvious than VIPs. For instance, at 01:00, IAT values were 31.93°C (70 mm) and 31.78°C (140 mm), both slightly cooler than the Base Case. Moreover, at the daily peak, Aerogel reduced indoor air temperatures from 33.11°C down to 33.09°C (70 mm) and 32.93°C (140 mm) around 10:00. By the evening, IAT settled at 32.27°C (70 mm) and 32.11°C (140 mm), showing modest reductions compared with XPS but consistently higher values than the VIP scenarios.

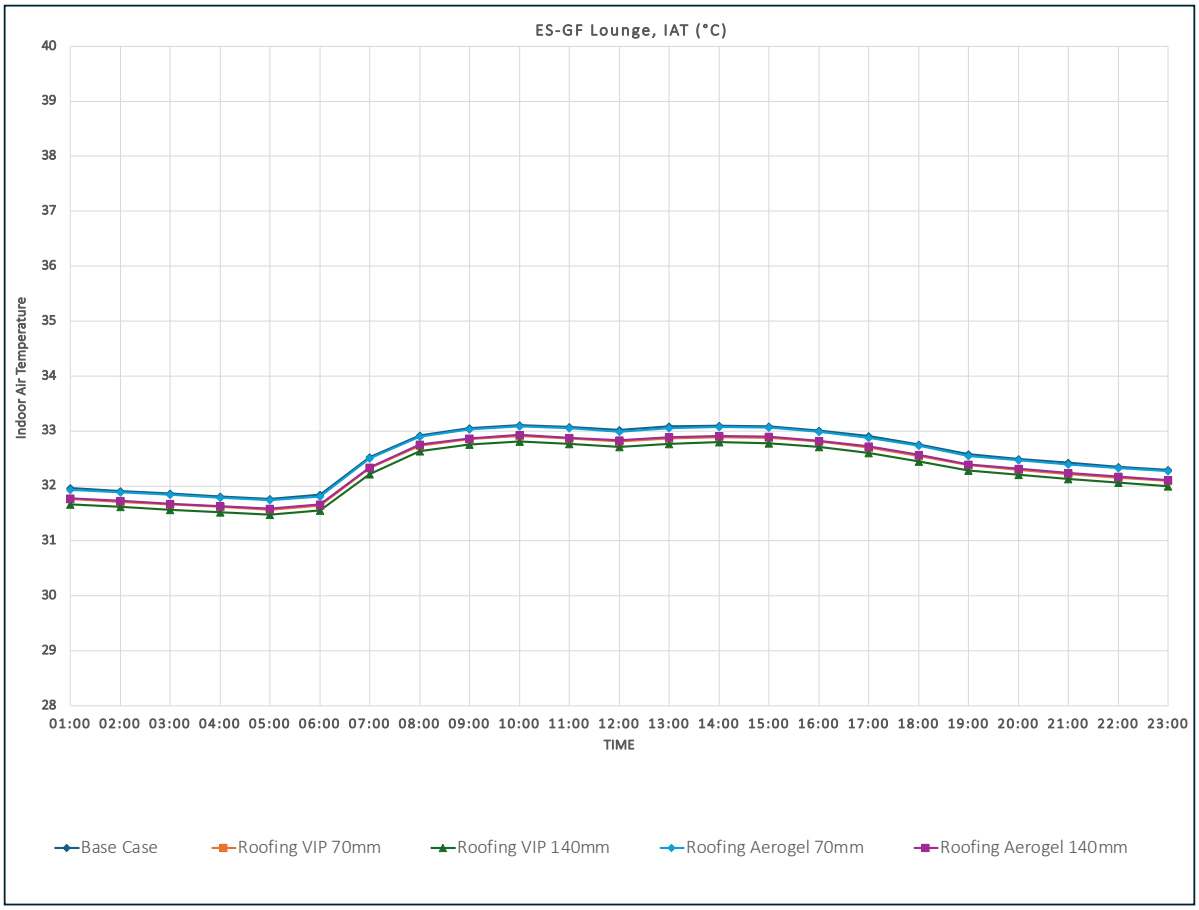


Figure 8.31. Free-Running Simulation Results Comparing Hourly IATs in the ES–GF Lounge: Base Case vs. Improvements Using Various Energy Efficiency Measures for Roofing by Advanced Insulation (15 July)

Third, Figure (8.32) demonstrates the free-running simulation results for indoor air temperature (IAT) in the E-FF Lounge Zone, comparing the base case roof with upgraded alternatives using 70 mm–140 mm Vacuum Insulation Panels (VIPs) and 70 mm–140 mm multi-Aerogel blankets. Similar to other scenarios for the Base Case, the E-FF Lounge Zone recorded

higher temperatures, with IATs fluctuating between 37.08°C and 38.18°C. The coolest condition appeared in the early morning at 37.08°C (05:00), while the hottest point occurred mid-morning at 38.18°C (09:00). After this peak, the indoor temperature showed a gradual decline, closing the day at 37.63°C (23:00). This trend underscores how strongly the upper-floor zone is affected by roof heat gains, with IAT persistently exceeding 37°C, even in the cooler evening hours.

However, the implementation of Vacuum Insulated Panels (VIPs) in roofing delivered a clear improvement in indoor thermal performance. For example, at 01:00, the indoor air temperature (IAT) decreased to 36.33 °C with 70 mm VIPs and 35.90 °C with 140 mm VIPs, compared to 37.22 °C in the Base Case. Peak values were also reduced considerably: instead of 38.18 °C, the maximum fell to 37.27 °C (70 mm) and 36.83 °C (140 mm) at 09:00. By late evening, the zone maintained cooler conditions of 36.76 °C (70 mm) and 36.33 °C (140 mm). Moreover, the application of Aerogel insulation also contributed to lowering IAT, though its effect was more moderate compared to VIPs. At 01:00, the values were 37.11 °C (70 mm) and 36.41 °C (140 mm), indicating small but noticeable reductions relative to the Base Case. During the morning peak, temperatures reached 38.06 °C (70 mm) and 37.35 °C (140 mm)—an improvement, but still above the levels achieved with VIP insulation. By 23:00, evening temperatures declined to 37.52 °C (70 mm) and 36.83 °C (140 mm). Therefore, the 140 mm VIP option proved to be the most effective, lowering indoor air temperatures by more than 1 °C throughout the day.

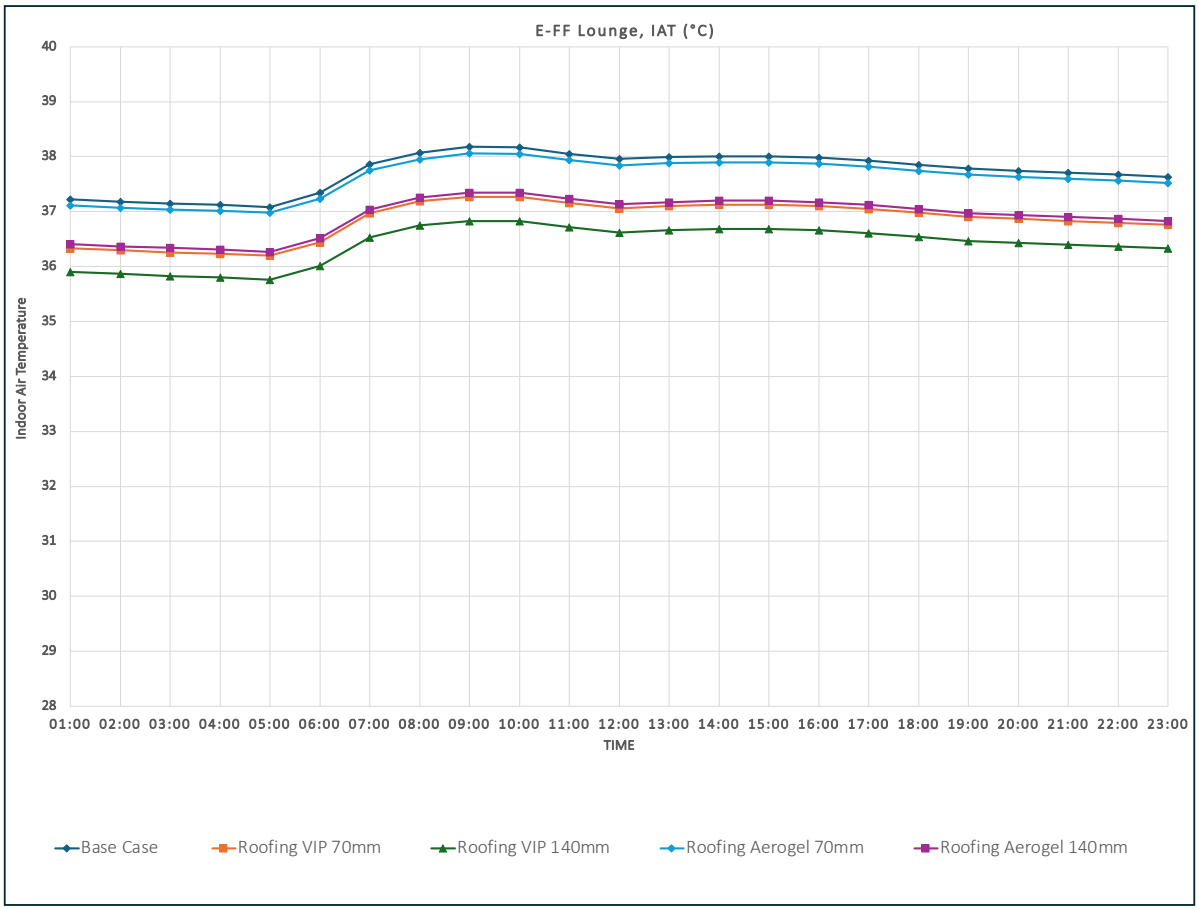


Figure 8.32. Free-Running Simulation Results Comparing Hourly IATs in the E–FF Lounge: Base Case vs. Improvements Using Various Energy Efficiency Measures for Roofing by Advanced Insulation (15 July)

The free-running simulation results for radiant temperature (RT) in the E-GF Dining Zone are shown in Figure (8.33), comparing the base case roof construction with upgraded systems using 70 mm–140 mm Vacuum Insulation Panels (VIPs) and 70 mm–140 mm multi-Aerogel blankets. In the Base Case, with XPS insulation, RTs remained relatively steady but at elevated levels, fluctuating between 30.94°C and 31.36°C. The lowest value occurred at 05:00 (30.94°C), while the highest was reached in the late morning at 10:00 (31.36°C).

On the other hand, after improving the base case roof insulation with 70 mm and 140 mm VIPs, the radiant temperatures exhibited a similar pattern of reductions to the indoor air temperatures (IATs) throughout the day. At 01:00, RT decreased to 30.78°C (70 mm) and 30.67°C (140 mm), compared with 31.01°C in the Base Case. The late-morning peak was also suppressed, dropping from 31.36°C down to 31.12°C (70 mm) and 31.01°C (140 mm) at 10:00. By evening, RT stabilised at 31.05°C (70 mm) and 30.94°C (140 mm), showing reductions of approximately 0.2–0.4°C across the day, with the thicker VIP providing the greatest improvement. Similarly, the implementation of Aerogel insulation also lowered RT, though its

impact was less pronounced than that of VIP. At 01:00, values were 30.98°C (70 mm) and 30.80°C (140 mm), slightly cooler than the Base Case. At 10:00, the peak was reduced to 31.33°C (70 mm) and 31.14°C (140 mm), compared with 31.36°C in the Base Case.

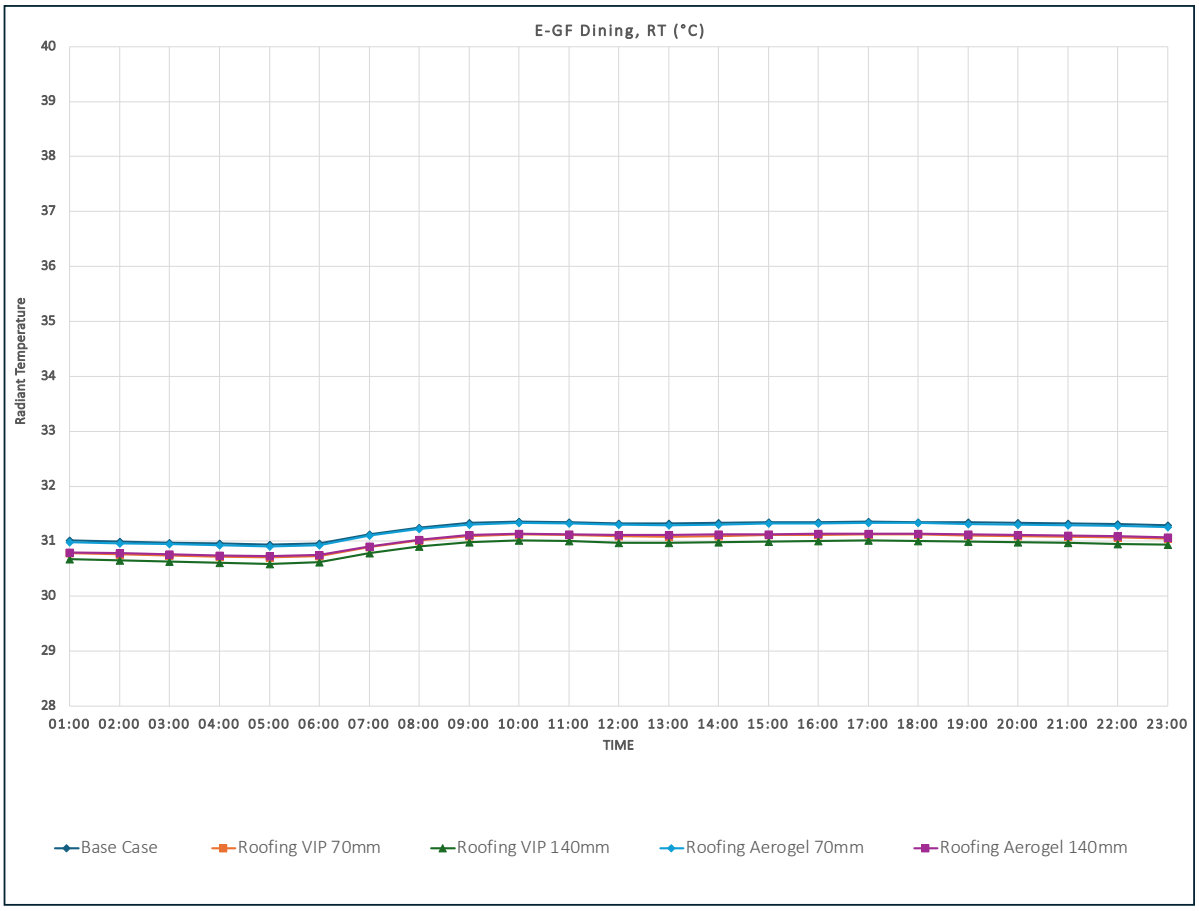


Figure 8.33. Free-Running Simulation Results Comparing Hourly RTs in the E-GF Dining Zone: Base Case vs. Improvements Using Various Energy Efficiency Measures for Roofing by Advanced Insulation (15 July)

Figure (8.34) presents the simulation outcomes for radiant temperature (RT) in the ES-GF Lounge Zone, comparing the baseline condition with enhanced roofing systems using 70 mm and 140 mm Vacuum Insulation Panels (VIPs) and Aerogel blankets of equivalent thicknesses. Under the Base Case, which incorporates XPS insulation, RTs remained relatively high, fluctuating between 31.72°C and 32.80°C. The lowest value was recorded at 05:00 (31.72°C), while the peak occurred at 14:00 (32.80°C).

Nevertheless, with the implementation of VIP insulation, the radiant temperature (RT) showed a steady reduction compared to the base case. For example, at 01:00, the RT dropped to 31.69°C with 70 mm VIP and 31.59°C with 140 mm VIP, while the Base Case recorded

31.89°C. Around midday, the peak temperature of 32.77°C in the Base Case decreased to 32.57°C (70 mm) and 32.47°C (140 mm). By late evening, the RTs settled at 32.01°C (70 mm) and 31.91°C (140 mm). These reductions are directly linked to the superior thermal resistance of VIPs, with thicker layers providing stronger protection against heat penetration. Similarly, the use of Aerogel insulation also lowered RTs, but the impact was smaller than that of VIPs. At 01:00, values reached 31.87°C (70 mm) and 31.71°C (140 mm), both slightly below the Base Case. During midday, the maximum RTs were 32.75°C (70 mm) and 32.58°C (140 mm), while by late evening they dropped to 32.19°C (70 mm) and 32.03°C (140 mm). However, these results suggest that Aerogel insulation can provide cooling benefits, particularly with the thickest blanket, although it remains less effective than VIPs in reducing radiant heat loads in the ES-GF Lounge Zone.

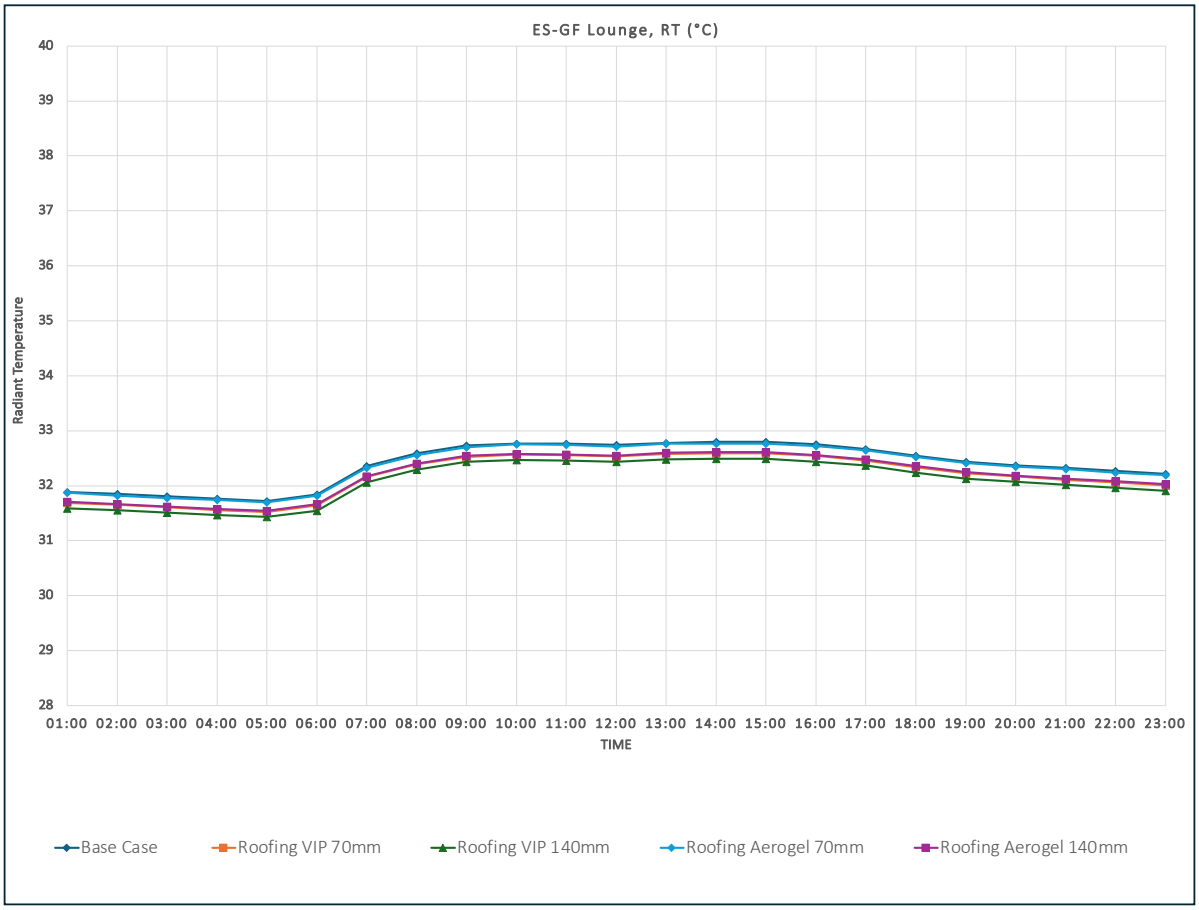


Figure 8.34. Free-Running Simulation Results Comparing Hourly RTs in the ES–GF Lounge: Base Case vs. Improvements Using Various Energy Efficiency Measures for Roofing by Advanced Insulation (15 July)

Figure (8.35) shows the radiant temperature (RT) profile for the E-FF Lounge, which is located directly under the roof and therefore experiences the strongest thermal effect from

external solar radiation compared to other zones. Hence, in the Base Case with XPS insulation, the RT values remained consistently high. The minimum temperature was 37.12 °C at 05:00, while the maximum reached 37.92 °C at 10:00. Even during the late evening, the RT was still 37.63 °C at 23:00, indicating that the base roof construction allowed significant heat transfer and limited thermal protection.

However, with the implementation of Vacuum Insulation Panels (VIPs), a clear reduction in RT was observed. At 70 mm thickness, the radiant temperature dropped to 36.33 °C at 01:00, with a peak of 37.02 °C, which is about 0.9 °C lower than the Base Case. Increasing the thickness to 140 mm enhanced the performance further, with a minimum of 35.89 °C and a maximum of 36.58 °C. By the end of the day, the RT declined to 36.30 °C, confirming the superior thermal resistance of VIPs and their effectiveness in reducing indoor heat stress. On the other hand, the use of Aerogel blankets for roofing also contributed to improvements, though to a lesser extent compared with VIPs. At 70 mm thickness, the RT was 37.12 °C at 01:00, peaking at 37.81 °C. With 140 mm Aerogel, the early value was 36.41 °C, and the highest reached only 37.10 °C, with the day closing at 36.82 °C.

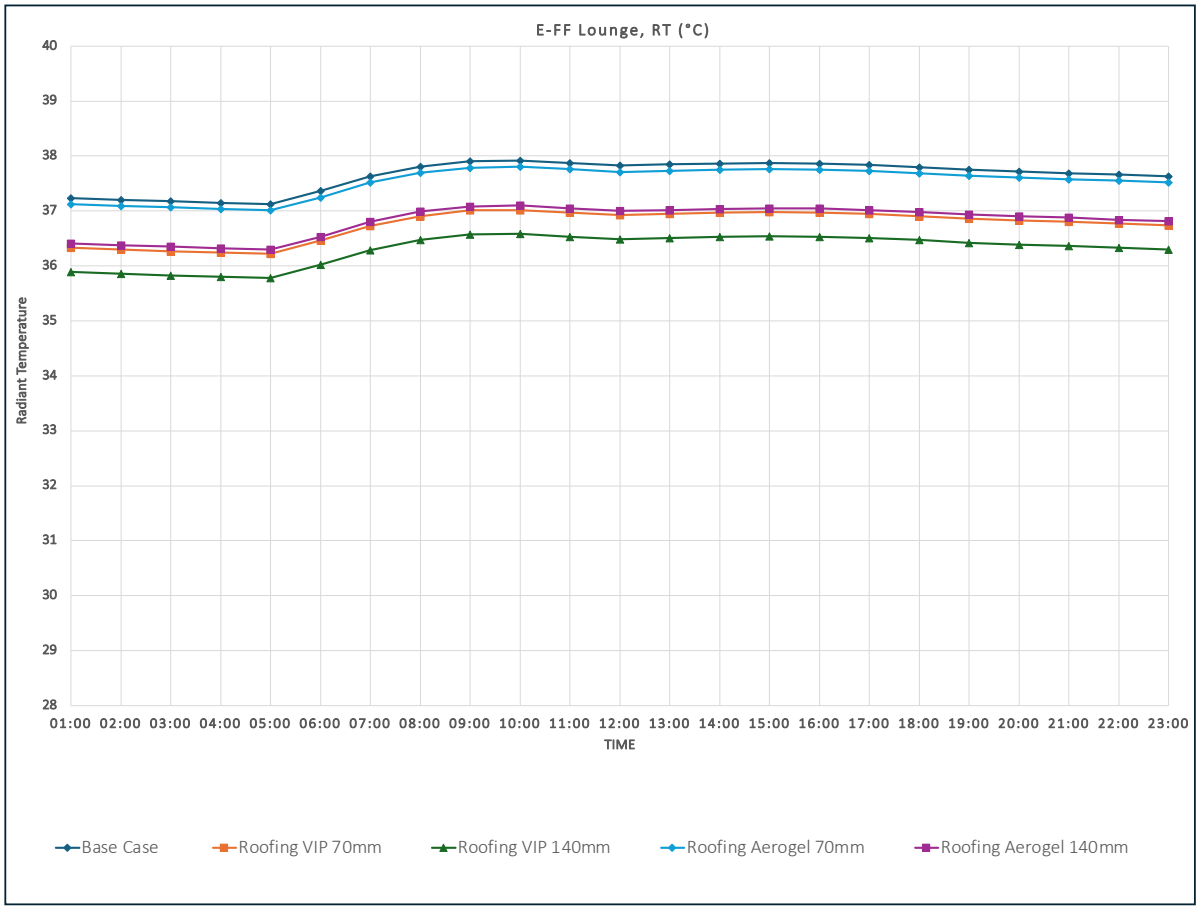


Figure 8.35. Free-Running Simulation Results Comparing Hourly RTs in the E–FF Lounge: Base Case vs. Improvements Using Various Energy Efficiency Measures for Roofing by Advanced Insulation (15 July)

Figure (8.36) demonstrates the results of the free-running simulation of operative temperatures (OTs) for the E-GF Dining zone in the base-case building after upgrading the roof insulation with 70 mm and 140 mm Vacuum Insulation Panels, as well as 70 mm and 140 mm multi-Aerogel blankets. In the base scenario, the operative temperature remained relatively high and stable throughout the day. The lowest reading around 30.96 °C occurred in the early morning at 05:00, while the peak of nearly 31.70 °C was recorded mid-morning at 10:00. Despite a gradual evening decline, the operative temperature reached 31.34 °C at 23:00, confirming that the base-case insulation provided limited thermal resistance.

When the roof was improved with 70 mm of Vacuum Insulation Panels, the OTs showed a clear reduction. The minimum operative temperature decreased to 30.73 °C during the early morning, and the maximum temperature rose only to 31.47 °C around 10:00. Compared with the base case, this represented a reduction of around 0.23 °C. Increasing the VIP thickness to 140 mm further enhanced the performance. Values ranged from 30.62 °C in the morning to a maximum of 31.35 °C, and by the end of the day the temperature dropped to 30.99 °C. This indicated a total reduction of approximately 0.35 °C compared with the original base case, highlighting the superior thermal efficiency of VIPs.

By contrast, Aerogel blankets achieved minor reductions in operative temperature. With 70 mm of Aerogel, OTs fluctuated between 30.93 °C in the morning and 31.67 °C at midday, showing only marginal improvement over the base condition. Increasing the thickness to 140 mm provided slightly better results, with values ranging from 30.75 °C in the early morning to a maximum of 31.49 °C at 10:00, and ending the day at 31.12 °C. Although these results confirm the insulating effect of Aerogel blankets, their impact was less significant than VIPs, mainly due to higher thermal conductivity, which was consistent with earlier observations.

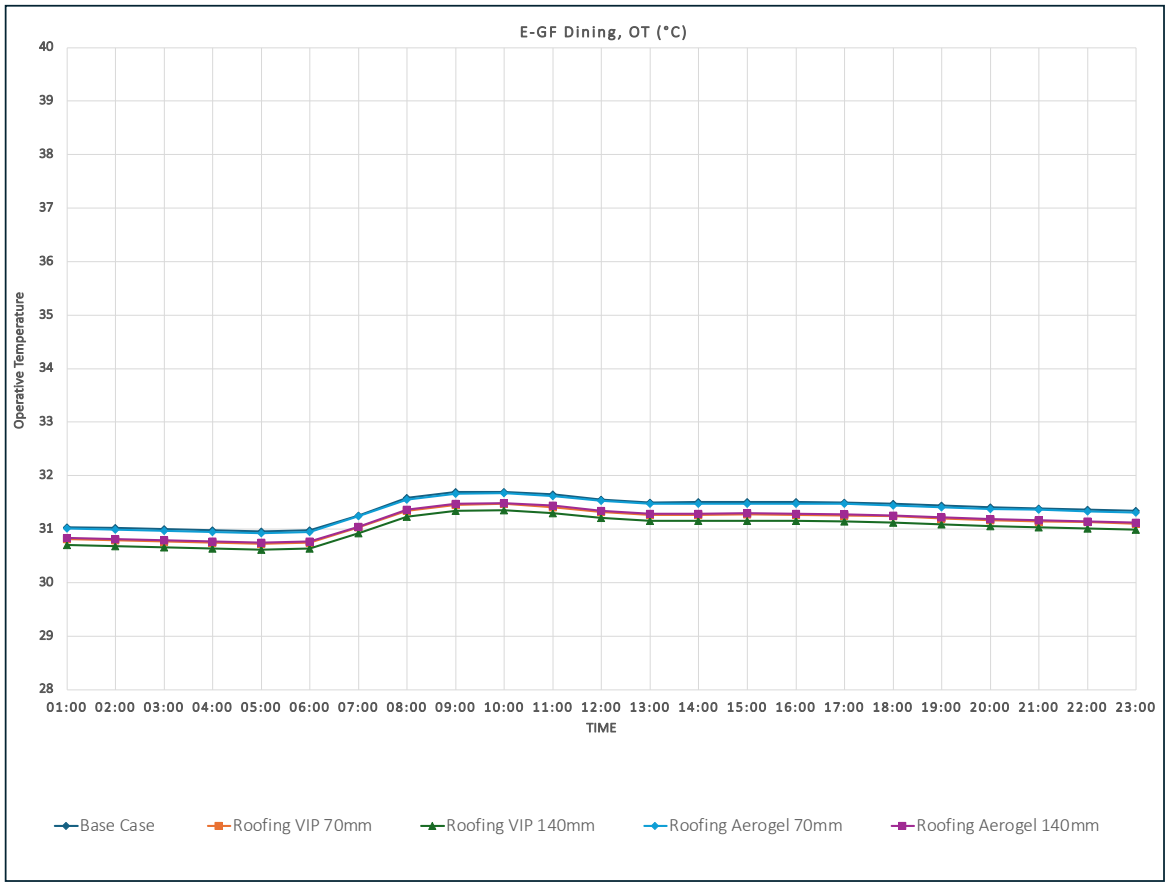


Figure 8.36. Free-Running Simulation Results Comparing Hourly OTs in the E-GF Dining Zone: Base Case vs. Improvements Using Various Energy Efficiency Measures for Roofing by Advanced Insulation (15 July)

Figure (8.37) illustrates the hourly variation of operative temperature of the ES-GF Lounge zone under different roof insulation scenarios. In the base case with existing XPS insulation, the operative temperature remained relatively high and steady across the 24-hour cycle. The lowest value was observed at 05:00 with 31.74 °C, while the peak reached 32.95 °C around 14:00. In the evening, the values showed a slight decline, yet by 23:00 the operative temperature was still 32.25 °C, indicating the limited effectiveness of the base roof insulation in reducing heat transfer.

However, once insulation was upgraded, a clear reduction in operative temperatures was observed. For instance, the application of 70 mm VIP roofing lowered the midday peak to about 32.74 °C, representing a modest improvement over the Base Case. Increasing the thickness to 140 mm provided further reductions, with the peak temperature decreasing to nearly 32.64 °C. This demonstrates the efficiency of VIPs, particularly at higher thicknesses. In comparison, aerogel roofing achieved slightly less pronounced improvements. At 70 mm thickness, the peak temperature remained high at 32.92 °C, which is nearly identical to the Base Case. However,

doubling the thickness to 140 mm resulted in a more noticeable effect, with peak OT reduced to approximately 32.76 °C.

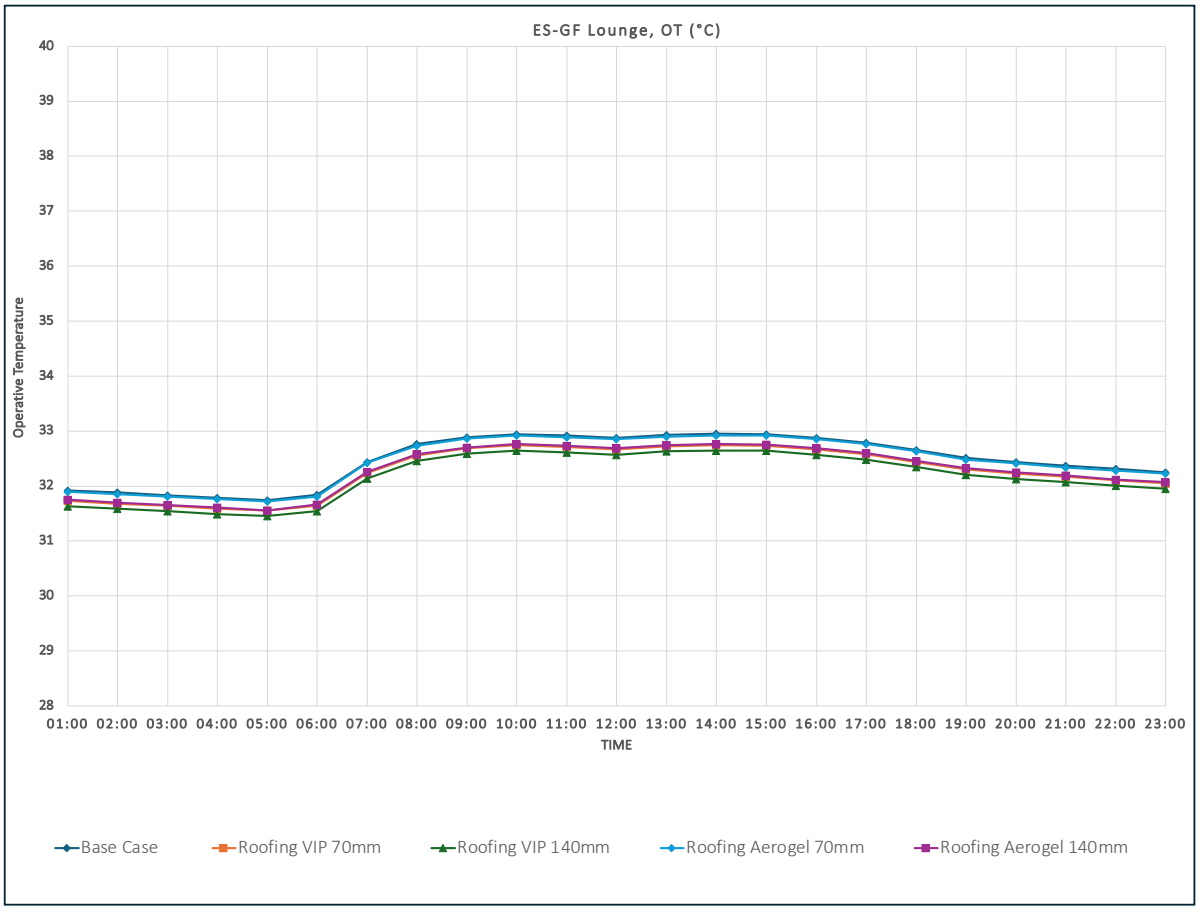


Figure 8.37. Free-Running Simulation Results Comparing Hourly OTs in the ES–GF Lounge: Base Case vs. Improvements Using Various Energy Efficiency Measures for Roofing by Advanced Insulation (15 July)

Figure (8.38) presents the hourly variation of operative temperature (OT) in the E–FF Lounge under different insulation scenarios. In the Base Case, OT remained the highest among all configurations, with values fluctuating between 37.1 °C (at 05:00) and a peak of 38.04 °C (observed at 09:00–10:00). This clearly indicates a significant overheating tendency in the absence of insulation.

When the roof was upgraded with 70 mm vacuum insulation panels (VIPs), reductions in operative temperature were observed. The early morning minimum decreased to 36.21 °C, while the peak temperature dropped to 37.14 °C around 09:00–10:00. By 23:00, the temperature stabilised at 36.75 °C, representing a reduction of nearly 0.9 °C compared with the base case. With 140 mm VIPs, the effect was even more obvious, where the operative temperature ranged from 35.77 °C at 05:00 to a maximum of 36.70 °C at 09:00–10:00. At the end of the day, the value was further reduced to 36.31 °C, offering more than 1.3 °C lower

conditions than the base case, confirming the high efficiency of thicker VIP insulation in mitigating heat transfer through the roof. However, the use of aerogel insulation followed a similar trend but with smaller improvements. With 70 mm aerogel, operative temperatures ranged from 36.99 °C at 05:00 to a peak of 37.93 °C at 09:00–10:00, providing only marginal reductions of about 0.1 °C compared with the base case. Increasing the thickness to 140 mm yielded better performance, with operative temperatures ranging between 36.29 °C and 37.22 °C across the day. By 23:00, the value reached 36.82 °C, which is about 0.8 °C lower than the base case but still higher than the performance of 70 mm VIP insulation.

In summary, the E-FF Lounge analysis shows that operative temperature is highly sensitive to roof insulation since the solar exposure is more intense. Vacuum insulation panels, particularly at 140 mm thickness, provided the greatest thermal comfort improvement, while aerogel insulation offered moderate benefits. This suggests that selecting advanced high-performance materials such as VIPs can reduce overheating in upper zones and improve indoor comfort in hot climates.

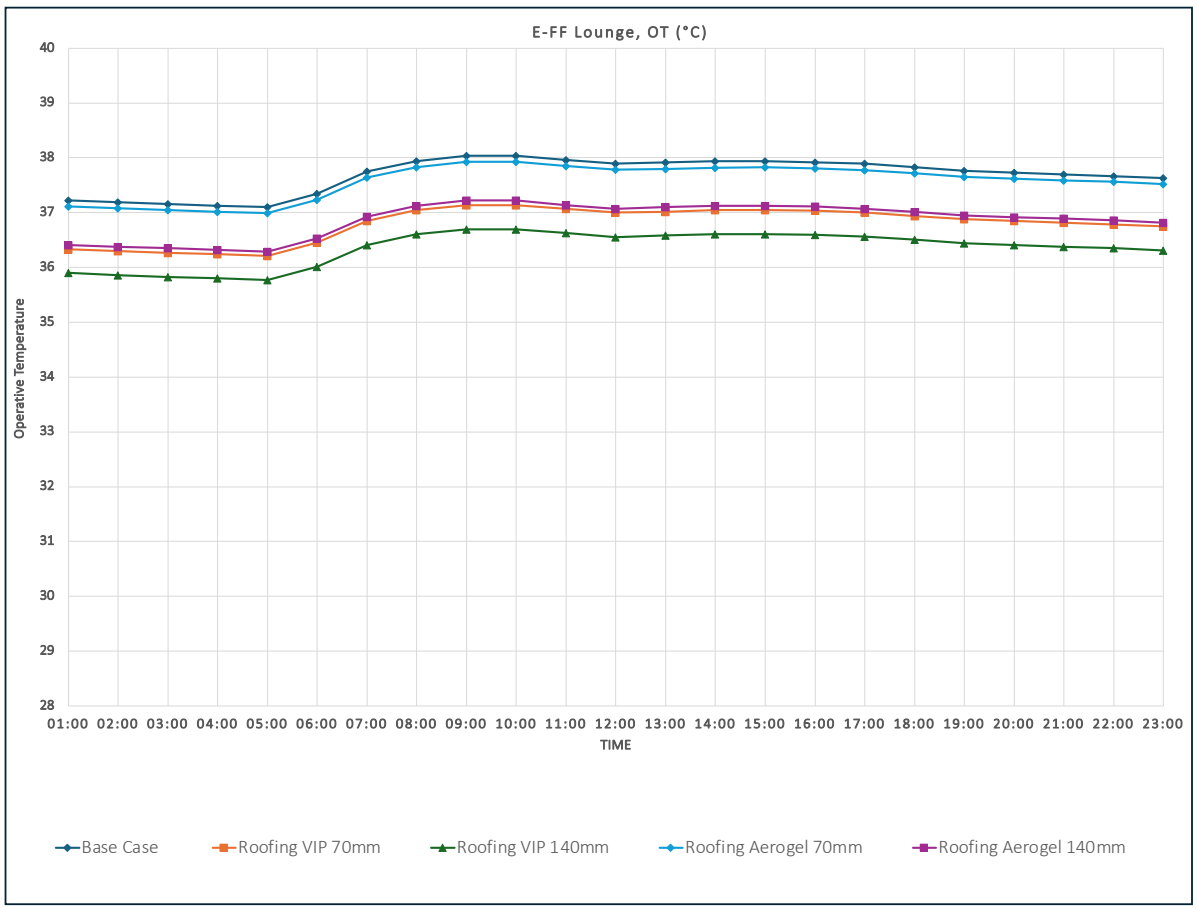


Figure 8.38. Free-Running Simulation Results Comparing Hourly OTs in the E–FF Lounge: Base Case vs. Improvements Using Various Energy Efficiency Measures for Roofing by Advanced Insulation (15 July)

Figure (8.39) illustrates the results of the free-running simulation of relative humidity for E-GF Dining zone in the base-case building, following roof insulation upgrades using 70 mm–140 mm Vacuum Insulation Panels (VIPs), as well as 70 mm–140 mm multi-Aerogel blankets. In the base case, RH values ranged from 15.43% in the early morning (05:00) to a minimum of 14.52% around mid-morning (09:00–10:00), before gradually recovering to 15.08% by 23:00. This daily cycle reflects the typical inverse relationship between rising indoor temperatures and declining relative humidity during daytime hours.

With the installation of 70 mm VIPs, RH levels increased slightly across the 24-hour cycle, peaking at 15.63% at 05:00, dropping to 14.71% by late morning, and ending the day higher than the base case at 15.27%. The thicker 140 mm VIP layer provided greater stabilisation, achieving a maximum of 15.72% at 05:00, limiting the midday decline to 14.81%, and concluding with an evening value of 15.37%. By contrast, aerogel blankets exhibited a more moderate effect. The 70 mm aerogel blanket recorded a maximum of 15.45% at 05:00, a minimum of 14.54% during late morning, and a closing value of 15.10%. Increasing the thickness to 140 mm raised the morning peak to 15.61%, with a minimum of 14.70% and an evening recovery to 15.26%.

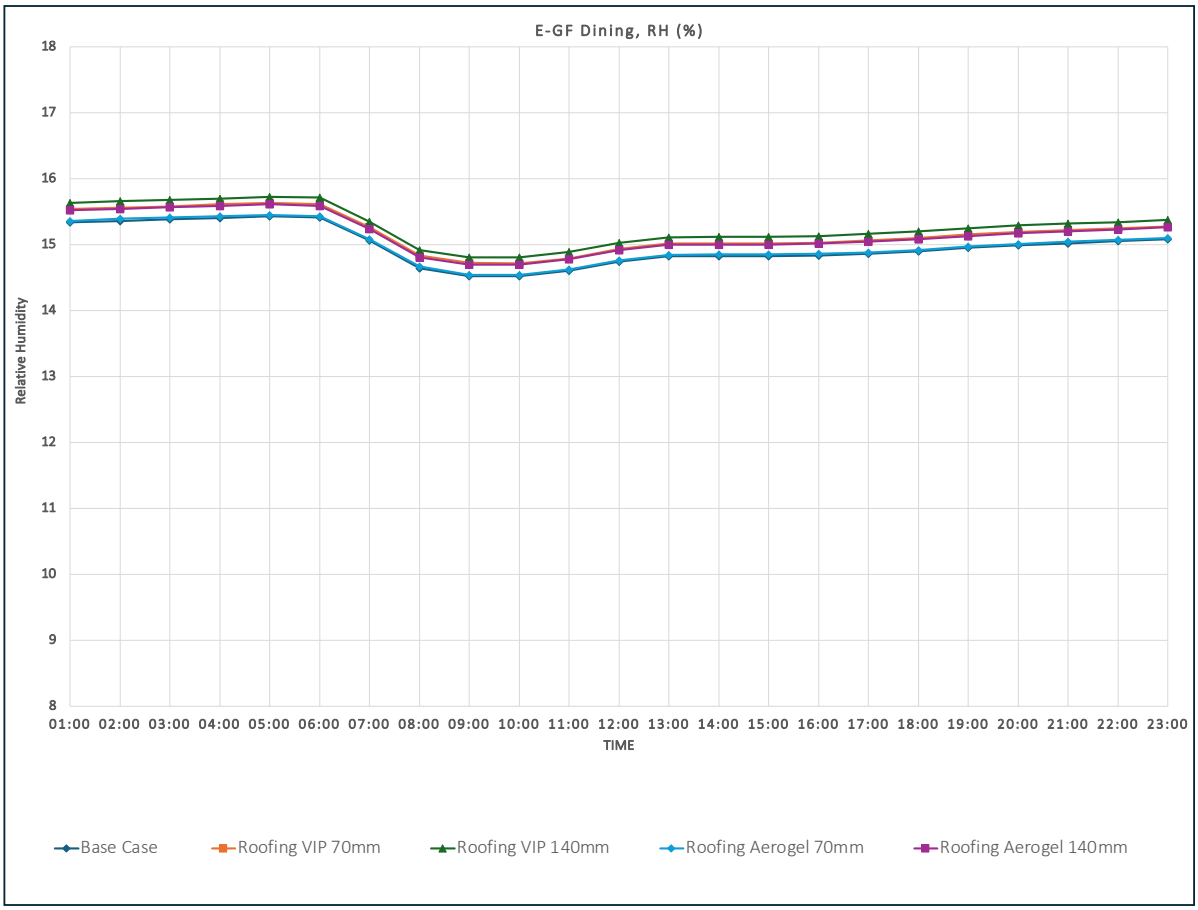


Figure 8.39. Free-Running Simulation Results Comparing Hourly RH in the E-GF Dining Zone: Base Case vs. Improvements Using Various Energy Efficiency Measures for Roofing by Advanced Insulation (15 July)

Figure (8.40) shows the outcomes of the free-running simulation of relative humidity in the ES-GF Lounge zone of the base-case building, after applying roof insulation upgrades with 70 mm and 140 mm Vacuum Insulation Panels (VIPs), as well as 70 mm and 140 mm multi-aerogel blankets. In the base case, relative humidity gradually increased during the early morning, starting at 14.59% at 01:00 and peaking at 14.75% at 05:00. This was followed by a noticeable decline, reaching its lowest point of 13.67% at 10:00. Around midday, the values stabilised within a narrow range of 13.7%–13.9%, before rising again in the evening to finish at 14.32% by 23:00.

However, when 70 mm of VIP insulation was applied, relative humidity levels became slightly higher than in the base case. The early-morning maximum was 14.92% at 05:00, with the lowest point at 13.8% at 10:00. By the end of the day, values recovered to 14.48%, indicating an overall improvement. Increasing the thickness to 140 mm further enhanced performance: relative humidity peaked at 15.00% at 05:00, dropped to 13.91% at 10:00, and closed the day at 14.56%. This configuration demonstrated the most consistent and stable performance among all insulation strategies. By comparison, the aerogel blankets yielded more moderate results. With 70 mm of aerogel, relative humidity peaked at 14.77% at 05:00, dropped to 13.69% around 10:00, and ended the day at 14.34%. Increasing the thickness to 140 mm recorded slightly higher values, with a morning peak of 14.90%, a late-morning minimum of 13.82%, and an evening value of 14.47%.

In the E-FF Lounge zone of the base-case building, relative humidity was simulated under free-running conditions; the results, shown in Figure (8.41), reflect the impact of roof insulation upgrades using both 70 mm and 140 mm Vacuum Insulation Panels and multi-Aerogel blankets.

It was obvious that in the base case, relative humidity showed a modest upward trend during the early morning, beginning at 10.9% at 01:00 and reaching its maximum of 10.98% by 05:00. This was followed by a gradual decline, with the lowest value of 10.35% occurring between 09:00 and 10:00. After midday, the trend became relatively stable, fluctuating within a narrow range around 10.4–10.6%, before ending at 10.66% at 23:00.

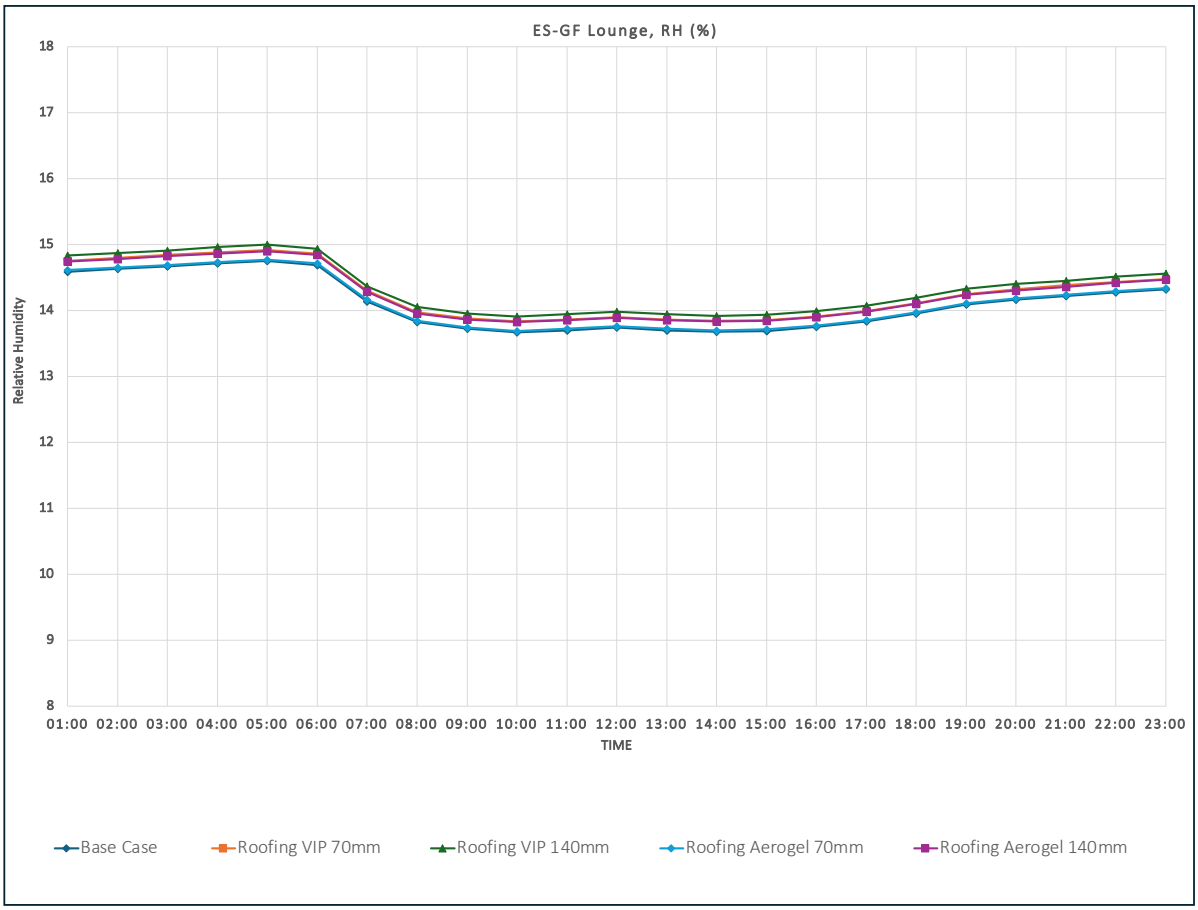


Figure 8.40. Free-Running Simulation Results Comparing Hourly RH in the ES–GF Lounge: Base Case vs. Improvements Using Various Energy Efficiency Measures for Roofing by Advanced Insulation (15 July)

However, implementation of 70 mm VIP insulation produced a marginal increase in relative humidity relative to the base case, with the maximum recorded at 11.52% (05:00), the minimum at 10.87% (09:00–10:00), and the final daily value at 11.18%. The 140 mm VIP configuration, however, yielded superior and more stable results, reaching a peak of 11.80% at 05:00, a minimum of 11.13% mid-morning, and closing at 11.44%. This option demonstrated the most consistent enhancement, maintaining values above both the base case and the 70 mm alternative throughout the day. On the other hand, the aerogel blankets registered moderate improvements. With 70 mm thickness, relative humidity peaked at 11.04% at 05:00, decreased to 10.41% at 09:00, and ended the day at 10.72%. The 140 mm aerogel insulation showed slightly better results, with an early-morning maximum of 11.48% at 05:00, a minimum of 10.82% at 09:00–10:00, and a closing value of 11.13% at 23:00.

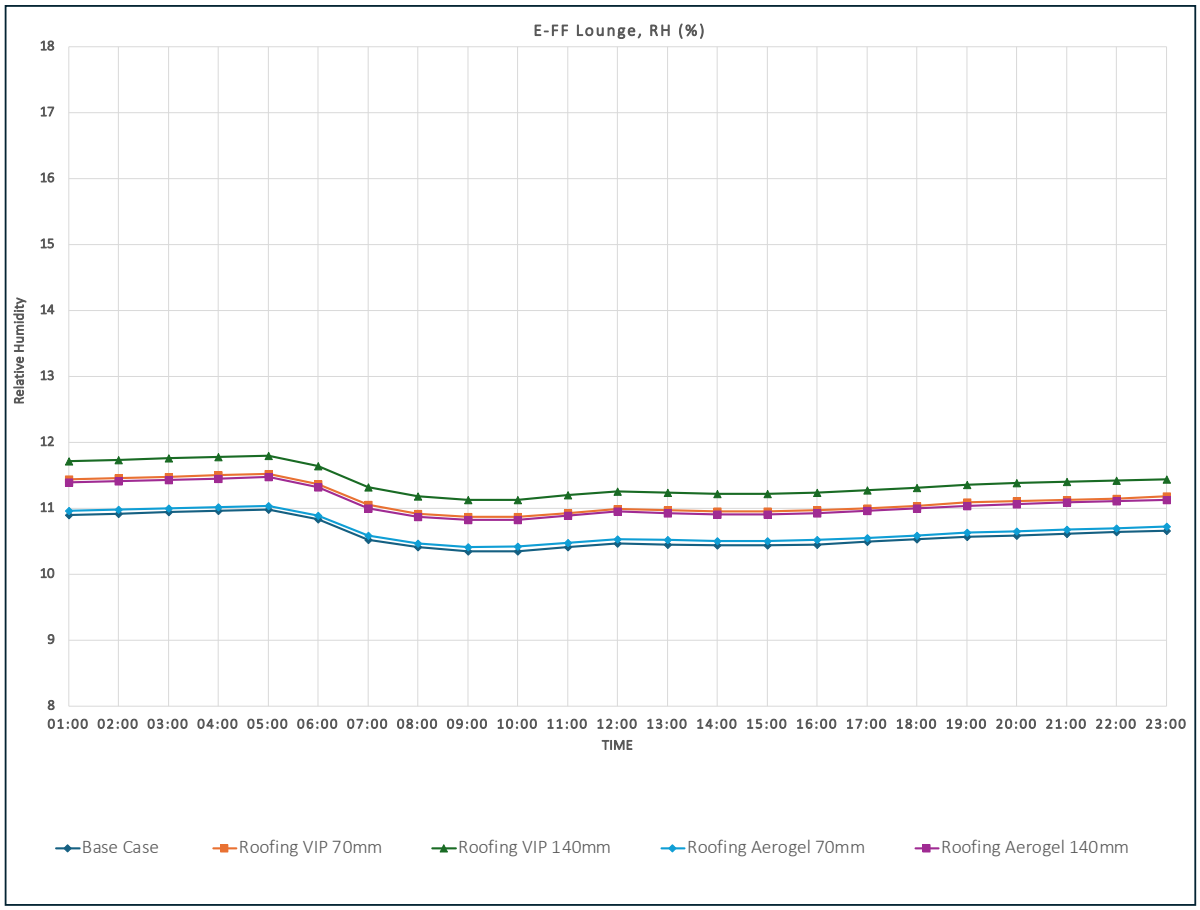


Figure 8.41. Free-Running Simulation Results Comparing Hourly RH in the E–FF Lounge: Base Case vs. Improvements Using Various Energy Efficiency Measures for Roofing by Advanced Insulation (15 July)

In summary, the analysis of roof insulation strategies shows that upgrading from the base case (XPS) to VIP and Aerogel significantly improves indoor thermal and moisture performance. For Indoor Air Temperature (IAT), Radiant Temperature (RT), and Operative Temperature (OT), both materials reduce overheating during peak hours, with the effect being stronger on first-floor zones due to direct roof exposure, while ground-floor zones experience smaller but still noticeable improvements. Relative Humidity (RH) increases slightly in all insulated cases, stabilising indoor conditions and reducing fluctuations throughout the day. Among the tested options, 140 mm VIP consistently delivers the best performance, showing lower peak temperatures and more stable RH levels, while Aerogel provides moderate improvements but with slightly less stability. These results highlight that roof insulation not only reduces thermal stress but also enhances comfort by balancing indoor temperature and humidity, with VIP outperforming Aerogel in overall efficiency.

8.2.4 Energy Efficiency Measures (Vacuum Insulated Glass Product series).

Figure (8.42) below shows a detailed thermal performance analysis from the free-running simulation of the E-GF Dining Zone in the base case after applying various glazing configurations of vacuum-insulated glass. It demonstrates significant variations in their effectiveness in regulating indoor air temperatures (IATs). The figure highlights how different glazing types influence heat transfer and overall thermal stability within the space. In the base case, IAT gradually decreased during the early morning, starting at 31.08 °C at 01:00 and reaching its lowest point of 30.98 °C at 05:00. Thereafter, a sharp increase was observed, with temperatures peaking at 32.05 °C at 09:00–10:00. From midday onwards, values stabilised within the narrow range of 31.7–31.9 °C, before declining gradually in the evening to close at 31.38 °C by 23:00.

When the 4T+0.3V+4TL (S1.16) glazing was applied, indoor air temperatures were slightly lower than in the base case. The early-morning minimum was 30.82 °C at 05:00, rising steadily to a peak of 31.85 °C at 09:00–10:00. By 23:00, the temperature had fallen to 31.19 °C, reflecting a modest improvement. In contrast, the 4T+0.3V+4TL (S1.10) series provided a stronger performance, with a minimum of 30.32 °C at 05:00, a morning peak of 31.34 °C at 09:00–10:00, and an evening value of 30.70 °C.

The 4T+0.3V+4TL (D80) series demonstrated further enhancement. Indoor air temperature started at 29.48 °C at 01:00, fell slightly to 29.40 °C at 05:00, and then peaked at 30.39 °C at 09:00–10:00. By the end of the day, values settled at 29.76 °C. The most effective configuration was the 4T+0.3V+5TL (XDTB0159) series, which achieved the lowest overall temperatures. The minimum of 28.83 °C was recorded at 05:00, the maximum of 29.80 °C at 09:00–10:00, and the closing value of 29.18 °C at 23:00. This represents nearly a 2 °C reduction compared with the base case.

The Argon-filled variant (4T+12Ar+4TL (S1.10)+0.3V+4T) showed performance almost identical to the S1.16 option, with early-morning and evening values of 30.82 °C and 31.19 °C, respectively, and a peak of 31.85 °C at 09:00–10:00. However, the laminated Argon-filled configuration (3T+0.76P+3T+12Ar+4TL (S1.10)+0.3V+4T) exhibited more stable behaviour. Temperatures began at 30.23 °C at 01:00, reached a low of 30.14 °C at 05:00, and peaked at 31.16 °C at 09:00–10:00, before closing the day at 30.51 °C.

On average, the 4T+0.3V+5TL (XDTB0159) glazing demonstrated the highest performance, reducing indoor air temperature by 2.18 °C compared with the base case. The 4T+0.3V+4TL (D80) series followed, with a mean reduction of 1.63 °C. More moderate improvements were observed with the 3T+0.76P+3T+12Ar+4TL (S1.10)+0.3V+4T and 4T+0.3V+4TL (S1.10) options, yielding reductions of 0.79 °C and 0.69 °C, respectively. By contrast, both the S1.16 series and the Argon-filled 4T+12Ar+4TL (S1.10)+0.3V+4T offered only marginal reductions of 0.19 °C, showing performance very close to the base case. These results confirm that advanced multilayer glazing systems, particularly XDTB0159, provide the greatest benefit in enhancing thermal comfort and mitigating heat gains in the Dining zone.

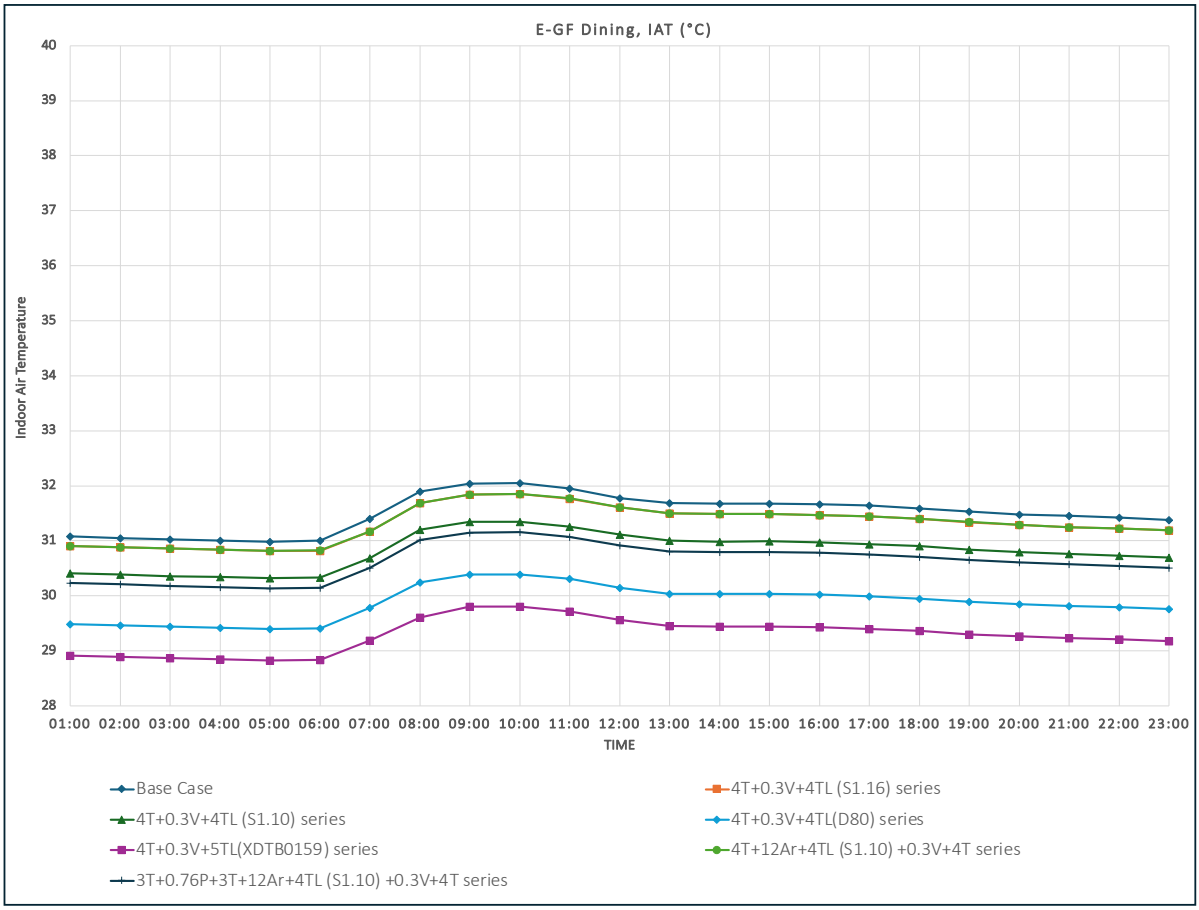


Figure 8.42. Free-Running Simulation Results Comparing Hourly IATs in the E-GF Dining Zone: Base Case vs. Improvements Using Various Energy-Efficiency Measures for Glazing with Vacuum Insulated Glass Product Series (15 July)

Following the assessment of the E-GF Dining zone, the analysis now focuses on the ES-GF Lounge to evaluate the impact of glazing improvements under free-running conditions. Figure (8.43) illustrates the IAT profiles for the base case and the alternative glazing systems.

For example, in the base case, temperatures decreased from 31.96 °C at 01:00 to 31.76 °C at 05:00, before rising sharply to a peak of 33.11 °C at 10:00. Thereafter, values stabilised around 33.0 °C until midday, before gradually declining to 32.29 °C at 23:00.

The 4T+0.3V+4TL (S1.16) glazing made only slight improvements, with an early-morning minimum of 31.33 °C, a peak of 32.30 °C, and a final value of 31.76 °C. The 4T+0.3V+4TL (S1.10) option performed better, lowering the morning minimum to 30.82 °C and closing the day at 31.24 °C. More substantial benefits were observed with the 4T+0.3V+4TL (D80), which kept indoor air temperatures between 29.70 °C and 30.48 °C, and especially with the 4T+0.3V+5TL (XDTB0159), which maintained the lowest range of 29.03–29.74 °C, representing up to 3.7 °C lower than the base case peak. The Argon-filled variants offered only limited gains. The 4T+12Ar+4TL (S1.10)+0.3V+4T mirrored the S1.16 case, with a peak of 32.36 °C, while the laminated Argon-filled glazing achieved more stable conditions, peaking at 31.46 °C and ending the day at 30.99 °C.

The daily averages show a clear difference in performance between the glazing options. The XDTB0159 system recorded the best result, lowering indoor air temperature by 3.07 °C compared with the base case. The D80 glazing followed with a reduction of 2.36 °C. In contrast, the S1.16 and Argon-filled S1.10 options reduced temperatures by only about 0.65 °C, showing little impact.! Overall, the results highlight the stronger effect of advanced multilayer glazing, particularly XDTB0159, while simpler systems offered only minor benefits.

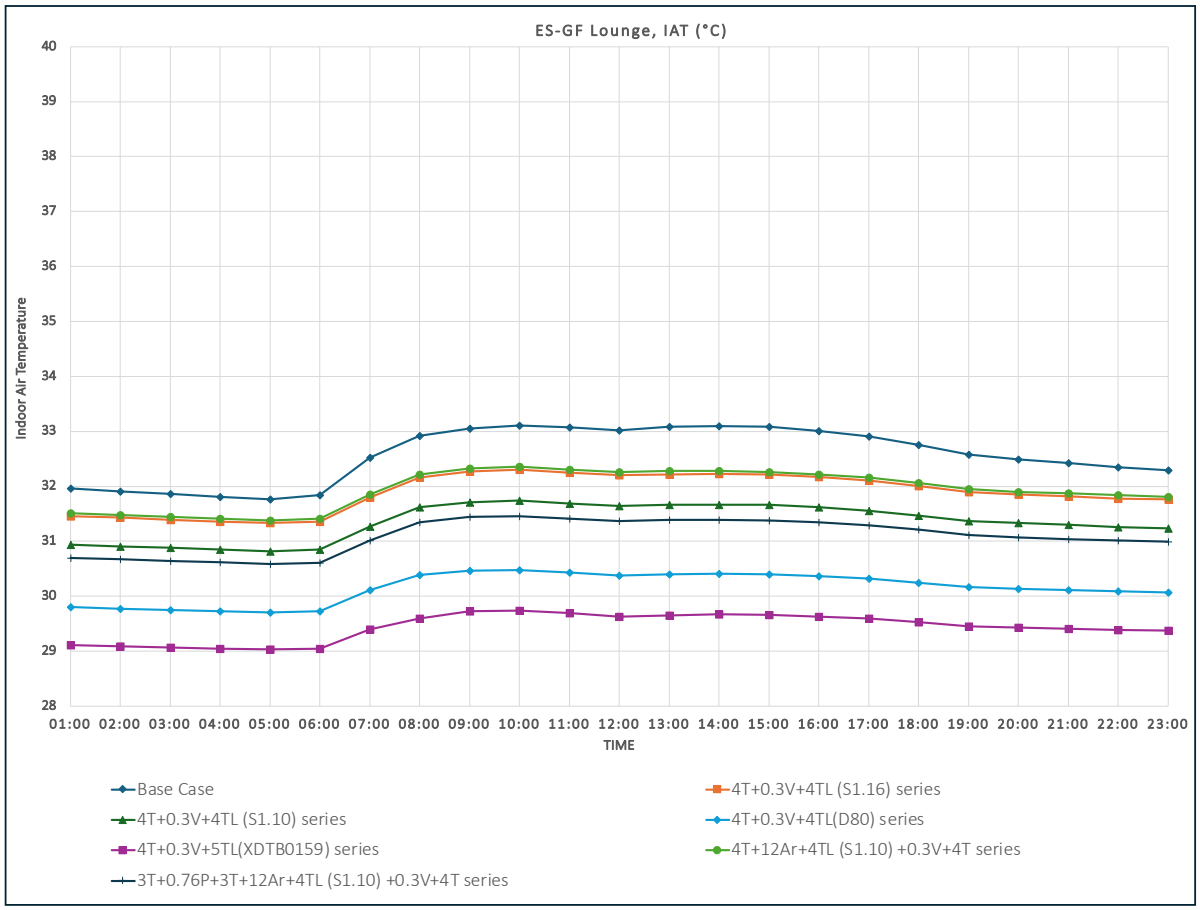


Figure 8.43. Free-Running Simulation Results Comparing Hourly IATs in the ES–GF Lounge: Base Case vs. Improvements Using Various Energy-Efficiency Measures for Glazing with Vacuum Insulated Glass Product Series (15 July)

Moving to the first floor, the E-FF Lounge was evaluated under free-running conditions to assess the influence of glazing upgrades. Therefore, Figure (8.44) illustrates the IAT variations for the base case and alternative configurations of glazing. In the base case, temperatures declined marginally in the early morning from 37.22 °C at 01:00 to 37.08 °C at 05:00, before rising sharply to a maximum of 38.18 °C at 09:00. From late morning onwards, values stabilised close to 38.0 °C before gradually falling to 37.63 °C by 23:00.

The 4T+0.3V+4TL (S1.16) series and the 4T+12Ar+4TL (S1.10)+0.3V+4T series showed limited effectiveness, with daily averages of 38.03 °C (around 0.30 °C higher than the base case) and peak values of 38.35 °C at 10:00. In contrast, the 4T+0.3V+4TL (S1.10) series provided a moderate improvement, reducing the daily average to 37.23 °C, with a minimum of 36.78 °C at 05:00 and a closing value of 37.25 °C. However, greater benefits were observed with the 4T+0.3V+4TL (D80) series, which maintained IAT between 35.30 °C and 35.97 °C, averaging 35.69 °C across the day. , Moreover, the most effective configuration was the 4T+0.3V+5TL

(XDTB0159) series, which consistently produced the lowest values, ranging from 34.36 °C at 05:00 to 35.01 °C at 09:00, with an average of 34.83 °C (equivalent to a 2.90 °C reduction compared with the base case). The 3T+0.76P+3T+12Ar+4TL (S1.10)+0.3V+4T series provided intermediate results, averaging 36.80 °C with a daily peak of 37.23 °C.

Overall, the results confirm that advanced multi-layer glazing systems, especially the 4T+0.3V+5TL (XDTB0159) and 4T+0.3V+4TL (D80) series, significantly reduce overheating on the first floor. In contrast, simpler configurations like the 4T+0.3V+4TL (S1.16) and the Argon-filled 4T+12Ar+4TL (S1.10)+0.3V+4T not only fail to improve performance but also increase thermal stress compared to the base case.

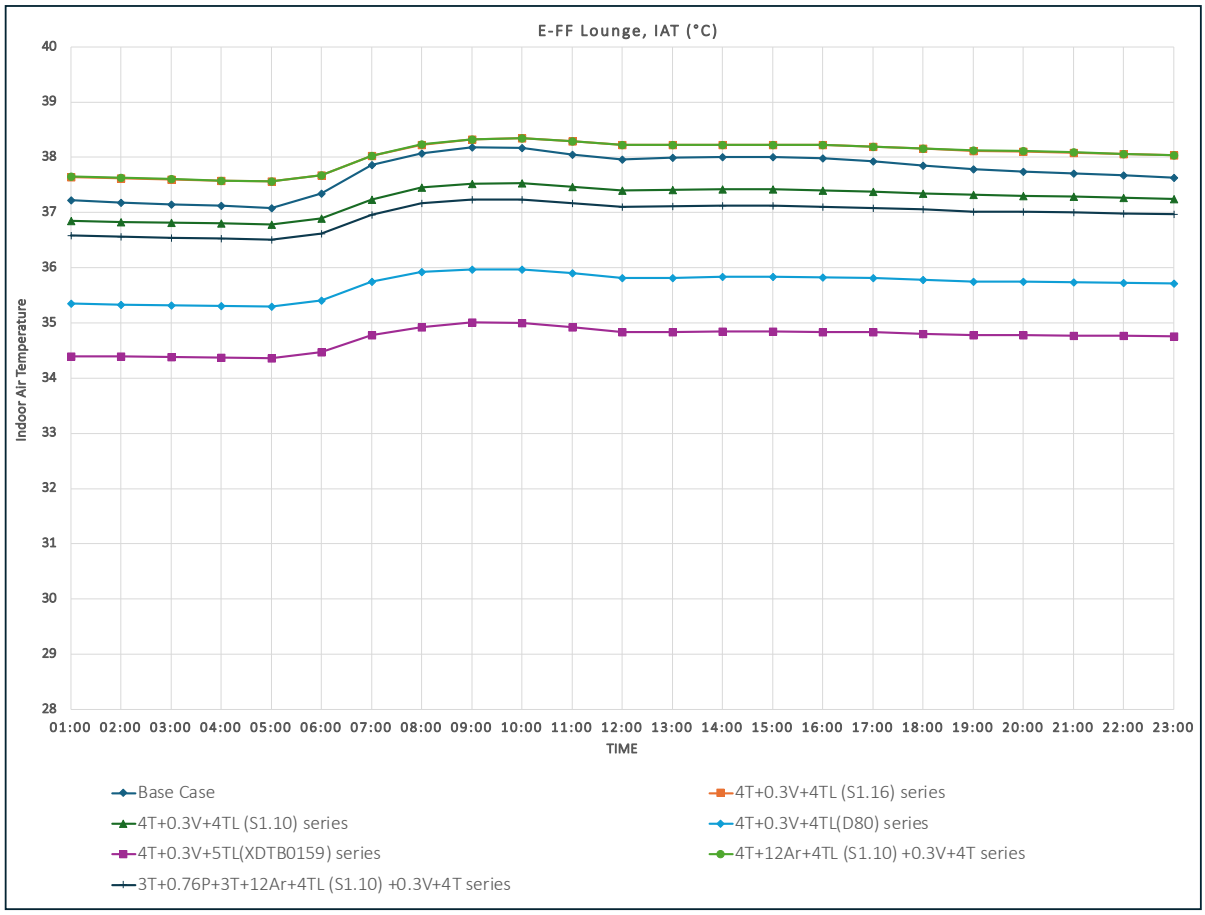


Figure 8.44. Free-Running Simulation Results Comparing Hourly IATs in the the E–FF Lounge: Base Case vs. Improvements Using Various Energy-Efficiency Measures for Glazing with Vacuum Insulated Glass Product Series (15 July)

With respect to radiant temperatures (RTs), Figure (8.45) illustrates the outcomes of the free-running simulation in the E-GF Dining zone on 15 July, comparing the base case with upgraded cases using vacuum-insulated glass (VIG) systems. The base case demonstrated consistently high temperatures, with a slight decline in the early morning hours, from 31.01 °C

at 01:00 to 30.94 °C at 05:00. Values then increased gradually, peaking at 31.36 °C around 10:00, and remained nearly stable in the afternoon before closing the day at 31.29 °C. The daily mean RT for the base case was 31.23 °C.

Upgrading the base case glazing with vacuum-insulated glass, such as the 4T+0.3V+4TL (S1.16) and 4T+0.3V+4TL (S1.10), resulted in modest reductions. For example, the former achieved a daily mean of 31.05 °C, showing little improvement. A slightly better outcome was recorded with the latter glazing, which reduced the average to 30.55 °C—a 0.68 °C reduction compared with the base case. The laminated Argon-filled glazing (3T+0.76P+3T+12Ar+4TL (S1.10)+0.3V+4T) performed more effectively, consistently maintaining values between 30.1 °C and 30.5 °C, with a daily mean of 30.31 °C. However, the greatest reductions were achieved with more advanced vacuum-insulated glass. For example, the 4T+0.3V+4TL (D80) lowered the daily average RT to 29.59 °C, while the 4T+0.3V+5TL (XDTB0159) delivered the best performance, achieving a mean of 28.99 °C. This represents a decrease of 2.24 °C compared with the base case.

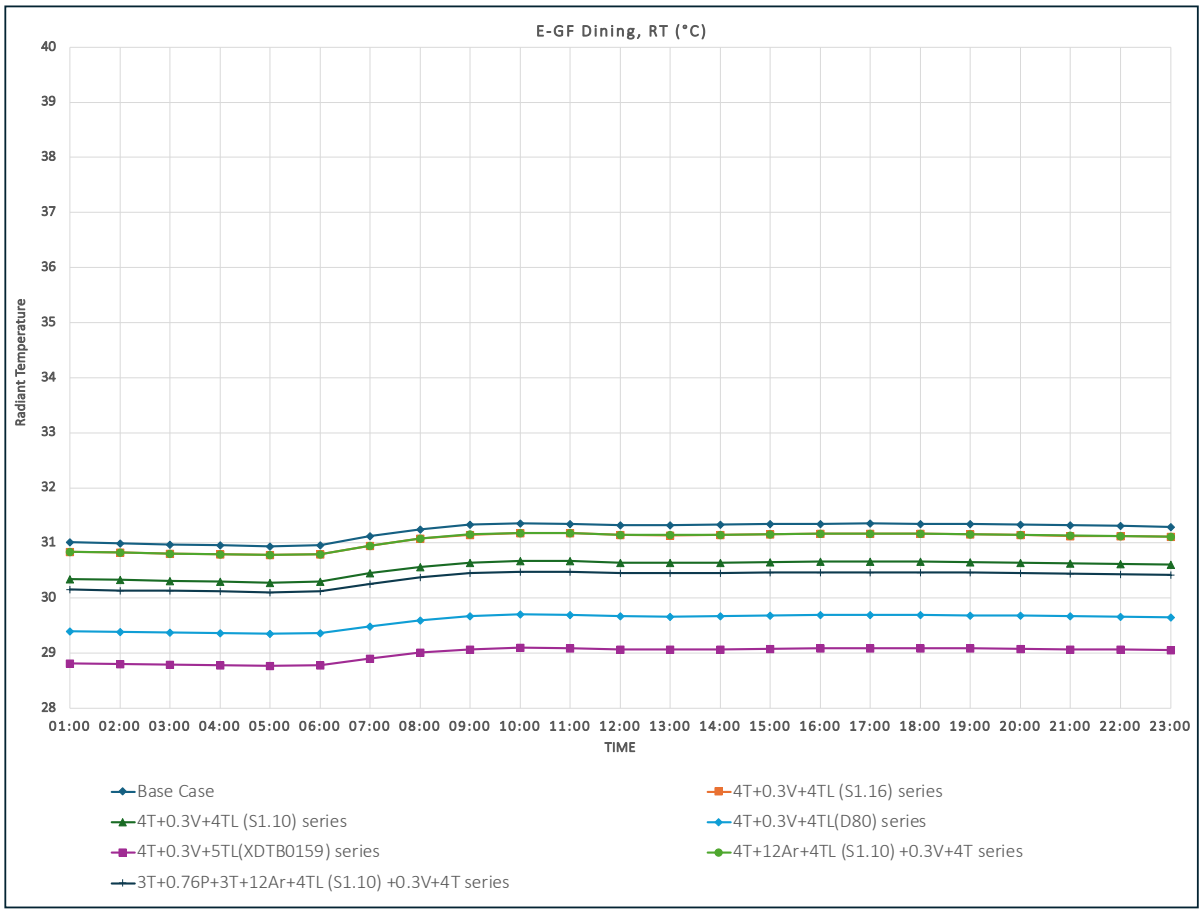


Figure 8.45. Free-Running Simulation Results Comparing Hourly RTs in the E-GF Dining Zone: Base Case vs. Improvements Using Various Energy-Efficiency Measures for Glazing with Vacuum Insulated Glass Product Series (15 July)

Figure (8.46) exhibits the free-running simulation of radiant temperature (RT) in the ES-GF Lounge on 15 July, comparing the base case with various vacuum-insulated glass. In the base case, RTs remained high, starting at 31.89 °C at 01:00, dropping slightly to 31.72 °C at 05:00, and peaking at 32.80 °C during the afternoon. The daily mean reached 32.19 °C, indicating continuous overheating. It is clear that the ES-GF Lounge zone exhibited slightly higher radiant temperatures than the E-GF Dining zone, with a base case daily mean of 32.19 °C compared with 31.23 °C.

However, applying vacuum-insulated glass to the base case building glazing led to limited improvements for some configurations. For example, the 4T+0.3V+4TL (S1.16) system lowered the daily mean by only 0.31 °C. Similarly, the 4T+0.3V+4TL (S1.10) configuration achieved a slightly greater reduction of 0.85 °C. In contrast, the 3T+0.76P+3T+12Ar+4TL (S1.10)+0.3V+4T glazing showed a stronger effect, maintaining daily averages around 30.98 °C. More advanced glazing achieved the greatest reductions: the 4T+0.3V+4TL (D80) decreased the mean to 29.96 °C, while the 4T+0.3V+5TL (XDTB0159) provided the best performance, with a daily mean of 29.37 °C. These results confirm that advanced multilayer glazing systems are considerably more effective in reducing radiant temperature and mitigating overheating in this zone.

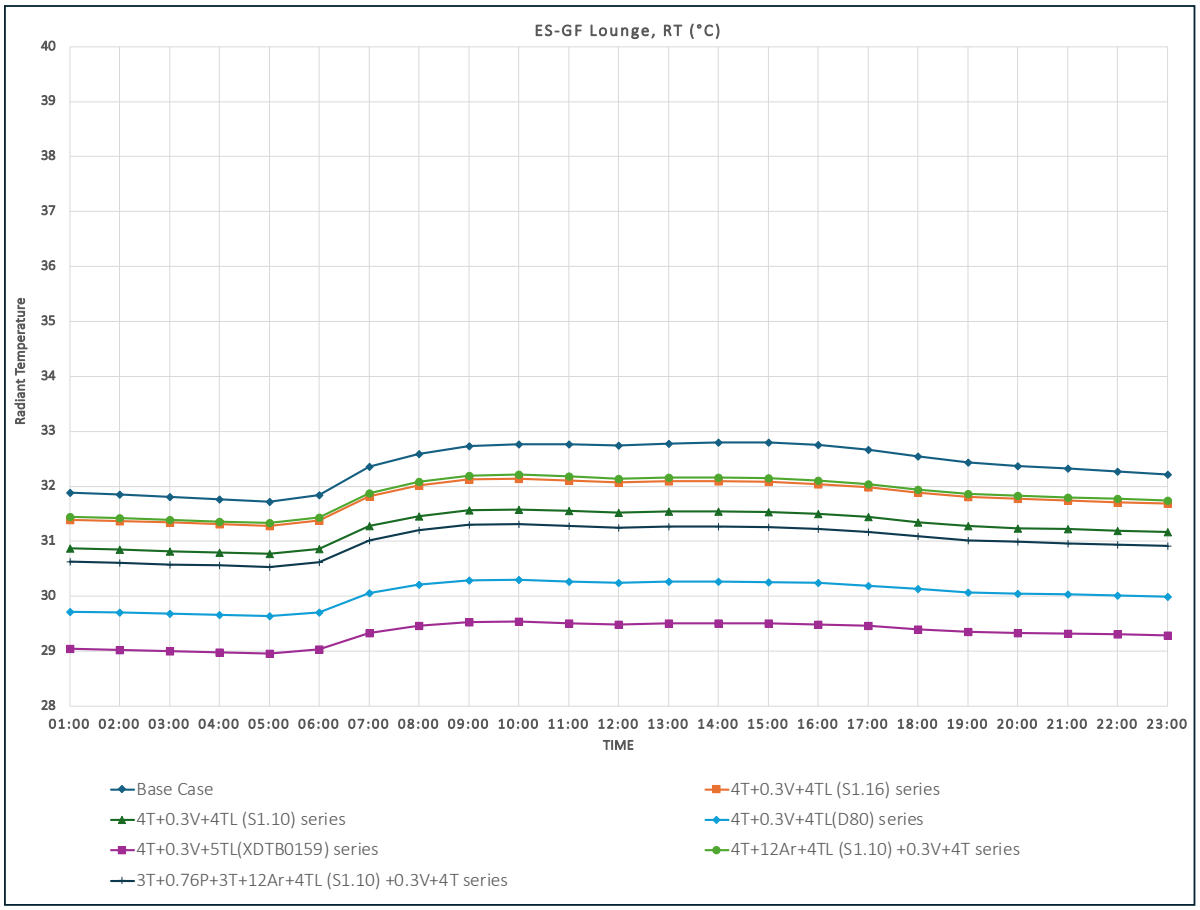


Figure 8.46. Free-Running Simulation Results Comparing Hourly RTs in the ES–GF Lounge: Base Case vs. Improvements Using Various Energy-Efficiency Measures for Glazing with Vacuum Insulated Glass Product Series (15 July)

In comparison, the E-FF Lounge zone, as shown in Figure 8.47 below, recorded the highest radiant temperatures among all previous zones, with a daily mean of 37.65 °C in the base case. During the early morning, RT declined slightly from 37.23 °C at 01:00 to 37.12 °C at 05:00. Afterward, values rose steadily, reaching a peak of 37.90 °C in the afternoon and remaining consistently high throughout the evening. This pattern highlights the severe overheating risk associated with first-floor spaces.

The use of vacuum-insulated glass produced varied results across the different series. For example, the 4T+0.3V+4TL (S1.16) glazing increased the daily mean RT to 38.00 °C, which was higher than the base case, indicating no effective benefit. A similar trend was seen with the Argon-filled configuration (4T+12Ar+4TL (S1.10)+0.3V+4T), where the daily mean also rose to 38.00 °C. In contrast, the 4T+0.3V+4TL (S1.10) glazing achieved a modest improvement, lowering the mean RT to 37.19 °C. More notable reductions occurred with the laminated

Argon-filled glazing (3T+0.76P+3T+12Ar+4TL (S1.10)+0.3V+4T), which decreased the daily average to 36.90 °C. Additionally, advanced multilayer systems delivered the greatest improvements: the 4T+0.3V+4TL (D80) glazing lowered the mean RT to 35.64 °C, while the 4T+0.3V+5TL (XDTB0159) system performed best, achieving 34.67 °C.

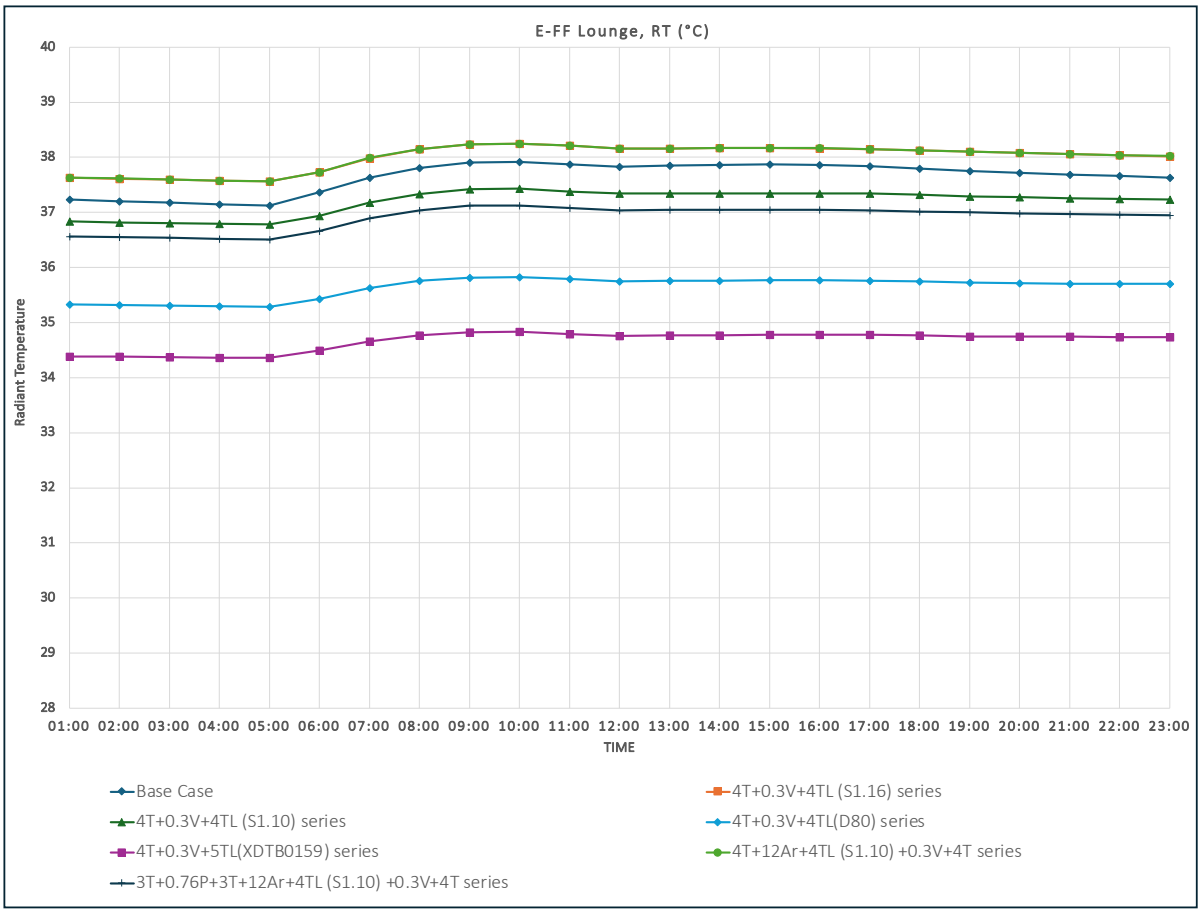


Figure 8.47. Free-Running Simulation Results Comparing Hourly RTs in the the E–FF Lounge: Base Case vs. Improvements Using Various Energy-Efficiency Measures for Glazing with Vacuum Insulated Glass Product Series (15 July)

On the other hand, evaluating the operative temperature (OT) in the E-GF Dining zone offers further insight into thermal comfort during free-running simulation. Figure (8.48) shows the daily profiles for the base case and alternative glazing setups. It is clear that, in the base case, OT slightly decreased during the early morning, from 31.04 °C at 01:00 to 30.96 °C at 05:00, before rising to a maximum of 31.70 °C at 10:00. Afterwards, the values stayed within a narrow range of 31.5–31.6 °C during the afternoon before gradually declining to 31.34 °C at 23:00.

The addition of 4T+0.3V+4TL (S1.16) and 4T+12Ar+4TL (S1.10)+0.3V+4T series showed similar behaviour with a slight reduction, averaging 31.23 °C, with morning lows of 30.80 °C and peaks of 31.52 °C. Additionally, the 4T+0.3V+4TL (S1.10) series showed moderate improvement, with an average OT of 30.71 °C, ranging from 30.30 °C at 05:00 to 31.01 °C at 10:00. Furthermore, the 3T+0.76P+3T+12Ar+4TL (S1.10)+0.3V+4T series performed slightly better, averaging 30.50 °C, with a minimum of 30.12 °C at 05:00 and a final value of 30.47 °C. Higher reductions were observed for the 4T+0.3V+4TL (D80) series, which averaged 29.74 °C, maintaining values between 29.37 °C and 30.04 °C. The most effective solution was the 4T+0.3V+5TL (XDTB0159) series, with an average of 29.15 °C, reaching a minimum of 28.80 °C at 05:00, a maximum of 29.45 °C at 10:00, and a closing value of 29.12 °C at 23:00. Compared to indoor air temperatures (IATs), these OT values indicate that, although operative temperature tends to be slightly lower than indoor air temperature, the relative performance of the glazing systems remains consistent across both measurements.

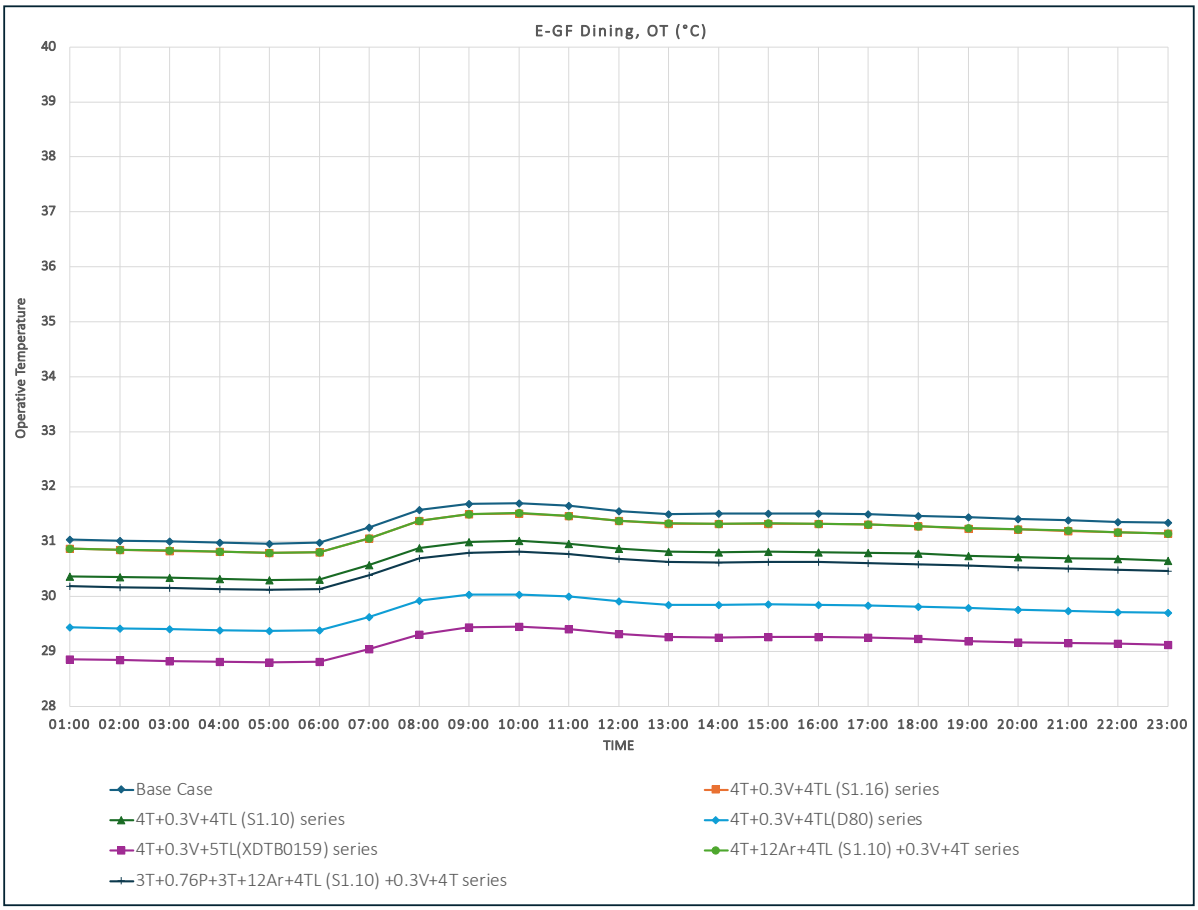


Figure 8.48. Free-Running Simulation Results Comparing Hourly OTs in the E-GF Dining Zone: Base Case vs. Improvements Using Various Energy-Efficiency Measures for Glazing with Vacuum Insulated Glass Product Series (15 July)

Figure (8.49) illustrates the results of the free-running simulation of operative temperature (OT) in the ES-GF Lounge, comparing the base case with various glazing systems. In the base case, OT slightly declined in the early morning, dropping from 31.92 °C at 01:00 to 31.74 °C at 05:00. It then rose steadily, reaching a peak of 32.94 °C at 10:00. During the afternoon, temperatures stayed nearly constant, fluctuating narrowly between 32.9 °C and 32.95 °C, before gradually dropping to 32.25 °C at 23:00.

After applying the 4T+0.3V+4TL (S1.16) glazing and the Argon-filled 4T+12Ar+4TL (S1.10)+0.3V+4T system, only minimal changes were observed, with average values of 31.84 °C—just 0.08 °C lower than the base case.

In contrast, using the 4T+0.3V+4TL (S1.10) glazing showed a more noticeable improvement, maintaining OT between 30.79 °C and 31.66 °C and recording a daily mean of 31.36 °C. Similarly, the laminated Argon-filled glazing (3T+0.76P+3T+12Ar+4TL (S1.10)+0.3V+4T) performed slightly better, with an average of 31.11 °C, reducing the temperature by 0.81 °C compared to the base case.

Moreover, the 4T+0.3V+4TL (D80) glazing had a stronger effect, keeping OT within the narrower range of 29.67 °C to 30.39 °C and recording a daily average of 30.14 °C. The greatest improvement was achieved by the 4T+0.3V+5TL (XDTB0159), which consistently provided the lowest operative temperatures. This glazing maintained values between 29.00 °C at 05:00 and 29.64 °C at 10:00, with an overall mean of 30.33 °C, reducing the temperature by 1.59 °C compared to the base case.

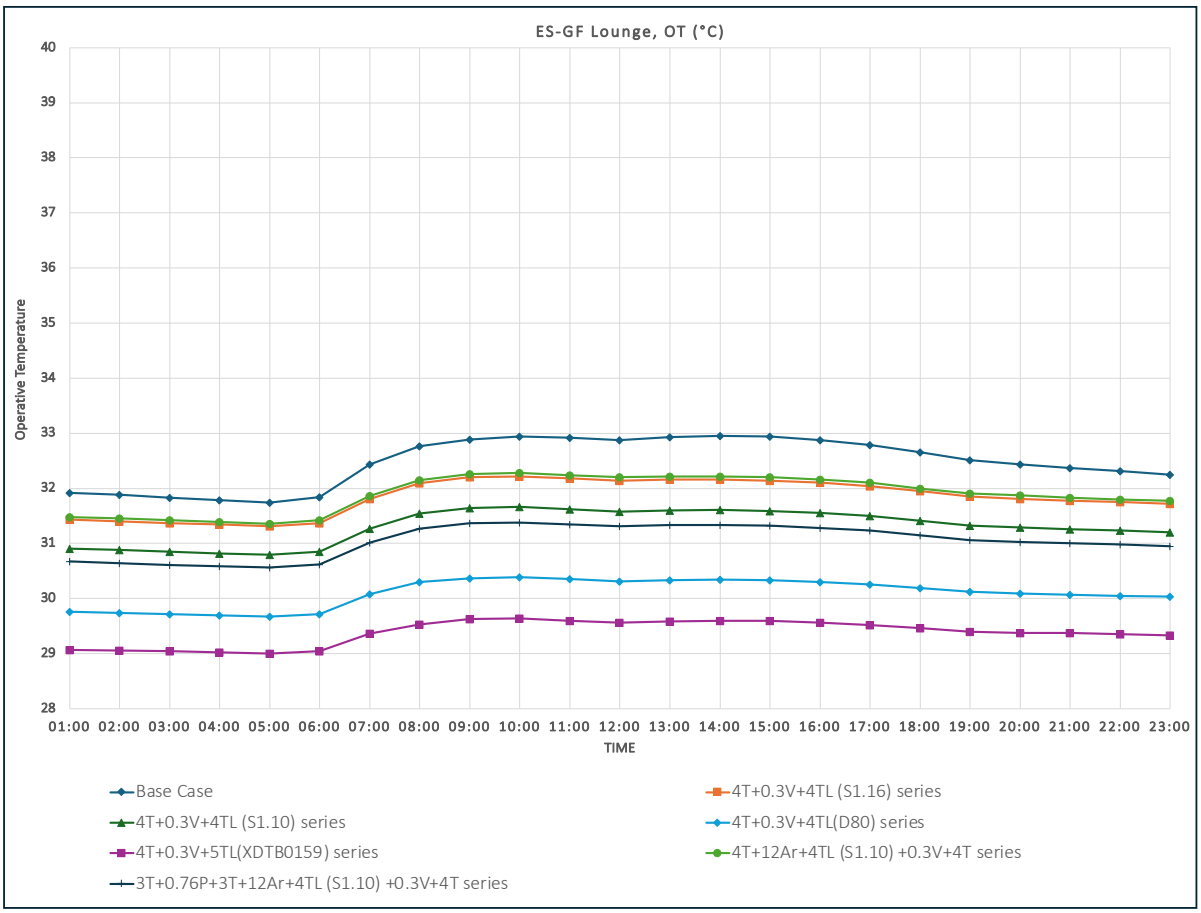


Figure 8.49. Free-Running Simulation Results Comparing Hourly OTs in the ES–GF Lounge: Base Case vs. Improvements Using Various Energy-Efficiency Measures for Glazing with Vacuum Insulated Glass Product Series (15 July)

It was clear that, among the ground-floor zones, moderate reductions in operative temperature (OT) were observed, whereas the first-floor zone, such as the E-FF Lounge, showed more critical overheating conditions. Thus, Figure (8. 50) displays the hourly OT pattern for the E- FF Lounge on July 15, comparing the base case with several glazing configurations.

In the base case, OT declined slightly in the early morning hours, from 37.22 °C at 01:00 to 37.10 °C at 05:00. Operative temperatures then rose steadily, reaching a peak of 38.04 °C between 09:00 and 10:00. During the afternoon, conditions remained almost constant, close to 37.9–38.0 °C, before gradually falling to 37.63 °C at 23:00.

After the application of the 4T+0.3V+4TL (S1.16) and the Argon-filled 4T+12Ar+4TL (S1.10)+0.3V+4T glazing, OT values became slightly higher than in the base case, with a daily average of 38.08 °C. Therefore, they failed to improve indoor conditions and instead worsened overheating. By contrast, the 4T+0.3V+4TL (S1.10) glazing achieved a modest improvement,

maintaining OT between 36.78 °C and 37.48 °C, with a daily mean of 37.25 °C. The laminated Argon-filled glazing (3T+0.76P+3T+12Ar+4TL (S1.10)+0.3V+4T) performed slightly better, with an average temperature of 37.03 °C, resulting in a reduction of 0.93 °C compared to the base case. More substantial reductions were achieved with the 4T+0.3V+4TL (D80) glazing, which maintained OT between 35.30 °C and 35.90 °C and reached a daily mean of 35.64 °C. Furthermore, the best performance was delivered by the 4T+0.3V+5TL (XDTB0159) glazing, which consistently recorded the lowest values, ranging from 34.36 °C at 05:00 to 34.91 °C at 10:00. This glazing achieved a daily mean of 34.70 °C, representing a significant reduction of 3.23 °C compared to the base case.

In summary, the free-running simulations indicate that the 4T+0.3V+5TL (XDTB0159) and 4T+0.3V+4TL (D80) glazing systems were the most effective in reducing operative temperatures. Their impact was particularly evident in the first-floor lounge, the zone with the most severe overheating, which benefited the most from these high-performance glazing configurations.

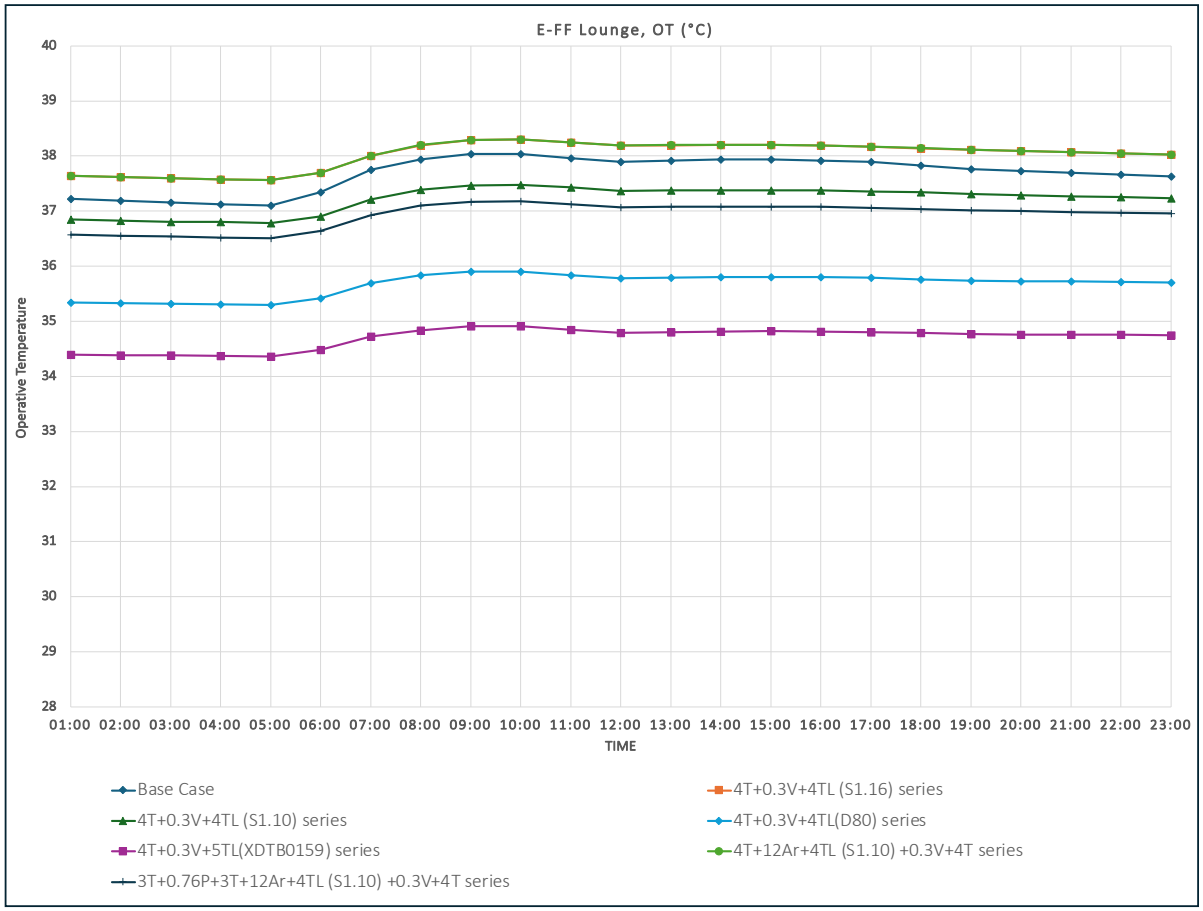


Figure 8.50. Free-Running Simulation Results Comparing Hourly OTs in the the E–FF Lounge: Base Case vs. Improvements Using Various Energy-Efficiency Measures for Glazing with Vacuum Insulated Glass Product Series (15 July)

On the other hand, Figure (8.51) illustrates the relative humidity (RH) levels for the E-GF Dining zone under free-running simulation on 15 July, after upgrading the base case with different vacuum-insulated glass series. In the base case, RH levels were generally low, with a daily mean of about 15.0%. A slight rise occurred during the early morning, from 15.34% at 01:00 to 15.43% at 05:00. As indoor air temperature increased throughout the morning, RH declined, reaching a minimum of 14.52%. Values then stabilised during the afternoon before showing a modest recovery in the evening. This trend highlights the sensitivity of RH to indoor temperature fluctuations, with reductions observed during peak heating periods.

However, the application of vacuum-insulated glass produced noticeable but varied effects. For instance, the 4T+0.3V+4TL (S1.16) system resulted in only a minor improvement, with a daily mean of 15.1%. A clearer increase was observed with the 4T+0.3V+4TL (S1.10), where the mean rose to 15.6%. Similarly, the 3T+0.76P+3T+12Ar+4TL (S1.10)+0.3V+4T glazing delivered a comparable performance, averaging 15.7%. These moderate improvements suggest that while such glazing systems provide some benefit, their effect on RH remains limited. Moreover, the most significant increases were achieved with the 4T+0.3V+4TL (D80), which improved the daily mean RH to 16.3%, and the 4T+0.3V+5TL (XDTB0159), which delivered the highest average at 16.9%. Compared with the base case, this corresponds to an increase of more than 1.8 percentage points.

Consequently, these improvements are particularly important in hot and arid climates, where even modest rises in RH contribute to better indoor comfort by reducing the drying effects of overheating. Nevertheless, it is essential to note that these RH gains should be evaluated together with changes in operative and radiant temperatures to ensure that overall thermal comfort is effectively achieved.

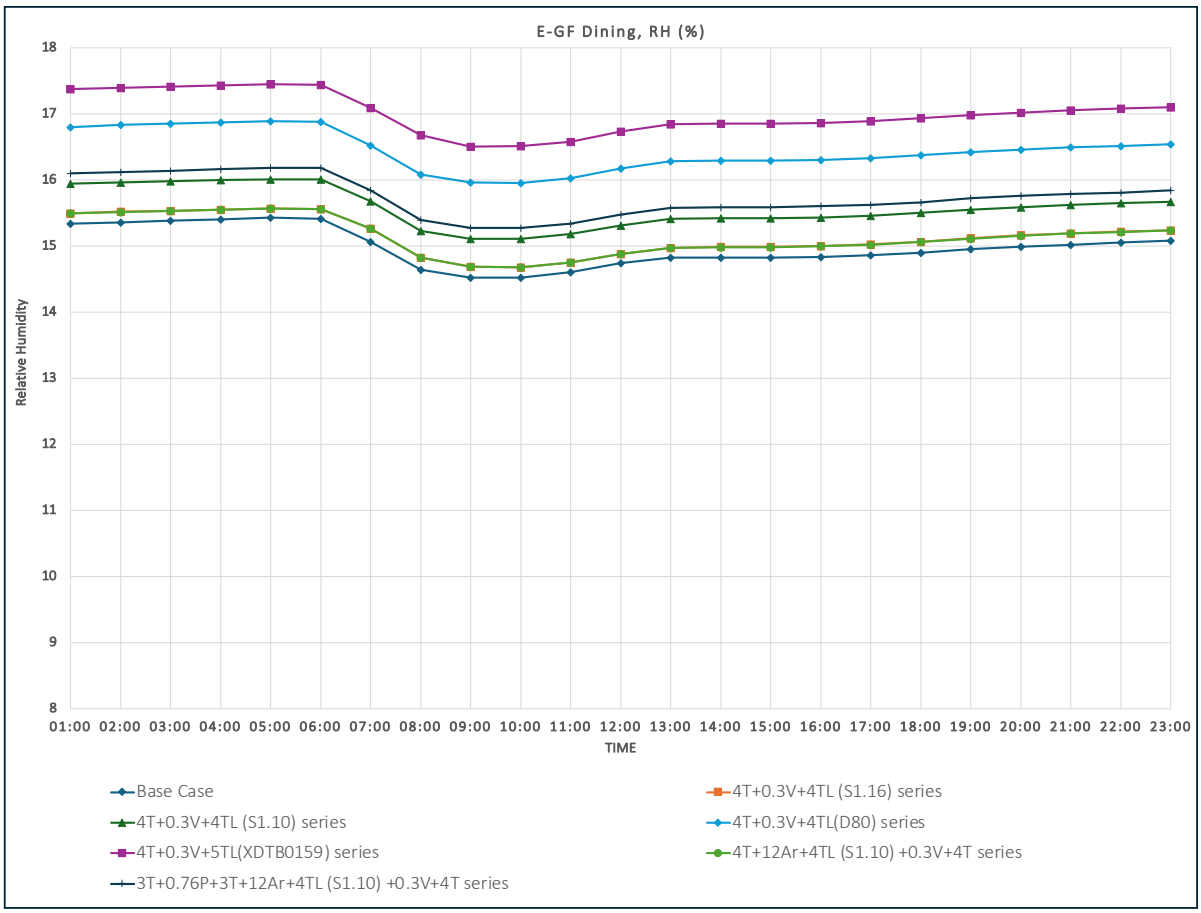


Figure 8.51. Free-Running Simulation Results Comparing Hourly RH in the E-GF Dining Zone: Base Case vs. Improvements Using Various Energy-Efficiency Measures for Glazing with Vacuum Insulated Glass Product Series (15 July)

Figure 8.52 illustrates the relative humidity (RH) trends in the ES-GF Lounge zone, obtained from a free-running simulation on 15 July, incorporating various energy-efficiency measures with the vacuum-insulated glass series. In the base case, this zone displayed lower humidity conditions, with a daily mean of only 14.3%, which is less than that of the E-GF Dining zone (≈15.0%). A slight increase was observed during the early morning hours, from 14.59% at 01:00 to 14.75% at 05:00, followed by a decline in response to rising indoor air temperatures. The lowest RH level was recorded at 13.67%, after which values stabilised during the afternoon and recovered modestly to reach 14.32% by the end of the day.

Additionally, the integration of vacuum-insulated glazing to the base case provided a measurable and varied improvement in this zone as well. For instance, 4T+0.3V+4TL (S1.16) raised the daily mean to 14.7%, indicating only a marginal effect. A stronger response was noted with the 4T+0.3V+4TL (S1.10), which increased the average to 15.2%. Similarly, the 3T+0.76P+3T+12Ar+4TL (S1.10)+0.3V+4T continued this improvement, registering an average

of 15.4%. Furthermore, the implementation of 4T+0.3V+4TL (D80) series resulted in far greater improvements. It elevated the daily mean to 16.2%, while the 4T+0.3V+5TL (XDTB0159) achieved the most notable outcome, with an average of 16.8%. These upgrades produced increases of 1.9–2.6 percentage points compared with the base case.

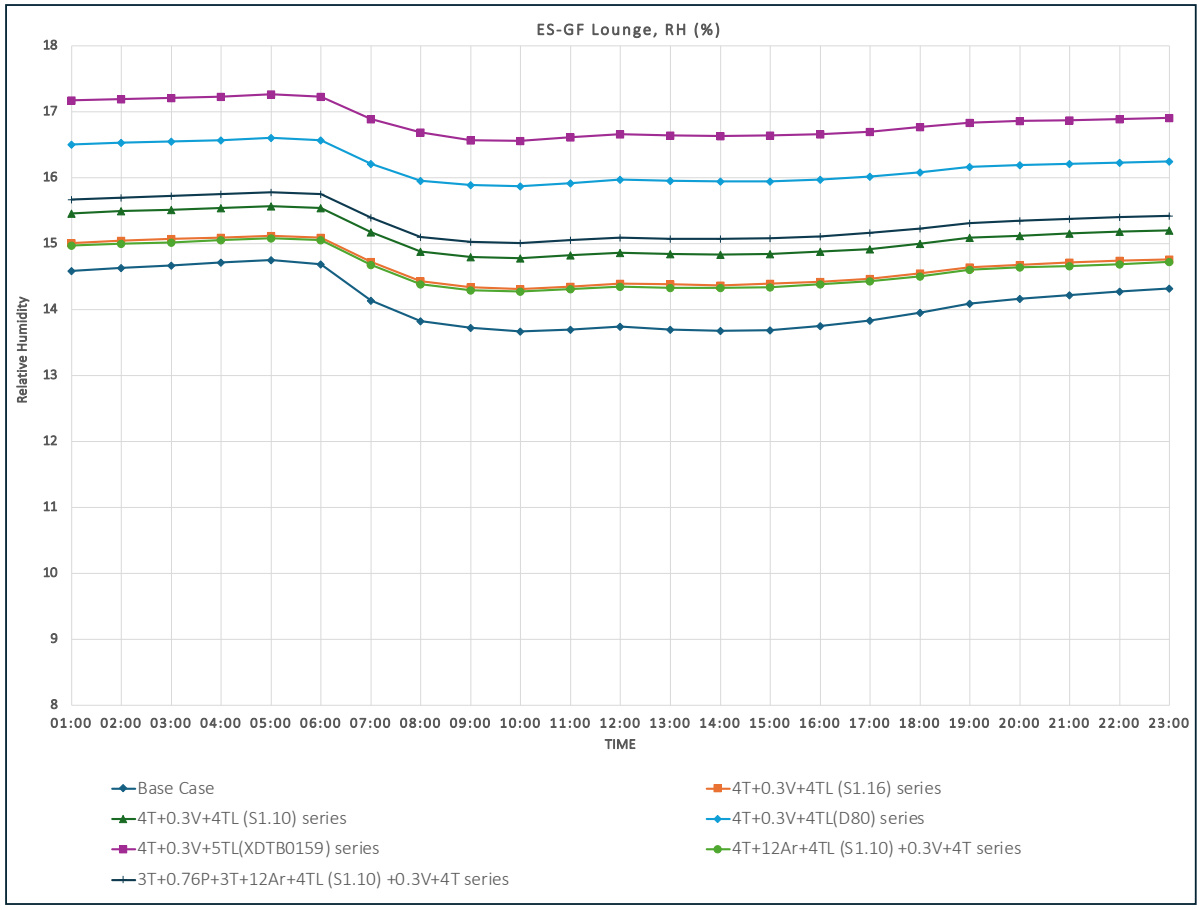


Figure 8.52. Free-Running Simulation Results Comparing Hourly RH in the ES–GF Lounge: Base Case vs. Improvements Using Various Energy-Efficiency Measures for Glazing with Vacuum Insulated Glass Product Series (15 July)

Figure (8.53) illustrates the relative humidity (RH) variation for the E-FF Lounge zone on 15 July under free-running simulation, using glazing with the vacuum-insulated glass product series. Among all examined zones, this space displayed the lowest RH levels, with a daily mean of only 10.6%, which indicates a critically dry indoor environment. In the base case, RH rose slightly in the early morning from 10.9% at 01:00 to 10.98% at 05:00, before declining to a minimum of 10.35% around mid-morning. Levels then remained almost constant throughout the afternoon, with only a marginal recovery in the evening, ending at 10.66%. This pattern

reflects the strong influence of higher first-floor temperatures, which provide more drying conditions compared with the ground-floor zones.

The effect of glazing upgrades on RH was varied considerably. For example, the 4T+0.3V+4TL (S1.16) and the 4T+12Ar+4TL (S1.10)+0.3V+4T did not improve building RH performance, with daily means of only 10.4%, even slightly below the base case. Moreover, the 4T+0.3V+4TL (S1.10) glazing offered a modest improvement, raising the daily mean to 10.9%, while the 3T+0.76P+3T+12Ar+4TL (S1.10)+0.3V+4T reached 11.1%. However, more meaningful improvements emerged from the 4T+0.3V+4TL (D80) system, which increased the daily mean to 11.8%, and the 4T+0.3V+5TL (XDTB0159) provided the highest outcome at 12.4%, representing an increase of nearly 1.8% compared with the base case. Overall, the RH levels in this first-floor zone remained at critically low values, suggesting that while glazing upgrades contribute to improvement, they must be integrated with other strategies to achieve acceptable indoor comfort.

In summary, the free-running simulations on 15 July revealed clear differences in temperature and humidity performance across the building zones. The first-floor E-FF Lounge consistently showed the most critical conditions, with daily means of 37.7 °C for IAT, 37.7 °C for OT, and 37.6 °C for RT, alongside the lowest RH of only 10.6%. This reflects an overheating and dryness compared with the ground-floor E-GF Dining (IAT ≈ 31.5 °C, OT ≈ 31.4 °C, RT ≈ 31.2 °C, RH ≈ 15.0%) and the ES-GF Lounge (IAT ≈ 32.6 °C, OT ≈ 32.5 °C, RT ≈ 32.4 °C, RH ≈ 14.1%). Although all three zones experienced overheating in the base case, the E-FF Lounge exhibited the most extreme conditions across all parameters. Notably, the 4T+0.3V+4TL (D80) and 4T+0.3V+5TL (XDTB0159) proved consistently effective in reducing IAT, OT, and RT while also modestly improving RH. However, glazing upgrades alone cannot resolve thermal comfort challenges; they should be combined with complementary strategies, including wall and roof insulation improvements and traditional Saudi passive design approaches, in order to reach holistic thermal comfort.

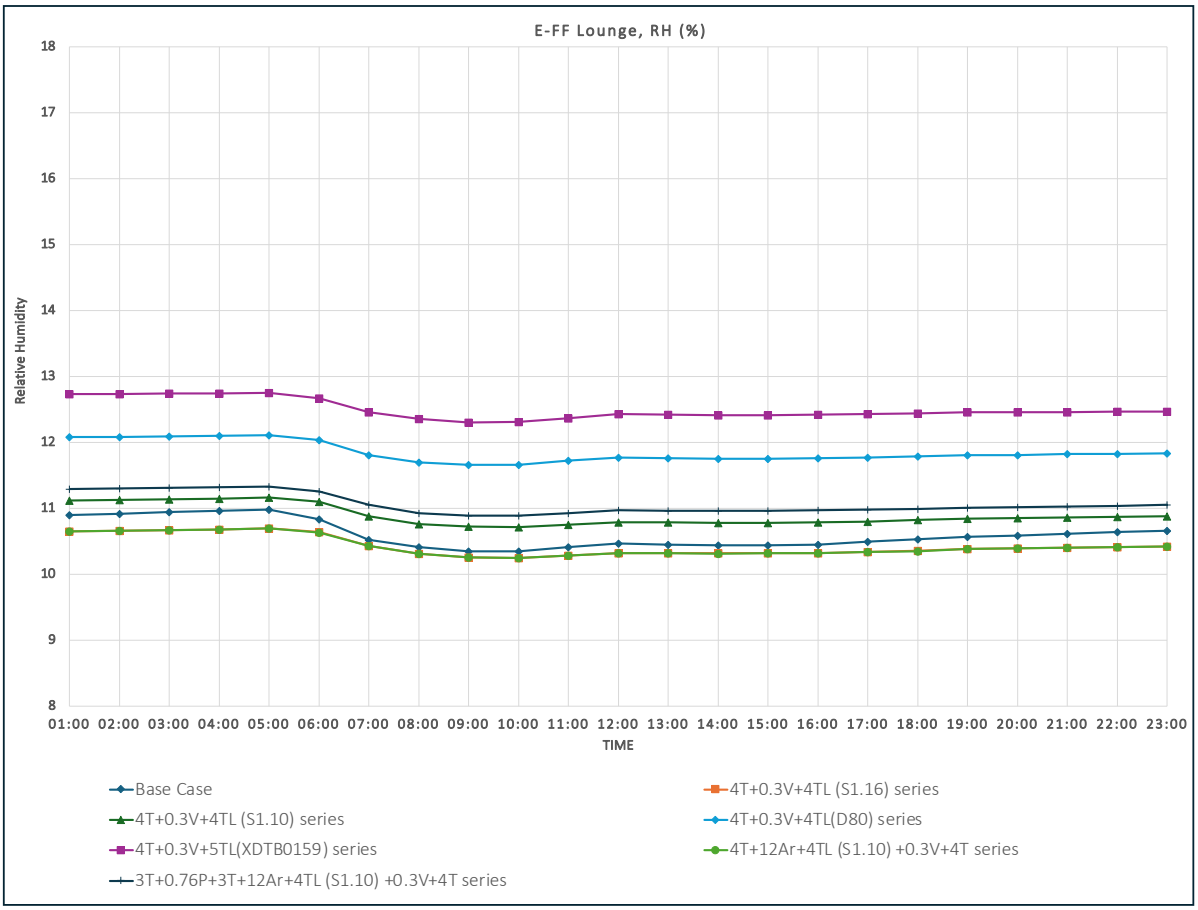


Figure 8.53. Free-Running Simulation Results Comparing Hourly RH in the the E–FF Lounge: Base Case vs. Improvements Using Various Energy-Efficiency Measures for Glazing with Vacuum Insulated Glass Product Series (15 July)

It is worth mentioning that there are more complex line charts in the appendices 1,2, and 3 of this research, which present an analysis that combines all the parameters evaluated during the free-running simulation of the hourly indoor thermal environment. This integration in one plot provides a comprehensive view of the simulation results in each zone. Moreover, it facilitates a detailed comparison of the individual effects of each parameter, allowing for a clearer understanding of how each solution interacts with each other over the given time. Such a comparative analysis is crucial for identifying which parameters have the most significant impact and for optimising thermal comfort control strategies effectively.

8.3 PV POTENTIAL GENERATION ANALYSIS

Mengelkamp et al. (2018) highlighted the fact that there are seven essential factors to take into account while developing a microgrid peer to peer (P2P) energy system. Zhang et al. (2018) moreover suggest a four-layer structure for a P2P energy trading system: a control layer, a power grid layer, a commercial layer, and an information and communication technologies layer. However, a three-layer structure, consisting of physical, information, and market layers, was proposed by Li and Ma (2022) for the development of a P2P electricity trading system in PV communities. Generally, researchers emphasised that the physical layer which involves several considerations is the most crucial aspect. Therefore, the potential of this layer was examined utilising the case study building of the ROSHN project, which includes the capacity for energy generation from P2P and consumption information, regardless of the financial or communication perspectives (see Figure 8.54).

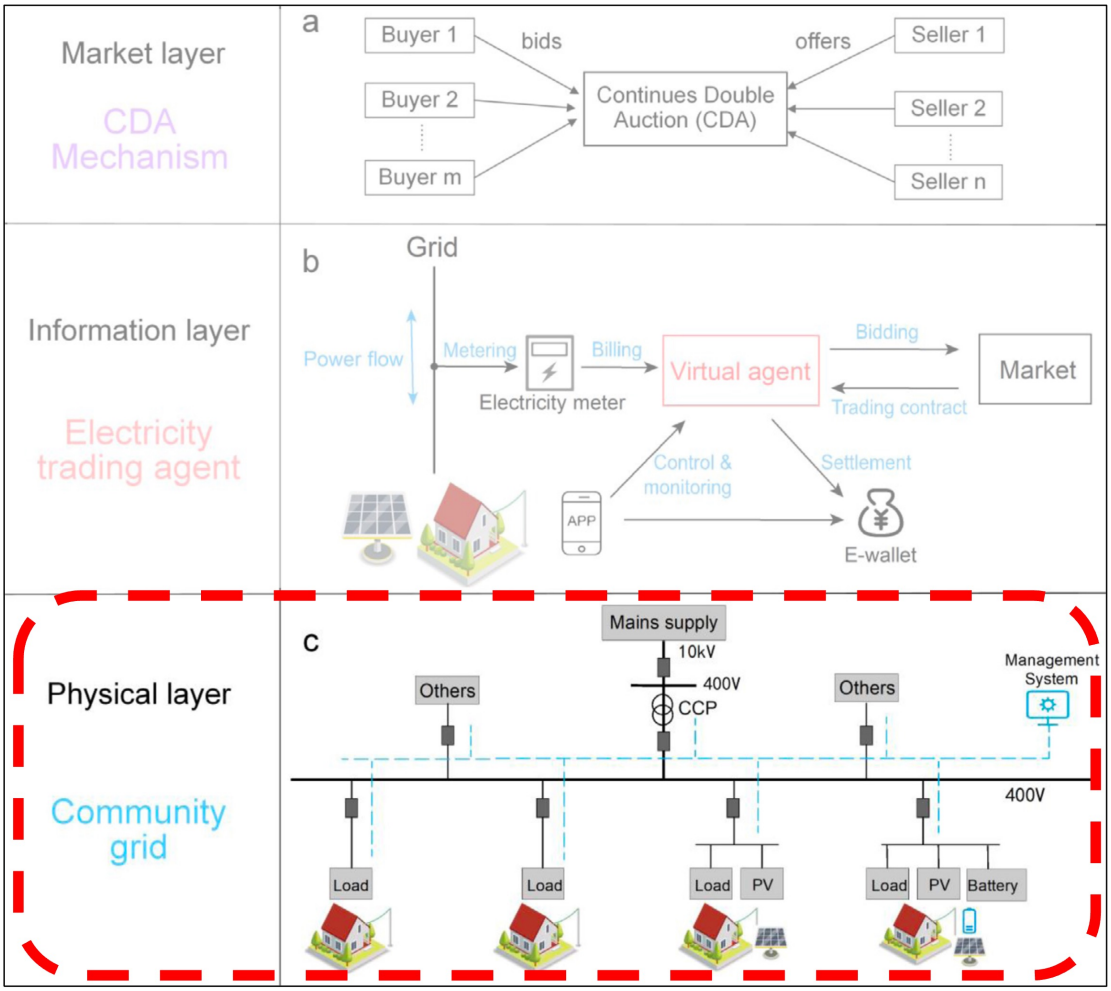


Figure 8.54. The Main Layers of Peer-To-Peer PV Systems With a Mark-Up of The Present Study Focused. (Picture source Li, Ma [43]).

The proposed system utilised the optimum design parameters gathered from the literature review and the best simulation results using DesignBuilder in the context of Riyadh's climate, such as tilt angle, suitable module specifications, array size, and orientations. Thus, Figure (8.55) illustrates the monthly electricity generation of one building from rooftop PV panels by covering only 34% of the gross roof area available (154.5m^2) and having a tilt angle of 30°. Furthermore, Table (8.1) below details the proposed peer-to-peer PV system across various scales of the case study's physical layer, along with its potential generation. Furthermore, Figure (8.56) illustrates an overview of the PV generation and load profiles of one building, showing the on-site PV energy consumed and energy absorbed from the grid, as well as the surplus PV energy.

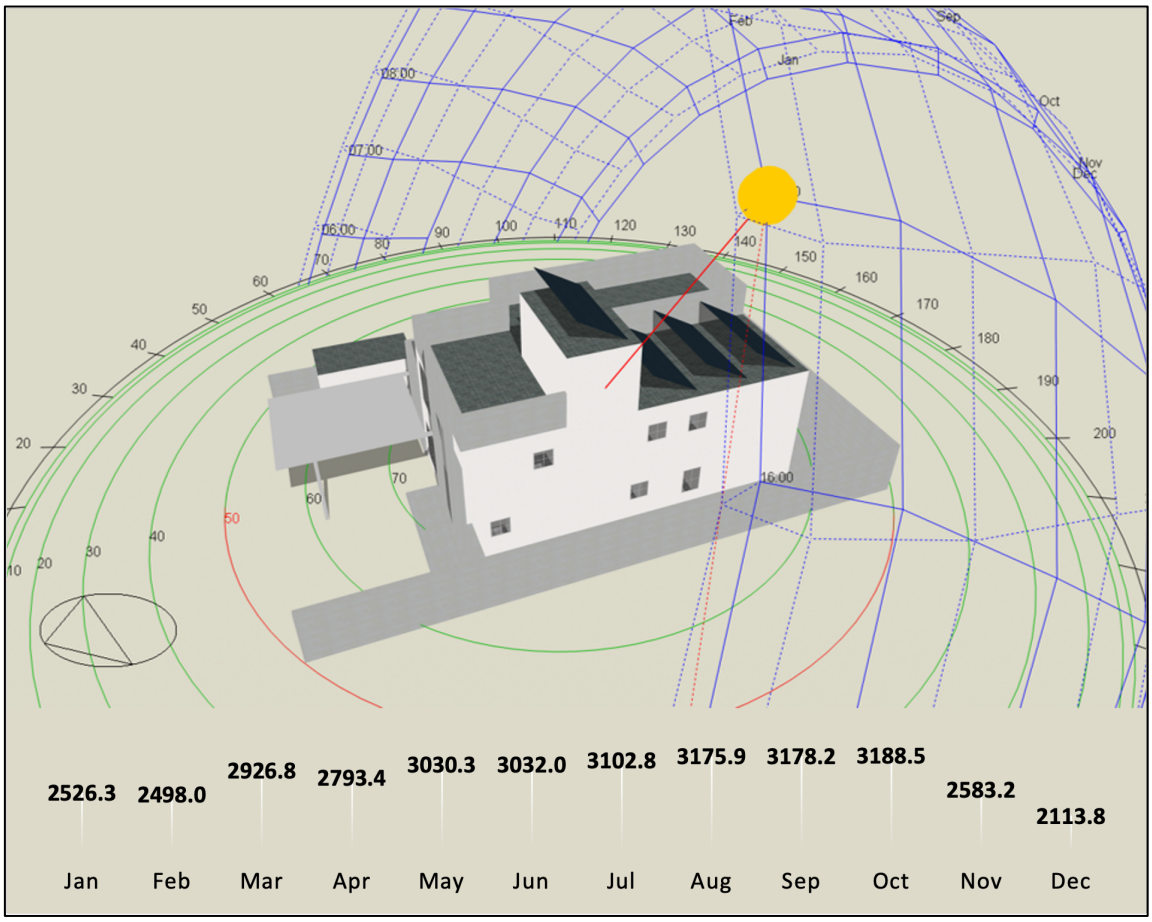


Figure 8.55. Monthly Electricity Generation (kWh) of One Building from PV Panels. (T= 34149.2 kWh)

Table 8.1. Potential Energy Generation from the P2P System for the ROSHN Project Case Study Buildings.

The Number of Participants in The System (Households0	The Space Available for Installation on The Rooftops	The Specifications of The PV Panels	The Average Total Energy Consumption Per Unit Area (kWh/M2/Yr.) (The author, Alyami, Omer 2021; Almushaikah, Almasri 2021; AL-Dossary, Kim 2020; Alayed et al. 2021))	The Total Energy Consumption (kWh/Yr.)	The Amount of Energy Be Generated (kWh/Yr.)
One block (7) Participants	368 m2 (34% of the Gross roof area of each building)	Model: TOPHiKu6 (CS6W 570T) Cell Type: Mono-Crystalline Cells. Dimensions: 2278 × 1134 × 30 mm. Maximum power output: 570 W. Module Efficiency: 22.1%. Performance: (Vmp = 42.7 V, Imp = 13.35 A, VOC = 51.8 V, ISC = 13.81 A). Operating Temperature: −40 °C~+85 °C.		275,047.13	239,044.13
A group of blocks (111) Participants	5831 m^2		129.294	4,361,461.57	3,790,556.87
District scale (4500) Participants	236,385 m^2			176,816,009.70	153,671,224.50

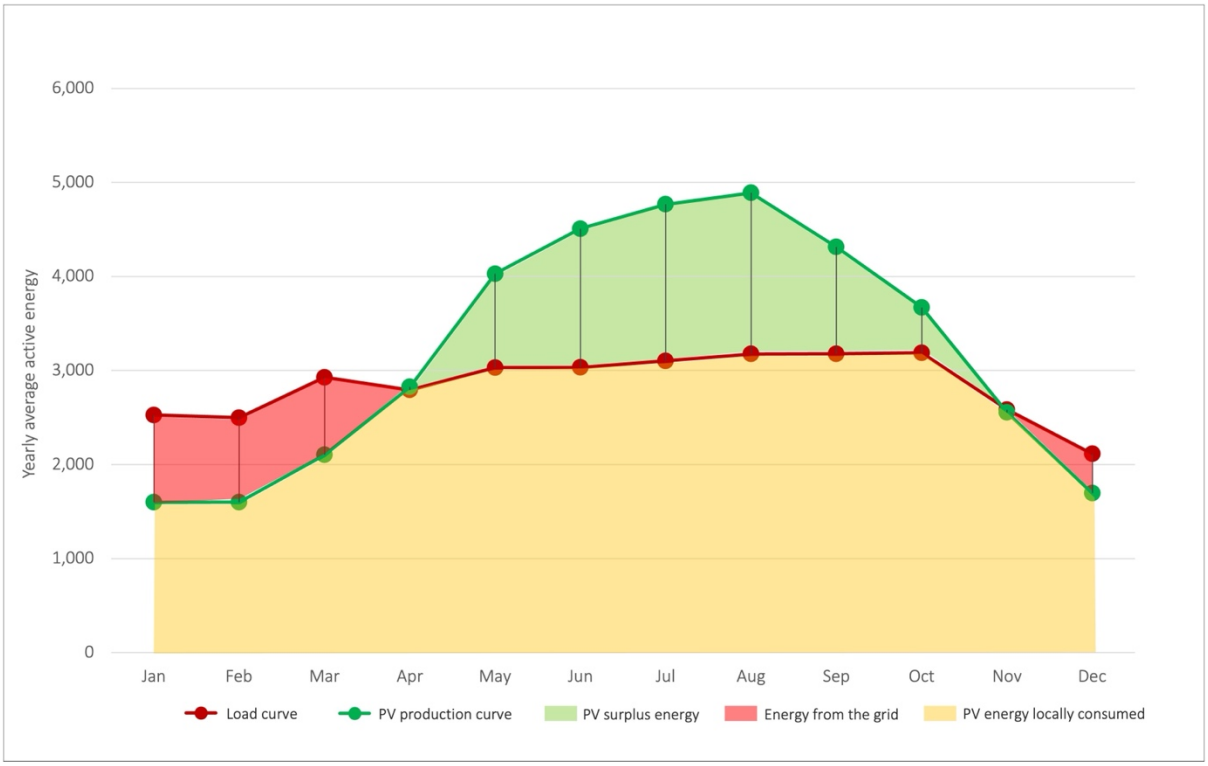


Figure 8.56. Overview of PV Generation and Load Profiles for a Single Building.

Moreover, in order to evaluate the peer-to-peer proposed system in depth, there was a scenario of assuming that all households have ownership of the PV system. The network comprises a total of 4500 households, evenly split between prosumers and consumers,

denoted as N = 4500, NC = 2250, and NP = 2250. Prosumers and consumers are connected to the community microgrid via smart metres to establish the P2P energy sharing network that forms the physical layer of P2P energy sharing. The purpose of these smart metres is to record the electricity exchanges between users and main grid interactions, as well as any electricity transfers.

Therefore, after assuming a reduction of 15% by implementing the proposed green engineering solutions there were tradeable yearly electricity of 5,254.07, 83,314.54, and 3,377,616.26 kWh for 7, 111, and 4500 participants respectively. Hence, the net energy community generated by the PV system over one year is 1,688,808.13 kWh from 2250 prosumers. On the other hand, the consumers assumed to remain on the base case condition with a demand of total energy of 88,408,004.85 kWh from the grid and their PV. Accordingly, there is still a demand for 11,572,392.60 kWh from the grid after installing rooftop PV panels.

The self-consumption rate, self-sufficiency rate, electricity demand, energy absorbed from the grid, and energy supplied to the grid define the energy profile of PV system components and the distribution of energy flow (Jaszczur et al. 2018). Furthermore, as outlined by Luthander et al. (2015) in the context of the PV/grid energy system, the self-consumption and self-sufficiency rates specifically relate to the electricity generated by the PV system and utilised locally to fulfil the intended electrical load. Hence, the subsequent equations were used to identify these five core indicators.

$$E_{Load,t} = E_{from\ grid,t} + E_{PV,t} \tag{7}$$

$$CE_{Load,t} = E_{from\ grid,t} \tag{8}$$

$$E_{Load,t} = \begin{cases} E_{from\ grid,t} & for\ E_{PV,t} = 0 \ ;\ E_{to\ grid,t} = 0 \\ E_{from\ grid,t} + E_{PV,t} & for\ E_{PV,t} < E_{Load,t} \ ;\ E_{to\ grid,t} = 0 \\ E_{PV,t} & for\ E_{PV,t} \geq E_{Load,t} \ ;\ E_{to\ grid,t} \geq 0 \end{cases} \tag{9}$$

$$Self\ Consumption\ Rate\ (SCR) = \frac{\left(E_{Load,t}\right)}{E_{PV,t}} \times 100 \tag{10}$$

$$Self\ Sufficiency\ Rate\ (SSR) = \frac{\left(E_{Load,t}\right)}{CE_{Load,t}} \times 100 \tag{11}$$

$$SCR = \frac{\left(1{,}688{,}808.13 + (176{,}816{,}009.70 \div 2)\right)}{153{,}671{,}224.50} \times 100 = 59\%$$

$$SSR = \frac{\left(1{,}688{,}808.13 + (176{,}816{,}009.70 \div 2)\right)}{88{,}408{,}004.85} \times 100 = 102\%$$

Where $E_{Load,t}$ is the total energy load demand over a specific time, $E_{from\ grid,t}$ energy consumed from the grid over a specific time, and $E_{PV,t}$ the total energy generated by the PV system over a specific time, $CE_{Load,t}$ is the total energy load demand over a specific time for the consumers.

Consequently, the result of SCR indicates that 59% of the energy generated by the PV system was consumed directly by the prosumers. However, the remaining portion could be exported to the grid in order to feed the consumers' buildings. On the other hand, an SSR of 102% indicates that the community energy demand slightly exceeded the energy generated on-site.

Chapter 9: Holistic Analysis

The fundamental objective of engineering research is to provide optimal solutions to complex problems. Kasser (2010) stated that holistic analysis encompasses an approach that emphasises understanding entire systems or wholes rather than breaking them down into individual components for analysis or treatment. In this research, this means developing and maintaining a holistic understanding of the interactions between each parameter and groups of integrated parameters. This chapter builds on the results obtained through earlier methods discussed in the literature review (Chapters 2, 3, and 4), the expert survey (Chapter 6), and the modelling process (Chapter 7). Additionally, the base case model simulation concerning of cooling energy load and thermal comfort aspects that is highlighted in Chapter 8.

Thus, this chapter's opening section presents the development of the previous parametric analyses simulation by conducting an optimisation analysis of the proposed green engineering solutions, both individually and in combination. Section 9.2 provides the final strategic solutions based on these analyses, which will be used in the subsequent assessment. Section 9.3 examines the performance of these final strategic solutions in different climatic zones of Saudi Arabia. Finally, Section 9.4 discusses the results of integrating the thematic analysis from the expert survey with the outcomes of the entire simulation process.

9.1 OPTIMISATION ANALYSIS.

The optimisation analysis comprises three stages. The first stage involves individually evaluating both the base case and various traditional passive architectural design scenarios. Each optimisation analysis employs a range of energy efficiency measures within the building envelope to determine its effectiveness in reducing cooling energy load and improving overall building thermal comfort. The second stage involves evaluating the integration of various traditional passive architectural designs alongside a range of energy efficiency measures within the building envelope to assess their combined effectiveness in decreasing cooling loads and discomfort hours. It is worth mentioning that the Clo levels were determined according to ASHRAE Standard 55-2010 by using DesignBuilder simulation software. A value of 0.5 Clo was

used for summer, and 1.0 Clo was used for winter. These values provide a reasonable average for estimating thermal clothing insulation factors in a typical Arabian Gulf area where the case study is located, as detailed in Table (9.1) below.

Table 9.1. Details of ASHRAE Standard 55-2010 for Garment Insulation.

Garment Description	I_{clu}(Clo)	Garment Description	I_{clu}(Clo)
Underwear		**Dress and Skirts**	
Bra	0.01	Skirt (thin)	0.14
Panties	0.03	Skirt (thick)	0.23
Men's briefs	0.04	Sleeveless, scoop neck (thin)	0.23
T-shirt	0.08	Sleeveless, scoop neck (thick), i.e., jumper	0.27
Half-slip	0.14	Short-sleeve shirtdress (thin)	0.29
Long underwear bottoms	0.15	Long-sleeve shirtdress (thin)	0.33
Full slip	0.16	Long-sleeve shirtdress (thick)	0.47
Long underwear top	0.20	**Sweaters**	
Footwear		Sleeveless vest (thin)	0.13
Ankle-length athletic socks	0.02	Sleeveless vest (thick)	0.22
Panty hose/stockings	0.02	Long-sleeve (thin)	0.25
Sandals/thongs	0.02	Long-sleeve (thick)	0.36
Shoes	0.02	**Suit Jackets and Vests**	
Slippers (quilted, pile lined)	0.03	Sleeveless vest (thin)	0.10
Calf-length socks	0.03	Sleeveless vest (thick)	0.17
Knee socks (thick)	0.06	Single-breasted (thin)	0.36
Boots	0.10	Single-breasted (thick)	0.44
Shirts and Blouses		Double-breasted (thin)	0.42
Sleeveless/scoop-neck blouse	0.12	Double-breasted (thick)	0.48
Short-sleeve knit sport shirt	0.17	**Sleepwear and Robes**	
Short-sleeve dress shirt	0.19	Sleeveless short gown (thin)	0.18
Long-sleeve dress shirt	0.25	Sleeveless long gown (thin)	0.20
Long-sleeve flannel shirt	0.34	Short-sleeve hospital gown	0.31
Long-sleeve sweatshirt	0.34	Short-sleeve short robe (thin)	0.34
Trousers and Coveralls		Short-sleeve pyjamas (thin)	0.42
Short shorts	0.06	Long-sleeve long gown (thick)	0.46
Walking shorts	0.08	Long-sleeve short wrap robe (thick)	0.48
Straight trousers (thin)	0.15	Long-sleeve pyjamas (thick)	0.57
Straight trousers (thick)	0.24	Long-sleeve long wrap robe (thick)	0.69
Sweatpants	0.28		
Overalls	0.30		
Coveralls	0.49		

Therefore, Figure (9.1) illustrates six scatterplots, each presenting the optimisations' results of applying various energy efficiency measures to the building envelope individually for each case. These scatterplots illustrate how different measures impact the building's performance in terms of energy efficiency, highlighting the variations and trends observed in each scenario. This figure presents a comparison of the most effective measures applied to the building's envelope for each individual case, showcasing a wide range of potential improvements in reducing cooling energy consumption and discomfort levels.

Correspondingly, Figure (9.2) contains six scatterplots as well, where the first two plots (A and B) illustrate the optimisation outcomes of individual cases using different energy efficiency measures for the building envelope. These two plots provide a direct comparison similar to those in Figure (9.1), offering additional insights into the performance of the energy efficiency measures when assessed separately. However, the remaining four plots in Figure (9.2) C to F demonstrate the integrated optimisation scenarios. These scenarios comprise the different courtyard configurations and different Mashrabiya materials, all integrated with diverse energy efficiency measures within the building envelope. These integrated plots highlight the combined effects of passive traditional architectural designs and modern energy efficiency improvements, providing a comprehensive view of their interaction and contribution with each other to overall building performance. These complicated solutions, which combine courtyard designs and Mashrabiya materials with energy efficiency measures, have the high potential to significantly reduce cooling energy loads and discomfort hours.

Overall, by comparing these integrated scenarios and the individual cases, the effectiveness of combining traditional passive design strategies with energy efficiency measures becomes evident. This shows potential pathways for achieving significant reductions in cooling energy loads and discomfort hours.

These two stages of analysis are crucial for making informed decisions about building design and retrofitting in the context of energy efficiency and thermal comfort levels. They help to identify the most effective strategies for improving building performance, whether through individual measures or through an integrated approach. In addition, deeper insights are gained into how traditional and modern approaches can work together to optimise building performance. It is clear that the potential for synergistic effects, where the combined impact of multiple strategies is greater than the sum of their individual effects.

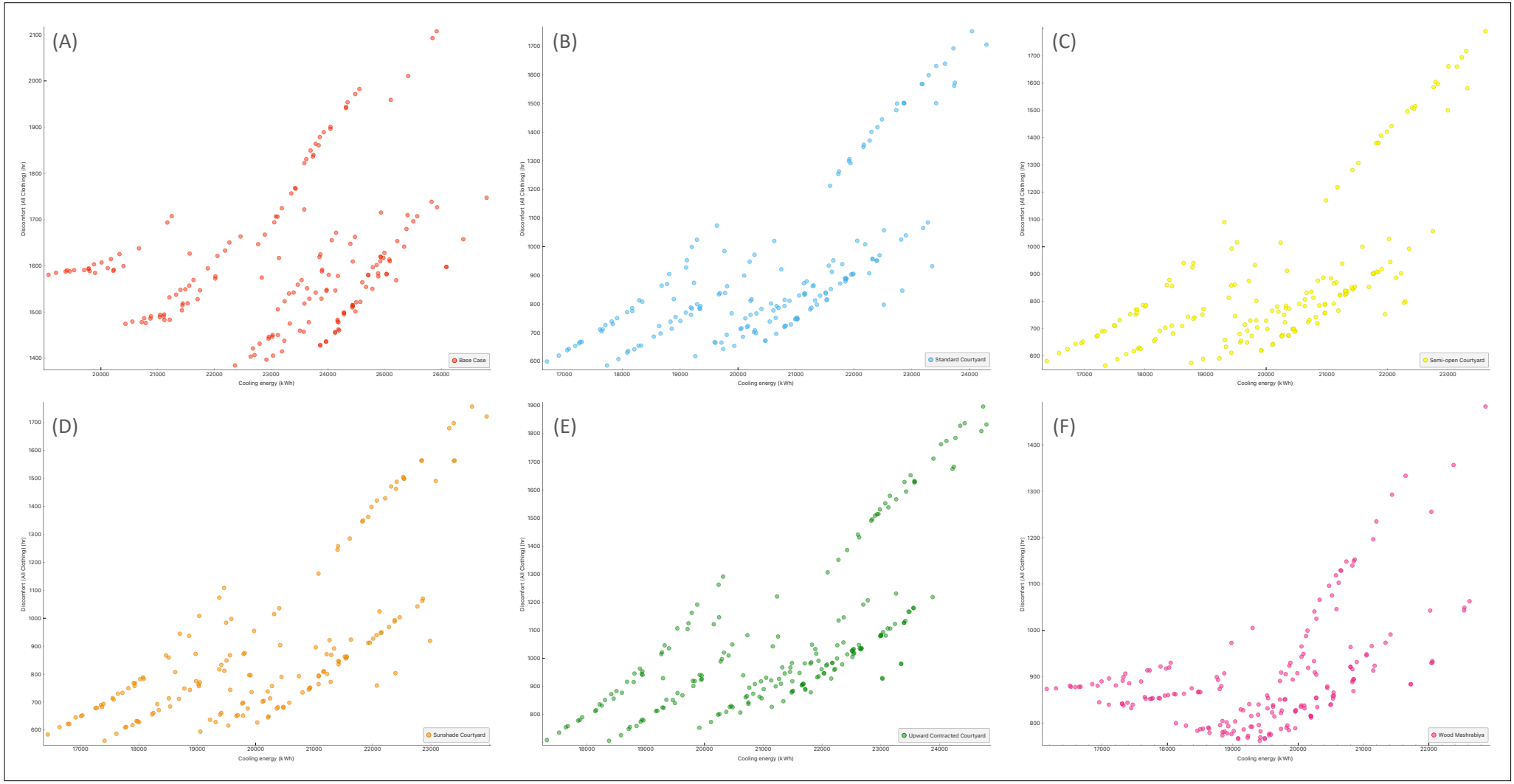


Figure 9.1. Optimisation Analysis Results of Individual Parameters: Minimising Cooling Load and Discomfort Hours Through Energy Efficiency Measures (EEM) of the Building Envelope.

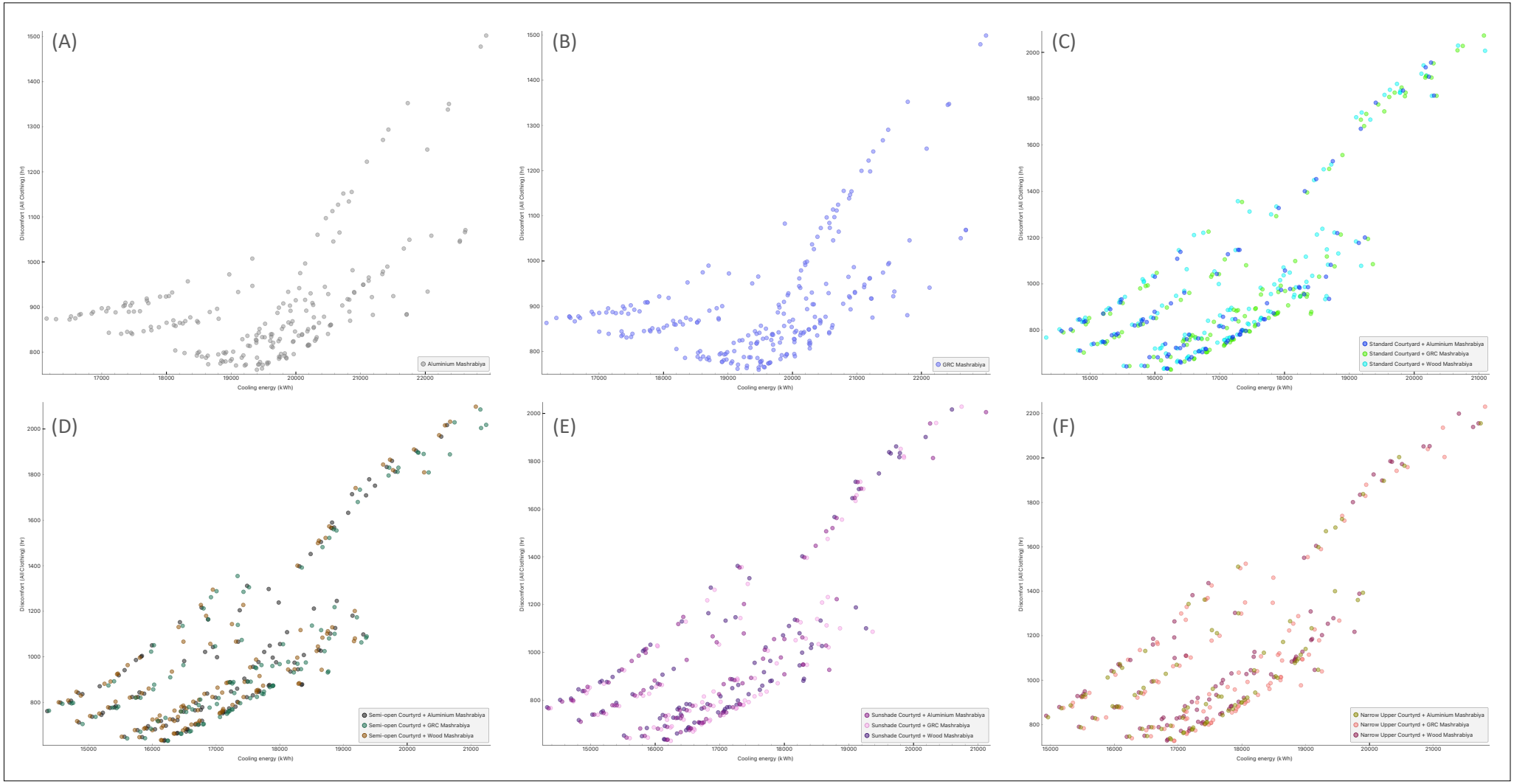


Figure 9.2. Optimisation Analysis Results of Individual and Integrated Parameters: Minimising Cooling Load and Discomfort Hours Through Energy Efficiency Measures of the Building Envelope.

Building upon the previous two stages, Figures (9.3) and (9.4) below illustrate the overlapping results from both individual and integrated cases. These cumulative analyses underscore the critical importance of integrated solutions, which combine various measures to optimise both energy efficiency and thermal comfort. For instance, although the base case adheres to the Saudi building code, it registered the highest levels of cooling energy consumption and discomfort, underscoring the need for more green engineering solutions. Semi-open courtyards, standard courtyards, and wood Mashrabiya, on the other hand, performed better by using less cooling energy and minimising discomfort hours. Furthermore, integrating various courtyard configurations, with appropriate Mashrabiya materials, and effective energy efficiency measures are demonstrated the potential for achieving significantly improved outcomes. However, there is an obvious trade-off: while certain strategies effectively reduce cooling energy consumption, they may not equally enhance comfort, and vice versa.

Overall, these cumulative scatterplots serve as a valuable tool for visualising and comparing the performance of various energy efficiency measures in building design in conjunction with integrated traditional passive architectural designs. These analyses of data distribution facilitate the identification of optimal strategies for optimising energy use and enhancing occupant comfort, guiding informed decisions of sustainable green engineering solutions in the building industry.

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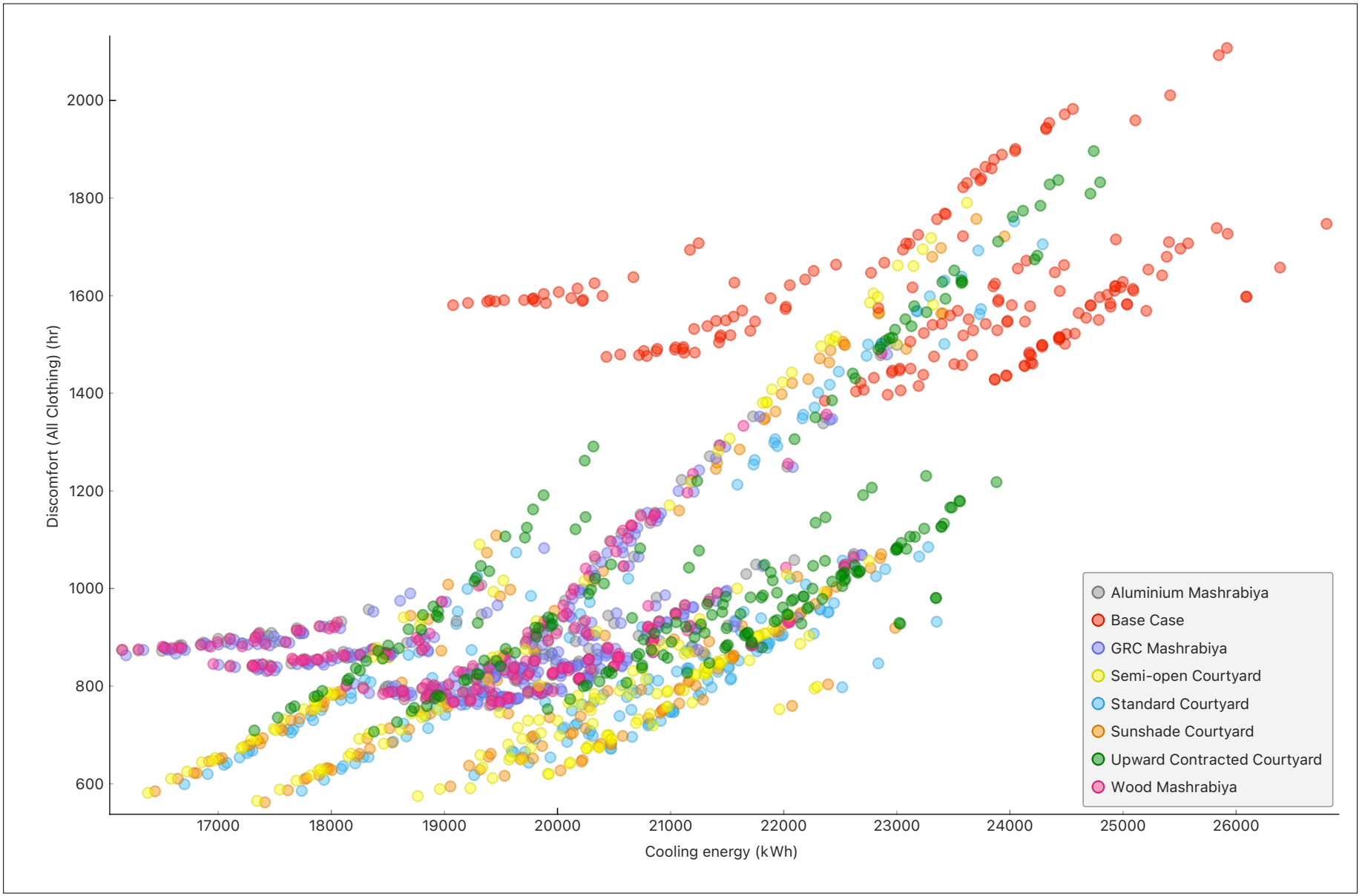


Figure 9.3. Combined Optimisation Analysis Results: Minimising Cooling Load and Discomfort Hours through Individual Passive Architectural Designs and EEM.

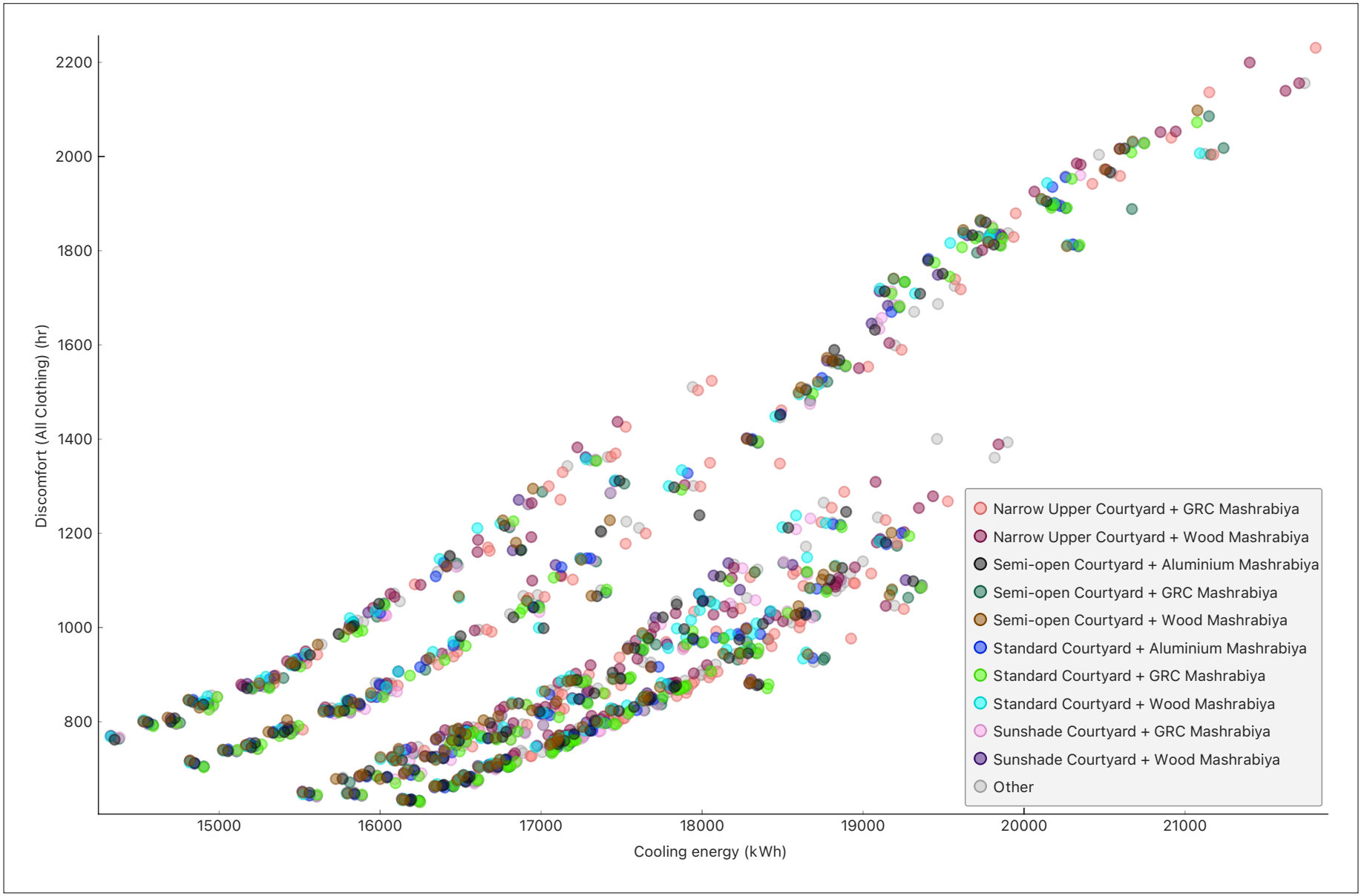


Figure 9.4. Combined Optimisation Analysis Results: Minimising Cooling Load and Discomfort Hours through Integration of Passive Architectural Designs and EEM.

In the third stage of the optimisation process, optimal strategies were simulative extracted by comparing the performance metrics of all evaluated designs from the preceding stages. The primary criteria for identifying the optimal strategics were their superior ability to minimise cooling energy loads and discomfort hours.

Therefore, Figure (9.5) outlines the Pareto front of the combined optimisation results, illustrating the trade-off between cooling energy load and discomfort hours. In this scatterplot, each grey dot represents a design configuration evaluated during the optimisation analysis. The distribution pattern observed in the grey dots provides insights into the strategic solutions and the inherent trade-offs between energy consumption and comfort. Clusters of grey dots suggest areas where small adjustments in design variables may lead to significant changes in performance. Nevertheless, the red dots on the scatterplot indicate the optimal strategics that form the Pareto front. These strategics represent the best possible trade-offs between the two target objectives: minimising cooling energy and reducing discomfort hours. This trade-off is crucial for making informed decisions, as it identifies the boundary of optimal performance, beyond which improvements in one objective would compromise the other.

For example, the lower left area of the scatterplot, where some red dots are clustered, represents strategics that achieve lower cooling energy consumption with relatively low discomfort hours. This area is particularly significant for stakeholders prioritising energy efficiency without substantially compromising occupant comfort. In contrast, the upper right area, with sparse red dots, indicates designs that, while minimising discomfort hours, require significantly higher energy consumption. This area might be considered by stakeholders for whom occupant comfort is paramount, even at the cost of increased energy use.

In conclusion, Figure (9.5) not only highlights the optimal strategies but also provides a comprehensive overview of the performance landscape. It enables decision-makers to understand the trade-offs and make informed choices that best align with their specific objectives, be it energy conservation, comfort maximisation, or an optimal balance of both. In addition, Table (A3. 1) at the appendix comprehensively details the parameters and variables of these optimal strategic solutions that were evaluated in the optimisation analysis. This table provides the design variables and their corresponding parameters, including the exact values of the cooling load and discomfort hours.

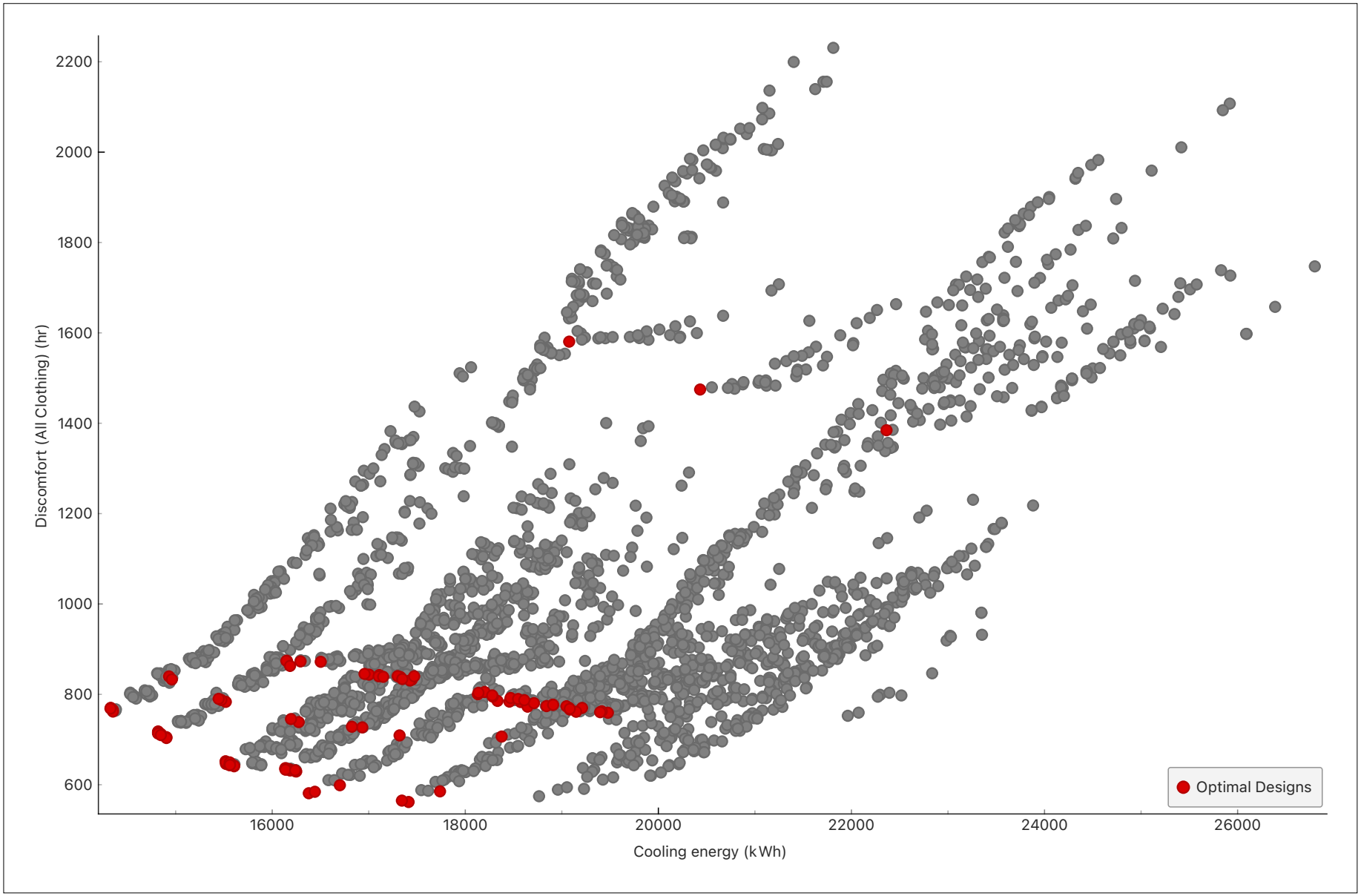


Figure 9.5. Simulated Pareto Front from Combined Optimisation Analysis Results.

9.2 THE FINAL STRATEGIC SOLUTIONS.

In order to determine the final strategic solutions from the optimal ones identified in the preceding three stages, a specific range was chosen: between 18,000 kWh of cooling load and 800 hours of discomfort. This range was selected to ensure that the evaluated designs fall within acceptable and practical performance parameters, thus qualifying them as final strategic solutions for further assessment. By focusing on this range, the assessment aims to filter out strategies that meet both energy efficiency and occupant thermal comfort and providing a balanced foundation for further evaluation and selection. Figure (9.6) shows the Pareto Front results and highlighting this final strategic solutions within this specified range. This graphic representation provides a clearer visualisation of how these strategics compare against each other in terms of their performance. Furthermore, Table (9.2) below provides a comprehensive breakdown of the parameters and variables for these final optimal strategic solutions evaluated in the optimisation analysis.

However, in order to effectively rank these final strategic solutions, prioritising key performance metrics (cooling load or occupant thermal comfort) is essential. For example, when evaluating cooling load, the Sunshade Courtyard with Aluminium Mashrabiya and glazing specified as 4T+0.3V+5TL (XDTB0159) series emerges as the top performer due to its superior performance. Conversely, in terms of enhancing occupant thermal comfort by minimising discomfort hours, the Sunshade Courtyard with glazing specified as 4T+0.3V+4TL (D80) series demonstrates superior effectiveness. Nonetheless, rankings may vary depending on the specific performance criteria prioritised in building design evaluations. These distinctions highlight the importance of aligning design choices with specific performance goals to optimise overall building performance.

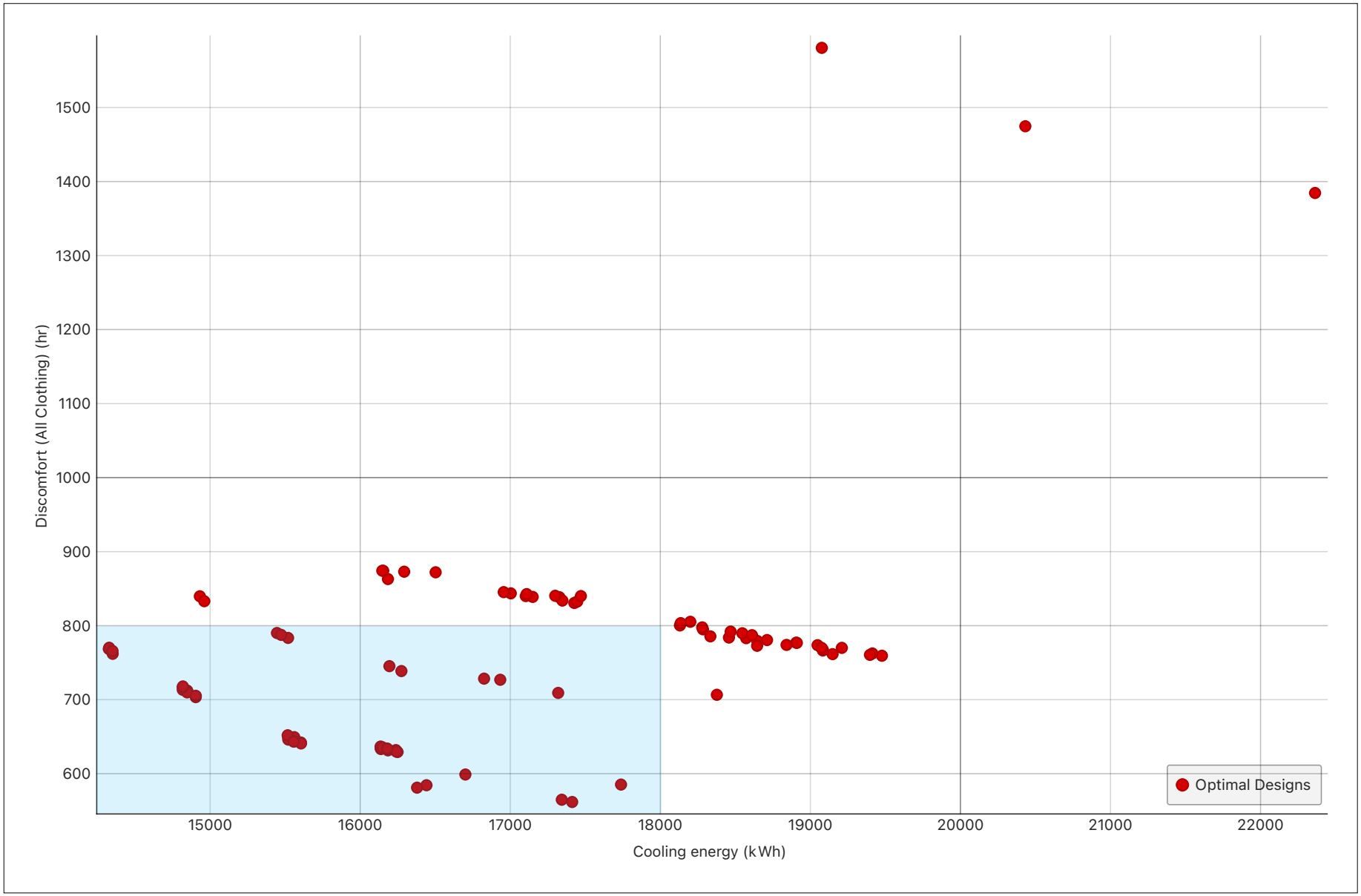


Figure 9.6. Optimal Pareto Front from Combined Optimisation Analysis, Highlighting Final Strategic Solutions Within the Specified Range.

Table 9.2. Details of Parameters and Variables for Optimal Final Strategic Solutions Chosen Within the Specified Range.

Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Insulation Type	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
42	1	Optimal Strategics	Standard Courtyard	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17738.18	585.29
112	7	Optimal Strategics	Standard Courtyard	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16700.93	598.90
65	3	Optimal Strategics	Semi-open Courtyard	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16378.88	581.13
71	3	Optimal Strategics	Semi-open Courtyard	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17343.49	564.84
62	3	Optimal Strategics	Sunshade Courtyard	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17412.61	561.76
103	7	Optimal Strategics	Sunshade Courtyard	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16441.76	584.41
135	9	Optimal Strategics	Upward Contracted Courtyard	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17319.33	709.14
98	4	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14817.53	713.28
127	6	Optimal Strategics	Standard Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14903.96	703.43
151	8	Optimal Strategics	Standard Courtyard + GRC Mashrabiya	4T+0.3V+4TL (S1.16) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16249.04	629.32
165	10	Optimal Strategics	Standard Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15562.45	643.78
191	12	Optimal Strategics	Standard Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14847.57	711.82
221	14	Optimal Strategics	Standard Courtyard + GRC Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16237.84	631.86
228	16	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15520.69	646.07
275	20	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14324.65	768.53
276	20	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16137.63	633.32
37	1	Optimal Strategics	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14846.60	712.33

Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Insulation Type	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
44	1	Optimal Strategics	Semi-open Courtyard + Aluminium Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16184.74	631.54
65	3	Optimal Strategics	Semi-open Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15560.68	649.36
126	6	Optimal Strategics	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14350.44	761.95
140	8	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15519.52	649.72
153	8	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16136.10	634.78
171	10	Optimal Strategics	Semi-open Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15605.03	642.08
207	13	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14818.34	717.89
243	16	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	4T+0.3V+4TL (S1.16) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16149.06	634.15
284	20	Optimal Strategics	Semi-open Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14904.28	705.25
37	2	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14817.36	716.53
41	2	Optimal Strategics	Sunshade Courtyard + Aluminium Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16180.66	633.93
63	3	Optimal Strategics	Sunshade Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14349.49	765.80
108	7	Optimal Strategics	Sunshade Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15556.54	643.31
119	7	Optimal Strategics	Sunshade Courtyard + GRC Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16241.04	629.81
128	8	Optimal Strategics	Sunshade Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14846.49	709.86
134	8	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14326.97	770.17
172	11	Optimal Strategics	Sunshade Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15605.64	640.86
190	12	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+4TL (S1.16) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16148.93	635.57

Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Insulation Type	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
199	13	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15516.79	651.90
212	14	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16135.80	636.65
80	4	Optimal Strategics	Narrow Upper Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15473.15	787.54
100	5	Optimal Strategics	Narrow Upper Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15519.40	783.43
127	7	Optimal Strategics	Narrow Upper Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15445.21	790.06
140	8	Optimal Strategics	Narrow Upper Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16274.61	738.65
156	9	Optimal Strategics	Narrow Upper Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16194.59	745.29
176	11	Optimal Strategics	Narrow Upper Courtyard + GRC Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16933.32	726.90
196	13	Optimal Strategics	Narrow Upper Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16825.54	728.41

9.3 FINAL STRATEGIC SOLUTIONS PERFORMANCE IN DIFFERENT SAUDI CLIMATE ZONES.

According to the Saudi Building Code (SBC-602), Saudi Arabia is divided into three climate zones: Zone (3) comprises the southern region and parts of the far north, Zone (2) includes the northern region and parts of the south, and Zone (1) covers the central region and all remaining areas. Table (9.3) below illustrates the selected cities that representing each climate zone as defined by the Saudi Building Code, along with their respective weather station information. Hence, the weather data from these stations would be used for evaluating the performance of final strategic solutions.

Table 9.3. Cities Selected to Represent Each Climate Zone of SBC-602 and Their Weather Station Data.

Country Saudi Arabia (SAU) Location	WMO Station ID	Latitude	Longitude	Saudi Building Code Climate Zone
RIYADH (Base Case)	404380	24.958	46.699	1
Dammam	404150	26.433	49.8	1
TABUK	403750	28.365	36.619	2
ABHA	411120	18.24	42.657	3

(Source: ASHRAE 169-2020 Stations and Climate Zones Data for Building Design Standards).

Therefore, the base case model employing the final strategic solutions that have been chosen in the previous section was assessed in these selected different climate zones based on the Saudi Building Code (SBC-602). This assessment aimed to determine how well these strategic solutions perform under the diverse climatic conditions specified by the code. By examining these solutions under varying environmental factors, the study aimed to understand their adaptability and efficiency, ensuring that the strategies meet the required standards and perform optimally across all specified climate zones.

Figure (9.7) showed the performance distinctions of these strategic solutions when implemented in diverse Saudi climate zones. Additionally, Table (9.5) provides a detailed breakdown of the optimal strategic solutions, including their parameters, variables, and specific values for cooling load and discomfort hours in Dammam, Tabuk, and Abha climate

zones. The results show significant variations in energy efficiency, thermal comfort levels, and overall building performance across the different climate zones compared to the base case located in Riyadh. Furthermore, Figure (9.8) highlights the differences observed after applying the base case across various Saudi climate zones, compared to the results from the optimal strategics.

For instance, in Riyadh, located in Climate Zone 1, results emphasise that passive traditional architectural techniques demonstrated superior performance in reducing cooling load and enhancing occupant thermal comfort compared to strategies designed for colder regions like Tabuk and Abha. In contrast, while these passive architectural designs worked well in most climate zones (Riyadh, Tabuk, and Dammam) in terms of reducing cooling load and enhancing occupant thermal comfort, the Abha climate zone witnessed a significant increase in discomfort hours despite a substantial reduction in cooling load. However, a more thorough analysis of the data from Abha's case indicated that the heating load had become as significant as the cooling load, which explains the observed increase in discomfort hours during the optimisation analysis. These findings confirm that there are serious opportunities that can be exploited by going beyond the basic requirements outlined in the SBC-602.

According to Saaty (2008) making any decision into the analytic hierarchy process comprises systematically establishing decision priorities, defining the goals, structuring a decision hierarchy from goals to alternatives, creating pairwise comparison matrices to evaluate the importance, and iteratively weighing and summarising priorities until final alternatives are identified.

Therefore, to effectively prioritise these design strategies that are adaptable to the various climatic conditions of Saudi Arabia, considering both performance indicators: cooling energy consumption and discomfort hours, the strategic alternatives marked by red circles in Figure (9.8) and highlighted in Table (A3. 2) at the appendix were selected for further theoretical discussion. It is worth mentioning that, since cooling energy and discomfort hours are on different units, the data were normalised before applying the priority weights to both performance indicators by utilising the equation (12) below. One of the pre-processing methods is data normalisation, which involves scaling or transforming the data to ensure that each feature contributes equally (Singh, Singh 2020). In our cases, the smallest grade would be the best strategy, as it represents the lowest combined normalised cooling energy and discomfort hours, which were the goals to minimise.

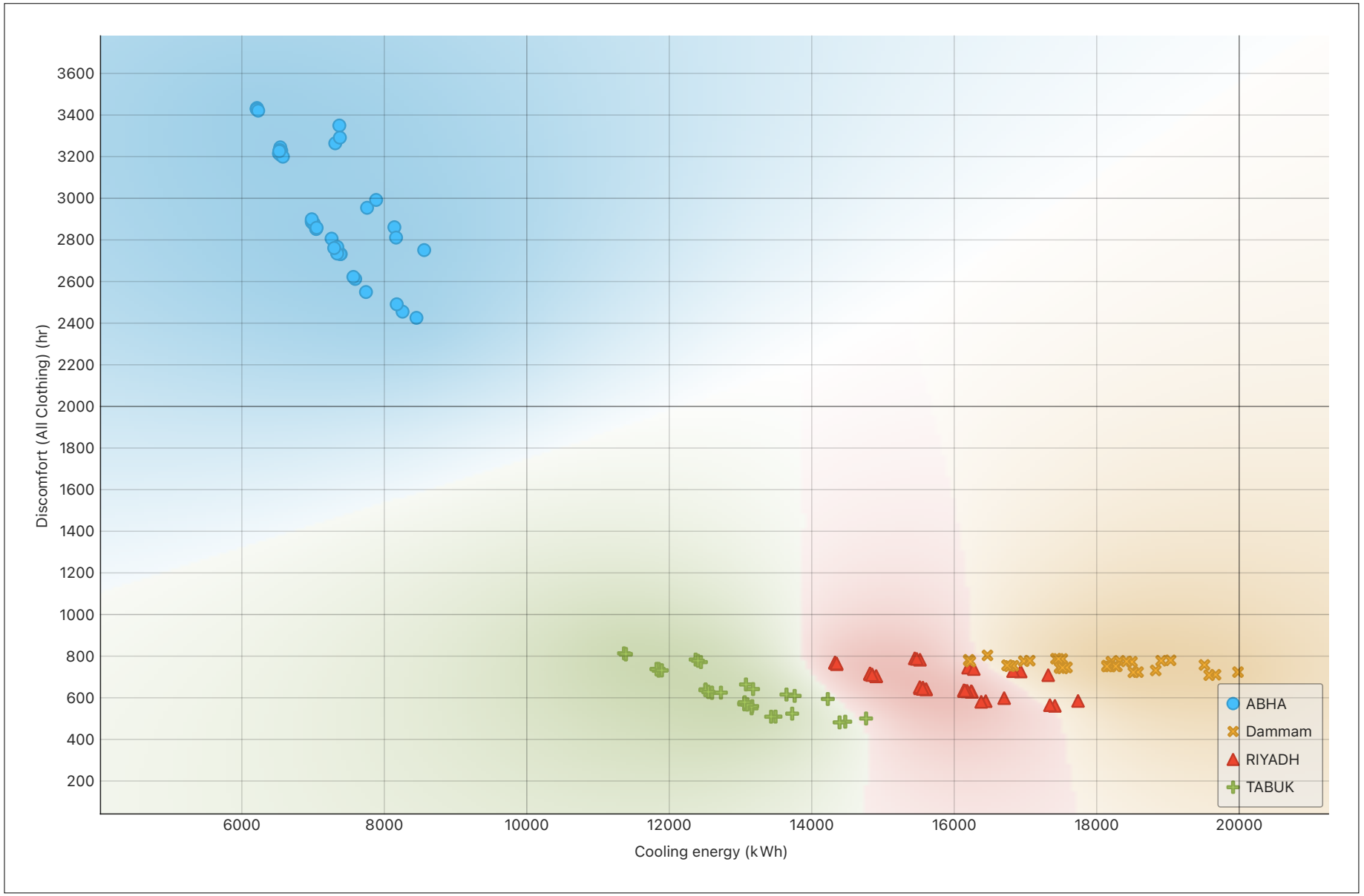


Figure 9.7. Evaluation of Optimal Final Strategic Solutions from Optimisation Analysis Across Different Saudi Building Code Climate Zones.

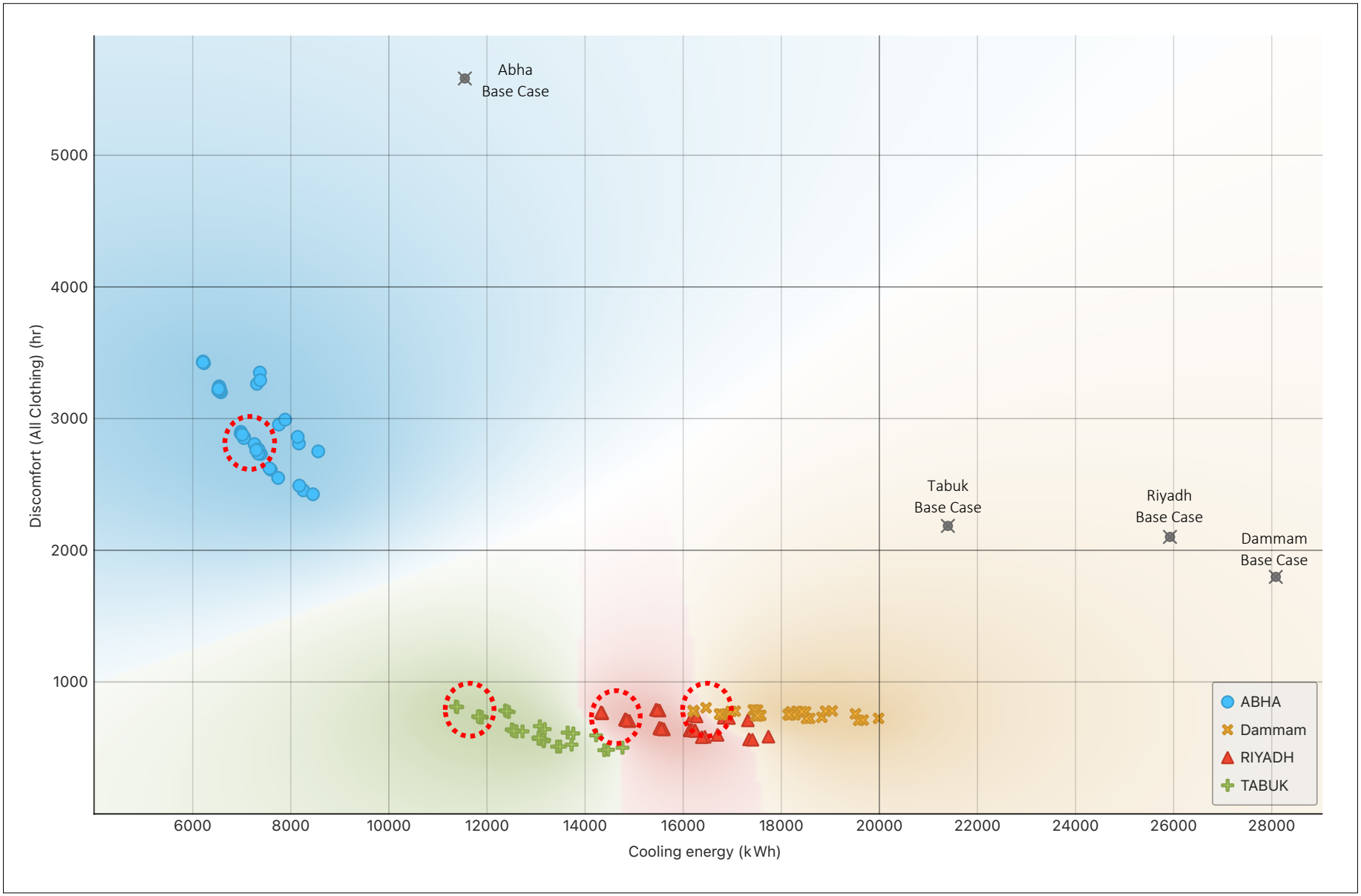


Figure 9.8. Evaluation of Optimal Final Strategic Solutions from Optimisation Analysis Across Different Saudi Building Code Climate Zones Compared to the Base Case.

$$MMN = \left\{ \frac{(x_C) - (min_{xc})}{(max_{xc} - min_{xc})} \times pw + \frac{(x_d) - (min_{xd})}{(max_{xd} - min_{xd})} \times pw \right\} \quad (12)$$

Where MMN (Min–Max Normalisation) The normalisation of the data used for rescaling.

x_C is the cooling load value.

min_{xc} is the minimum value of cooling load.

max_{xc} is the maximum value of cooling load.

pw is the percentage weight that adjustable in each case.

x_d is the discomfort hours value.

min_{xd} is the minimum value of discomfort hours.

max_{xd} is the maximum value of discomfort hours.

Table (9.6) and Figure (9.9) below conclude the analysis by presenting the rankings of strategies for Riyadh, Tabuk, Abha, and Dammam. It is worth mentioning that, since the insulation types for walls and roofs (70mm VIP for external walls and 140mm VIP for roofing) were consistent across all strategies, they have been eliminated from further consideration in this analysis. These strategic solutions were ranked based on achieving a balance between two critical performance indicators: cooling energy load (kWh) and discomfort hours. First, by assigning equal percentage priority weights to both performance indicators, the decision-makers treat energy efficiency and occupant comfort as equally important in their design and evaluation process. Second, cooling load was the primary ranking criterion with a 70% weight, as minimising energy usage is essential for sustainable and efficient green building design. However, in cases where designs exhibited equal cooling energy consumption, the secondary criterion, discomfort hours with a 30% weight, was employed to prioritise strategics. This ensured that energy efficiency was not achieved at the expense of occupant comfort. Finally, a 70% priority weight was assigned to discomfort hours, while the cooling load was given a 30% weight as the secondary ranking criterion. This approach allows decision-makers to prioritise thermal comfort in specific scenarios, such as Abha's case.

For example, in Riyadh, the “Standard Courtyard + Wood Mashrabiya” strategy in Case 4 emerged as having the lowest energy consumption by 14,324.65 kWh, although it has slightly higher discomfort hours of 768.53 h. This strategic used a 4T+0.3V+5TL (XDTB0159) glazing type, contributing to its efficiency. However, this solution is considered to be one of the worst strategies after applying a 70% priority weight to discomfort hours and a 30% to the cooling load as the secondary ranking criterion. In addition, the 'Semi-open Courtyard + Aluminium Mashrabiya' strategy in Case 6 exhibited a low cooling energy load of 14,350.44 kWh and slightly improved comfort, reducing discomfort hours to 761.95, while utilising the same glazing type.

In Tabuk, the "Standard Courtyard + Wood Mashrabiya" in Case 4 witnessed the best cooling energy efficiency, registering 11,365.04 kWh; however, it came with the maximum discomfort hours of 813.53. This solution utilises a 4T+0.3V+5TL (XDTB0159) glazing type. This was followed by the "Semi-open Courtyard + Aluminium Mashrabiya" in Case 6 that offered an enhanced balance, with slightly higher cooling energy consumption of up to 11,389.59 kWh while improving the comfort by reducing the discomfort hours to 807.89 h, utilising similar glazing type.

In Abha, the "Standard Courtyard + Wood Mashrabiya" in Case 2 excelled in cooling energy efficiency, achieving the lowest cooling energy load by 6,981.22 kWh, however, accompanied by the highest discomfort hours of 2,890.25. This strategy employed the 3T+0.76P+3T+12Ar+4TL (S1.10) glazing type, that even though energy efficient, does not fully address comfort. In contrast, the "Sunshade Courtyard + Wood Mashrabiya" in Case 12 provided slightly improved discomfort hours up to 2,884.69 with almost similar cooling energy consumption of 6,983.11 kWh, using similar glazing type.

In Dammam, the “Sunshade Courtyard + Aluminium Mashrabiya” employing the 4T+0.3V+5TL (XDTB0159) series glazing type in Case 8, emerged as the top-ranked strategic solution that consumed up to 16,226.26 kWh of cooling energy. However, it had relatively high discomfort hours, reaching 774.12 h. Similarly, the “Standard Courtyard + Wood Mashrabiya” in Case 4 performed slightly lower cooling energy consumption of 16,205.53 kWh and slightly higher discomfort hours of 782.58 h, employing the same glazing type as the former. This suggests that the standard courtyard with wood Mashrabiya might be an excellent solution because of its energy efficiency while maintaining similar levels of thermal discomfort.

Overall, the energy efficiency measures within the building envelope constitute a significant factor in improving both cooling load and thermal comfort level. Moreover, the application of traditional passive architectural solutions across the selected Saudi cities proves its potential to provide a more balanced approach to design that integrates effective energy use while maintaining an acceptable thermal comfort level. Moreover, the glazing type in a building used across the evaluated Saudi cities plays a critical role in affecting both cooling energy performance and occupants' comfort. However, applying appropriate weightings to prioritise between indicators (cooling load or discomfort hours) based on building requirements is essential for decision-makers to select optimal alternatives, as explained in the Riyadh case above and highlighted in Table (9.4) and Figure (9.9).

Table 9.4. Ranking of Optimal Final Strategic Solutions Across Different Saudi Climate Zones After Normalising and Applying Different Weights to Both Performance Indicators Cooling Energy (kWh) and Discomfort Hours.

Case Number	Parameter	Glazing type	External Wall Insulation Type (EIFS)	Flat Roof Insulation Type	Cooling energy (kWh)	Discomfort (All Clothing) (hr)	Total Score (Apply Weights, 50% for Cooling and 50% for Discomfort)	Total Score (Apply Weights, 70% for Cooling and 30% for Discomfort)	Total Score (Apply Weights, 30% for Cooling and 70% for Discomfort)
				RIYADH					
Case 1	Standard Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm VIP	140mm VIP	14817.53	713.28	0.998	0.640	0.358
Case 2	Standard Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm VIP	140mm VIP	14903.96	703.43	0.999	0.700	0.300
Case 3	Standard Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm VIP	140mm VIP	14847.57	711.82	1.028	0.669	0.359
Case 4	Standard Courtyard + Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm VIP	140mm VIP	14324.65	768.53	0.975	0.293	0.683
Case 5	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm VIP	140mm VIP	14846.60	712.33	1.034	0.670	0.364
Case 6	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm VIP	140mm VIP	14350.44	761.95	0.921	0.294	0.627
Case 7	Semi-open Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm VIP	140mm VIP	14818.34	717.89	1.068	0.661	0.407
Case 8	Semi-open Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm VIP	140mm VIP	14904.28	705.25	1.027	0.708	0.319
Case 9	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm VIP	140mm VIP	14817.36	716.53	1.046	0.654	0.392
Case 10	Sunshade Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm VIP	140mm VIP	14349.49	765.80	0.977	0.310	0.667
Case 11	Sunshade Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm VIP	140mm VIP	14846.49	709.86	0.997	0.659	0.338
Case 12	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm VIP	140mm VIP	14326.97	770.17	1.004	0.303	0.701
				TABUK					
Case 1	Standard Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series (3)	70mm VIP	140mm VIP	11821.51	738.29	0.962	0.633	0.329
Case 2	Standard Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series (3)	70mm VIP	140mm VIP	11892.11	731.16	1.010	0.701	0.309
Case 3	Standard Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series (3)	70mm VIP	140mm VIP	11853.72	736.61	1.003	0.670	0.333
Case 4	Standard Courtyard + Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series (4)	70mm VIP	140mm VIP	11365.04	813.53	1.000	0.300	0.700
Case 5	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm VIP	140mm VIP	11850.70	729.87	0.917	0.642	0.275
Case 6	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm VIP	140mm VIP	11389.60	807.90	0.979	0.312	0.667
Case 7	Semi-open Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm VIP	140mm VIP	11822.62	737.30	0.953	0.631	0.321
Case 8	Semi-open Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm VIP	140mm VIP	11894.70	731.95	1.025	0.707	0.317
Case 9	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm VIP	140mm VIP	11822.41	737.05	0.949	0.630	0.319
Case 10	Sunshade Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm VIP	140mm VIP	11391.00	810.32	1.011	0.323	0.688
Case 11	Sunshade Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm VIP	140mm VIP	11849.70	738.85	1.022	0.673	0.350
				ABHA					
Case 1	Standard Courtyard + GRC Mashrabiya	4T+0.3V+4TL (S1.16) series (1)	70mm VIP	140mm VIP	7381.43	2731.83	1.000	0.700	0.300
Case 2	Standard Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm VIP	140mm VIP	6981.22	2890.25	0.946	0.284	0.663
Case 3	Semi-open Courtyard + Aluminium Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm VIP	140mm VIP	7338.75	2738.71	0.935	0.638	0.297
Case 4	Semi-open Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm VIP	140mm VIP	7007.39	2878.37	0.941	0.308	0.632
Case 5	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm VIP	140mm VIP	7336.64	2751.94	1.008	0.658	0.351
Case 6	Semi-open Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm VIP	140mm VIP	6981.89	2899.21	1.002	0.301	0.700
Case 7	Semi-open Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm VIP	140mm VIP	7049.86	2858.24	0.927	0.347	0.580
Case 8	Semi-open Courtyard + Wood Mashrabiya	4T+0.3V+4TL (S1.16) series	70mm VIP	140mm VIP	7296.23	2760.87	0.961	0.603	0.358
Case 9	Sunshade Courtyard + Aluminium Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm VIP	140mm VIP	7338.06	2734.43	0.907	0.629	0.278
Case 10	Sunshade Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm VIP	140mm VIP	7010.78	2878.22	0.948	0.314	0.634
Case 11	Sunshade Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm VIP	140mm VIP	7042.94	2852.34	0.874	0.324	0.550
Case 12	Sunshade Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm VIP	140mm VIP	6983.11	2884.69	0.918	0.277	0.641
Case 13	Sunshade Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm VIP	140mm VIP	7304.63	2764.90	1.006	0.625	0.381
				DAMMAM					
Case 1	Standard Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series (3)	70mm VIP	140mm VIP	16745.93	756.31	0.951	0.631	0.320
Case 2	Standard Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series (3)	70mm VIP	140mm VIP	16831.06	753.93	1.041	0.712	0.329
Case 3	Standard Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series (3)	70mm VIP	140mm VIP	16777.01	752.96	0.936	0.646	0.290
Case 4	Standard Courtyard + Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series (4)	70mm VIP	140mm VIP	16205.53	782.58	0.595	0.179	0.416
Case 5	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm VIP	140mm VIP	16776.74	753.02	0.937	0.646	0.290
Case 6	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm VIP	140mm VIP	16466.52	803.59	1.418	0.592	0.825
Case 7	Semi-open Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm VIP	140mm VIP	16742.50	755.63	0.932	0.623	0.309
Case 8	Sunshade Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm VIP	140mm VIP	16226.26	774.12	0.465	0.153	0.312
Case 9	Sunshade Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm VIP	140mm VIP	16779.96	751.81	0.918	0.643	0.276
Case 10	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm VIP	140mm VIP	16204.87	779.25	0.530	0.159	0.371



Figure 9.9. Ranking of Optimal Final Strategic Solutions Across Different Saudi Climate Zones After Normalising and Applying Different Weights to Both Performance Indicators Cooling Energy (kWh) and Discomfort Hours.

9.4 THE INTEGRATION OF THE THEMATIC AND SIMULATION ANALYSES.

To achieve the research project objectives and answer the research questions, the methodology incorporates both expert surveys and simulation methods as part of the case study approach. Data collection and analysis were executed concurrently; however, each was subjected to independent analysis, shaping in a convergent parallel design that enhances the robustness and validity of the findings as shown in Figure (9.10) below. The researcher compares and contrasts the findings to see how they complement, converge, or diverge from each other. The primary objective is to integrate the two datasets to provide a complete understanding of the research outcomes.

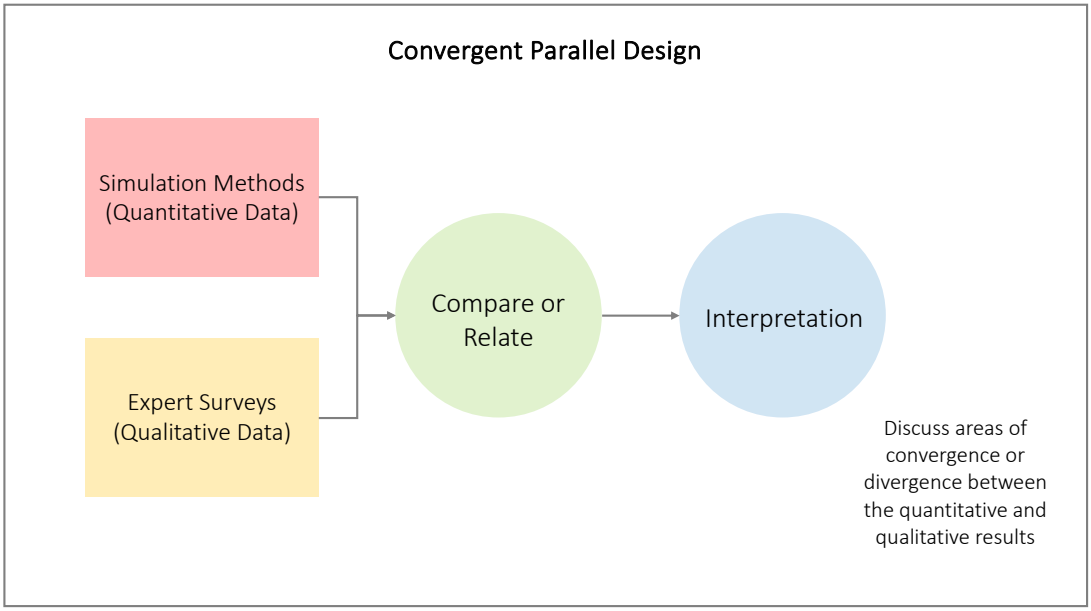


Figure 9.10. Concept of Convergent Parallel Design to Integrate Both Methods.

Thus, the data from each method is summarised and displayed in a matrix following the meta-matrix approach of Miles's et al. (2014). In this mixed methods matrix, the rows represent the parameters of analysis, and the columns display the thematic analysis outcomes derived from qualitative data alongside the results of the simulation methods.

Table (9.5) below presents a matrix integrating the outcomes of both thematic and simulation analyses. This matrix is designed to draw comparisons and highlight contrasts of the findings from thematic analysis (qualitative insights or research themes) with simulation outcomes (quantitative or model-based predictions). Each intersection of the matrix highlights how a given theme (columns) correlates with a specific simulation outcome (rows). The

coloured dots (red, blue, green and yellow) indicate varying levels of relevance and importance. This table provides a breakdown of the effects of varying levels of implementation of traditional passive architectural design and energy efficiency measures in the Saudi Arabian building case, focusing on both cooling energy consumption and discomfort hours.

Traditional passive architectural design has been divided into three levels of implementation. First, low implementation, constrained by limited resources and minimal application, results in minimal reductions in cooling energy load of up to 12% and in discomfort hours of up to 28%. Second, moderate implementation, characterised by a balanced application of passive strategies aligning with existing building codes, results in moderate reductions of up to 16% in cooling energy load and up to 13% in discomfort hours. Finally, high implementation involving extensive integration of passive design parameters and strict adherence to building codes (and even exceeding them) achieves significant reductions, with a decrease of up to 20% in cooling energy load and 6% in discomfort hours.

On the other hand, the implementation of energy efficiency measures at low levels that are constrained by financial considerations results in reductions up to 9% in cooling energy load and up to 13% in discomfort hours. Moderate implementation, reflecting gradual improvements aligned with evolving building codes, leads to greater reductions, achieving 19% in cooling energy load and 29% in discomfort hours. Finally, a high implementation that is distinguished by advanced energy efficiency measures and comprehensive code adherence could achieve significant reductions of up to 28% in cooling energy load and 35% in discomfort hours. However, the combination of both approaches in the case study achieved the greatest outcomes, with potential reductions of up to 49% in cooling energy load and 73% in discomfort hours.

Table 9.5. The Matrix Integrating Thematic and Simulation Analyses Outcomes.

Parameters Implementation Level	Associated Theme(s)	Code Count			Cooling Energy Reduction (%)	Discomfort Hours Reduction (%)	Scenario Description
Low Traditional Passive Architectural Design	- Managing consumers requirements.	8	🔴	🟢	Up to -12%	Up to -28%	Minimal use of passive designs due to limited resources or constraints.
	- Having Sustainability awareness.	16	🔵	🟢			
Moderate Traditional Passive Architectural Design	- Navigating Implementation Complexities	26	🔴	🟡	Up to -16%	Up to -13%	Balanced implementation of passive strategies, aligning with current building codes and sustainability goals.
	- Enhancing awareness and addressing undesirable behaviour.	41	🔵	🟢			
High Traditional Passive Architectural Design	- Having comprehensive obliged Building Code.	38	🔴	🟡	Up to -20%	Up to -6%	Extensive use of passive designs, fully leveraging natural resources and strict adherence to building codes.
	- Considering Environmentally resources.	20	🔵	🟡			
	- Appreciating Stakeholder Expectations	28	🔵	🟡			
Low Energy Efficiency Measures	- Optimising Returns, Minimising Initial Costs	51	🔵	🟢	Up to -9%	Up to -13%	Basic energy efficiency measures, constrained by budget or design limitations.
	- Supply Chain & Design Constraints	3	🔵	🟡			
Moderate Energy Efficiency Measures	- Building Code Evolution & adherence	41	🔴	🟡	Up to -19%	Up to -29%	Cost-effective measures with moderate improvements in energy savings and comfort.
	- Managing consumers requirements.	8	🔵	🟢			
High Energy Efficiency Measures	- Having comprehensive obliged Building Code.	38	🔴	🟡	Up to -28%	Up to -35%	Advanced energy efficiency measures, delivering significant improvements in both energy use and comfort.
	- Supply Chain & Design Constraints	3	🔵	🟡			
	- Contractors Supportance.	18	🔵	🟡			
Combination of both	- ALL	N/V			Up to -49%	Up to -73%	

🔴 Direct Effect on Cooling Energy Reduction
🟢 Direct Effect on Discomfort Hours Reduction
🔵 Indirect Effect on Cooling Energy Reduction
🟡 Indirect Effect on Discomfort Hours Reduction

Chapter 10: Research Conclusion

In concluding this research project, it is essential to critically evaluate the extent to which the aim and objectives were fulfilled. This requires a comprehensive assessment of the research findings in relation to the original research questions outlined in Section 1.4 to ensure they have been appropriately addressed. Therefore, Section 10.1 discusses the answers to research questions in the context of research project outcomes. Following this, Section 10.2 highlights the contributions of this research to the broader scholarly context by examining the theoretical, methodological, and practical implications of its outcomes. Subsequently, Section 10.3 provides the key recommendations to all parties involved in the Saudi building industry. However, Section 10.4 presents a detailed of the limitations encountered during the PhD research journey, such as methodological challenges, sample size, data availability, and other factors that may have influenced the results. Finally, Section 10.5 explores how the outcomes of this thesis may offer valuable insights for future research and potential advancements in the field.

10.1 RESPONSES TO THE RESEARCH QUESTIONS.

This section examines the findings stemming from the research project to systematically address each of the key questions formulated at the outset of the study. The responses to these questions are directly linked to the aims and objectives outlined previously. The following discussion provides a structured evaluation of how the research questions were addressed, offering insights into the alignment between the research objectives and the resultant data.

1. *RQ1: What is the state of the Saudi building industry, including its current challenges and problems? How can the new KSA residential building be classified in a sustainability context? Recently, many developers have claimed that their projects constitute sustainable buildings, including the Saudi-based ROSHN housing project; are they really 'green' or sustainable?*

Saudi Arabia's extreme desert climate constitutes a significant challenge for building design and energy consumption. With temperatures frequently exceeding 48°C, the reliance on air conditioning becomes a critical concern. This dependency not only drives considerable energy consumption but also exposes a systemic flaw in the sector's approach to climate adaptation. Buildings are often designed with minimal regard for passive cooling strategies, relying instead on energy-intensive HVAC systems to maintain indoor comfort. This reliance highlights a broader issue: the lack of innovative architectural solutions that address the specific climate challenges of the region. The heavy reliance on air conditioning also underscores the broader issue of fossil fuel dependency. Despite Vision 2030's push toward a more diversified energy mix, the transition has been slow, and the building sector remains heavily reliant on electricity generated from fossil fuels. This continued dependence exacerbates environmental degradation and highlights a significant gap between policy ambitions and practical implementation.

Compounding these issues is the regulatory framework, particularly the Saudi Building Code (SBC). Recent updates to the SBC, including the introduction of the SBC-602 section focused on energy-efficient building envelopes, represent a positive step forward. However, the effective implementation and enforcement of these standards are inconsistent. Moreover, the "Mostadam" sustainability rating system, designed to enhance the environmental performance of new buildings, aims to address these shortcomings. While it represents an important advance, its impact is depending upon widespread adoption and rigorous adherence. However, the real-world application of this rating often reveals discrepancies between theoretical performance and actual outcomes, indicating a need for more robust implementation and monitoring practices.

Furthermore, cultural and economic factors further complicate the pursuit of sustainability. Saudi Arabia's residential designs are heavily influenced by cultural expectations of luxury and privacy, which often conflict with the principles of energy efficiency. The emphasis on high-end, energy-intensive features in residential architecture reflects clients' expectations that prioritise immediate economic and social gains over long-term environmental sustainability. This tension between traditional Saudi values and sustainability goals highlights the challenges of balancing cultural preferences with the need for energy-efficient design.

Therefore, the Saudi building industry is at a crossroads, shaped by ambitious goals under Vision 2030 yet constrained by deep-rooted challenges that complicate the transition toward sustainability. Despite notable efforts to modernise, the sector struggles with fundamental issues in climate adaptation, regulatory enforcement, and cultural expectations, which collectively challenge its capacity to meet contemporary sustainability demands.

On the other hand, one of the most obvious issues with new residential building projects including the ROSHN project is its lack of cultural and social integration. Saudi Arabia has distinct cultural preferences, such as the importance of privacy, luxury, and traditional aesthetics, which play a crucial role in residential architecture. Hence, in a country where cultural values significantly influence residential design, the project's sustainability claims are insufficient because they do not address these critical aspects appropriately.

Although ROSHN's project adheres to the Saudi Building Code (SBC), this compliance does not necessarily indicate leading-edge sustainability. The project's adherence to the regulations should be seen as a starting point rather than an endpoint. True sustainability requires going beyond the minimum standards set by regulatory frameworks. The project's current focus on meeting existing regulations without pushing for additional improvements or embracing cutting-edge technologies suggests a limited vision of sustainability. By not seeking to exceed SBC standards or explore new, innovative approaches to green building, ROSHN's project may miss opportunities to make a more substantial impact on environmental and social sustainability. Hence, a project that is truly sustainable should be designed with the flexibility to adapt to future environmental standards and technological advancements. New residential building projects including the ROSHN's approach appear to lack a forward-looking perspective that embraces ongoing improvements and adaptability. If the building's design and technologies are static and do not accommodate future advancements or changes in sustainability practices, its long-term viability as a green development is questionable.

2. *RQ2: How can new buildings apply energy efficiency measures, renewable energy, and traditional passive architectural design? Would it be possible to implement a complex retrofitting strategy without affecting a building's architectural values?*

The experts' survey highlighted that the Building Code Evolution & Adherence theme as a pivotal element, indicating that the current Saudi Building Code does not adequately mandate or incentivise energy efficiency measures or the integration of renewable energy. This indicates a fundamental regulatory gap that must be addressed to ensure that new buildings can adopt energy-efficient technologies and renewable energy sources. Without a stronger regulatory push, the application of these technologies will likely remain limited. The call for evolving building codes suggests that regulatory frameworks need to be updated to encourage the use of eco-friendly materials, energy-saving techniques, and renewable energy systems, such as solar panels. However, some experts mention that certification programmes like LEED or Estidama could motivate the application of energy efficiency measures, renewable energy, and traditional passive architectural design to enhance sustainability efforts in new buildings. These certification frameworks could serve as a powerful tool by providing benchmarks for architects, developers, and builders to follow. By pursuing these certification criteria, developers will have a clear roadmap for applying energy-efficient measures and green engineering solutions.

Moreover, a notable concern from the survey participants is the inadequacy of the Saudi Building Code in promoting Saudi traditional passive architectural design. These traditional passive techniques, for example, Mashrabiya as shading, and courtyard, are effective elements of sustainable design, particularly in climates like Saudi Arabia's as the simulation results confirmed. However, without regulatory requirements or incentives to adopt these strategies, developers may neglect them in favour of more contemporary approaches that ignore sustainability. For new residential buildings to successfully apply traditional passive architectural techniques alongside modern energy efficiency and renewable energy solutions, building codes must be reformed to actively promote the integration of them. This would ensure that traditional passive designs—tailored to local environmental conditions—can complement modern technologies. For example, designing buildings to maximise shading or natural airflow can reduce the need for air conditioning, while simultaneously integrating solar panels can enhance energy efficiency. The evolution of the building code to include these measures would create a holistic approach to energy-efficient building design.

Although the survey does not explicitly discuss retrofitting, the emphasis on adapting building codes and incorporating sustainable options provides indirect insights into the

feasibility of retrofitting existing structures. The experts' call for flexibility and innovation in the regulatory framework implies that with appropriate guidelines, retrofitting could be possible while preserving a building's architectural values. However, retrofitting strategies must be carefully designed. As the emergence of the survey's "Considering Environmental Resources theme" indicates a growing industry shift towards green engineering solutions, driven by government initiatives and community awareness. Hence, a comprehensive retrofitting strategy would require similar support from both the government and the community, alongside regulatory adjustments that allow for innovation in how buildings are upgraded. For example, retrofitting might involve installing energy-efficient systems, such as advanced insulation or renewable energy systems, while maintaining the external or internal features that define the building's architectural values. With the right balance, it is possible to enhance energy performance without sacrificing the aesthetic or value of the building.

However, a significant challenge identified in the survey pertains to the theme of "Contractors Supportance", which underscores the necessity of a skilled workforce adept at implementing green technologies. The success of retrofitting strategies relies substantially on the availability of professionals trained in renewable energy systems, energy efficiency upgrades, and traditional passive architectural design. Without such expertise, even the most carefully developed retrofitting plans may encounter difficulties during execution. Addressing this issue may require the implementation of financial incentives, such as tax breaks or subsidies, for both contractors and developers. Developing a skilled workforce involves considerable investment in terms of time and financial resources. Financial incentives can help alleviate these costs, thereby encouraging the training of labourers or the hiring of specialists in sustainable building practices. For instance, developers might be more motivated to invest in advanced energy-saving technologies or renewable energy systems if they benefit from tax breaks that offset the costs associated with employing specialised contractors.

3. *RQ3: To what extent can energy consumption and thermal comfort be enhanced by a single unique integrated model that combines energy efficiency measures, renewable energy, and traditional passive architectural design for the case of Saudi Arabia?*

Simulation data indicates that the efficacy of traditional passive architectural design is significantly influenced by the extent of its implementation. In cases of minimal

implementation, reductions in cooling energy consumption decrease by up to –12%, while discomfort hours decrease by –28%. These findings suggest that even the basic application of traditional passive design measures can provide noticeable energy savings and comfort enhancements. However, the impact of such measures remains limited without broader application. Moderate implementation, aligned with existing building codes and reflecting a balanced adoption of traditional passive strategies, leads to reductions of up to –16% in cooling energy consumption and up to –13% in discomfort hours. This level of implementation underscores the importance of adhering to regulatory standards in achieving notable improvements in building performance. Conversely, high implementation, characterised by extensive integration of traditional passive design principles and strict adherence to building codes, results in more substantial reductions in cooling energy load, up to –20%. However, it produces only modest additional decreases in discomfort hours (–6%), indicating a diminishing return in terms of occupant comfort. These findings highlight that while traditional passive design plays a critical role in reducing energy consumption, its impact on thermal comfort is constrained unless combined with other strategies.

Energy efficiency measures, including the use of advanced building materials, enhanced wall systems, and high-performance glazing, play a crucial role in optimising energy consumption. The simulation results show that such improvements have more significant energy savings and improvements in thermal comfort compared to traditional passive design alone. Low implementation of energy efficiency measures achieves reductions in cooling energy consumption of up to –9% and decreases discomfort hours by up to –13%. Moderate implementation, representing gradual advancements, results in reductions of up to –19% in energy consumption and up to –29% in discomfort hours. In contrast, high implementation, incorporating advanced technologies and full compliance with comprehensive building codes, produces the most significant reductions up to –28% in cooling energy consumption and up to -35% in discomfort hours. This evidence underscores the superior efficacy of advanced energy efficiency measures in improving both energy performance and occupant comfort. Compared to traditional passive architectural design, energy efficiency measures prove more effective in reducing discomfort hours, thereby emphasising their critical role in enhancing the indoor thermal environment.

However, to maximise their effectiveness, energy efficiency measures should be integrated with renewable energy systems Moreover, integrating traditional passive architectural design with energy efficiency measures yielded the most significant benefits compared to the baseline building condition, reducing cooling energy consumption by up to –49% and discomfort hours by up to –73%. This integration stemmed from the complementary effects of both strategies: while passive design reduces energy demand through natural means, energy efficiency measures optimise mechanical systems to further decrease energy consumption and enhance comfort. Furthermore, the incorporation of renewable energy further enhances building energy performance by offsetting remaining energy demand through local electricity generation, which can reach up to 80% of base-case energy consumption. While traditional passive design and energy efficiency measures reduce overall energy demand, renewable energy systems provide an additional solution by generating the remaining required energy.

In conclusion, the simulation data confirms that while each strategy— traditional passive architectural design, energy efficiency measures, and renewable energy systems—offers significant individual benefits, the most substantial impact is achieved when they are applied together. The integrated model represents a highly effective approach to enhancing the energy performance and thermal comfort of new residential buildings in Saudi Arabia.

4. ***RQ4: Even though the simulation results of the current research project and most of the previous studies evaluated through the literature review confirm that green engineering solutions (such as passive traditional architectural design, energy-efficient measures, and low-carbon technology) have a significant positive impact on energy performance and thermal comfort, why have these proposed green engineering solutions not been implemented in new residential building projects in KSA to exploit their benefits? (Barriers to application)***

An examination of expert survey data revealed several critical barriers that clarify this phenomenon. The primary barrier identified is the substantial economic challenge posed by the high upfront costs of green engineering solutions. Survey participants consistently highlighted that the initial financial investment required for these technologies often outweighs the perceived immediate financial returns. This economic obstacle is compounded

by a lack of awareness regarding the long-term economic benefits and cost savings associated with these solutions. Consequently, stakeholders—including architects, developers, and clients—may exhibit hesitated to adopt green engineering practices due to concerns about financial issue and uncertainty regarding return on investment.

Another significant obstacle is the absence of comprehensive and supportive building codes. The survey data indicated that without obvious regulations or incentives embedded within building codes, there is insufficient motivation for stakeholders to prioritise or implement green solutions. Comprehensive building codes that provide clear standards and guidelines could facilitate the integration of sustainable practices.

In addition, awareness and user behaviour also emerge as critical barriers. The survey yielded a general lack of engagement and understanding among users regarding the advantages of green engineering solutions. This insufficiency in knowledge contributes to a resistance to invest in energy-efficient and sustainable options. Clients' hesitancy to afford higher costs, coupled with inadequate awareness, obstructs the broader adoption of green technologies. Thus, effective community engagement and educational programs are essential to bridge this knowledge gap and promote a more supportive environment for the implementation of these solutions.

To address these barriers effectively, a holistic approach is required:

Regulatory Reforms: Establishing and enforcing comprehensive building codes that mandate or incentivise the integration of green engineering solutions could significantly enhance their adoption. Clear regulatory frameworks would provide necessary directives for incorporating sustainable practices in new residential projects.

Economic Incentives: Financial mechanisms such as subsidies, tax incentives, or grants could mitigate the high initial costs associated with green technologies. Economic incentives would make these solutions more attractive to developers and designers by improving their financial feasibility.

Enhanced Awareness: Increasing awareness through targeted educational and outreach programs is crucial. Informational campaigns, workshops, advertisements, and training sessions can progress stakeholders' understanding of the long-term benefits of green engineering solutions and shift perceptions towards their adoption.

Behavioural Change: Addressing user behaviour through education and engagement initiatives can promote more active participation in energy-saving practices. Developing strategies to modify consumer attitudes towards green technologies is essential for creating a market environment conducive to their widespread implementation.

5. *RQ5: How can this research help develop a future roadmap for enhancing new Saudi residential building projects by going beyond the current building code to explore the potential of comprehensive, sustainable design?*

This research can help develop a future roadmap for enhancing new Saudi residential building projects by providing a comprehensive understanding of how to integrate sustainability aspects beyond the requirements of the current Saudi Building Code (SBC). By identifying gaps in existing standards, evaluating sustainable design practices, and exploring innovative materials, technologies, and traditional passive architectural solutions, this research provides actionable insights to optimise energy efficiency and thermal comfort. The study investigated best practices in sustainable context, including innovative materials, traditional passive architectural strategies, and advanced energy systems, tailored to the unique climatic, cultural, and economic case of Saudi Arabia. This holistic approach aims to explore how residential buildings can achieve optimal energy use, taking into consideration the acceptable indoor environmental quality, and integrate renewable energy sources more effectively that current regulations neglect.

Furthermore, the research critically examined the selection of parameters within the dimensions of sustainable design: socio-cultural, economic, and environmental. By exploring how local customs, lifestyle preferences, and environmental conditions can be integrated into building design, the study can propose a context-specific framework that aligns with both global sustainability goals and local values. This is essential in promoting community acceptance and ensuring that sustainable design solutions are not only technically feasible but also socially and culturally appropriate.

The final outcome—a comprehensive and phased roadmap—might not only offer practical guidelines for architects, engineers, and planners but also propose revisions to the Saudi building code itself. For example, by moving beyond regulatory standards toward performance-based criteria or competition between the developers, the roadmap advocates

for a flexible yet rigorous framework that encourages innovation while maintaining regulatory oversight. This approach ensures that future residential projects can be both resilient and adaptable to changing environmental, social, and technological landscapes.

In summary, this research contributes critically to the development of a future roadmap for enhancing new Saudi residential building projects by going beyond the current Saudi building code to explore the unexploited potential of comprehensive sustainable design. By addressing technical, cultural, economic, and regulatory dimensions, the research provides a holistic vision for the future of residential buildings in Saudi Arabia, presenting the country as a leader in sustainable development aligned with the national priorities of Saudi Vision 2030.

10.2 CONTRIBUTION TO KNOWLEDGE

This section outlines the original contributions of this research to the existing body of knowledge within the field of sustainable building practices in Saudi Arabia. Specifically, the contributions are in three dimensions: first, theoretical, as they enrich the literature on sustainability in building design; second, methodological, through the use of a unique mixed-method approach; and third, practical, offering an actionable roadmap for different parties in the field.

1. Theoretically.

The study critically examined how sustainable residential building design intersects with the unique climatic context of Saudi Arabia (KSA). The study attempted to theoretically establish a framework for parameter selection within the context of sustainability, grounded in an intensive critical review of the literature. Thus, it developed a model or method that systematically evaluates and selects design elements based on their contribution to a sustainable approach. The parameters should be selected based on three main pillars of sustainability: environmental, social, and economic factors that are tailored to the local context of Saudi Arabia. As a result, and as a first step in addressing environmental impact, parameters were chosen to maximise energy efficiency while minimising environmental harm. For example, courtyards and Mashrabiya were nominated for their ability to reduce reliance on mechanical cooling, thereby lowering electricity use and emissions in Saudi Arabia's hot climate. In addition, energy measurements within the building envelope, such as wall insulation

and glazing, were integrated to enhance thermal efficiency, further reducing the building's cooling load by minimising heat transfer. The use of solar energy was also selected as a renewable resource, capitalising on Saudi Arabia's high solar exposure to reduce carbon emissions. Second, in terms of economic viability, parameters are needed to provide long-term financial benefits. Although traditional passive architectural design (courtyards and Mashrabiya) and advanced insulation might require higher initial costs, they offer significant long-term savings by lowering cooling energy load by up to –50% and maintenance costs, making them economically viable for the local context. Finally, for social and cultural fit, design choices were required to respect local traditions and enhance social well-being. Courtyards and Mashrabiya were selected not only for their passive cooling benefits but also because they reflect traditional architectural practices, promoting thermal comfort and privacy, both of which are highly valued in the region's cultural context.

2. Methodologically.

After theoretical selection of the parameters, it was crucial to verify these parameters through empirical validation methods such as building simulations or case studies. This validation is crucial for translating theoretical constructs into practical, real-world applications, thereby ensuring the theoretical model's relevance and efficacy in practical scenarios. The study significantly advanced the methodological framework by employing a convergent parallel design approach. This design methodology integrates both quantitative and qualitative research methods concurrently, enabling a comprehensive assessment of the research problem. Specifically, this approach facilitated an in-depth evaluation of how experts appraised the Saudi building industry's state in relation to green engineering solutions.

The convergent parallel design not only permitted a thorough examination of theoretical parameters through empirical data but also validated these parameters' practical benefits using advanced modelling and simulation techniques. By employing these validation strategies, the study effectively demonstrated the applicability of theoretical models within the context of the Saudi building industry, offering evidence-based insights into the optimisation of building designs for sustainability. This methodological approach ensured that theoretical propositions were rigorously tested against real-world conditions, thereby bridging the gap between theoretical assumptions and practical implementation. Consequently, the study made a substantial methodological contribution by providing a precise understanding of

sustainable building practices and validating the theoretical framework through empirical evidence. This enhances the robustness and applicability of the study's findings, underscoring their relevance to the field of sustainable building design.

3. Practically.

The practical contributions of the current research are multifaceted. By evaluating the performance and adaptability of the identified parameters in diverse climatic scenarios, the study offers actionable insights directly relevant to the design and implementation of sustainable building practices across the country. This examination ensures that the proposed theoretical models through the methodology are rigorously validated and adaptable to the unique needs of various regional climates, enhancing their practical relevance and utility. A significant aspect of the current research is its provision of a balanced approach to addressing two critical elements of building design: reducing cooling energy loads and minimising discomfort hours. The study presents a framework that effectively balances these essential factors by optimising these parameters. This framework is crucial in developing strategies that enhance energy efficiency while maintaining occupant comfort across diverse environmental conditions. Overall, the research bridges the gap between theoretical research and practical application by providing a foundation for the development of context-specific, evidence-based design solutions. The research makes a practical contribution by offering empirically validated recommendations tailored to the specific climatic challenges of various Saudi cities. It addresses the critical balance between reducing cooling energy loads and minimising discomfort hours, thereby advancing sustainable building design through context-sensitive solutions that meet both theoretical and practical needs.

10.3 RESEARCH RECOMMENDATIONS.

In light of the findings from this research, which employed expert surveys and simulation modelling to explore sustainability and green engineering solutions in the context of Saudi residential buildings, several critical recommendations were proposed. The following recommendations were designed to enhance the sustainability of residential buildings, support data-driven decision-making, and contribute to the realisation of Saudi Arabia's Vision 2030

goals, particularly in promoting energy efficiency, reducing carbon emissions, and ensuring long-term environmental resilience.

10.3.1 Recommendations for governmental authorities.

In order to facilitate a successful transition towards sustainable Saudi residential buildings that align with the objectives of Saudi Arabia's Vision 2030, governmental authorities must take a proactive role in advancing design regulatory standards. The following recommendations are designed to inform policy development and regulatory reform, aiming to promote energy efficiency, resource conservation, and the integration of innovative sustainable technologies in residential buildings.

1. Strengthening regulatory frameworks to be more innovative.

The Saudi government should further enhance and enforce regulatory frameworks that mandate the adoption of green building standards, particularly for residential buildings. Expanding the reach of the Saudi Building Code to include more specific requirements for sustainability and energy management, such as Saudi traditional passive architectural design and solar energy, since they are crucial for achieving long-term sustainability. The regulatory framework should remain flexible, allowing for the continuous integration of emerging technologies and innovative green engineering solutions. This flexibility will encourage developers, engineers, and architects to innovate and adapt sustainable practices as they evolve, promoting a culture of collaboration and advancement in green construction methods across the private and public sectors.

2. Incentivising sustainable building practices.

To encourage the widespread adoption of sustainable building practices, the government should provide financial incentives, such as tax credits, subsidies, or low-interest loans, for developers and homeowners who implement energy-efficient technologies and materials. These economic measures would serve to mitigate the initial costs associated with sustainable technologies, thereby facilitating greater participation in the transition toward environmentally responsible building practices.

3. Investing in public awareness and education campaigns.

Raising public awareness of the advantages of green engineering solutions and sustainable practices is essential for ensuring their widespread adoption. Governmental

authorities should invest in national awareness campaigns, community workshops, and educational programs aimed at informing occupants, developers, and other stakeholders regarding the long-term benefits of these green building practices for both communities and individuals.

4. Promoting research and development in sustainable technologies.

The government should allocate funding and establish research grants to support the development of innovative green technologies specifically tailored to Saudi Arabia's unique climatic and environmental conditions. This should include research into building energy optimisation through advanced modelling, materials designed for the Saudi climate, cooling control technologies, and renewable energy solutions such as solar and wind power.

5. Expand the energy performance certification programs to include residential buildings.

Introducing mandatory energy performance certification for residential buildings would provide a standardised measure of energy efficiency for new and existing properties.

6. Monitoring and evaluation of sustainability initiatives.

To ensure the success and long-term impact of sustainability initiatives, it is essential for the Saudi government to establish a comprehensive monitoring and evaluation system. This system might involve regular data collection and reporting, evaluation of policy effectiveness, stakeholder engagement, flexibility for policy adjustments, and a commitment to transparency and public accountability. Effective models for such systems can be seen in Germany's National Climate Initiative (NKI) and the UK's Committee on Climate Change (CCC), which have successfully driven sustainable development through rigorous monitoring and continuous policy refinement.

10.3.2 Recommendations for the building industry.

The building industry needs to prioritise the adoption of sustainable construction practices by integrating green engineering solutions into design, materials, and construction methods. The following recommendations are proposed in order to encourage the building industry to promote energy efficiency, resource conservation, and the integration of innovative sustainable technologies, especially for Saudi residential buildings.

1. Develop skills and training programs.

The survey of experts confirmed that developing a skilled workforce in green building practices is essential for meeting the Kingdom's Vision 2030 sustainability targets and complying with future regulatory requirements. Hence, in order to effectively implement sustainable construction techniques in Saudi Arabia, the building industry must prioritise offering specialised training programs in that context for designers, engineers, and construction workers.

2. Invest in research and innovation.

Developers in the residential Saudi building industry need to boost investment in research and development to create innovative solutions tailored to the local Saudi climate, such as materials that can withstand extreme heat or advanced insulation technologies to improve energy efficiency. This investment could be conducted in collaboration with academic institutions and research centres, which could accelerate the development of innovative solutions. Innovation is pivotal to the transformation of the building industry toward more sustainable practices.

3. Promote the adoption of green certifications for residential buildings.

Encouraging property developers to pursue green building certifications, such as Saudi Arabia's Mostadam or the internationally recognised LEED certification, will significantly accelerate the adoption of sustainable practices in the Kingdom's residential building sector. These certifications not only promote energy efficiency and environmental responsibility but also enhance the market value of properties, making green construction more appealing to both developers and buyers.

4. Increase the availability of green building financing.

The industry needs to collaborate with financial institutions to develop innovative financing models that address the lack of support for sustainable residential building projects in Saudi Arabia. This can be achieved by take the advantage of certifications such as Mostadam locally or LEED internationally to attract favourable financing, as sustainable residential buildings are viewed as lower-risk, high-value investments.

5. Encourage retrofitting of existing buildings and under construction building designs.

An open approach to retrofitting existing buildings and the designs of those still under construction with up-to-date sustainable engineering solutions is crucial to reducing the environmental impact of the built environment. The building industry should prioritise upgrading older structures with advanced insulation, renewable energy systems, and modern green technologies. Additionally, new residential designs should integrate these sustainability measures alongside the optimal use of Saudi Arabia's traditional passive architectural design, which can extend the lifespan of buildings while enhancing their environmental performance.

6. Partnerships between governmental authorities and the building industry for green initiatives.

Establishing strong partnerships between governmental authorities and the building industry is essential for driving the adoption of green initiatives and promoting sustainability within Saudi Arabia's residential buildings sector. These collaborations can bridge the gap between regulatory frameworks, technological innovation, and practical implementation to ensure that sustainability goals are effectively achieved. For example, government authorities should work closely with industry stakeholders to co-create and regularly update green building codes. Additionally, partnerships could involve co-funding and promoting joint research initiatives. Moreover, risk-sharing mechanisms, such as government-backed insurance or guarantee schemes for innovative green technologies, could help mitigate the financial risks associated with new and untested sustainable practices. These collaborations will provide the financial and technical resources necessary to scale up sustainability initiatives across the sector.

10.3.3 Recommendations for building designers.

Building designers can play a central role in shaping the future of sustainable Saudi residential buildings. They can help reduce environmental impact by creating buildings that are more resilient, adaptive, and in harmony with both consumers and the environment. The recommendations below are made to encourage the building designers to enhance the

adoption of advanced technologies, resource-efficient materials, and climate-responsive design strategies.

1. Incorporate energy efficiency measures and low carbon technologies into climate-adaptive design.

Designers should prioritise climate-responsive architecture to address Saudi Arabia's extreme heat and arid conditions. For example, using advanced insulation materials can independently reduce cooling energy consumption by up to 9% in buildings that comply with the Saudi building code. Furthermore, applying advanced glazing technologies can achieve an additional reduction of over 13% in cooling energy consumption for the same building. These strategies also help regulate indoor temperatures, thereby decreasing reliance on air conditioning and overall energy consumption.

Additionally, incorporating on-site renewable energy systems, such as solar panels, into climate-adaptive design at the design stage ensures that buildings can generate part or all of their energy needs. Moreover, implementing a peer-to-peer energy sharing system further enhances this approach by allowing buildings to exchange surplus energy within the community.

2. Prioritise traditional passive design strategies.

Building designers should integrate traditional passive design principles that optimise the use of natural resources such as sunlight, wind, and thermal mass to minimise energy consumption. Incorporating courtyards, a characteristic element of traditional Saudi architecture, can enhance natural ventilation and cool indoor spaces, potentially reducing cooling energy by approximately 8%. Additionally, the use of shading devices, such as Mashrabiya, can further decrease cooling energy consumption by over 11%. These passive strategies significantly reduce reliance on mechanical cooling systems, thereby improving energy efficiency and enhancing occupant comfort.

3. Preserve and integrate cultural heritage.

Sustainable building design in Saudi Arabia should emphasise not only environmental efficiency but also the preservation of the country's rich cultural and architectural heritage. Designers should draw inspiration from traditional Islamic architecture by incorporating elements such as courtyards and Mashrabiya as shading devices, which this research project has demonstrated to be effective in reducing building cooling loads and enhancing occupant

comfort. Moreover, by merging modern sustainability practices with these traditional design features, architects can create buildings that are both functionally efficient and culturally meaningful.

4. Engage stakeholders and the public in sustainable design.

Designers and the experts in the residential Saudi building industry should engage in collaborative efforts with stakeholders, developers, and the governmental authorities to advance awareness and facilitate the adoption of sustainable building practices. This collaboration might involve educating clients and future occupants about the benefits of energy-efficient and sustainable designs. On the other hand, they can explain the benefits of sustainable design to developers by utilising both Life-Cycle Assessments (LCAs) and Life-Cycle Costing (LCC) approaches. These tools assist decision-makers in identifying the most cost-effective options while also considering environmental impacts throughout the building's life cycle. Additionally, engage with governmental authorities about any obstacles that hinder the implementation of sustainable practices.

5. Continuous professional development.

Building designers should actively seek opportunities to expand their knowledge of sustainable practices through education, professional development, and certification programs. For example, they can engage with organisations that promote green building standards, such as the Leadership in Energy and Environmental Design (LEED) and the Building Research Establishment Environmental Assessment Method (BREEAM). Additionally, they should keep up to date with emerging technologies and global best practices in sustainability.

10.3.4 Recommendations for public awareness and occupants' usage.

In Saudi Arabia, where per capita energy use is among the highest in the world, raising awareness and changing behaviour at the individual level will be essential to achieving the country's Vision 2030 goals. Hence, the following recommendations are aimed at enhancing public awareness and encouraging occupants to engage in sustainable usage practices.

1. Proper use of cooling systems.

Given that air conditioning is essential in Saudi Arabia due to its hot climate, it is one of the largest consumers of energy in residential buildings. Consequently, occupants should engage in sustainable usage practices by setting cooling system thermostats to reasonable

temperatures during the summer season that balance thermal comfort with energy savings. They may also utilise programmable thermostats or smart HVAC systems to automatically adjust temperatures based on occupancy and the time of day, thereby reducing unnecessary cooling. Furthermore, occupants should invest in energy-efficient cooling systems and other appliances, particularly those with high energy efficiency ratings, such as Energy Star-rated or Saudi energy-efficiency-labelled products.

2. Monitor and adapt behaviour for continuous improvement.

The process of monitoring and adapting behaviours for continuous improvement is essential for promoting energy efficiency and sustainability within Saudi Arabia residential building occupants. To achieve energy efficiency, occupants should consistently track their energy consumption and make informed decisions based on their findings. This can be accomplished by utilising energy monitoring devices that provide real-time feedback on energy usage, thereby enabling residents to identify high-consumption appliances and habits. Furthermore, occupants can establish monthly goals for reducing energy usage and regularly review their progress to refine their behaviours and strategies as needed.

3. Educate children and family members on energy efficiency.

Educating children and family members regarding energy efficiency is a critical aspect of promoting sustainable practices in Saudi Arabia. This could be achieved by incorporating energy efficiency and sustainability aspects into school curricula and organising community events to develop a robust culture of sustainability. The active participation of families in energy-saving initiatives is anticipated to contribute significantly to a more sustainable future, aligning with Saudi Arabia's national objectives for sustainability and responsible resource management as outlined in Vision 2030.

10.4 RESEARCH LIMITATIONS.

In any research, the pursuit of knowledge is often challenged by various constraints that might impact the outcomes and interpretations of findings. Understanding these limitations is crucial for enhancing the rigour and credibility of any academic endeavour. First, the limited timeframe of the PhD may restrict the scope of this research, which possibly hinders a more comprehensive exploration of the research questions. For instance, time constraints restricted the ability to evaluate a broader range of parameters and modelling alternatives.

Additionally, the timeframe for conducting the expert survey also limited the number of participants.

In terms of the literature review, existing studies that concentrate on the Saudi Arabia case for optimising the balancing between the two indicators—cooling energy and thermal comfort—of residential buildings are limited. However, there are studies that address these two critical indicators separately, and they often fail to provide a holistic view of their interrelationship, neglecting key factors such as Saudi climatic variations, occupant behaviour, and long-term sustainability impacts.

Regarding the simulation, the modelling software used (DesignBuilder) has limitations in terms of the ability to extract indoor air movements for each zone individually. However, it provides an accurate overall value of the thermal comfort levels for the entire building based on the established requirements. Moreover, it does not conduct an optimisation analysis for building shape, such as comparative assessments of different courtyard designs. To address this deficiency, the researcher conducted the analysis separately and integrated the results using analytical tools (Orange 3.37). Furthermore, DesignBuilder and most simulation software limit the number of shading devices to a maximum of 50 louvers. This limitation required the researcher to manually design the Mashrabiya to effectively evaluate its advantages.

Even though it was taken into consideration the most appropriate aspects while choosing the building to fit the Saudi case, it might not be representative of the broader condition, and the findings may not be generalisable. Additionally, limitations in accessing certain datasets, such as information on occupant behaviour in the case study building, may have hindered the analysis. Furthermore, the experts survey section may have been affected by biases based on participants' backgrounds or experiences, which can affect the validity of their responses.

10.5 FUTURE RESEARCH.

As the field of Saudi residential building industry continues to evolve, several avenues for future research emerge from the findings and limitations of this research project. This thesis has provided valuable insights into the integration of green engineering solutions in the context of sustainability, yet it has also identified gaps and challenges that deserve further investigation. Future research can build upon the following insights that extracted from the journey of this research project.

Future research could explore a broader range of parameters and modelling alternatives in Saudi traditional passive architectural design, along with advanced energy efficiency measures and other low-carbon technologies, to assess their potential improvements in cooling energy efficiency and thermal comfort levels. Additionally, researchers could incorporate additional evaluation indicators to assess these green engineering solutions, such as CO2 emissions, heating energy consumption, life-cycle assessments (LCAs), and life-cycle costing (LCC) approaches. This would enable a deeper and more comprehensive evaluation of the variables that may influence the outcomes.

It is crucial for future studies to concentrate on the potential of the latest engineering solutions that are available in the building industry, whether materials or practices. This might include advanced insulation and glazing technologies, 3D-printed buildings, smart sensors and IoT-enabled buildings, or artificial intelligence (AI) in construction. The exploration of these solutions might have the ability to revolutionise building practices and improve overall efficiency, as this multidisciplinary approach is essential for maximising the benefits of up-to-date techniques and addressing the challenges posed by climate change and energy consumption.

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Appendices

Appendix 1: An analysis of each parameter evaluated during the free-running simulation of indoor thermal environments in the building's rooms.

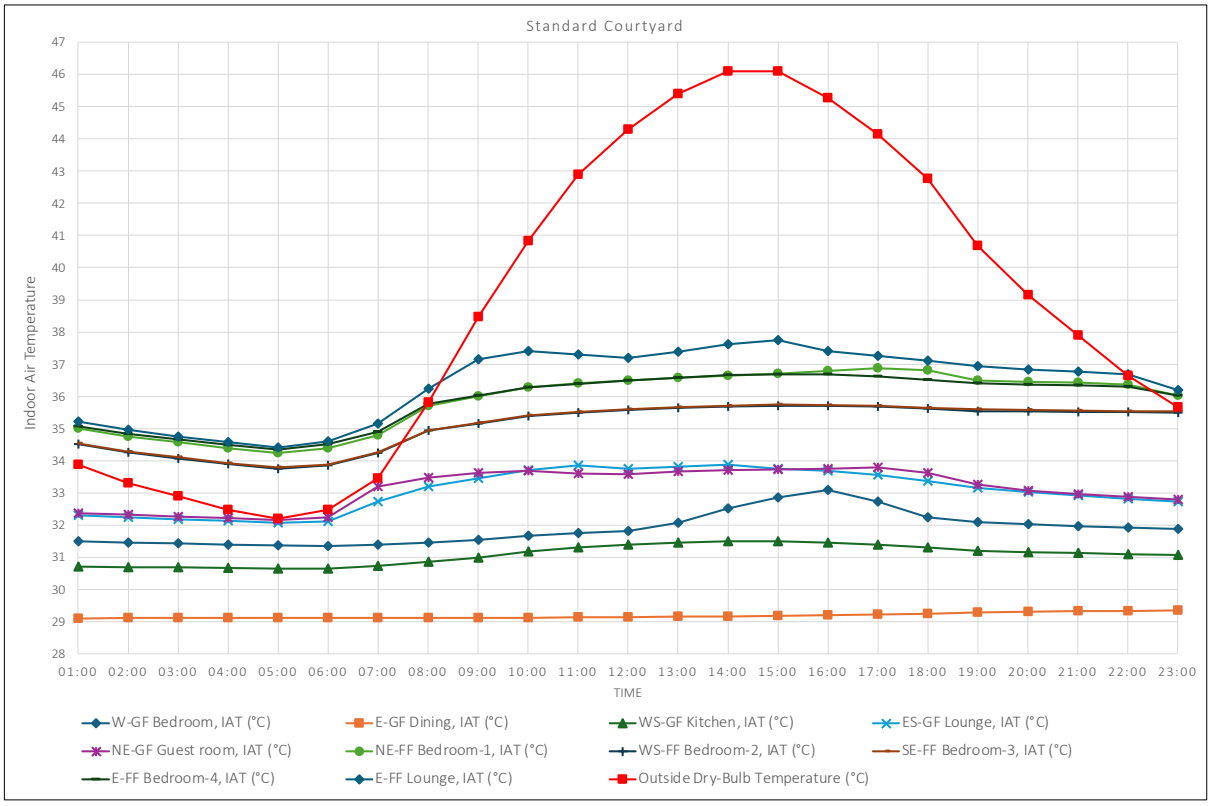


Figure A-1. 1. The free-running simulation of hourly indoor air temperature in the base case building zones after applying the standard courtyard (15th July).

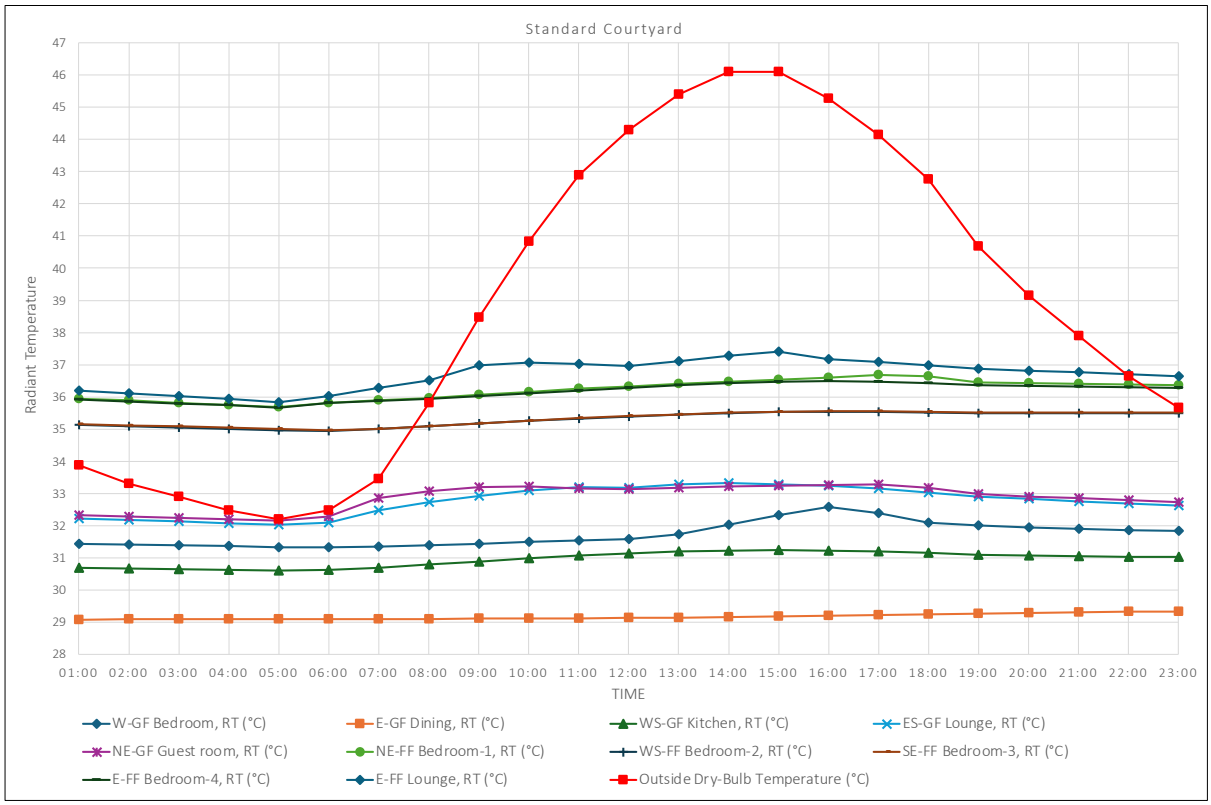


Figure A-1. 2. The free-running simulation of hourly radiant temperature in the base case building zones after applying the standard courtyard (15th July).

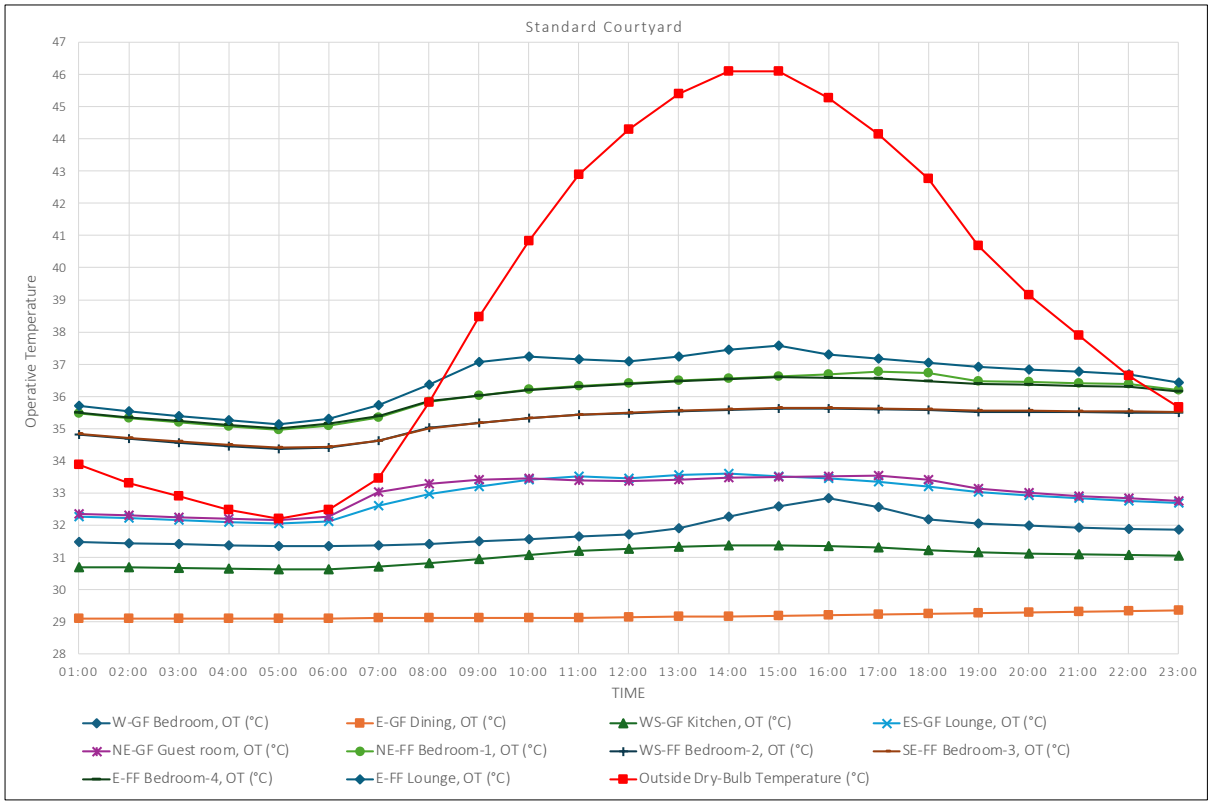


Figure A-1. 3. The free-running simulation of hourly operative temperature in the base case building zones after applying the standard courtyard (15th July).

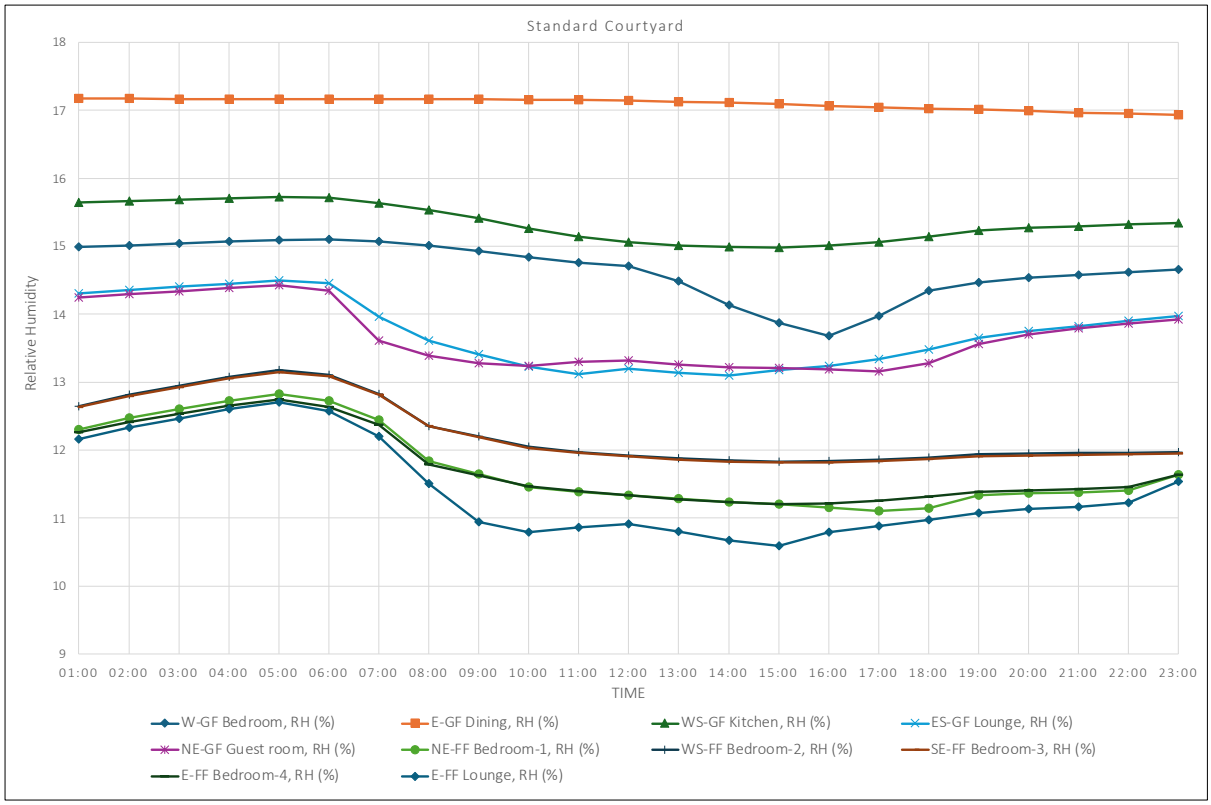


Figure A-1. 4. The free-running simulation of hourly relative humidity in the base case building zones after applying the standard courtyard (15th July).

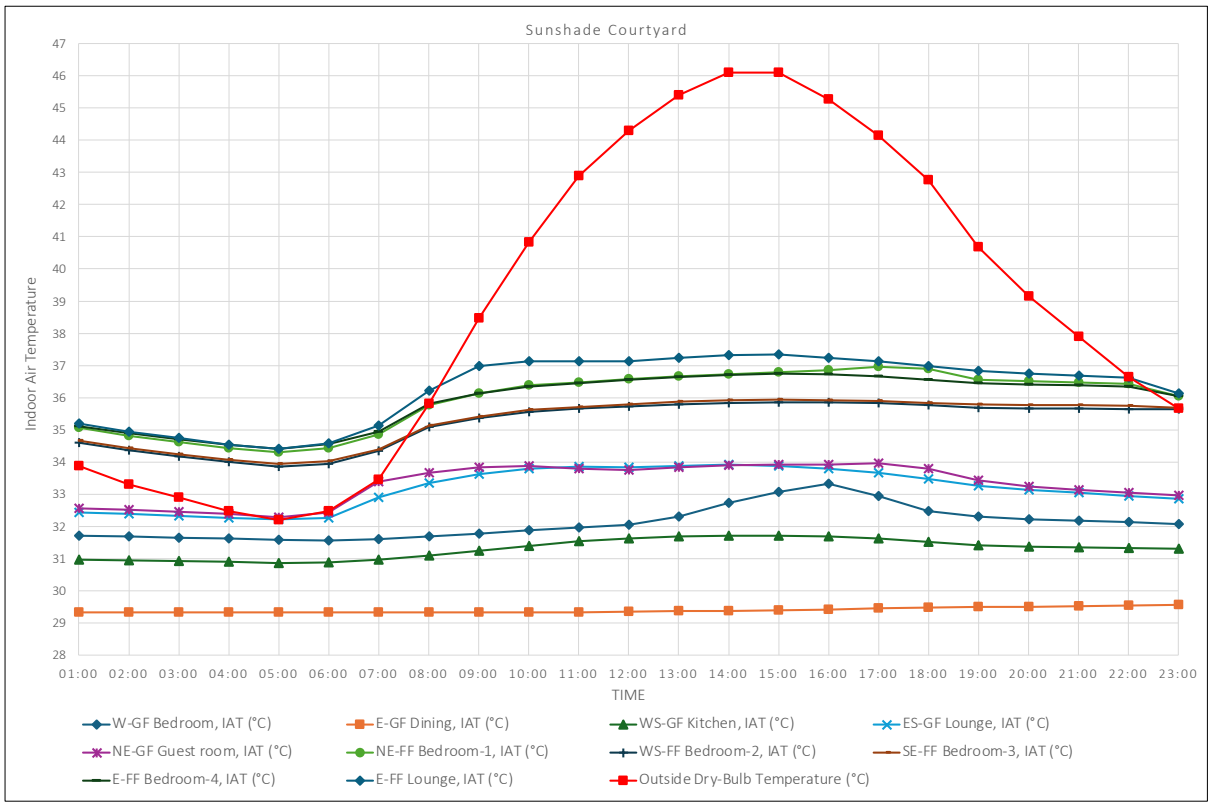


Figure A-1. 5. The free-running simulation of hourly indoor air temperature in the base case building zones after applying the sunshade courtyard (15th July).

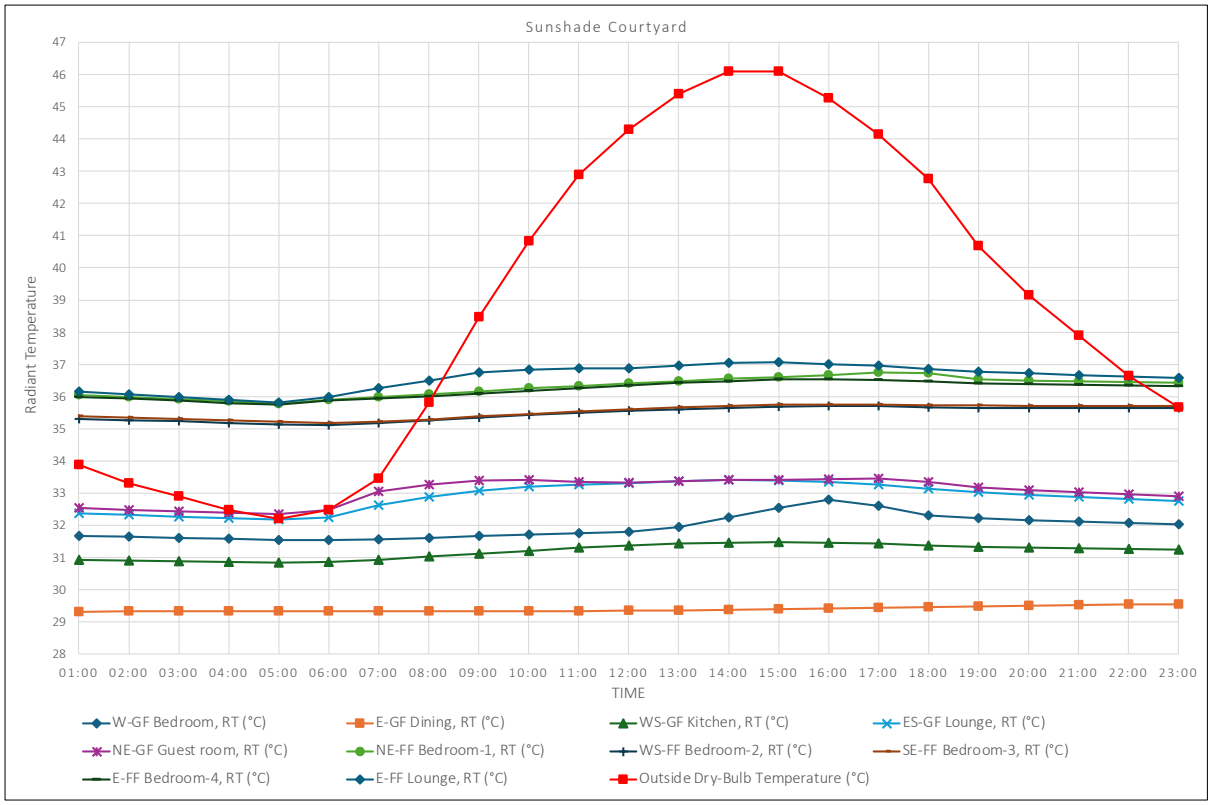


Figure A-1. 6.The free-running simulation of hourly radiant temperature in the base case building zones after applying the sunshade courtyard (15th July).

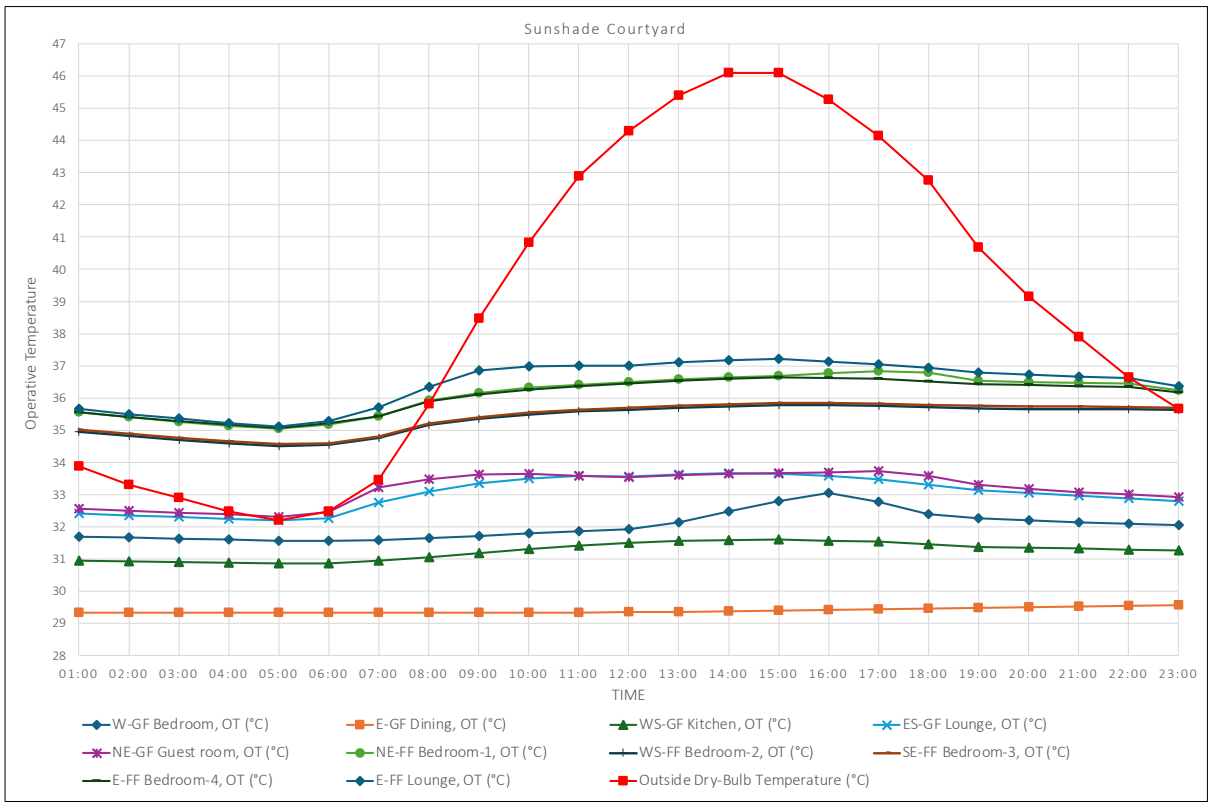


Figure A-1. 7. The free-running simulation of hourly operative temperature in the base case building zones after applying the sunshade courtyard (15th July).

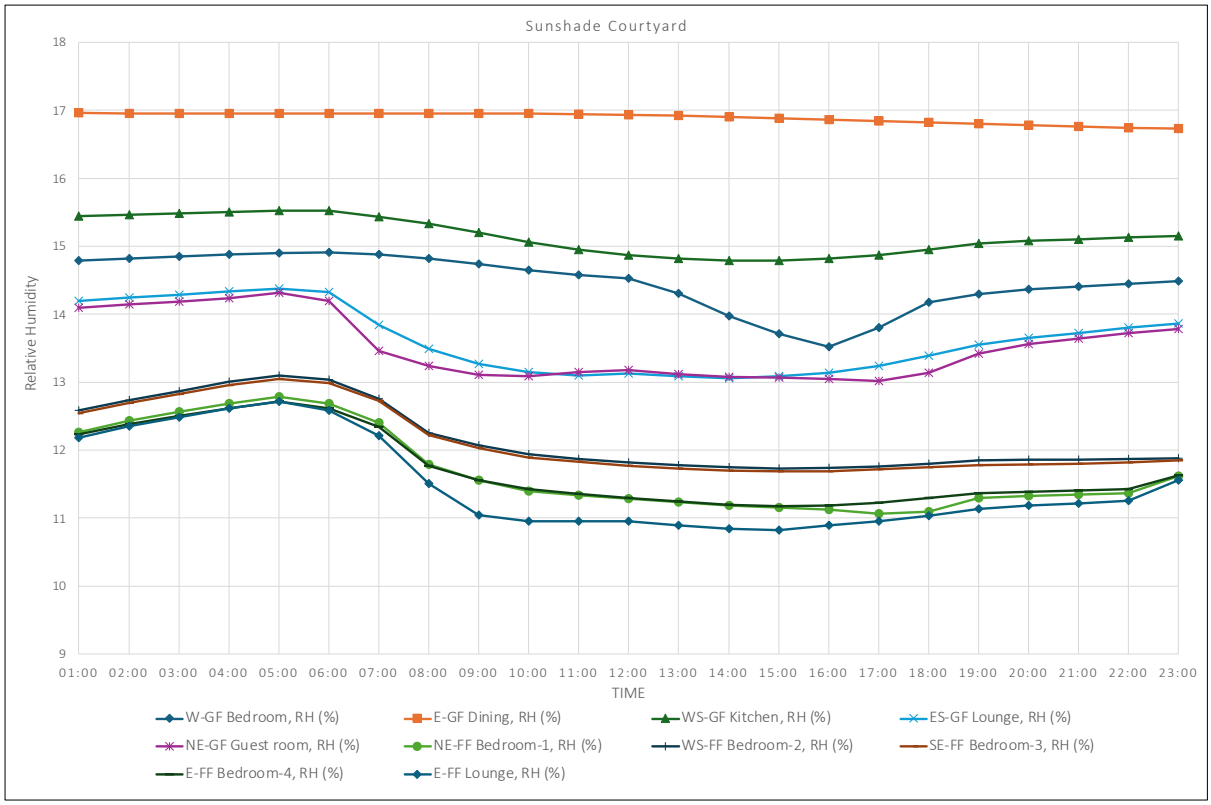


Figure A-1. 8.The free-running simulation of hourly relative humidity in the base case building zones after applying the sunshade courtyard (15th July).

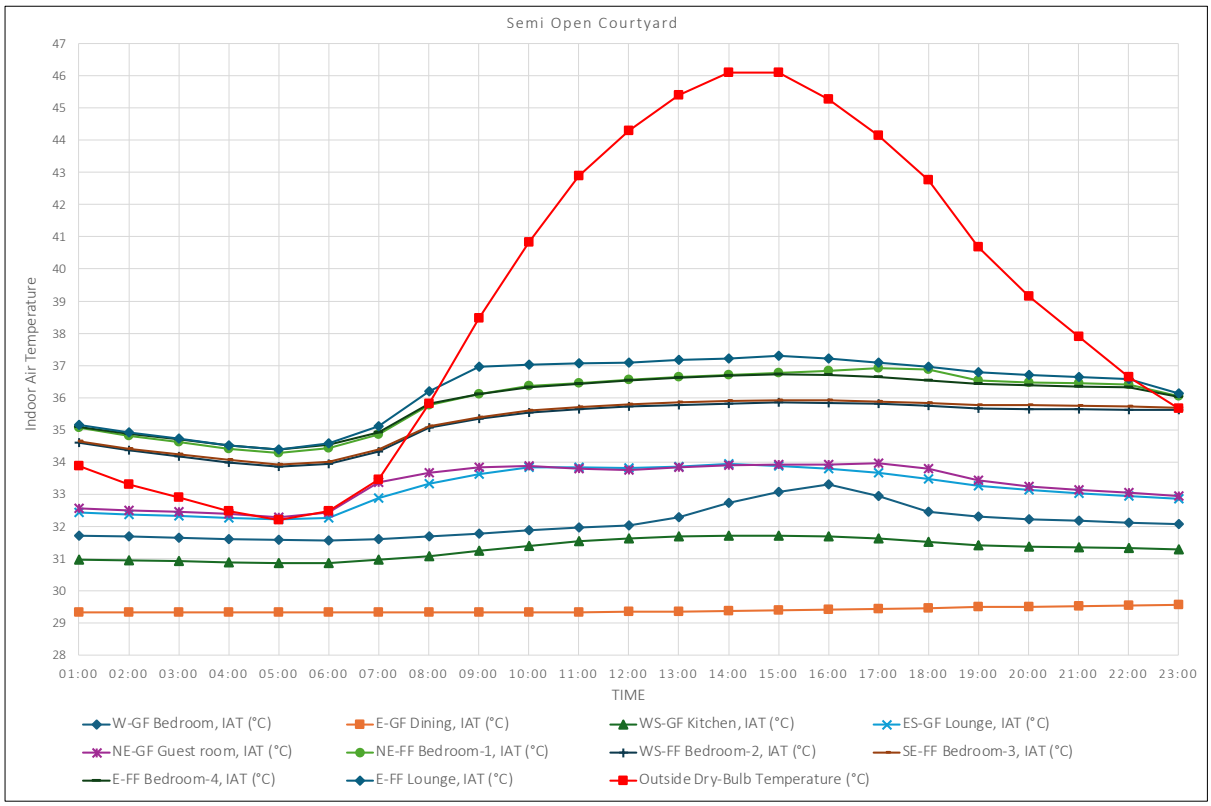


Figure A-1. 9.The free-running simulation of hourly indoor air temperature in the base case building zones after applying the semi-open courtyard (15th July).

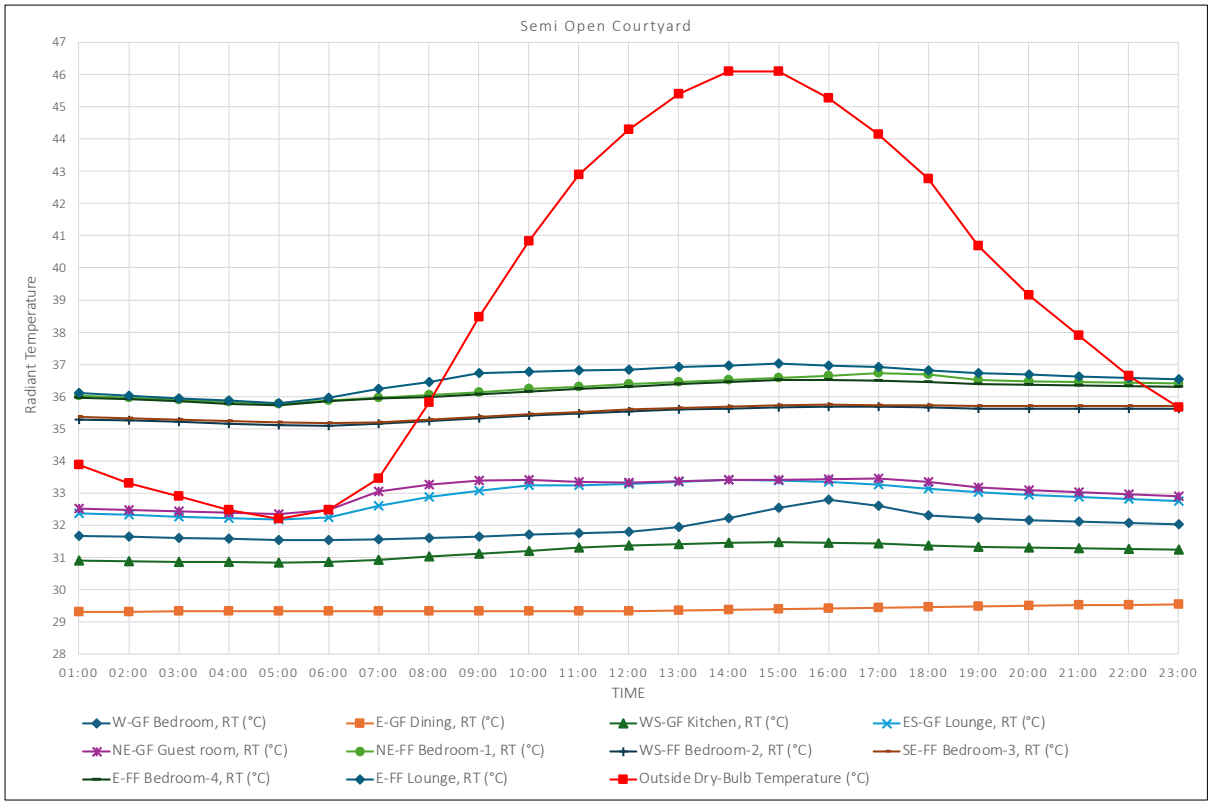


Figure A-1. 10.The free-running simulation of hourly radiant temperature in the base case building zones after applying the semi-open courtyard (15th July).

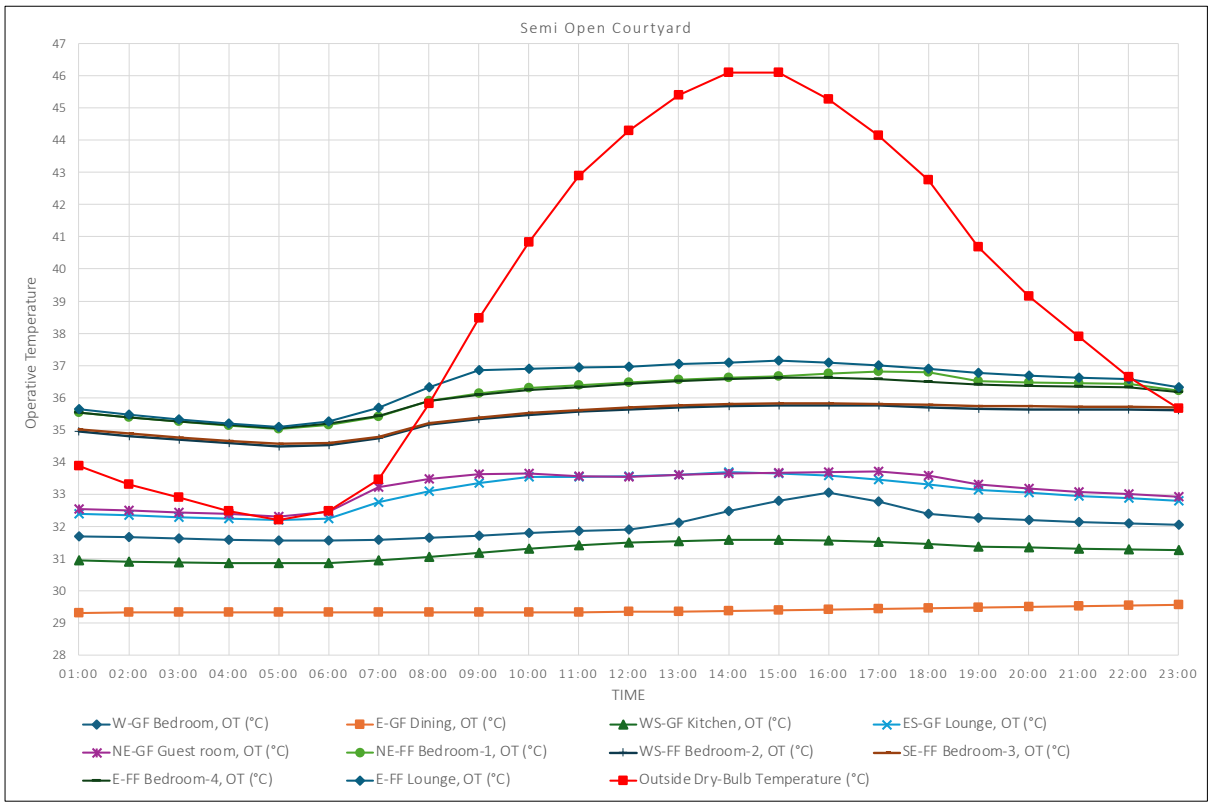


Figure A-1. 11. The free-running simulation of hourly operative temperature in the base case building zones after applying the semi-open courtyard (15th July).

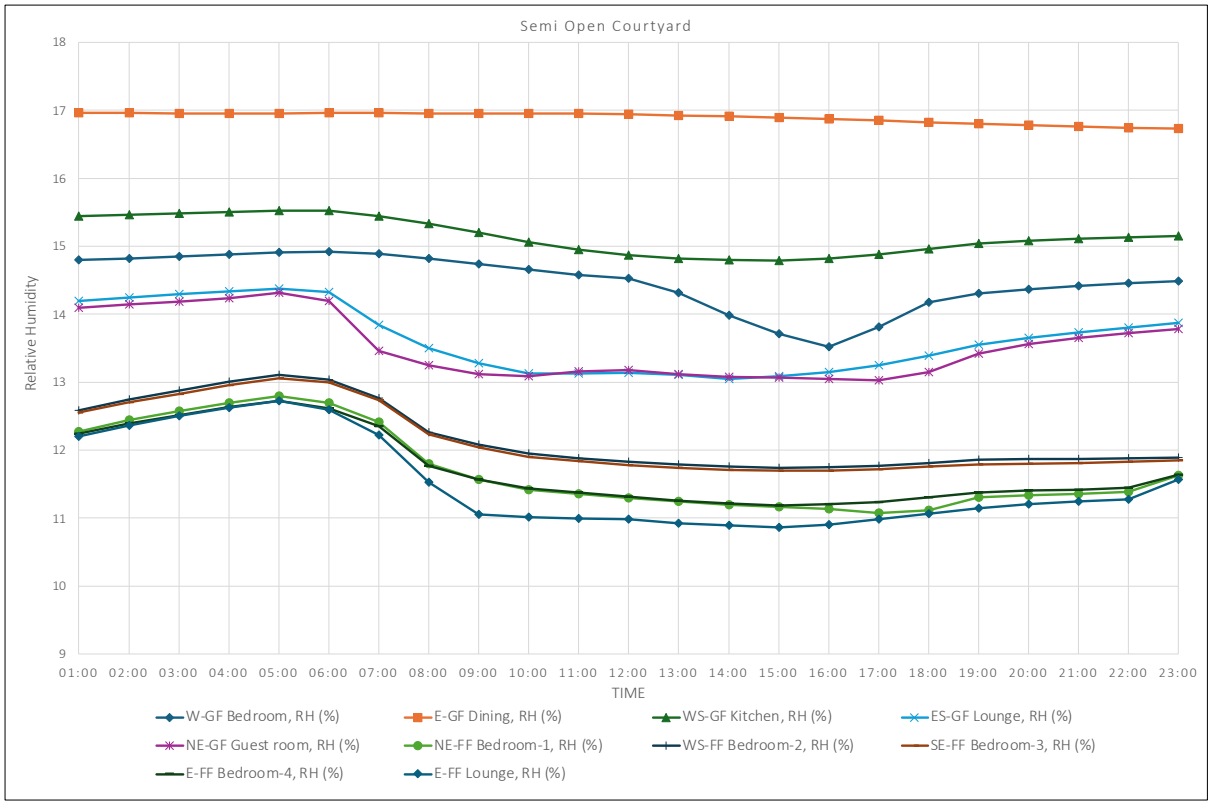


Figure A-1. 12.The free-running simulation of hourly relative humidity in the base case building zones after applying the semi-open courtyard (15th July).

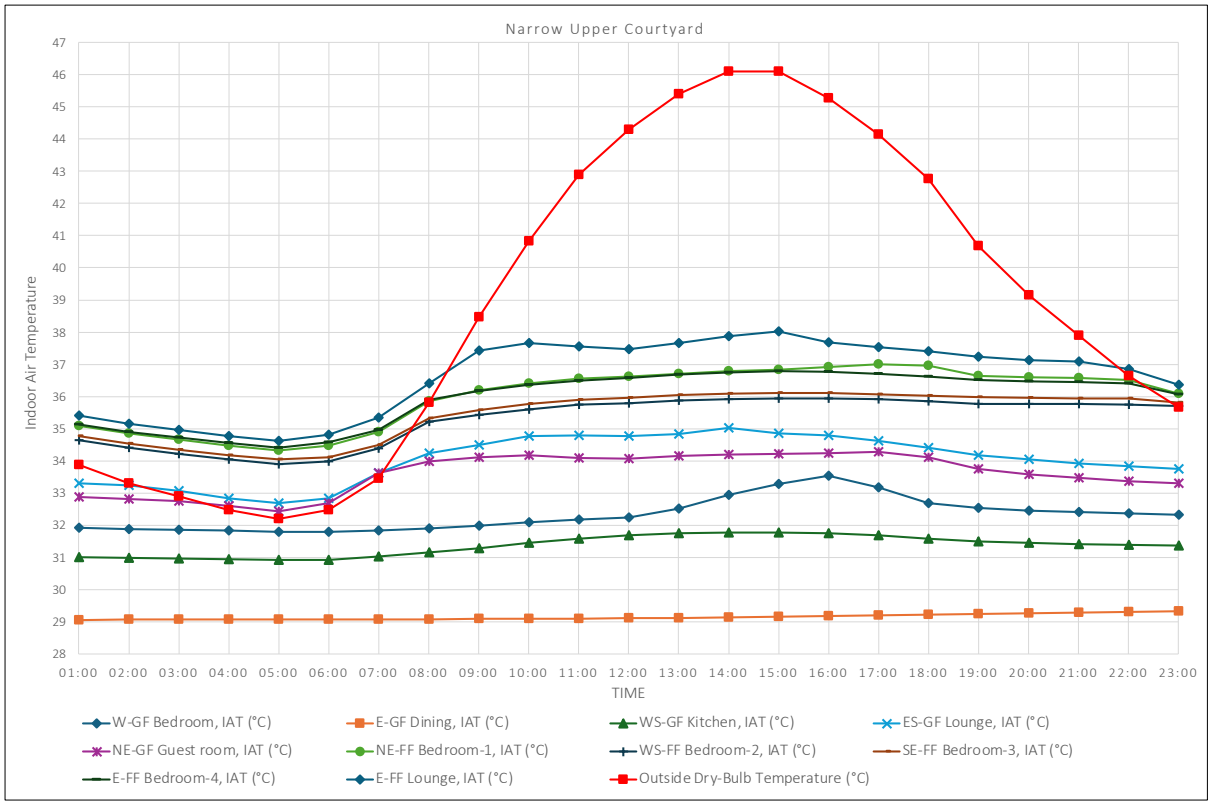


Figure A-1. 13.The free-running simulation of hourly indoor air temperature in the base case building zones after applying the upward contracted courtyard (15th July).

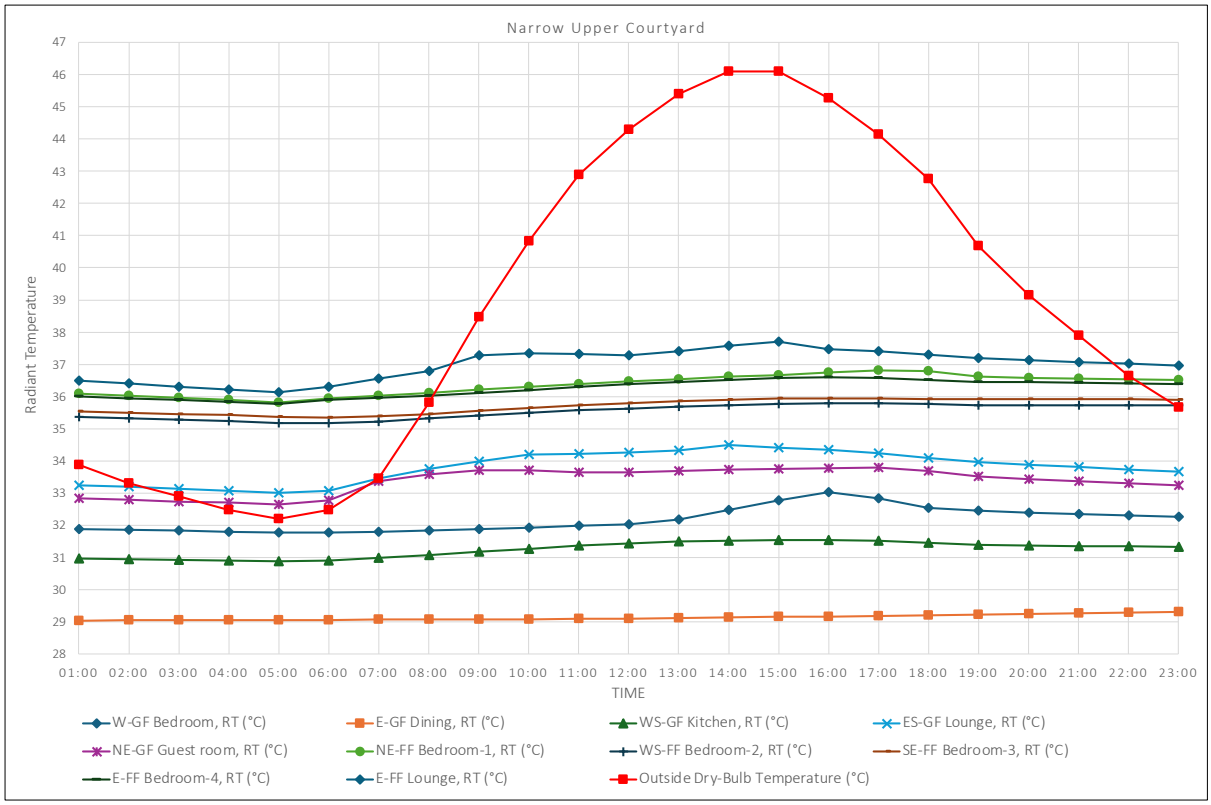


Figure A-1. 14.The free-running simulation of hourly radiant temperature in the base case building zones after applying the upward contracted courtyard (15th July).

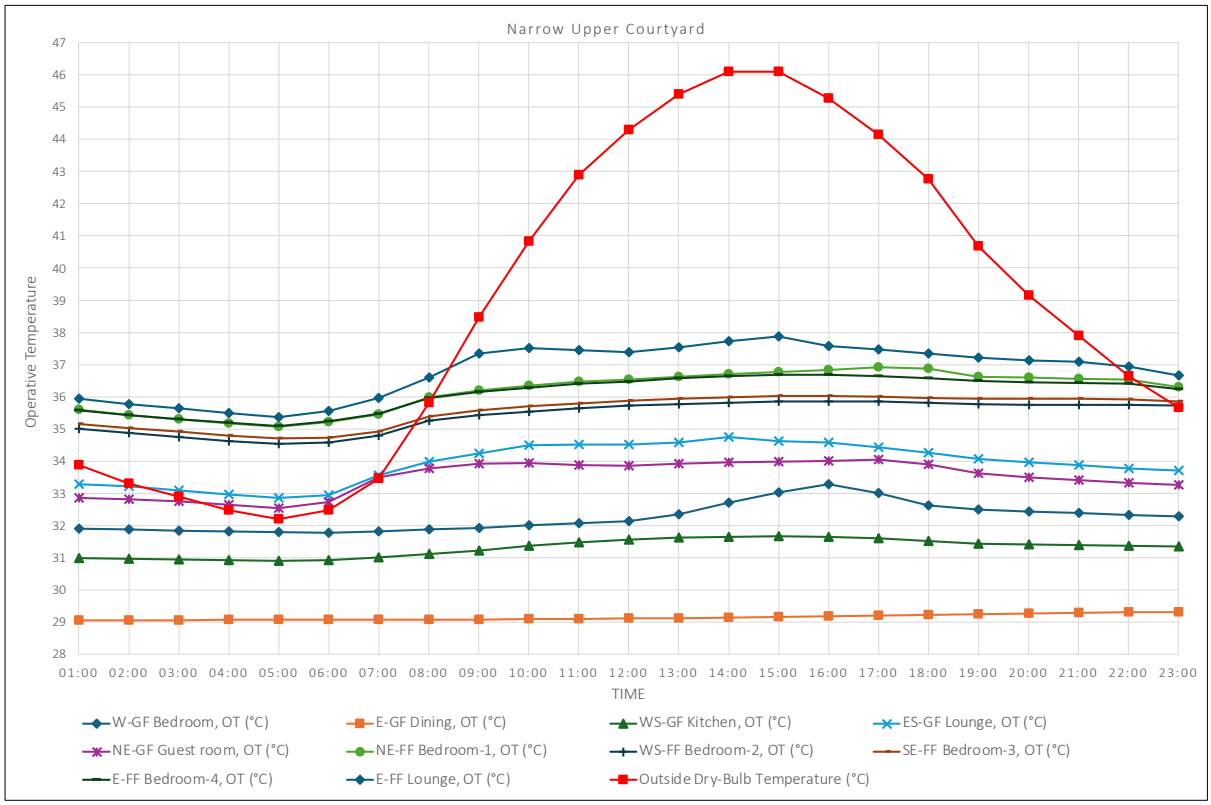


Figure A-1. 15.The free-running simulation of hourly operative temperature in the base case building zones after applying the upward contracted courtyard (15th July).

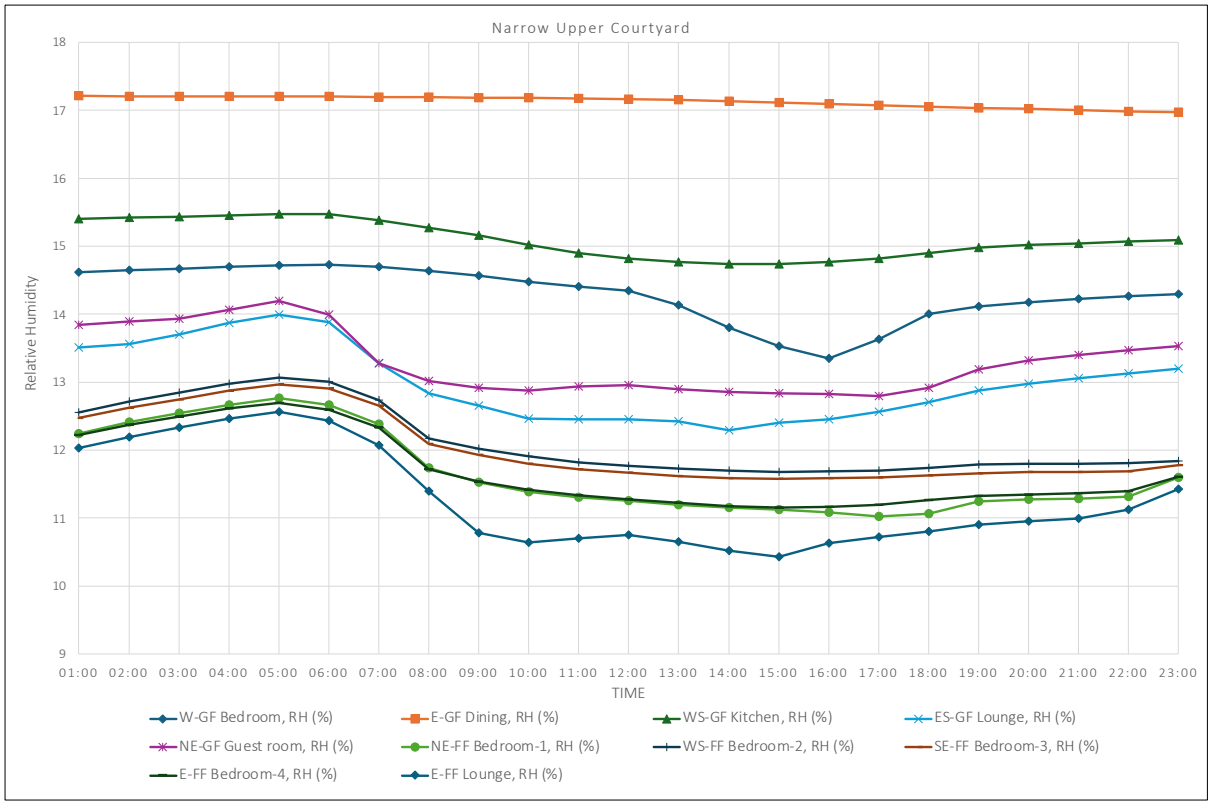


Figure A-1. 16. The free-running simulation of hourly relative humidity in the base case building zones after applying the upward contracted courtyard (15th July).

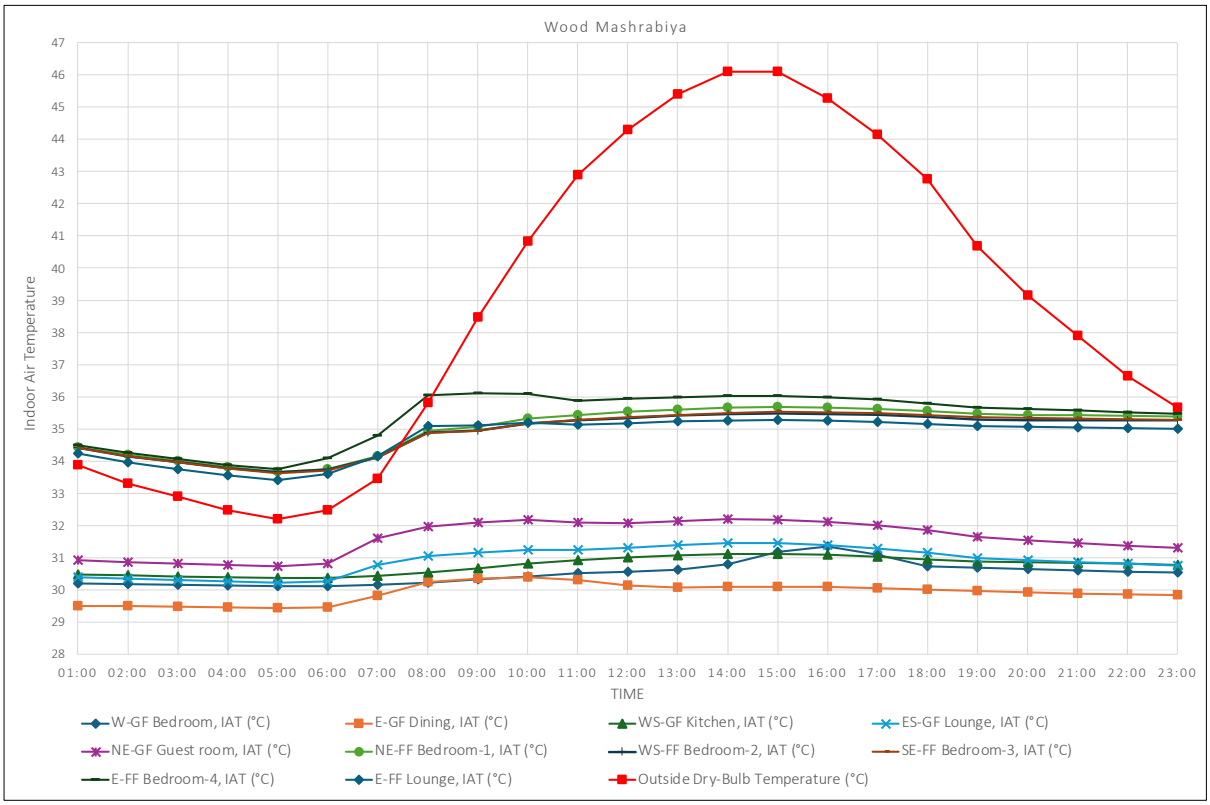


Figure A-1. 17. The free-running simulation of hourly indoor air temperature in the base case building zones after applying Wood Mashrabiya (15th July).

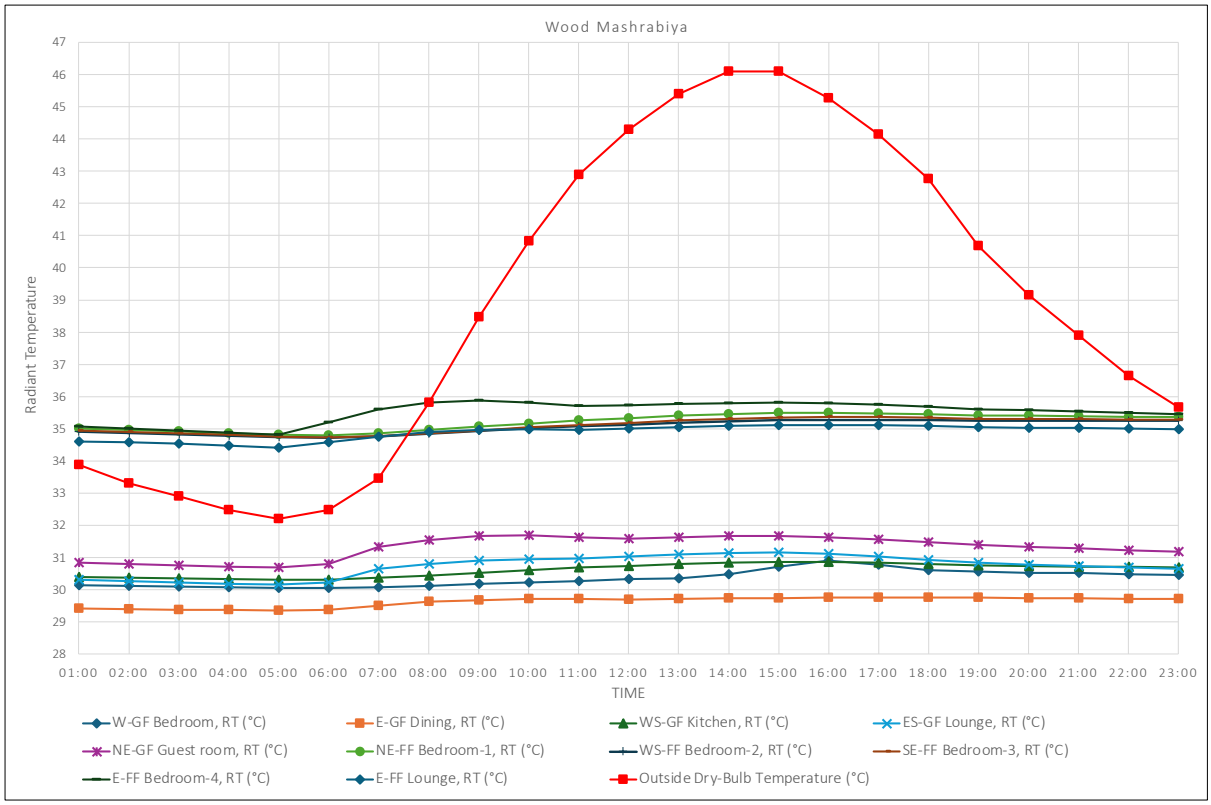


Figure A-1. 18. The free-running simulation of hourly radiant temperature in the base case building zones after applying Wood Mashrabiya (15th July).

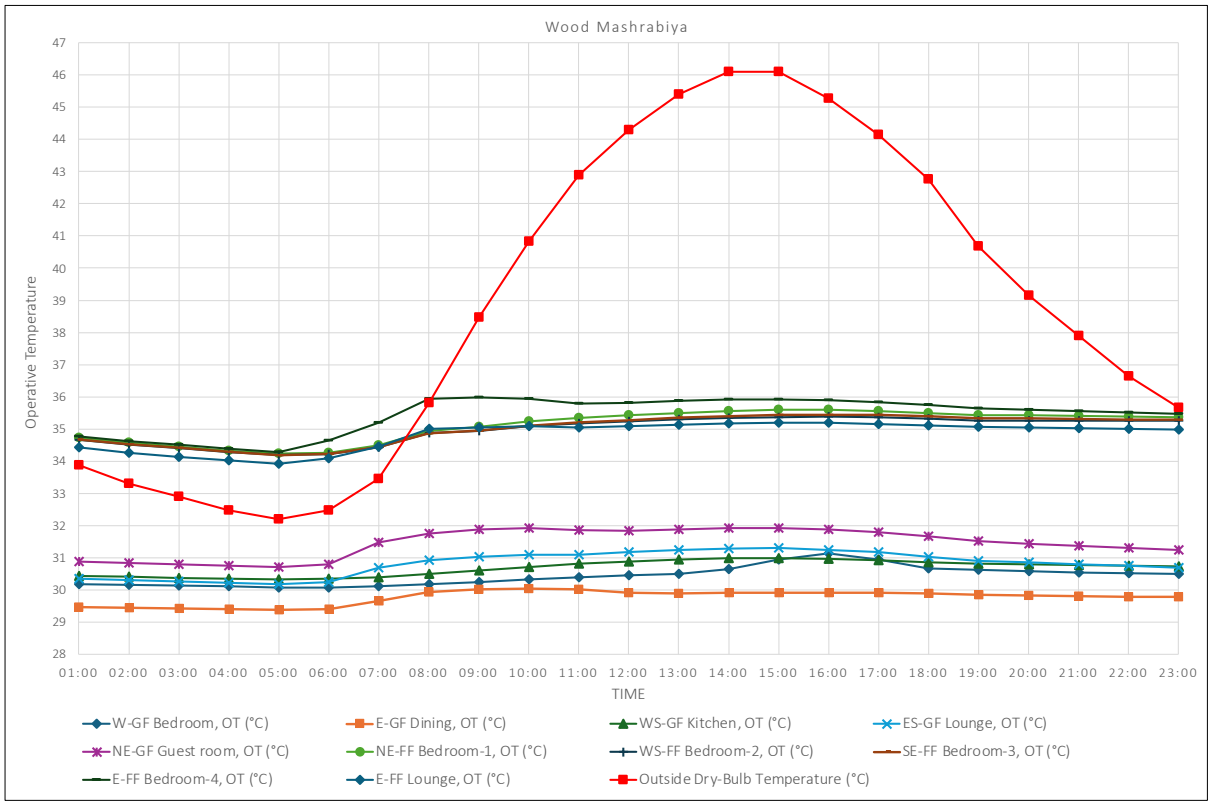


Figure A-1. 19. The free-running simulation of hourly operative temperature in the base case building zones after applying Wood Mashrabiya (15th July).

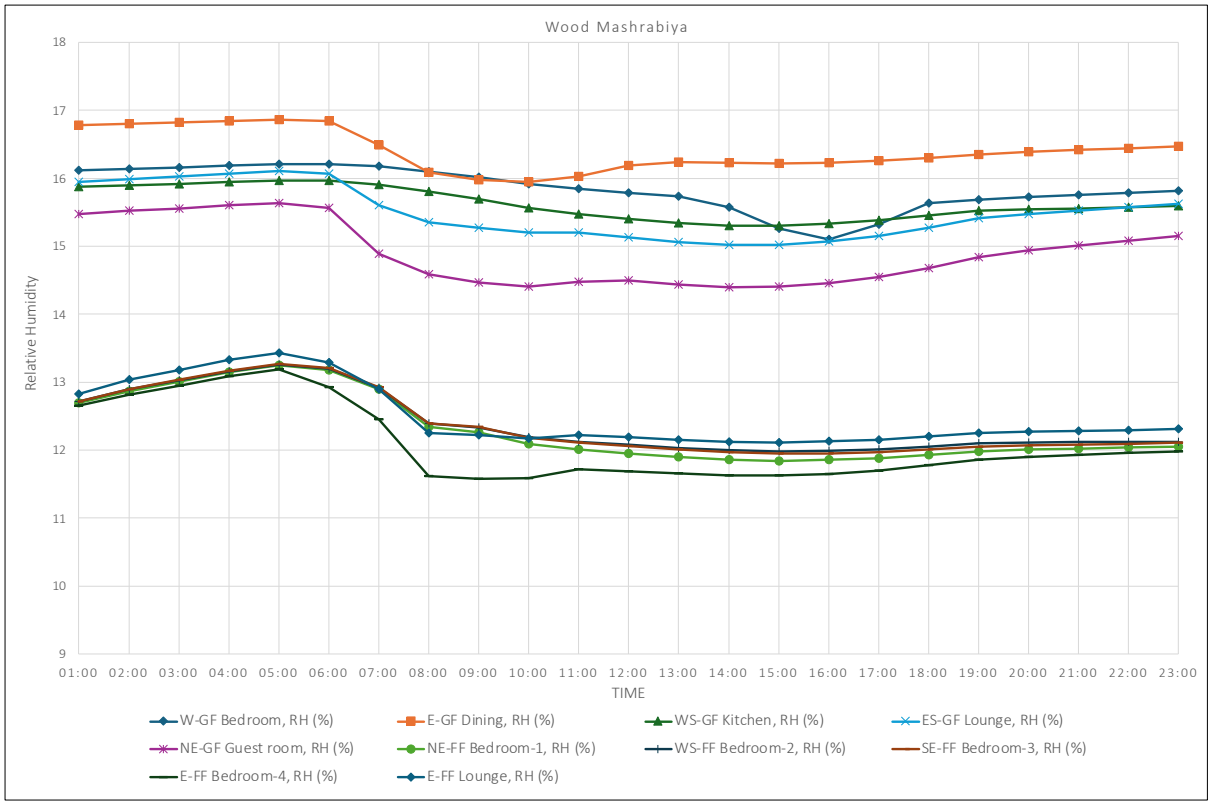


Figure A-1. 20. The free-running simulation of hourly relative humidity in the base case building zones after applying Wood Mashrabiya (15th July).

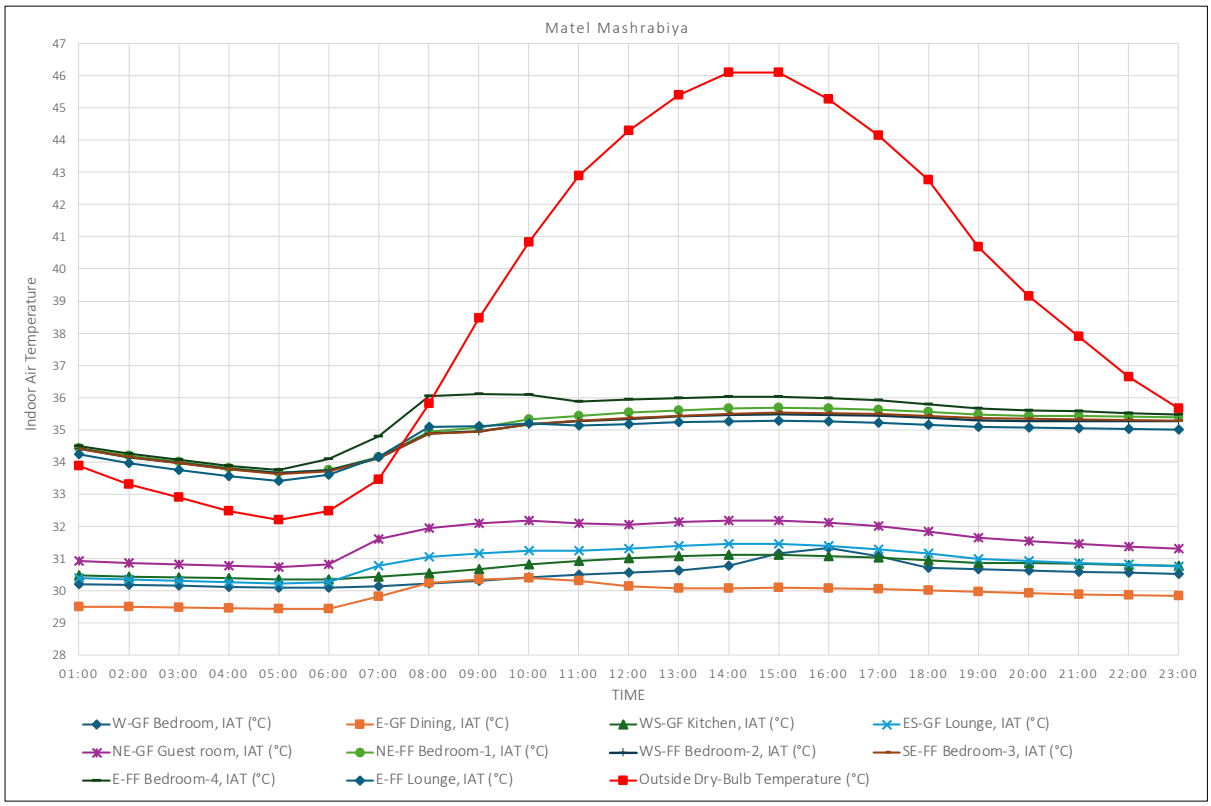


Figure A-1. 21. The free-running simulation of hourly indoor air temperature in the base case building zones after applying Matel Mashrabiya (15th July).

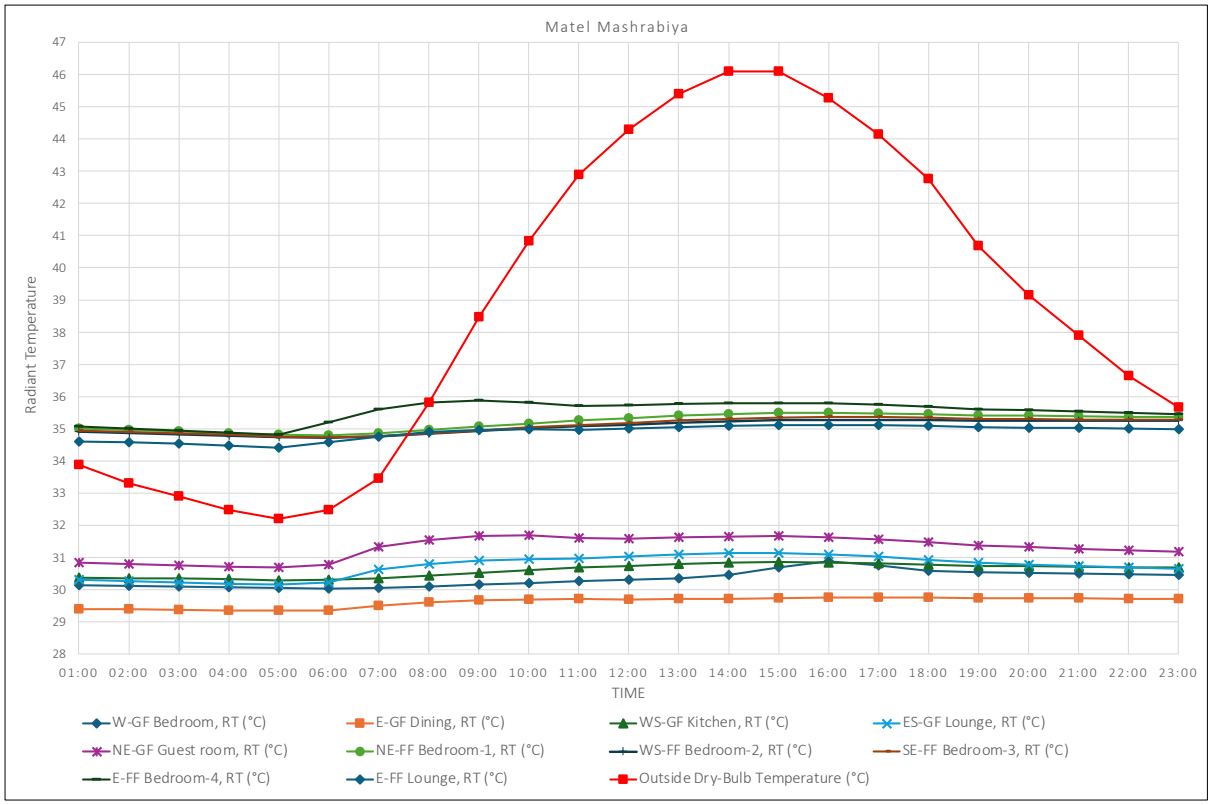


Figure A-1. 22. The free-running simulation of hourly radiant temperature in the base case building zones after applying Matel Mashrabiya (15th July).

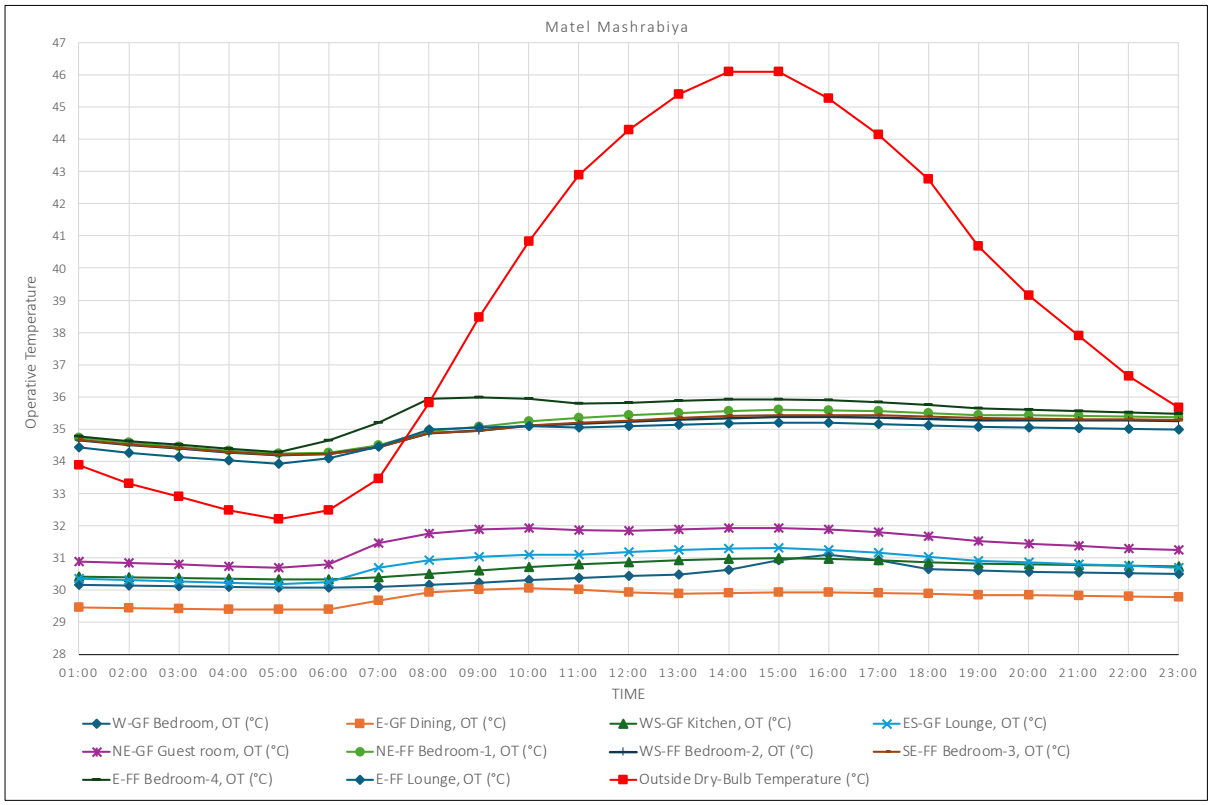


Figure A-1. 23. The free-running simulation of hourly operative temperature in the base case building zones after applying Matel Mashrabiya (15th July).

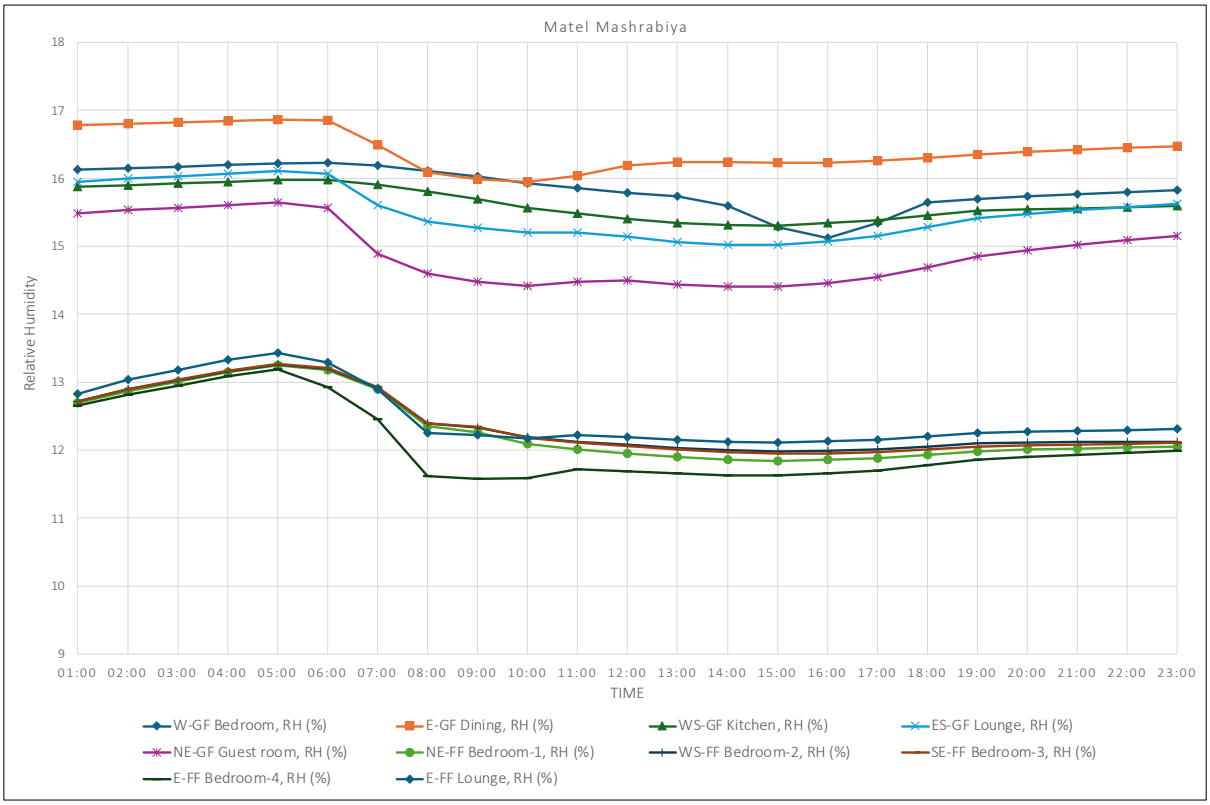


Figure A-1. 24. The free-running simulation of hourly relative humidity in the base case building zones after applying Matel Mashrabiya (15th July).

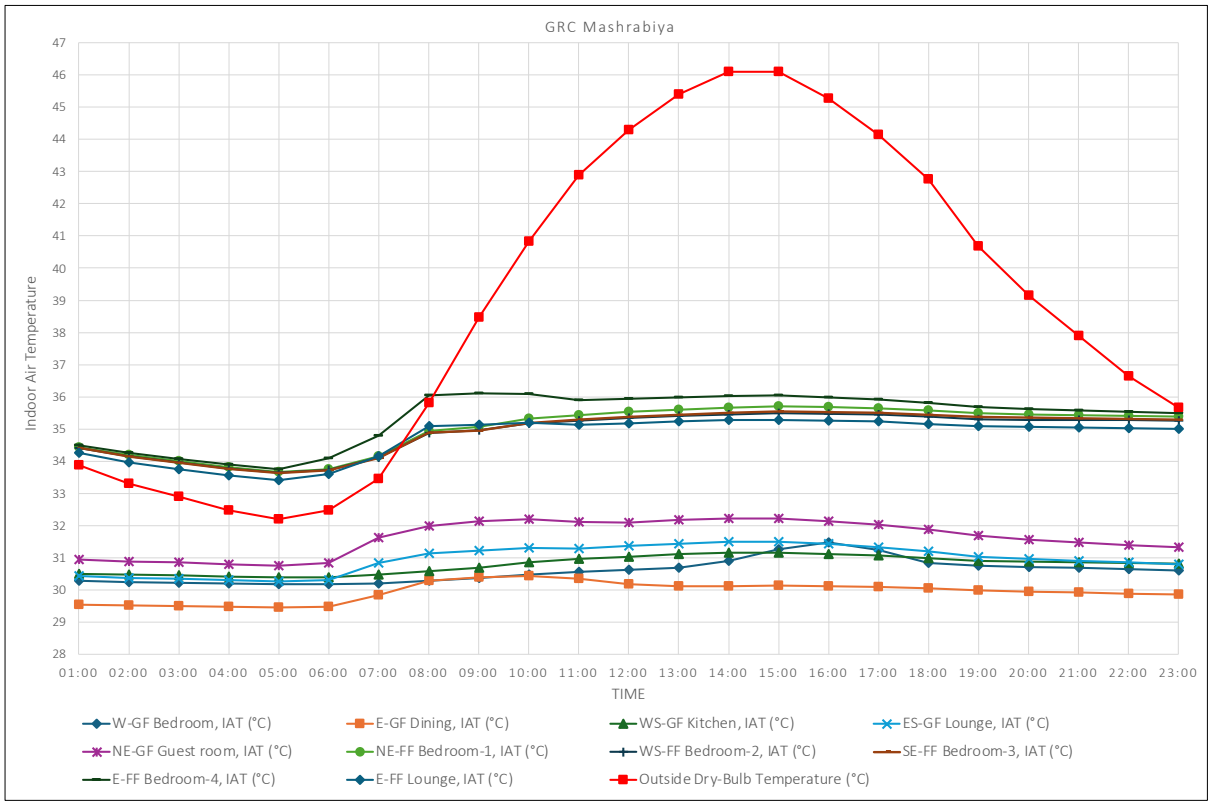


Figure A-1. 25. The free-running simulation of hourly indoor air temperature in the base case building zones after applying GRC Mashrabiya (15th July).

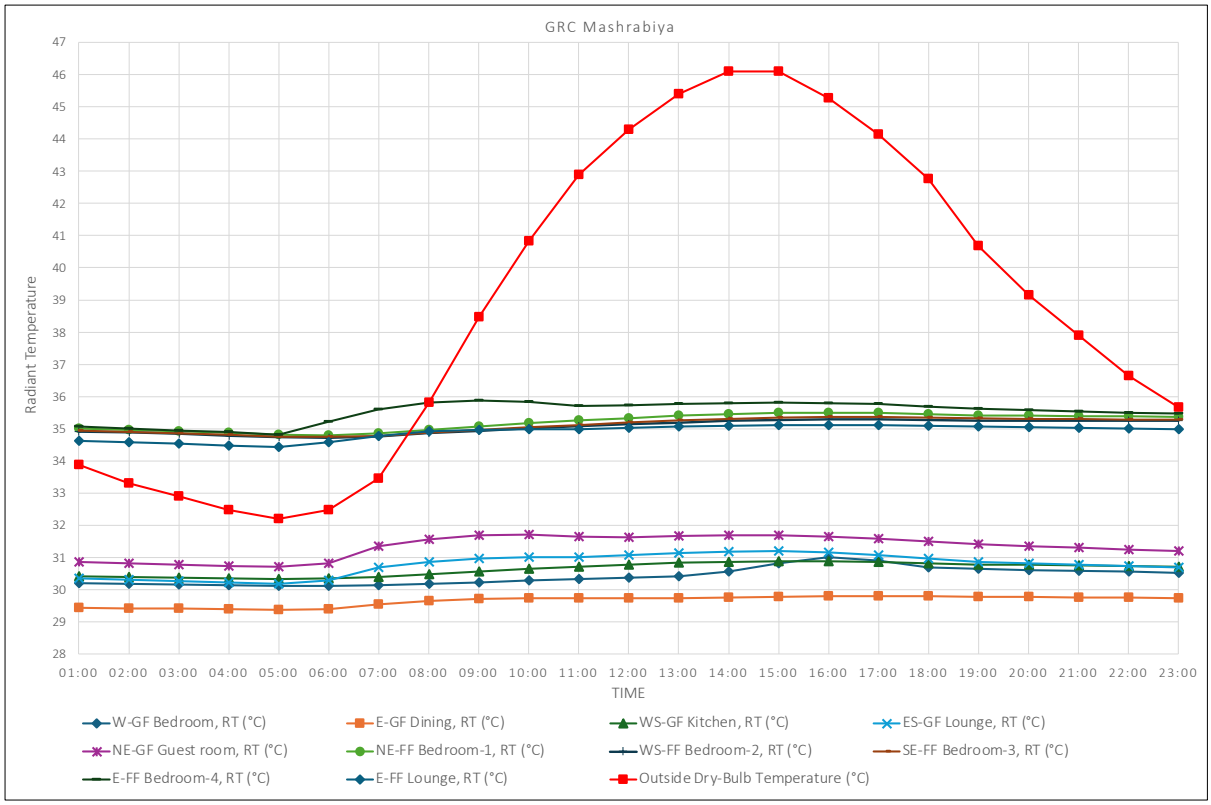


Figure A-1. 26. The free-running simulation of hourly radiant temperature in the base case building zones after applying GRC Mashrabiya (15th July).

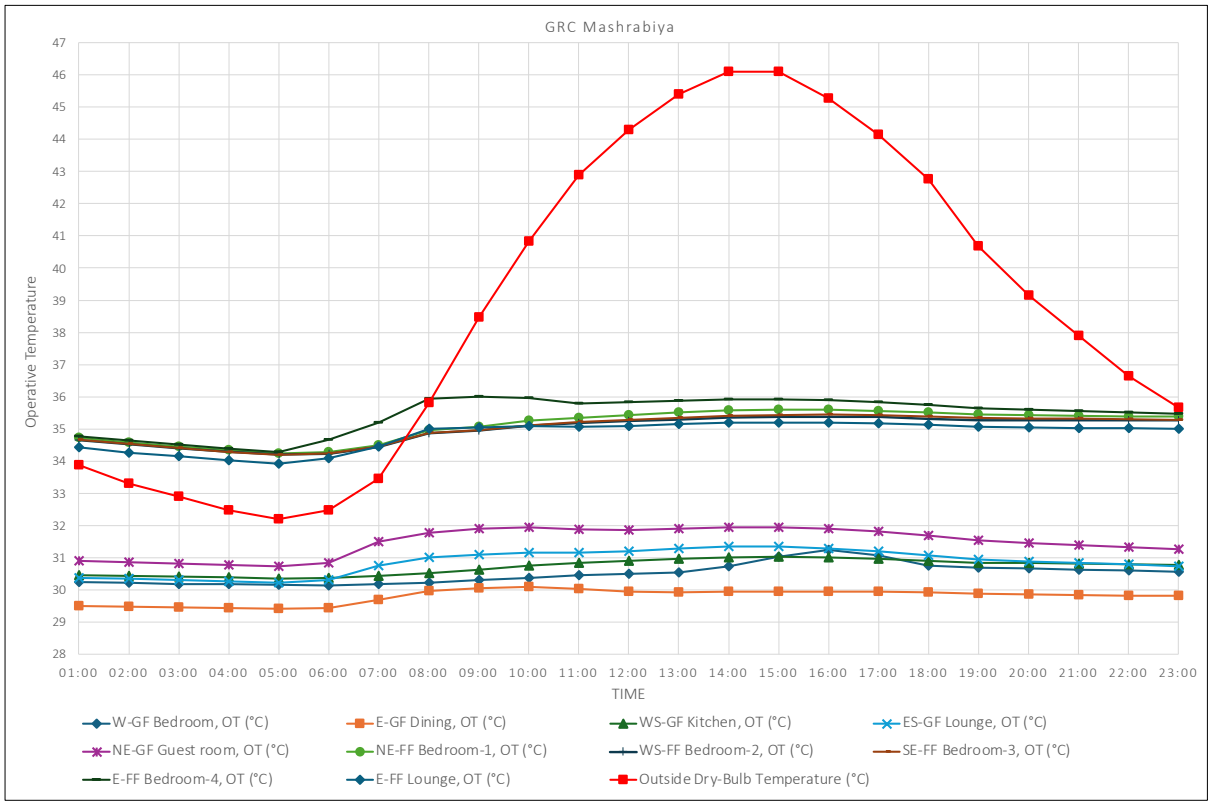


Figure A-1. 27. The free-running simulation of hourly operative temperature in the base case building zones after applying GRC Mashrabiya (15th July).

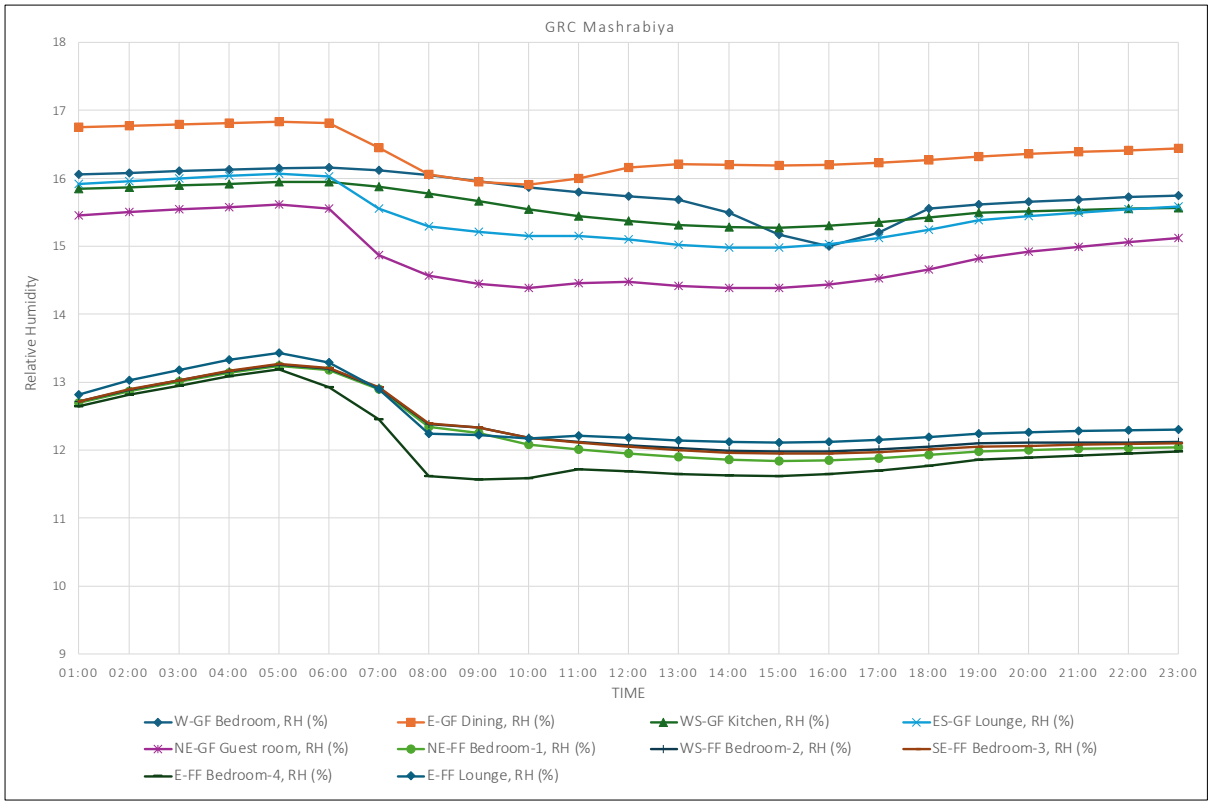


Figure A-1. 28. The free-running simulation of hourly relative humidity in the base case building zones after applying GRC Mashrabiya (15th July).

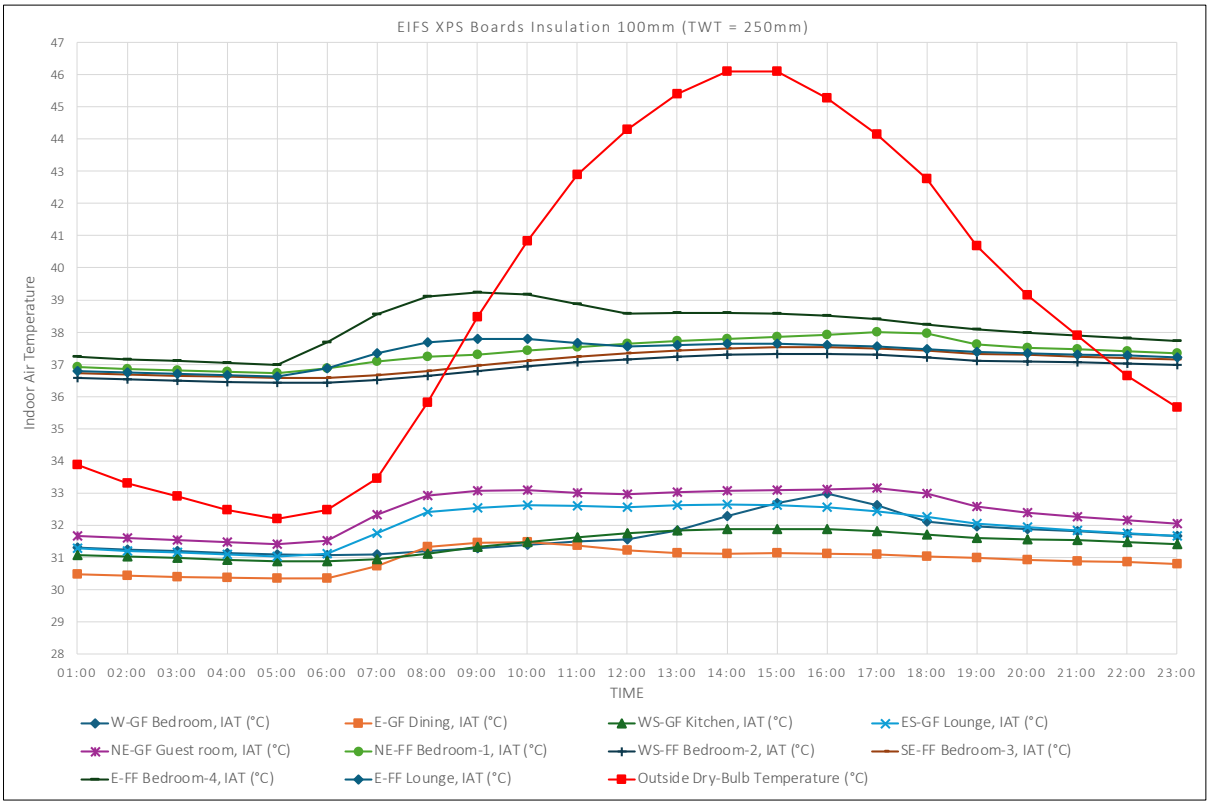


Figure A-1. 29. The free-running simulation of hourly indoor air temperature in the base case building zones after employing an EIFS of 100mm XPS Boards Insulation (15th July).

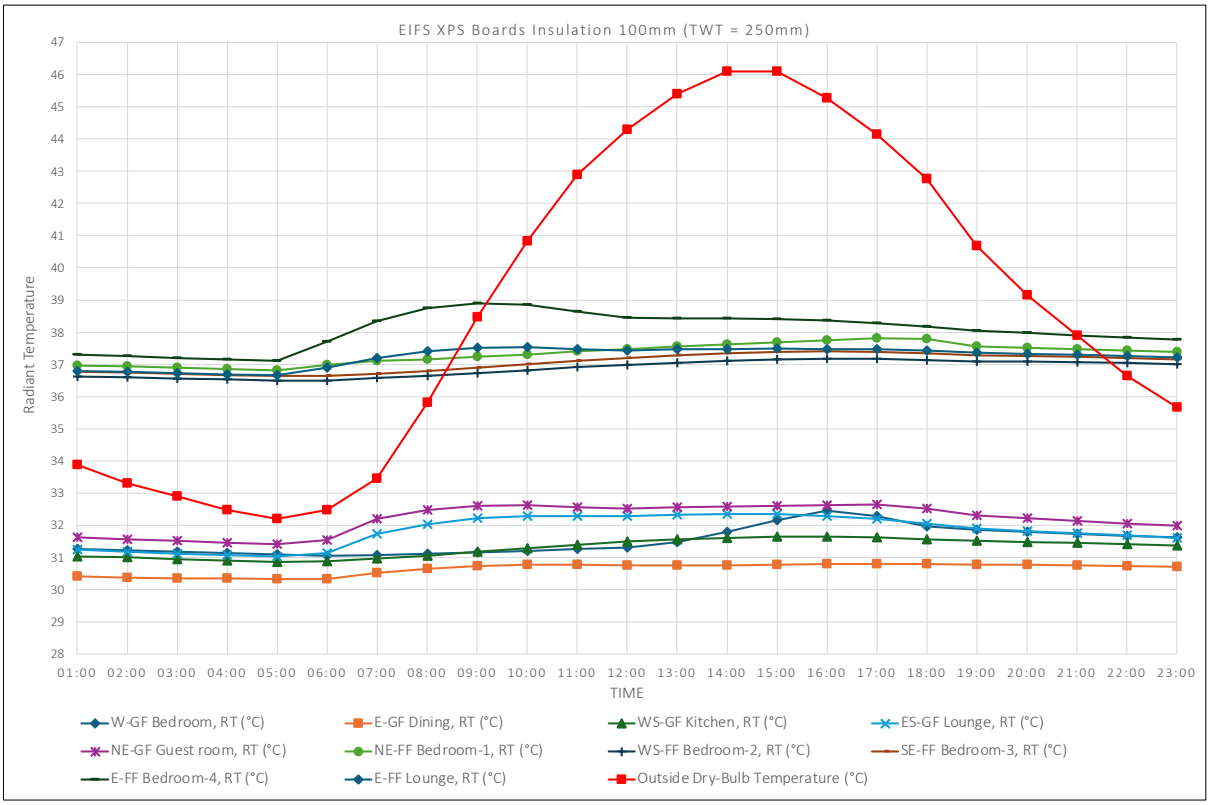


Figure A-1. 30. The free-running simulation of hourly radiant temperature in the base case building zones after employing an EIFS of 100mm XPS Boards Insulation (15th July).

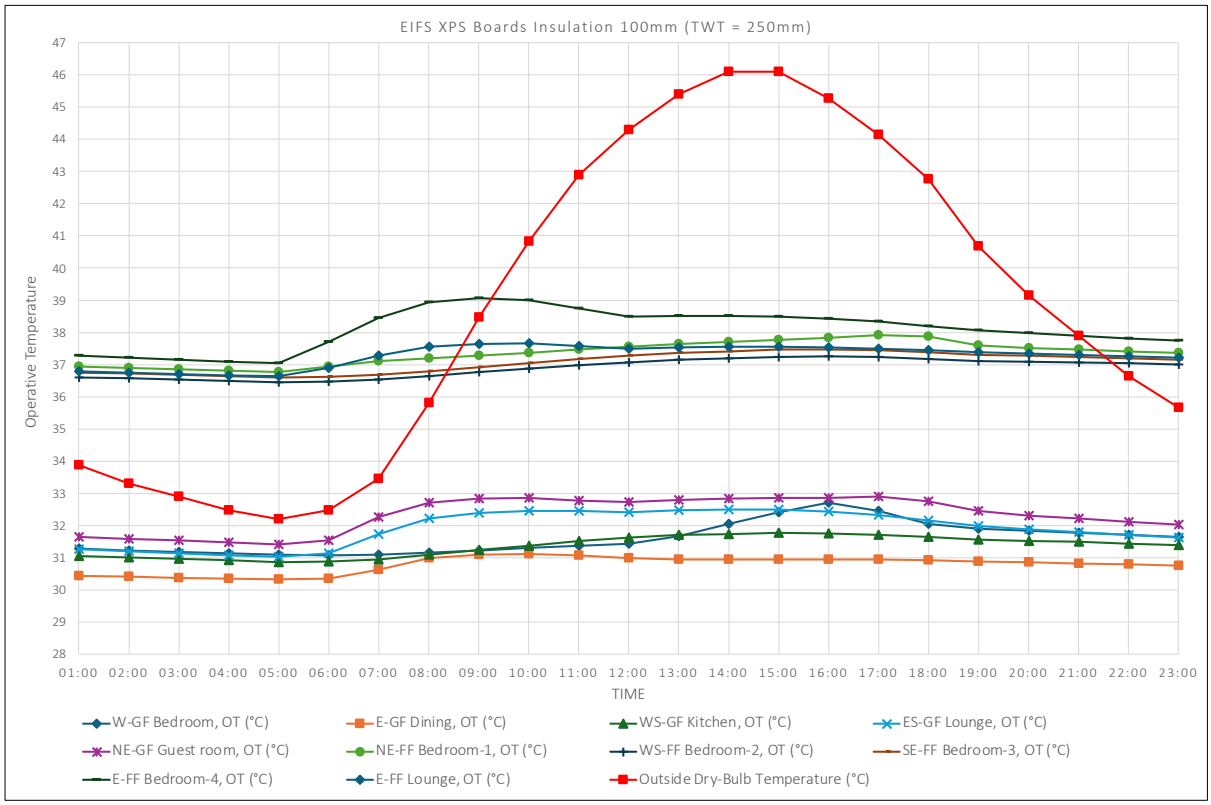


Figure A-1. 31. The free-running simulation of hourly operative temperature in the base case building zones after employing an EIFS of 100mm XPS Boards Insulation (15th July).

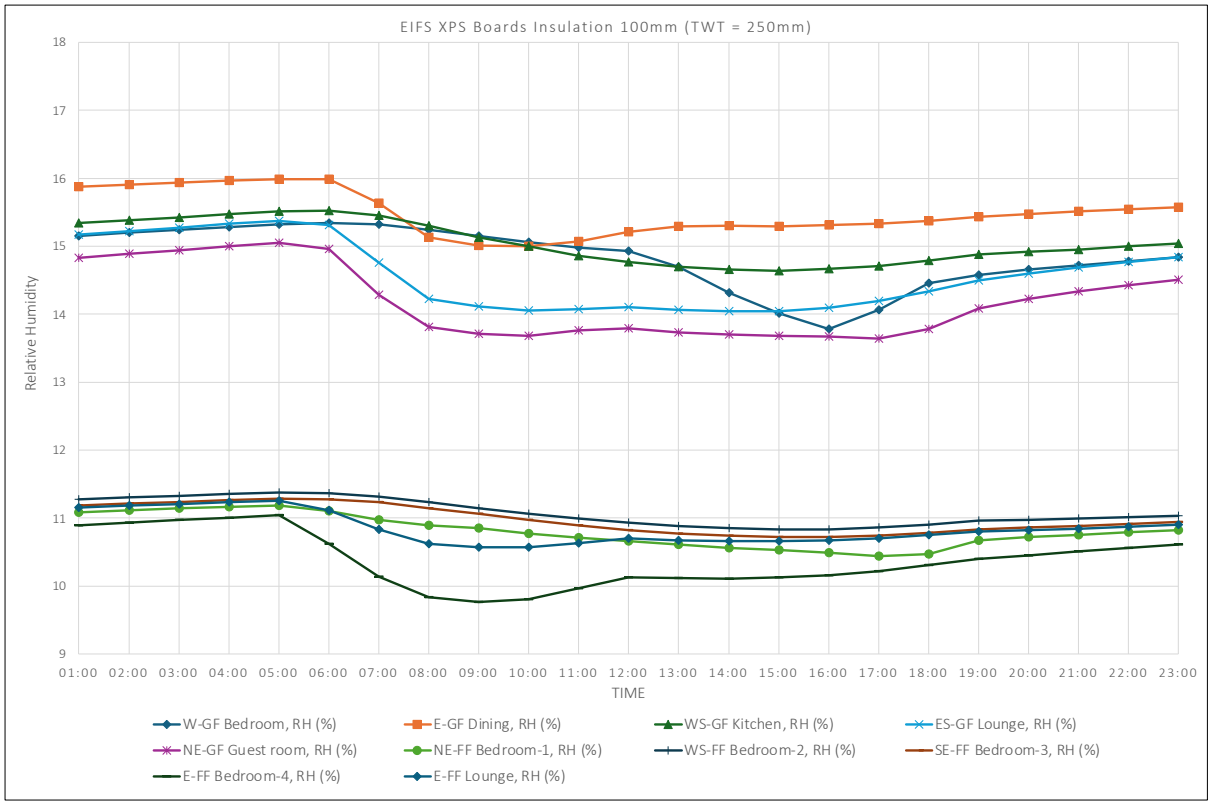


Figure A-1. 32. The free-running simulation of hourly relative humidity in the base case building zones after employing an EIFS of 100mm XPS Boards Insulation (15th July).

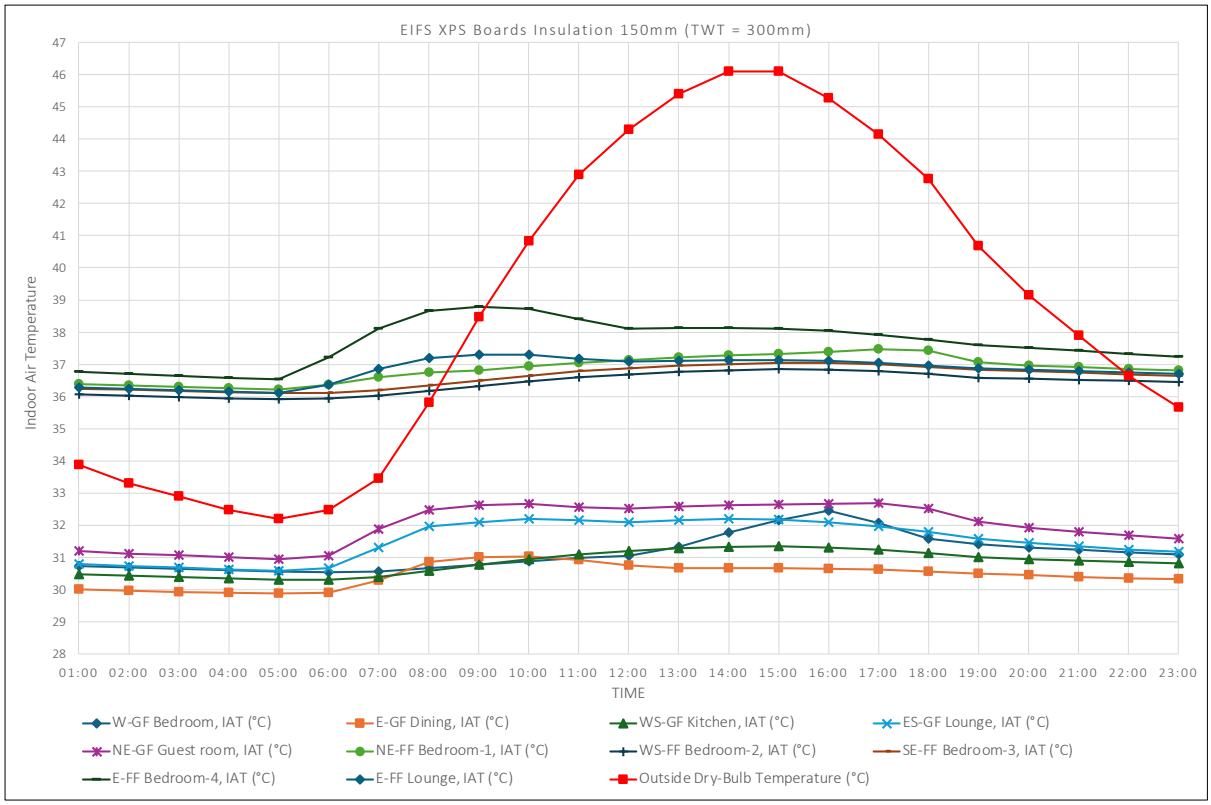


Figure A-1. 33. The free-running simulation of hourly indoor air temperature in the base case building zones after employing an EIFS of 150mm XPS Boards Insulation (15th July).

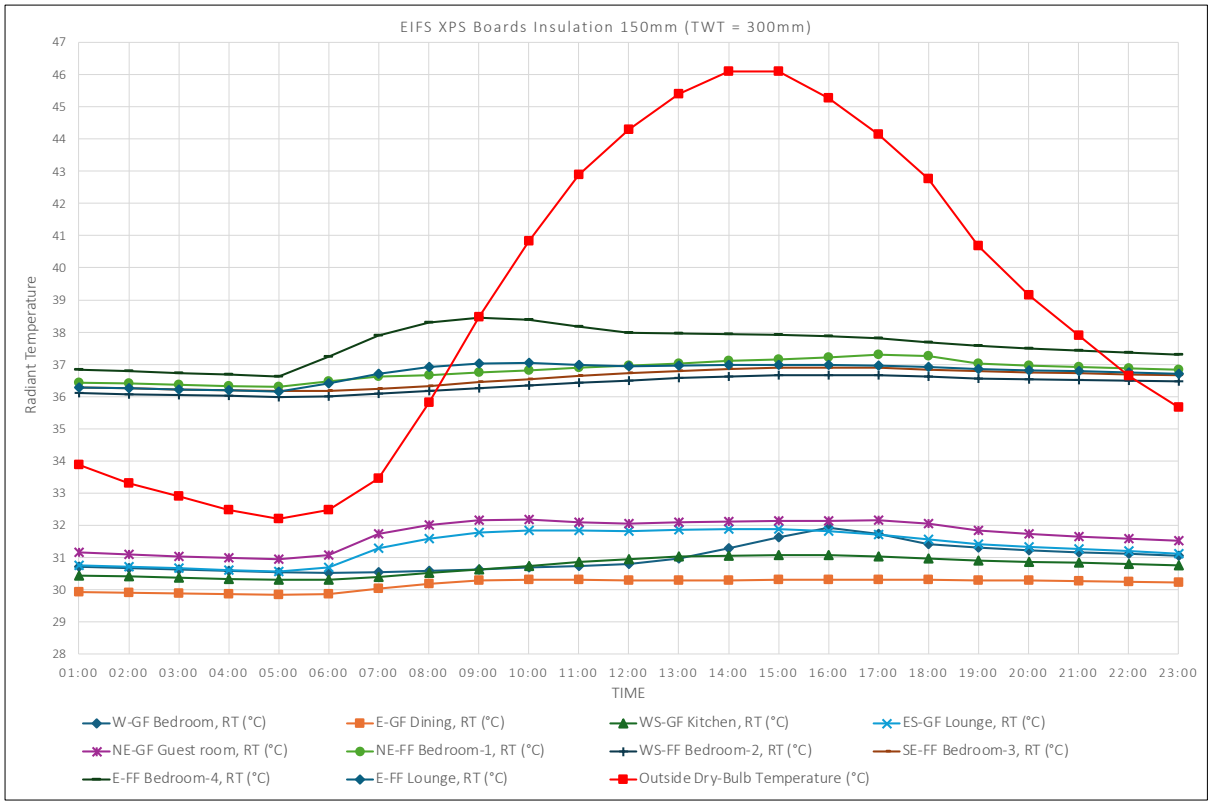


Figure A-1. 34. The free-running simulation of hourly radiant temperature in the base case building zones after employing an EIFS of 150mm XPS Boards Insulation (15th July).

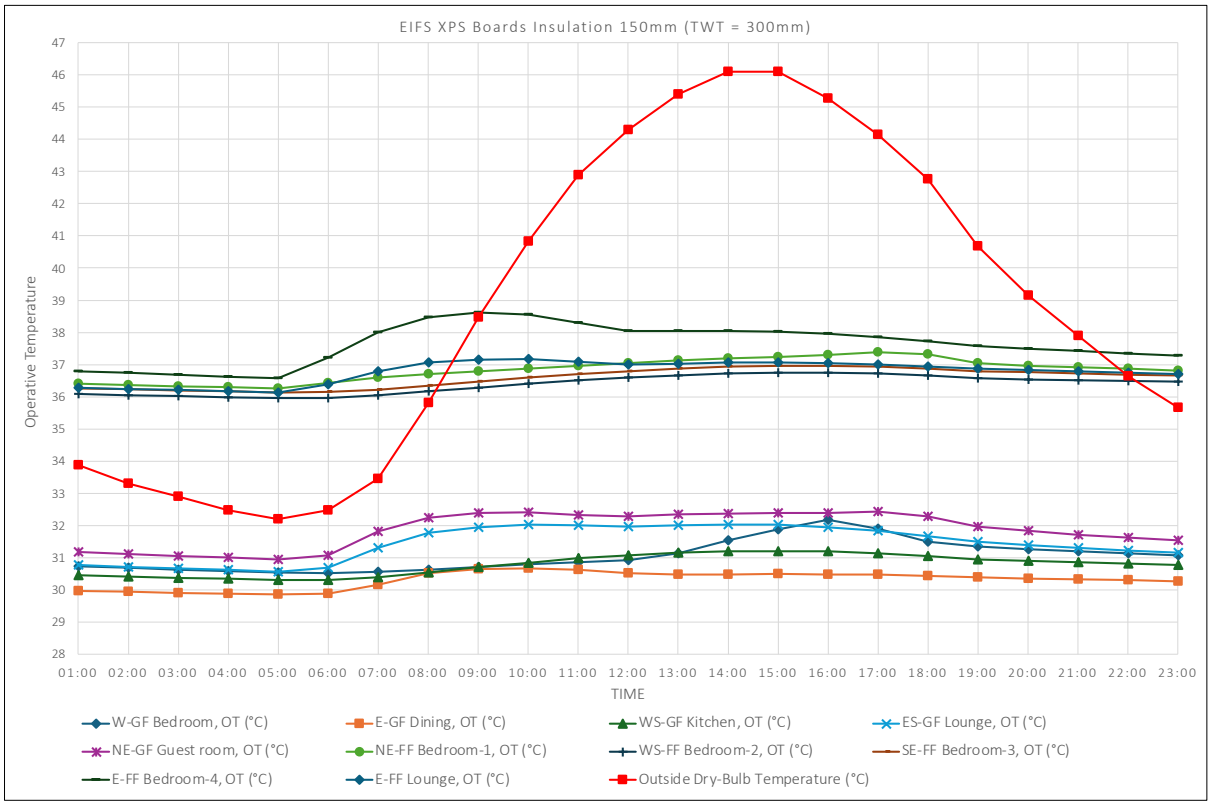


Figure A-1. 35. The free-running simulation of hourly operative temperature in the base case building zones after employing an EIFS of 150mm XPS Boards Insulation (15th July).

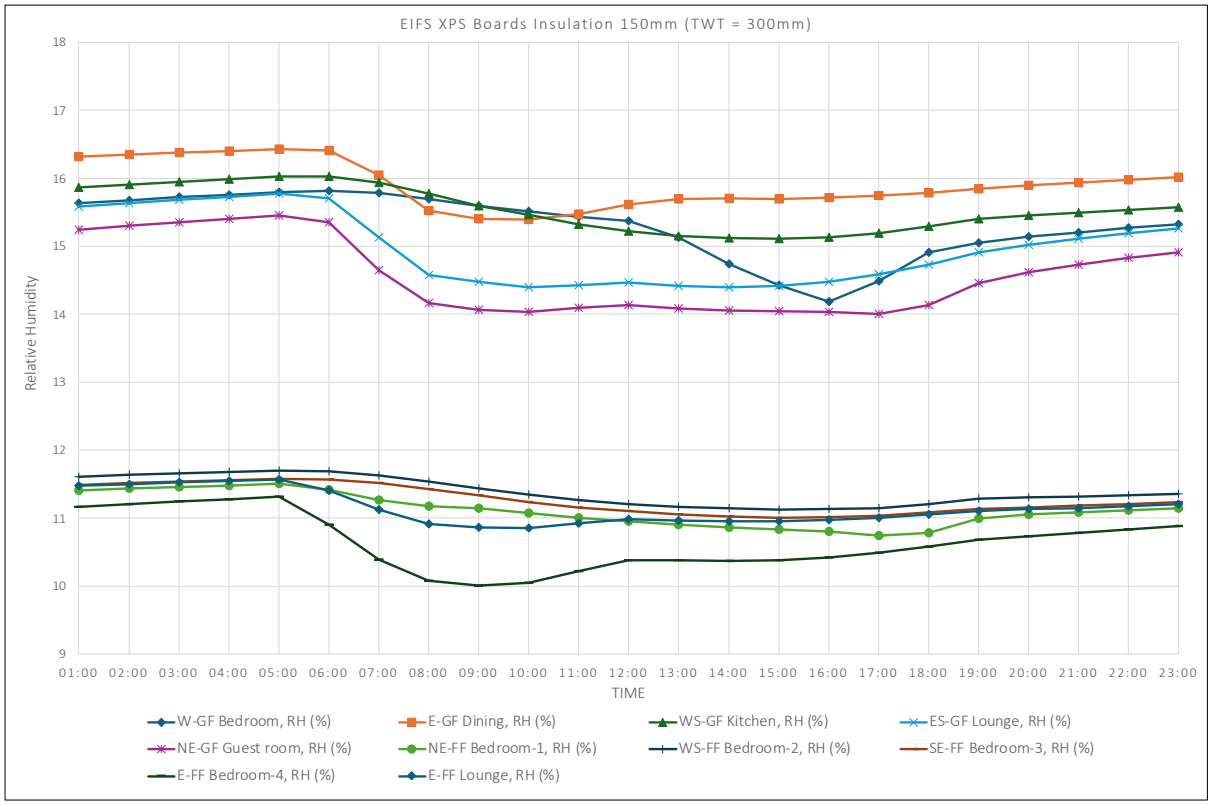


Figure A-1. 36. The free-running simulation of hourly relative humidity in the base case building zones after employing an EIFS of 150mm XPS Boards Insulation (15th July).

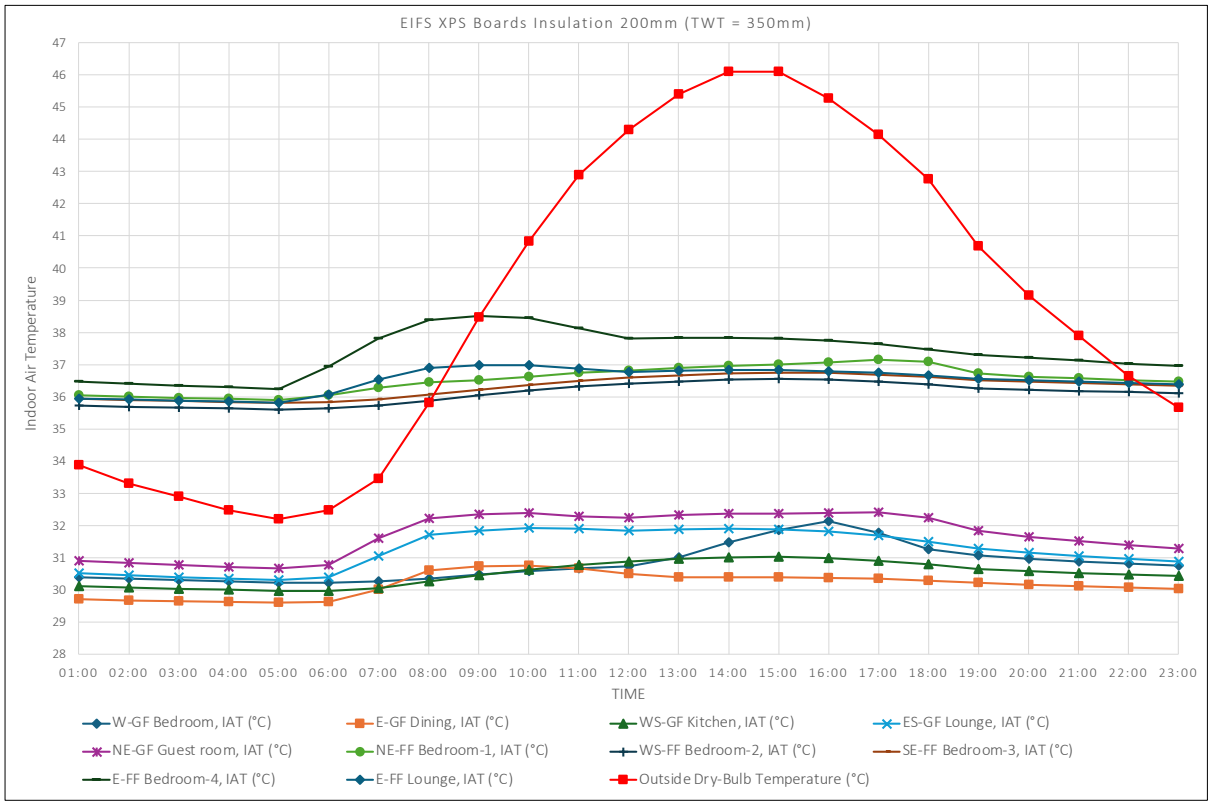


Figure A-1. 37.The free-running simulation of hourly indoor air temperature in the base case building zones after employing an EIFS of 200mm XPS Boards Insulation (15th July).

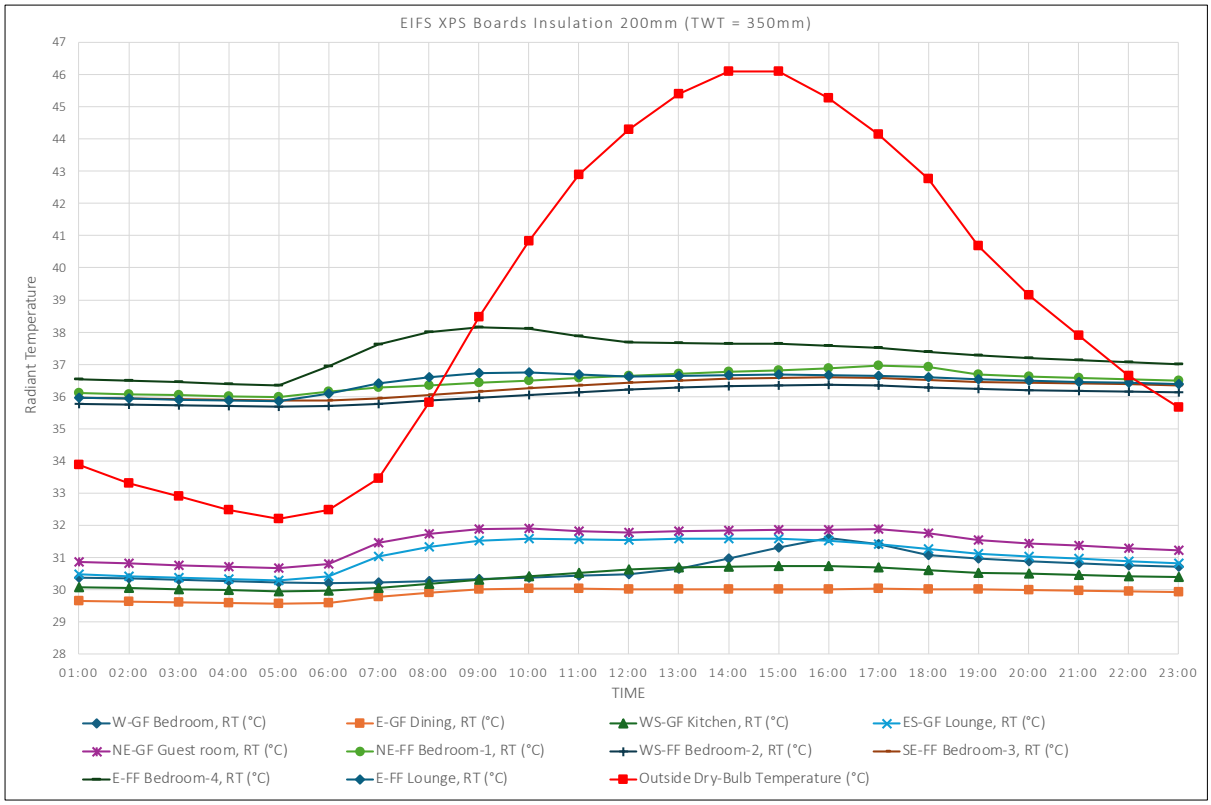


Figure A-1. 38. The free-running simulation of hourly radiant temperature in the base case building zones after employing an EIFS of 200mm XPS Boards Insulation (15th July).

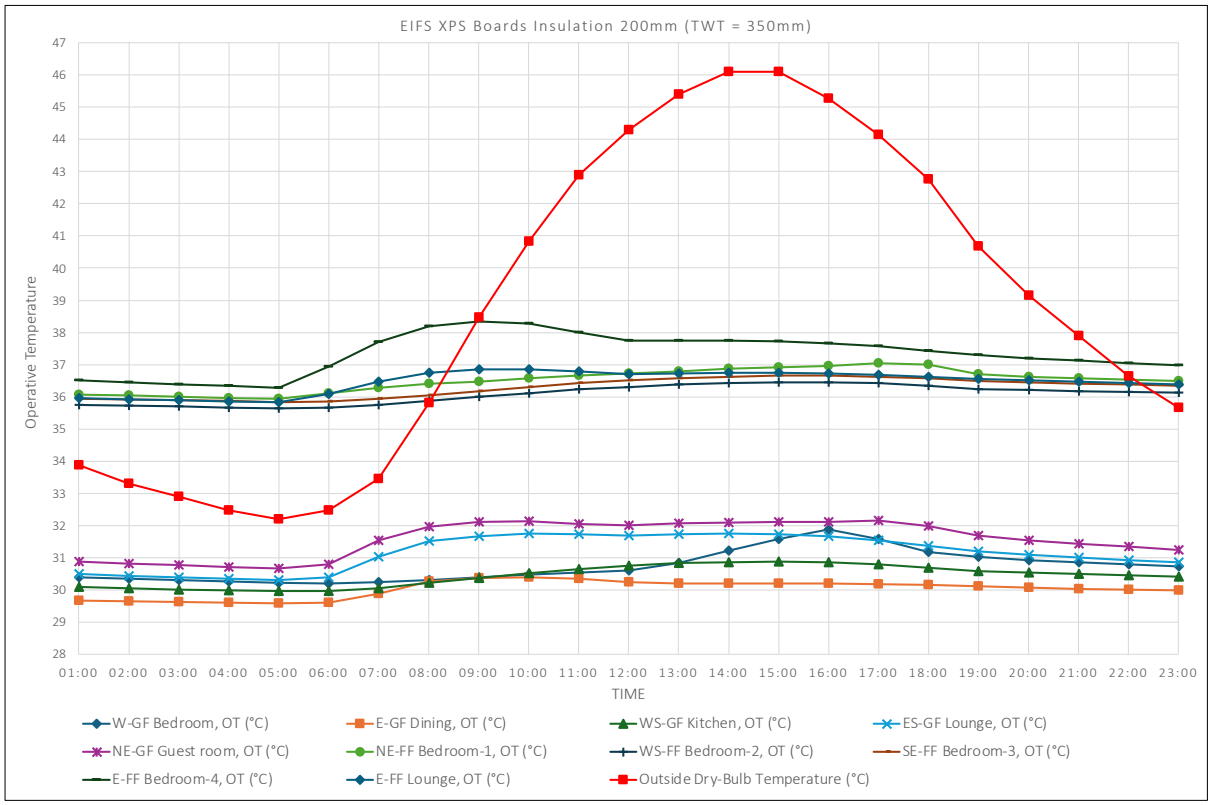


Figure A-1. 39. The free-running simulation of hourly operative temperature in the base case building zones after employing an EIFS of 200mm XPS Boards Insulation (15th July).

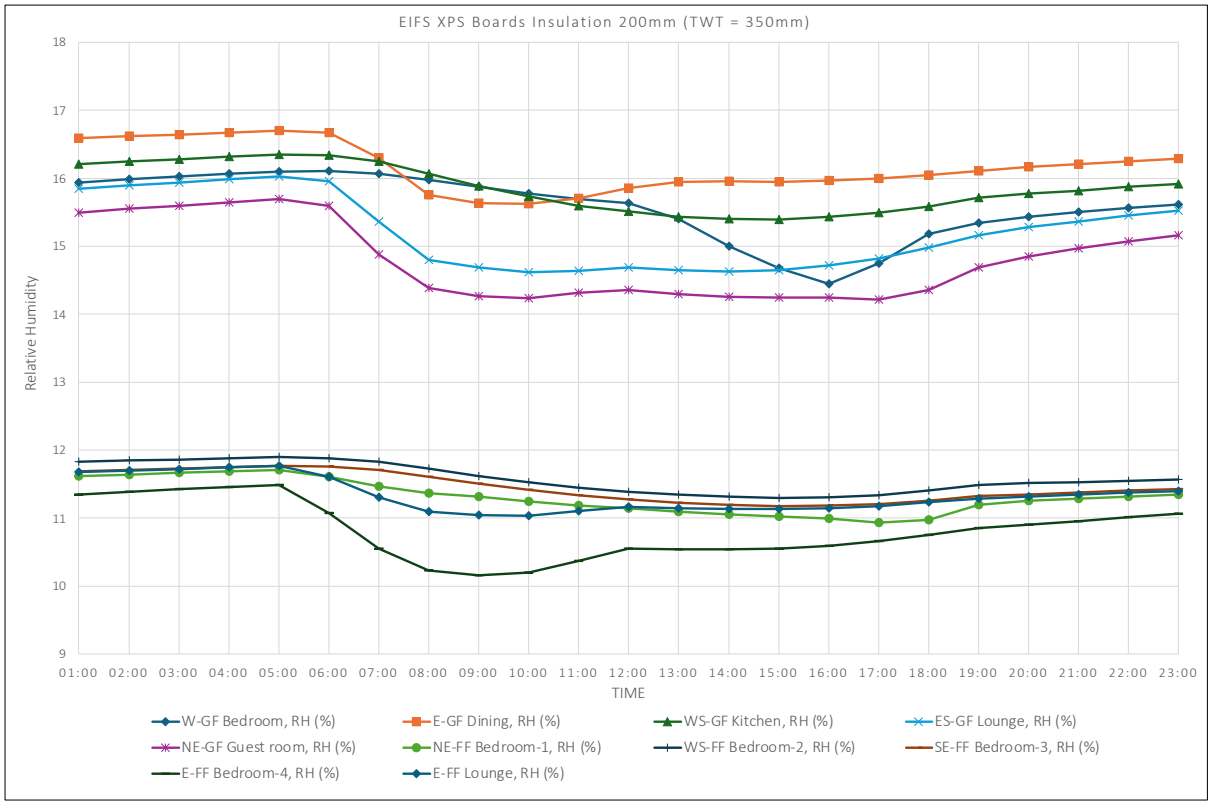


Figure A-1. 40. The free-running simulation of hourly relative humidity in the base case building zones after employing an EIFS of 200mm XPS Boards Insulation (15th July).

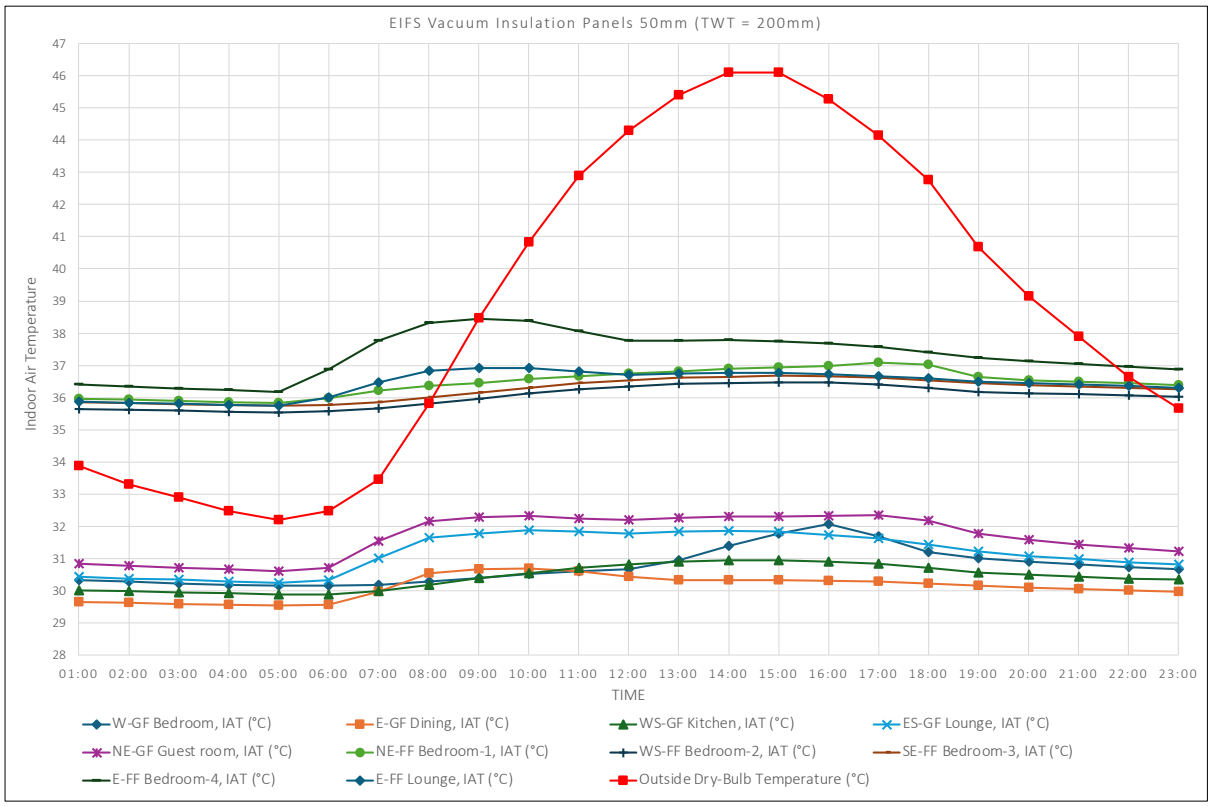


Figure A-1. 41. The free-running simulation of hourly indoor air temperature in the base case building zones after employing an EIFS of 50mm vacuum insulation panels (15th July).

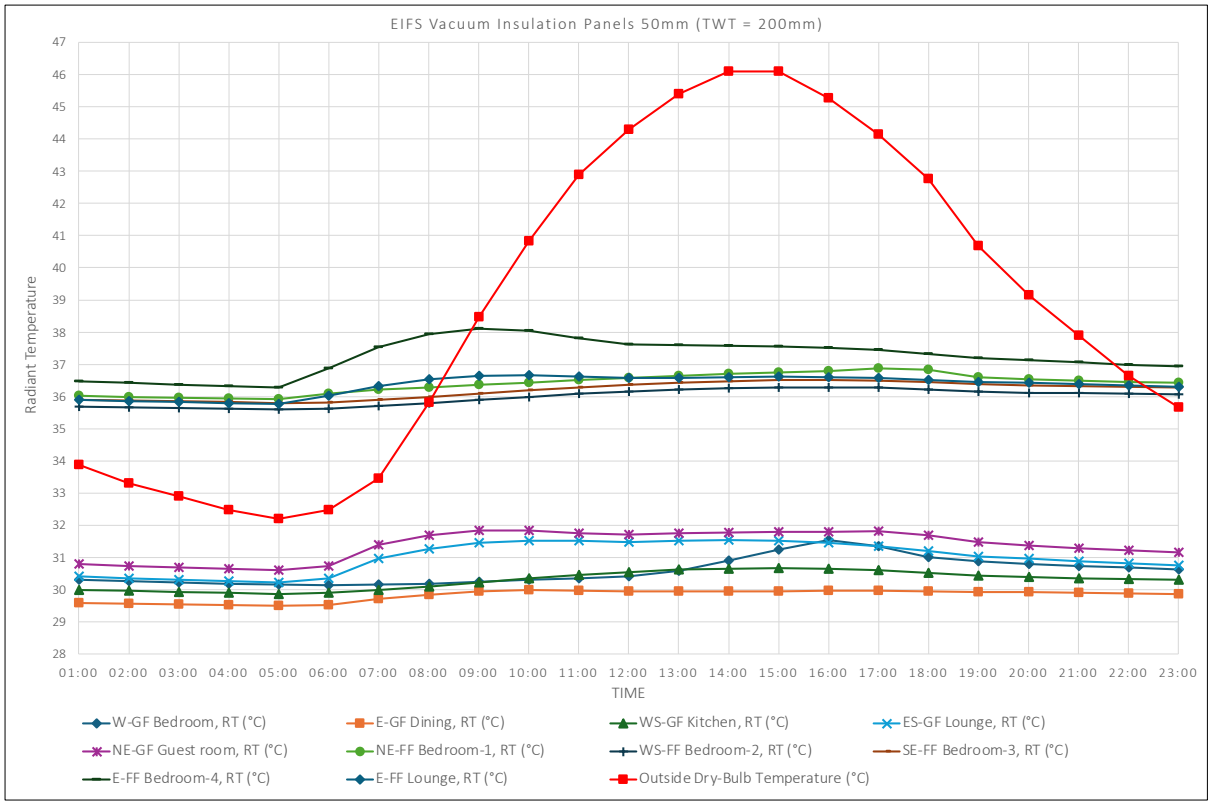


Figure A-1. 42. The free-running simulation of hourly radiant temperature in the base case building zones after employing an EIFS of 50mm vacuum insulation panels (15th July).

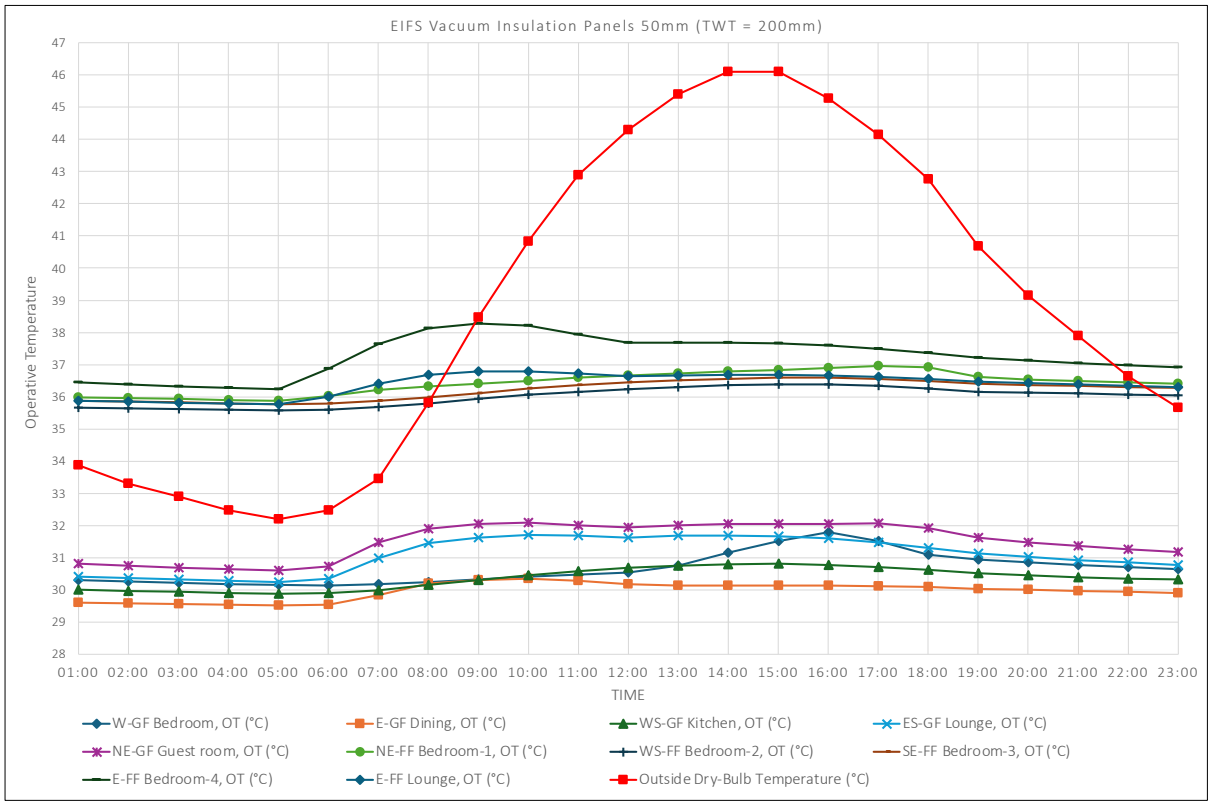


Figure A-1. 43. The free-running simulation of hourly operative temperature in the base case building zones after employing an EIFS of 50mm vacuum insulation panels (15th July).

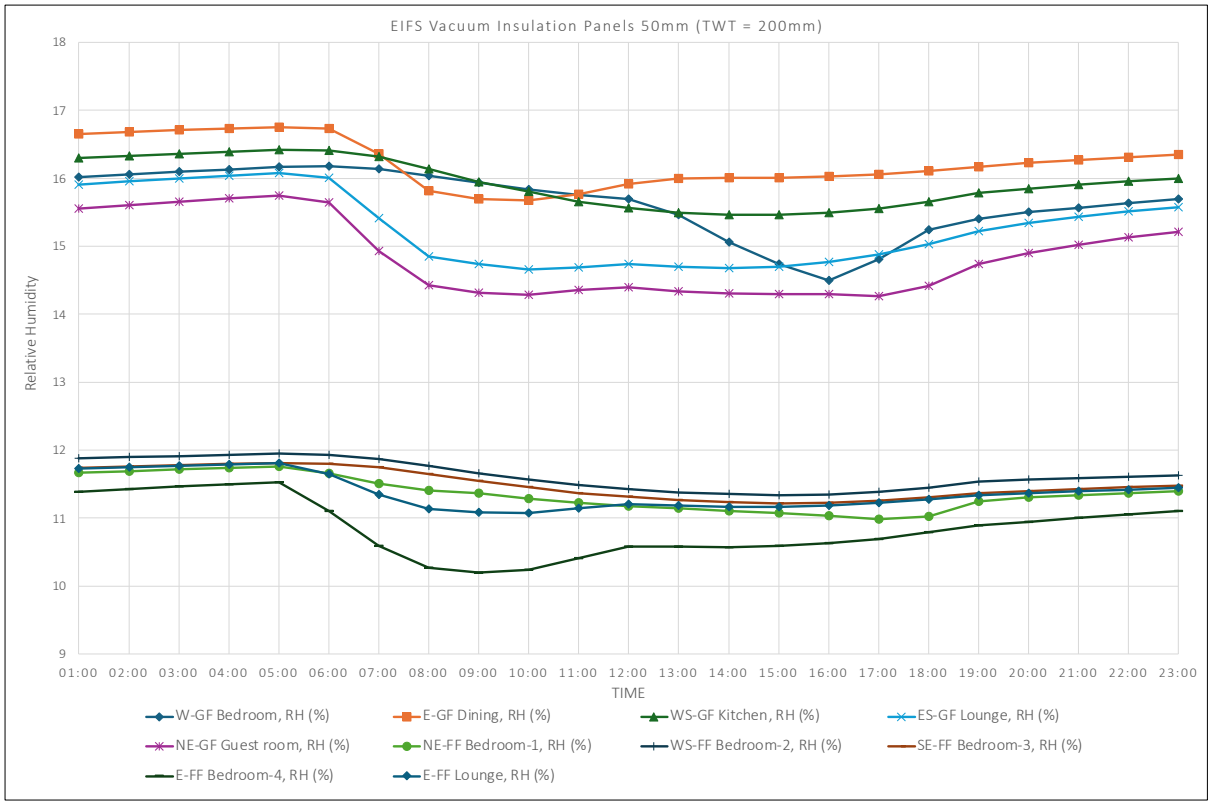


Figure A-1. 44. The free-running simulation of hourly relative humidity in the base case building zones after employing an EIFS of 50mm vacuum insulation panels (15th July).

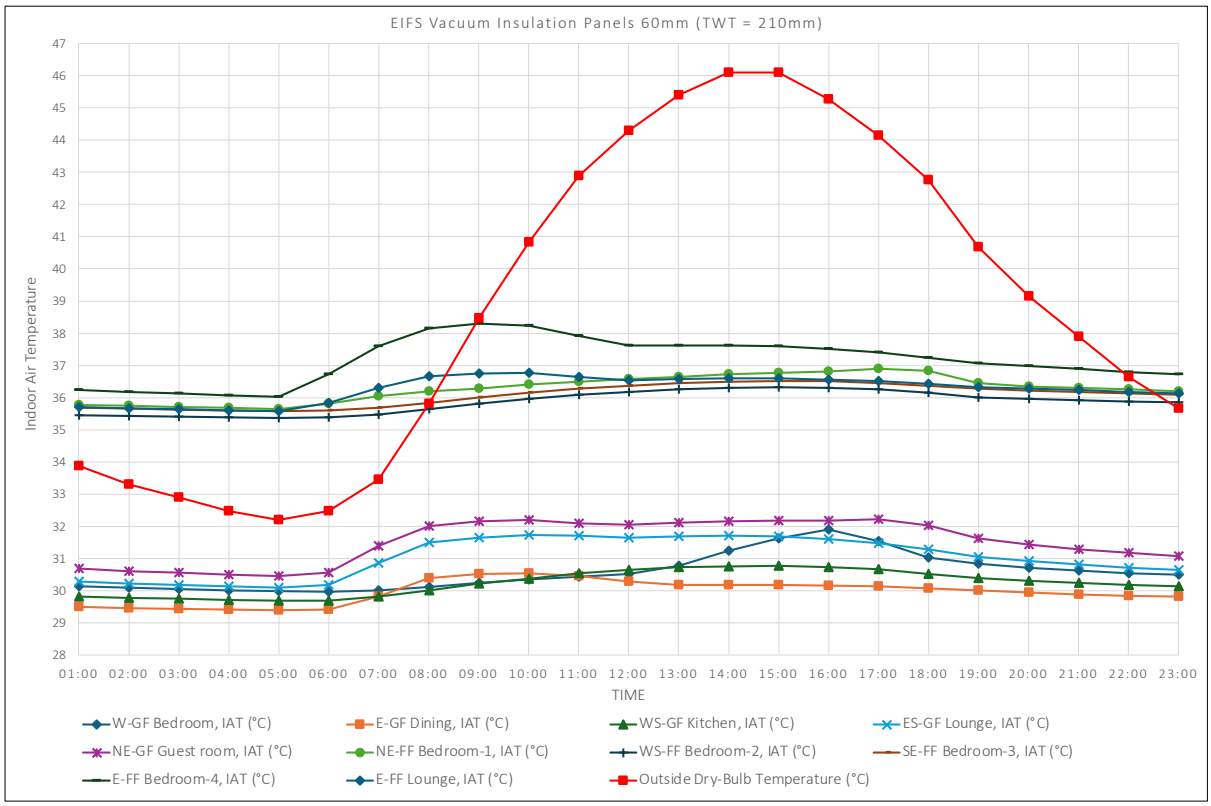


Figure A-1. 45. The free-running simulation of hourly indoor air temperature in the base case building zones after employing an EIFS of 60mm vacuum insulation panels (15th July).

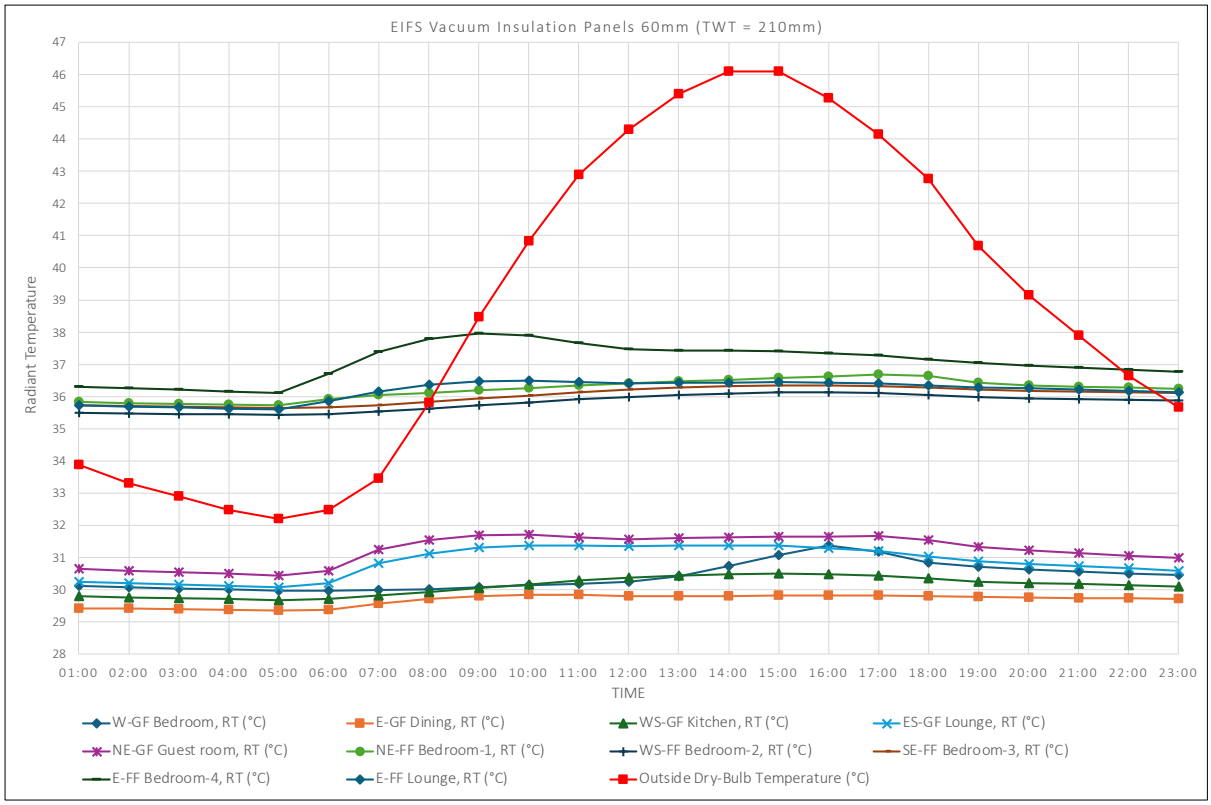


Figure A-1. 46. The free-running simulation of hourly radiant temperature in the base case building zones after employing an EIFS of 60mm vacuum insulation panels (15th July).

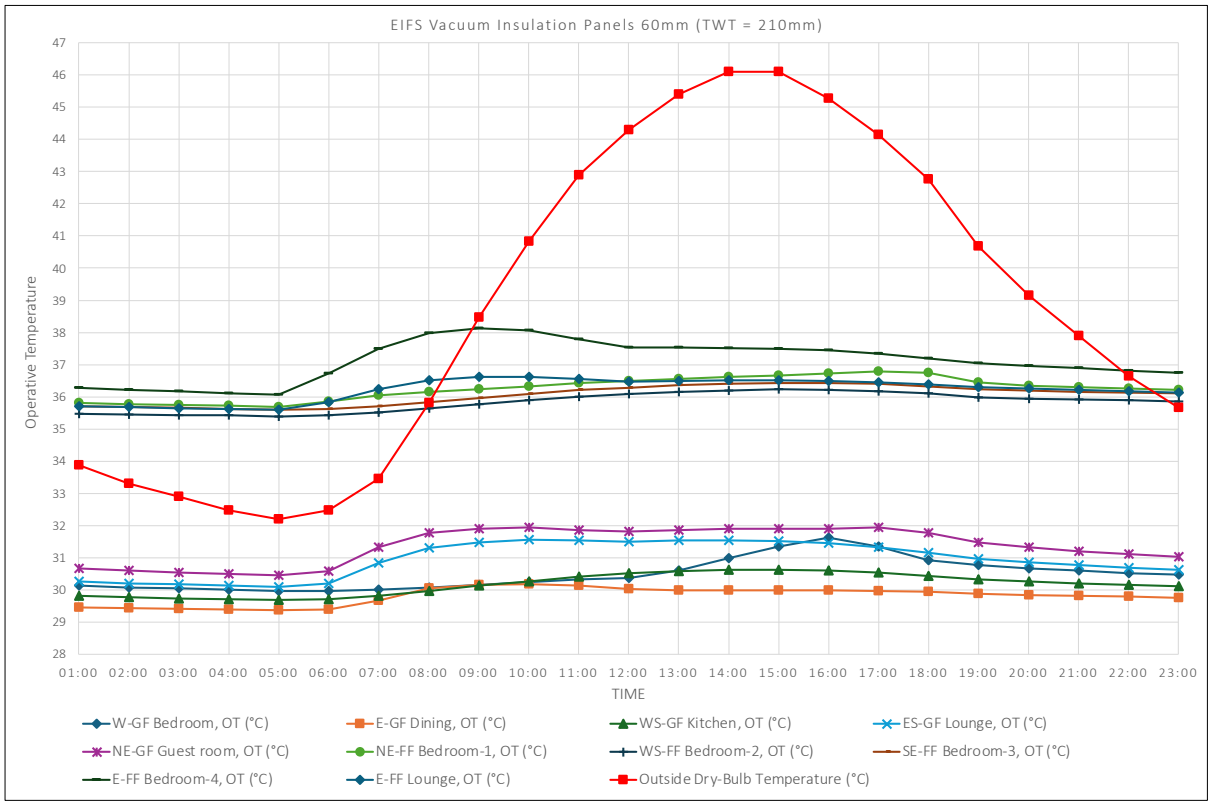


Figure A-1. 47. The free-running simulation of hourly operative temperature in the base case building zones after employing an EIFS of 60mm vacuum insulation panels (15th July).

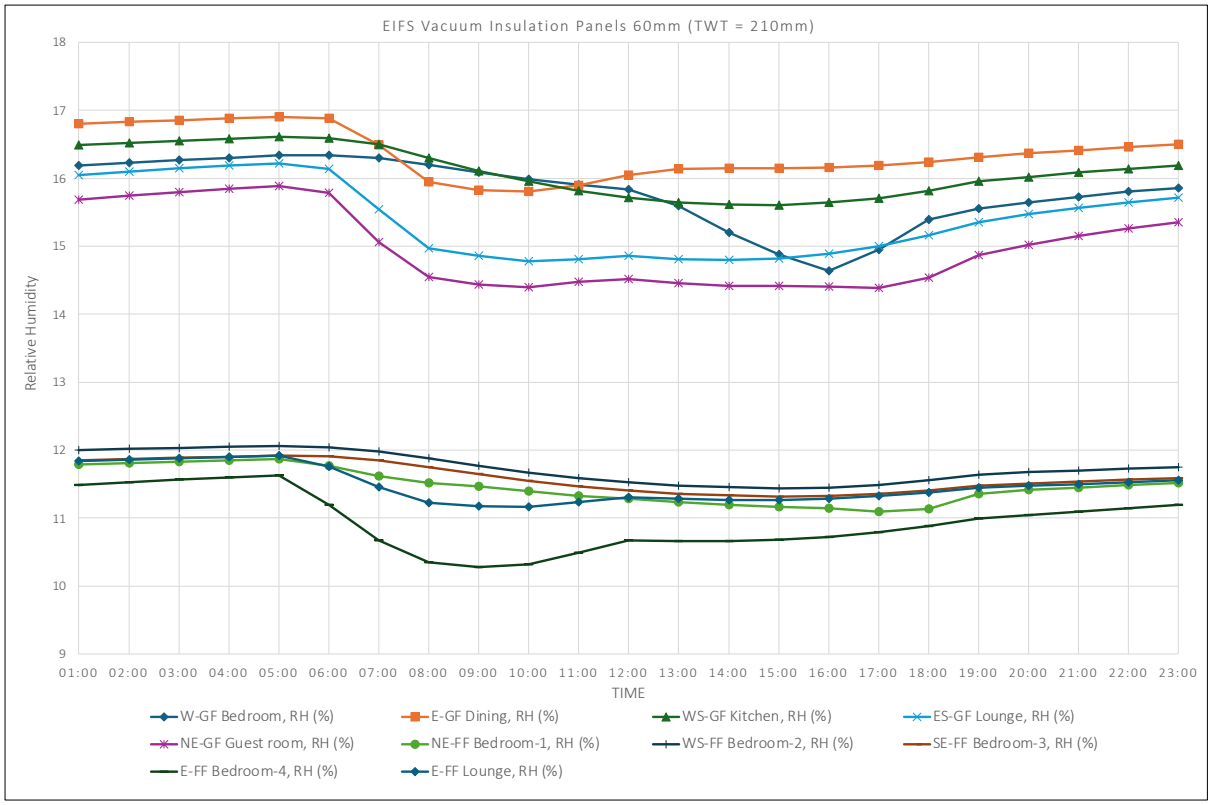


Figure A-1. 48. The free-running simulation of hourly relative humidity in the base case building zones after employing an EIFS of 60mm vacuum insulation panels (15th July).

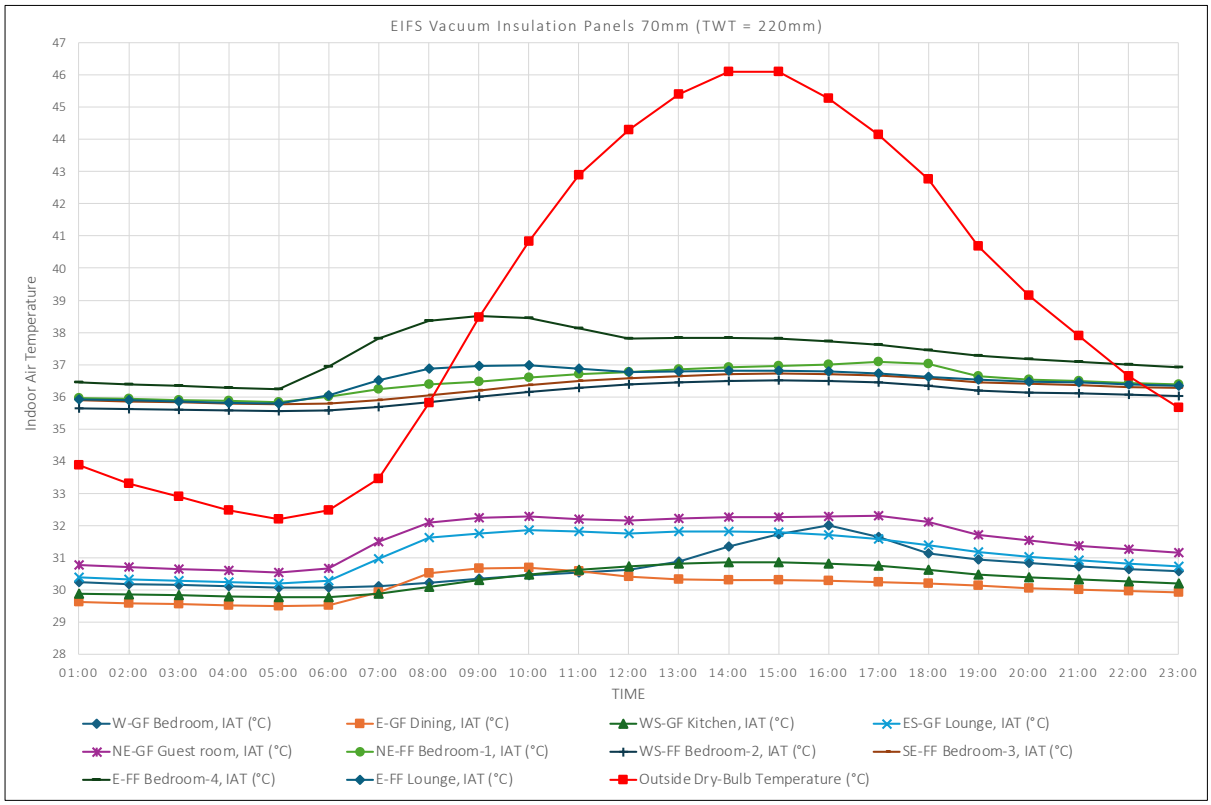


Figure A-1. 49. The free-running simulation of hourly indoor air temperature in the base case building zones after employing an EIFS of 70mm vacuum insulation panels (15th July).

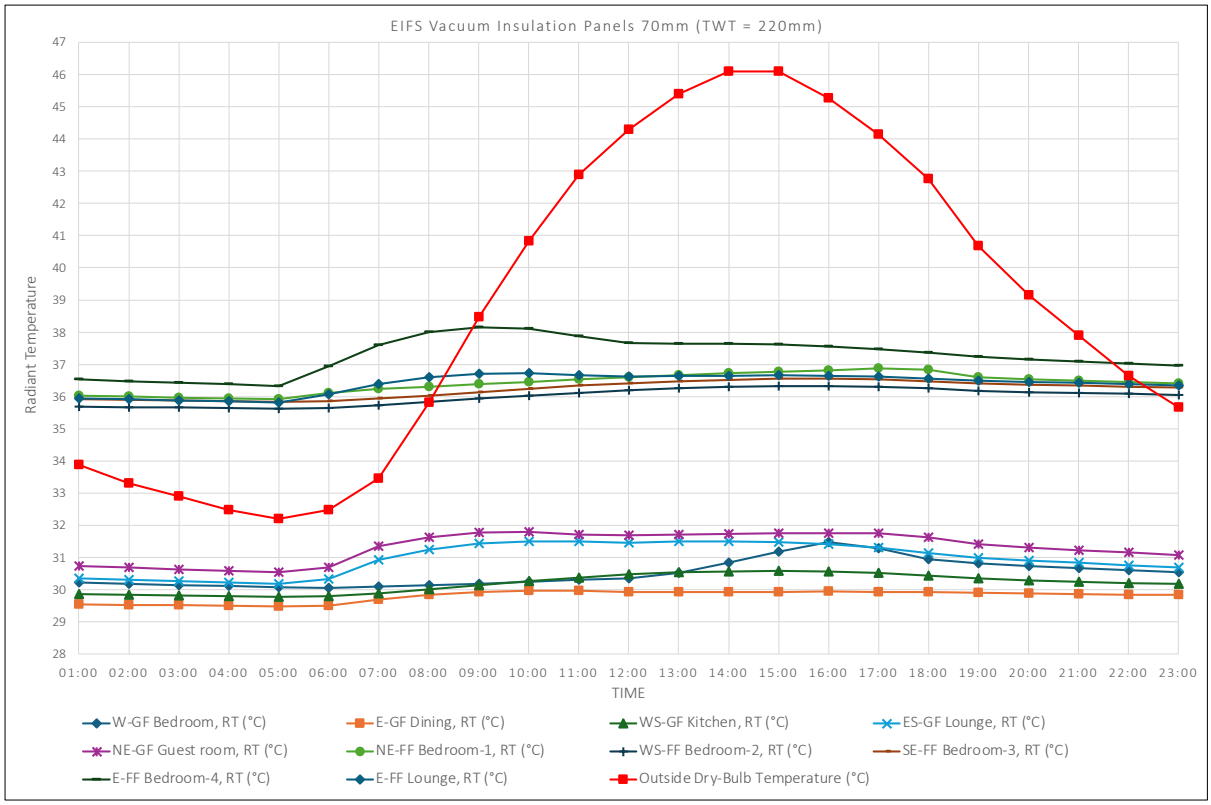


Figure A-1. 50. The free-running simulation of hourly radiant temperature in the base case building zones after employing an EIFS of 70mm vacuum insulation panels (15th July).

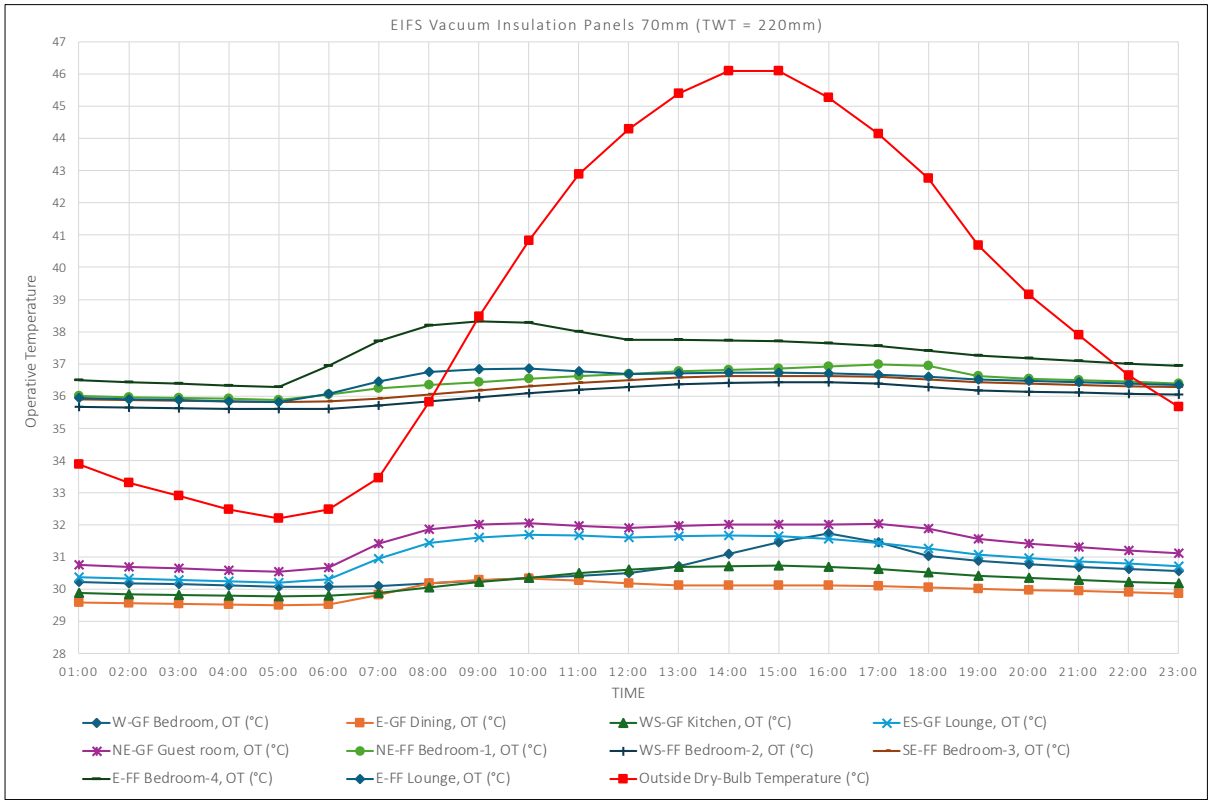


Figure A-1. 51. The free-running simulation of hourly operative temperature in the base case building zones after employing an EIFS of 70mm vacuum insulation panels (15th July).

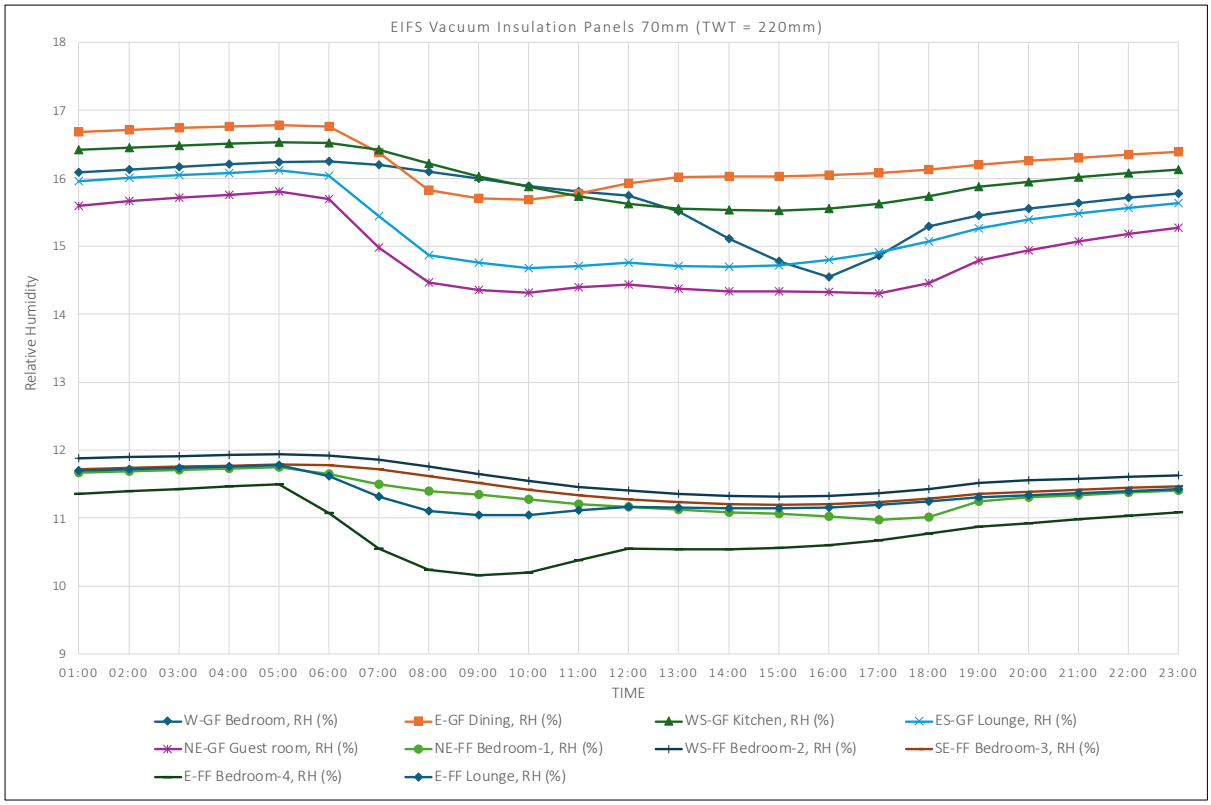


Figure A-1. 52. The free-running simulation of hourly relative humidity in the base case building zones after employing an EIFS of 70mm vacuum insulation panels (15th July).

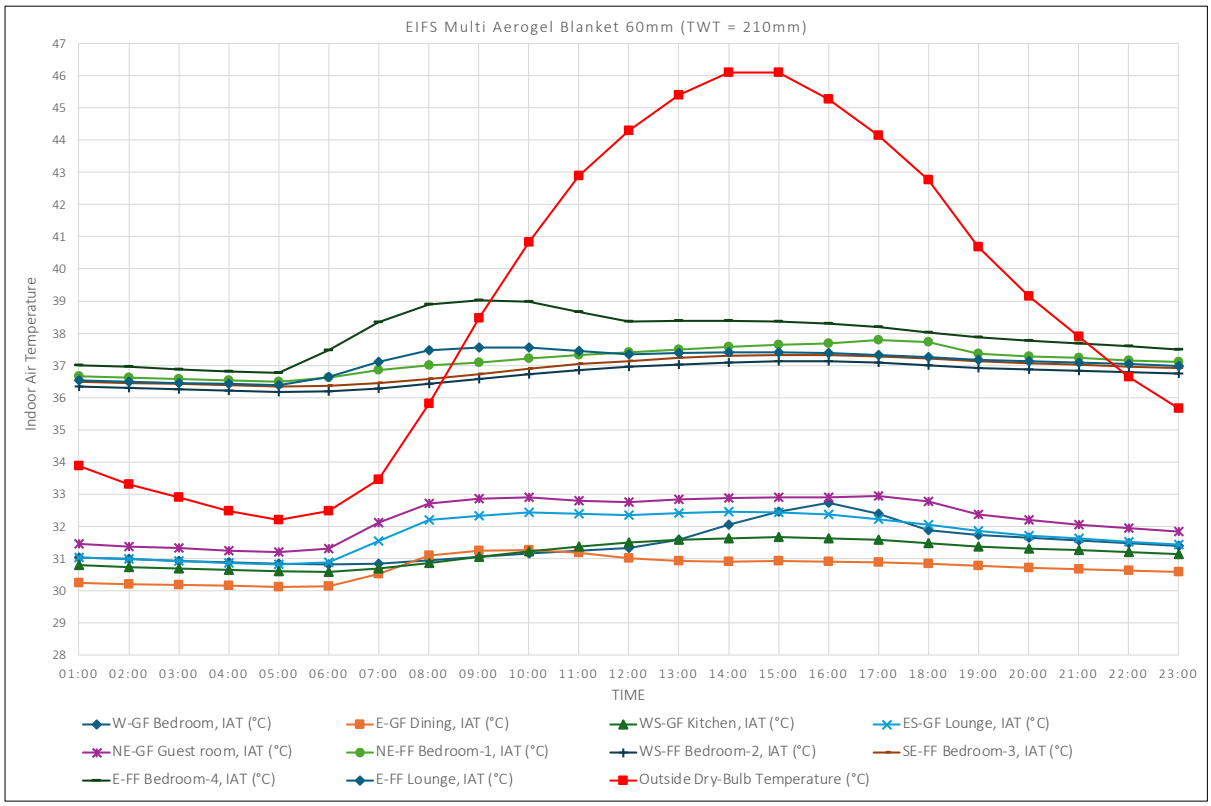


Figure A-1. 53. The free-running simulation of hourly indoor air temperature in the base case building zones after employing an EIFS of 60mm Multi Aerogel Blanket (15th July).

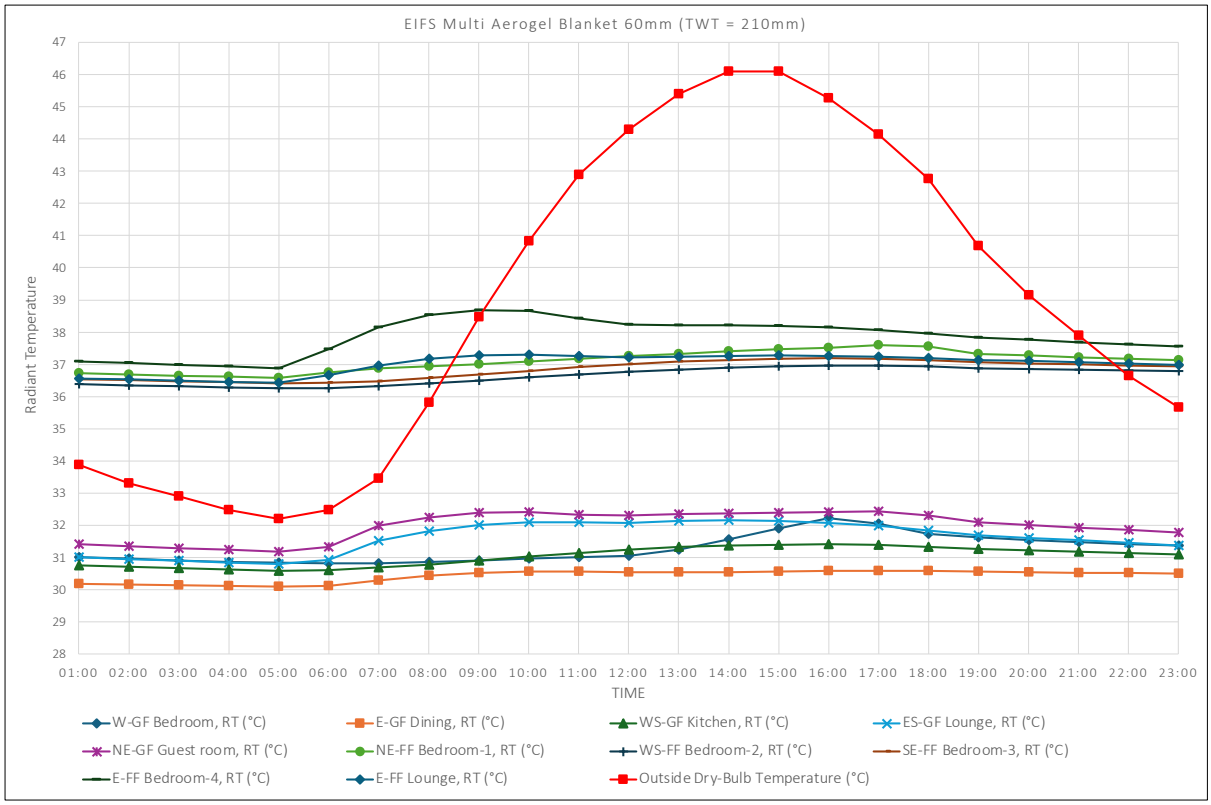


Figure A-1. 54. The free-running simulation of hourly radiant temperature in the base case building zones after employing an EIFS of 60mm Multi Aerogel Blanket (15th July).

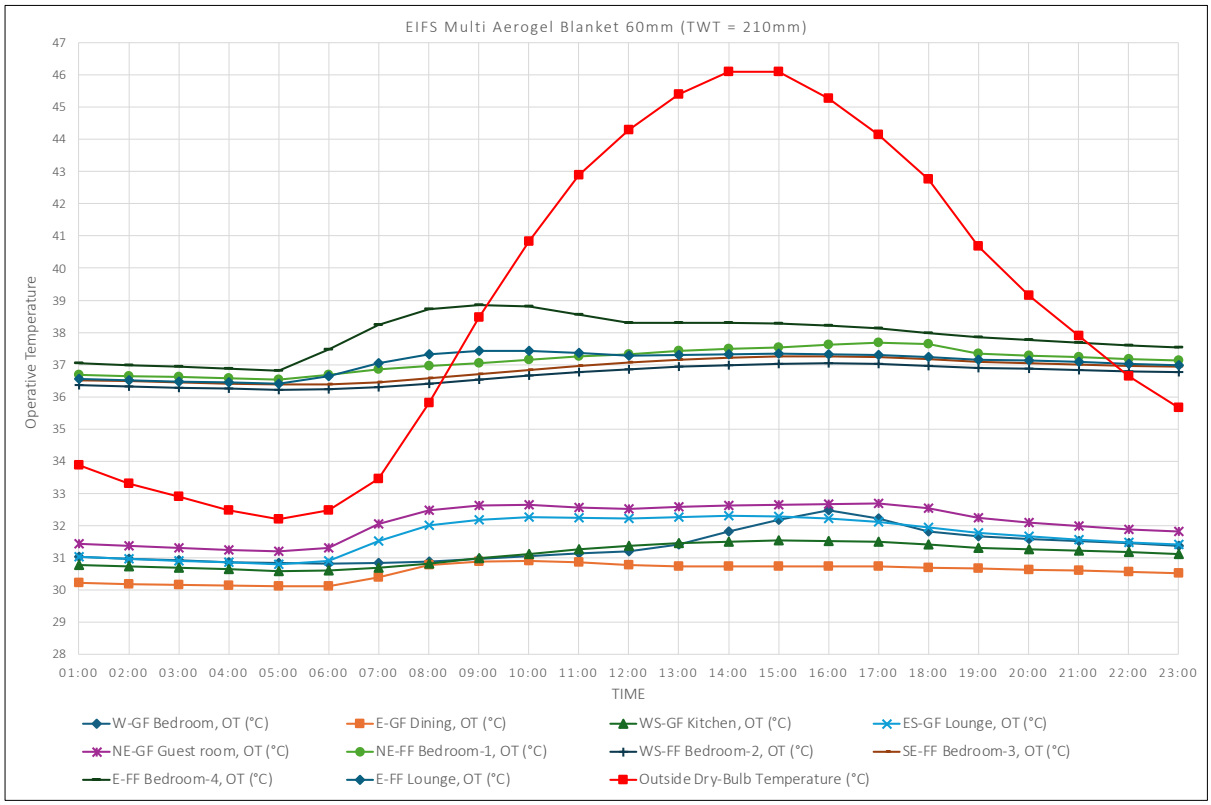


Figure A-1. 55. The free-running simulation of hourly operative temperature in the base case building zones after employing an EIFS of 60mm Multi Aerogel Blanket (15th July).

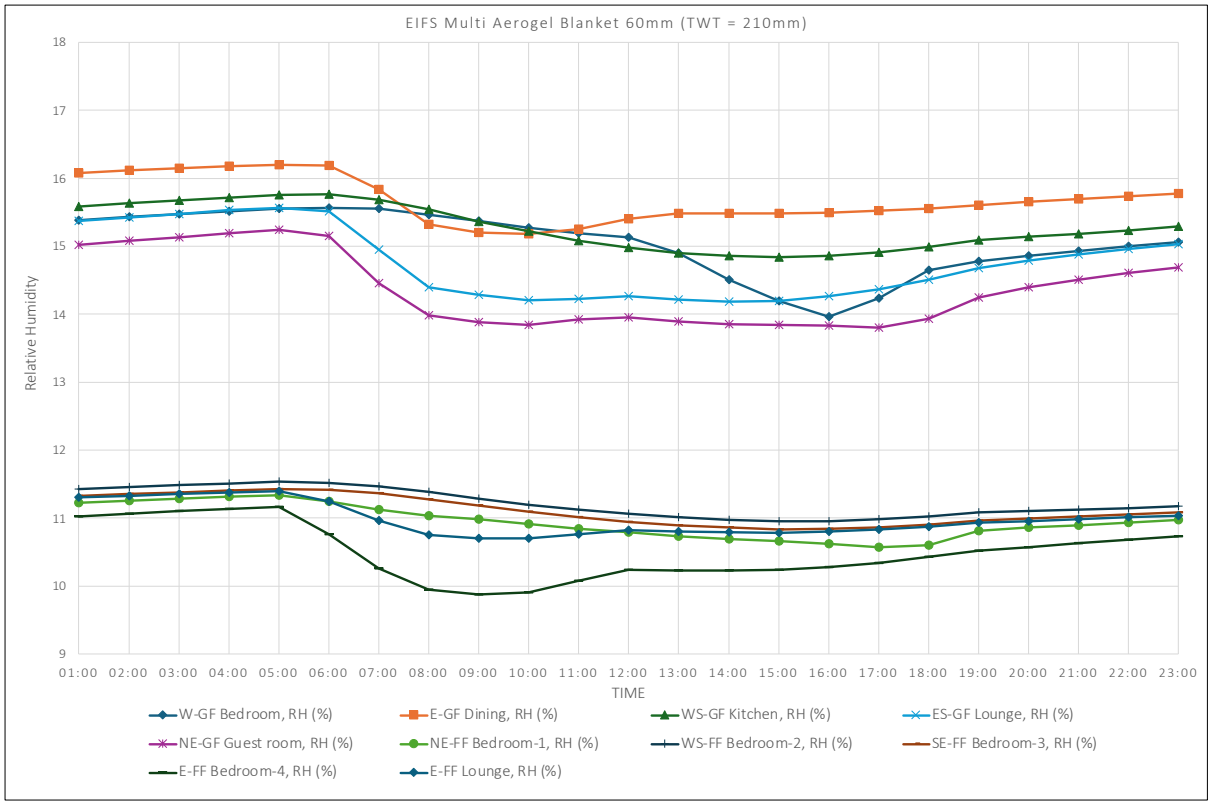


Figure A-1. 56. The free-running simulation of hourly relative humidity in the base case building zones after employing an EIFS of 60mm Multi Aerogel Blanket (15th July).

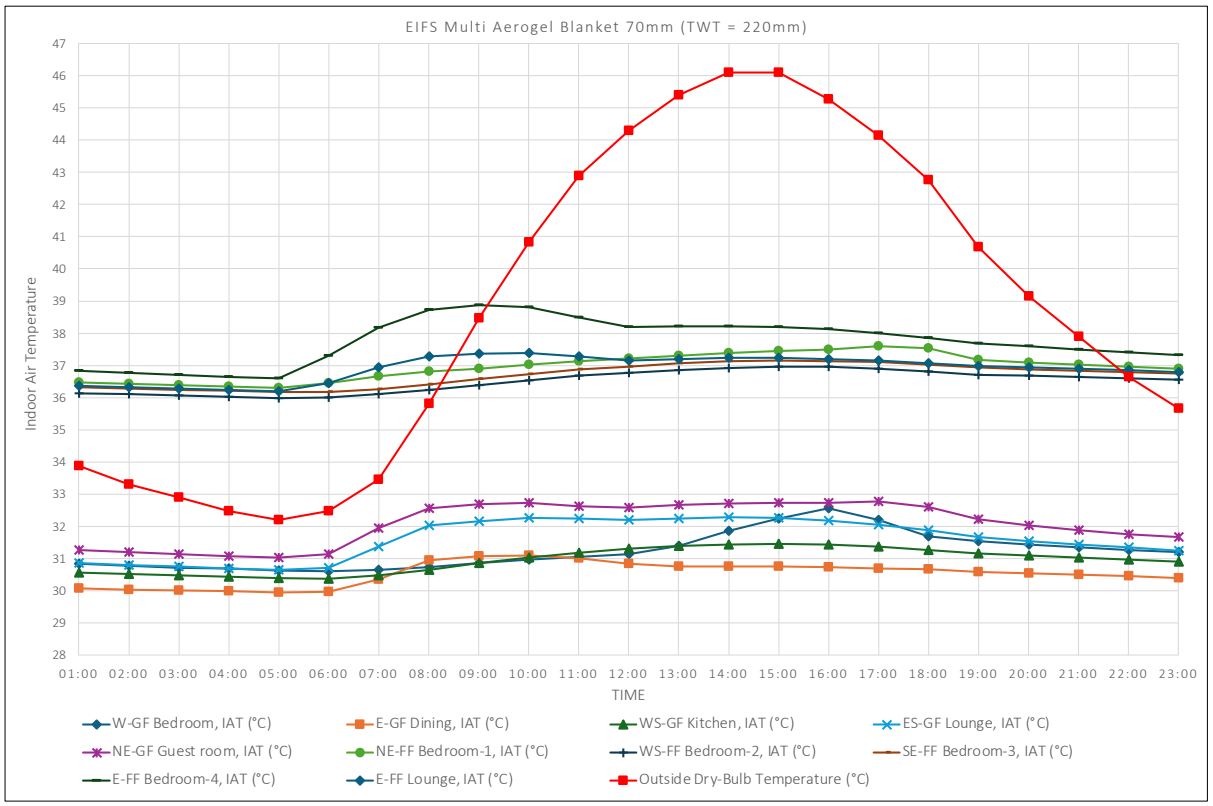


Figure A-1. 57. The free-running simulation of hourly indoor air temperature in the base case building zones after employing an EIFS of 70mm Multi Aerogel Blanket (15th July).

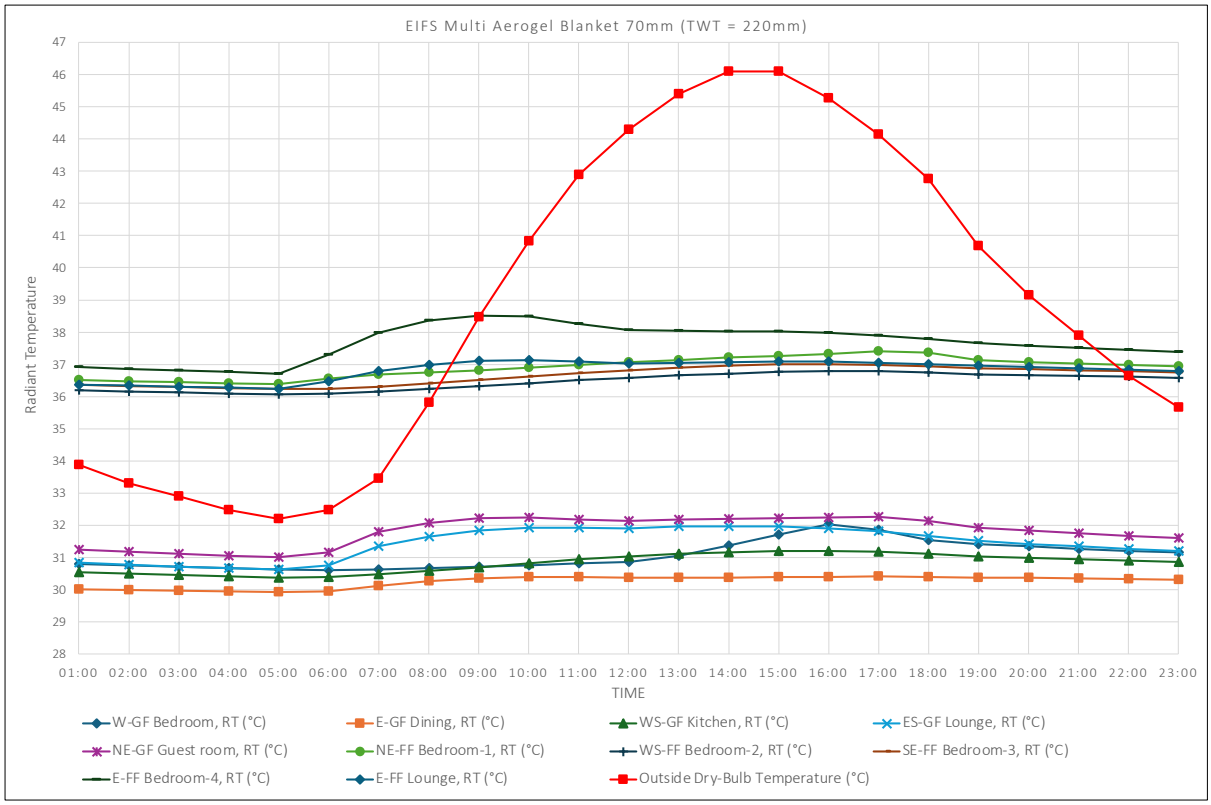


Figure A-1. 58. The free-running simulation of hourly radiant temperature in the base case building zones after employing an EIFS of 70mm Multi Aerogel Blanket (15th July).

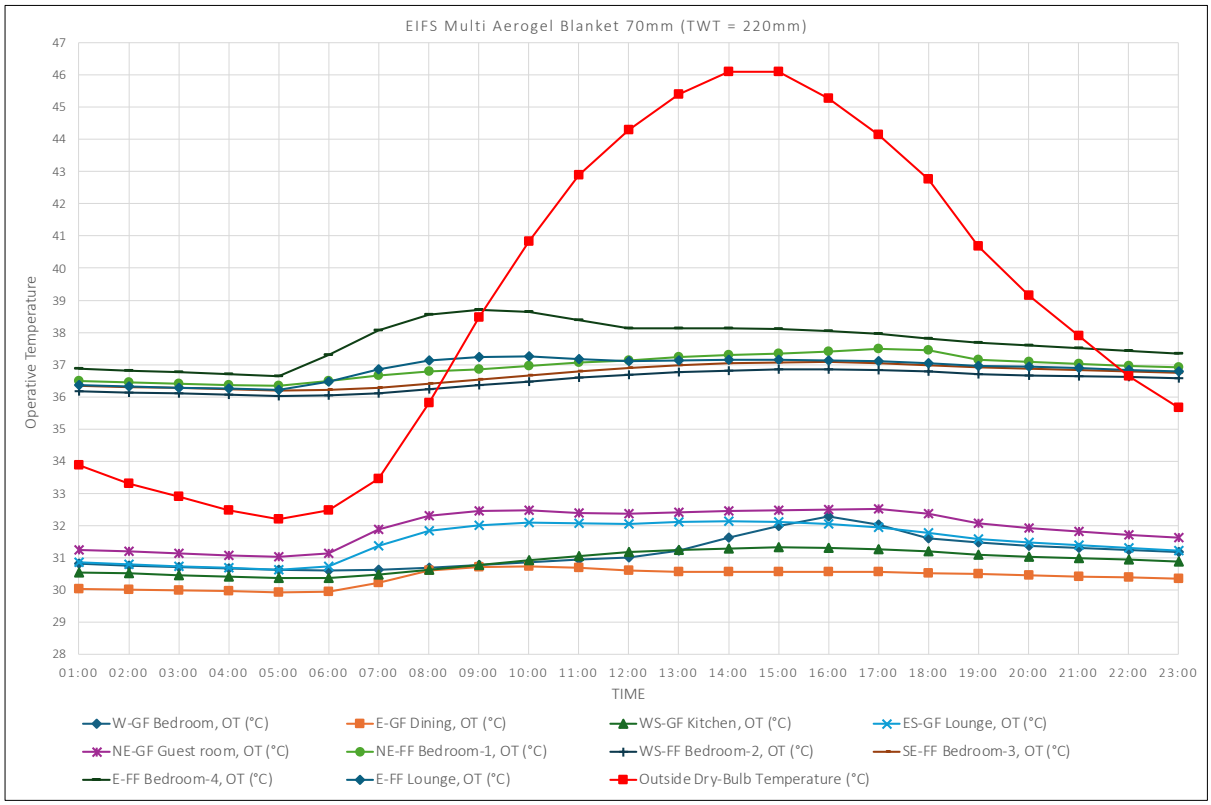


Figure A-1. 59. The free-running simulation of hourly operative temperature in the base case building zones after employing an EIFS of 70mm Multi Aerogel Blanket (15th July).

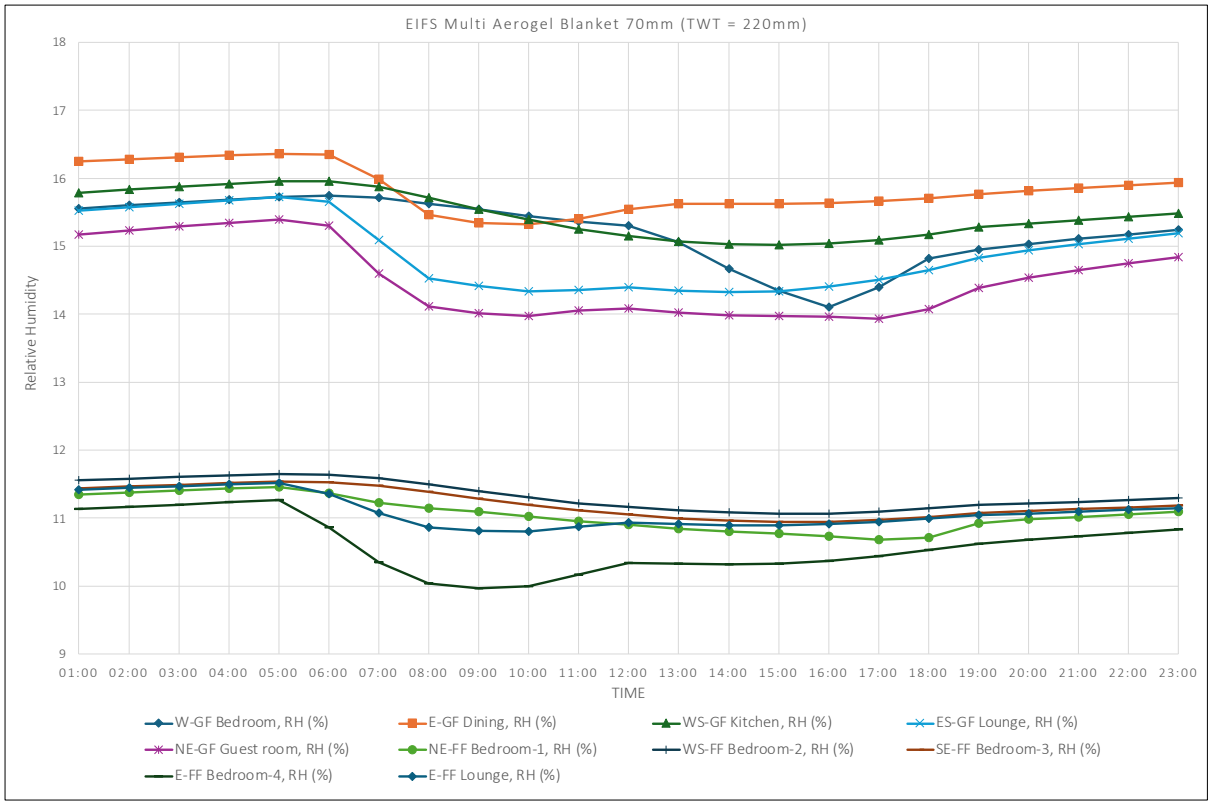


Figure A-1. 60. The free-running simulation of hourly relative humidity in the base case building zones after employing an EIFS of 70mm Multi Aerogel Blanket (15th July).

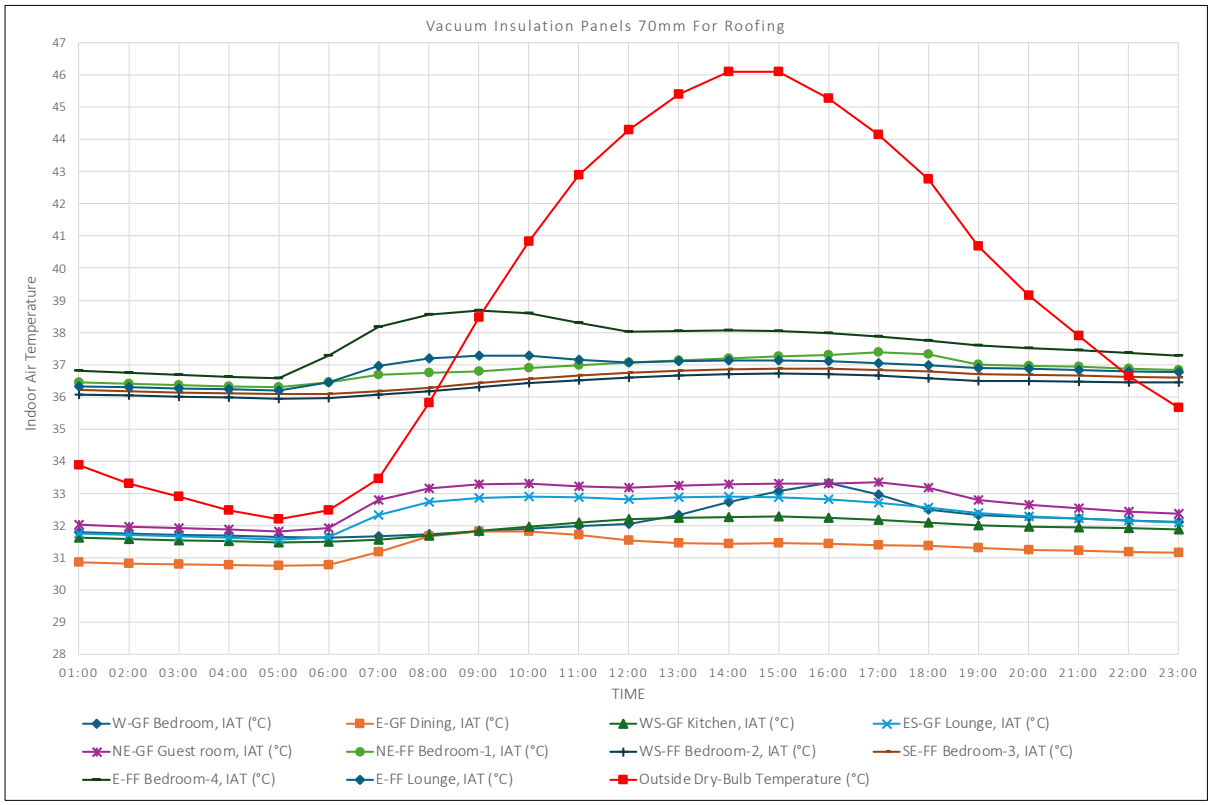


Figure A-1. 61. The free-running simulation of hourly indoor air temperature in the base case building zones after employing 70mm vacuum insulation panels for roofing (15th July).

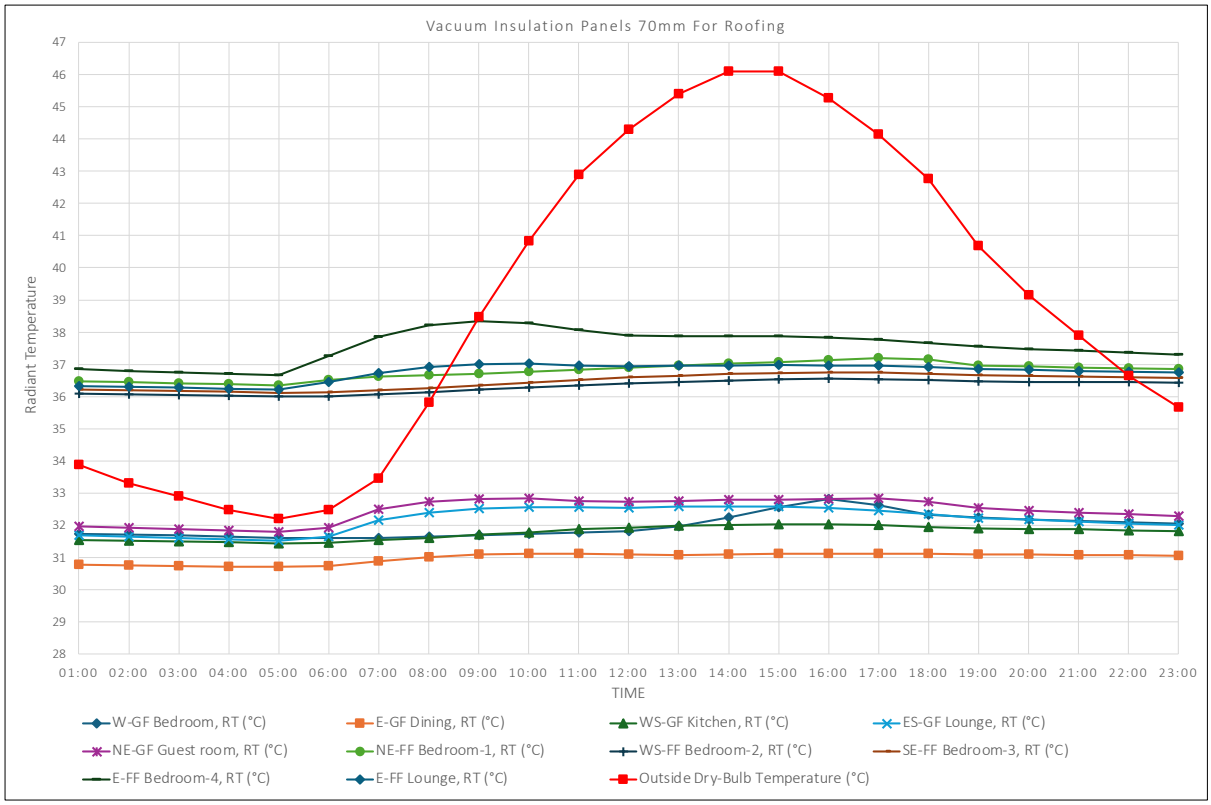


Figure A-1. 62. The free-running simulation of hourly radiant temperature in the base case building zones after employing 70mm vacuum insulation panels for roofing (15th July).

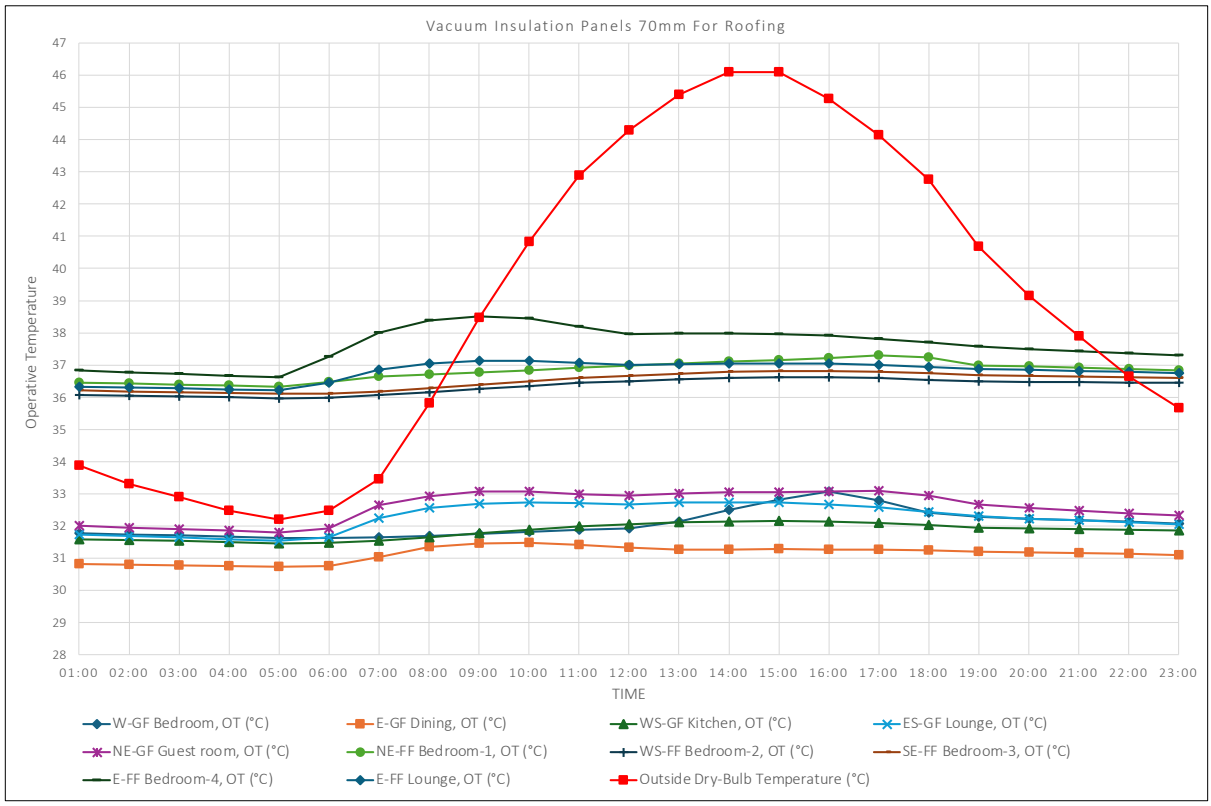


Figure A-1. 63. The free-running simulation of hourly operative temperature in the base case building zones after employing 70mm vacuum insulation panels for roofing (15th July).

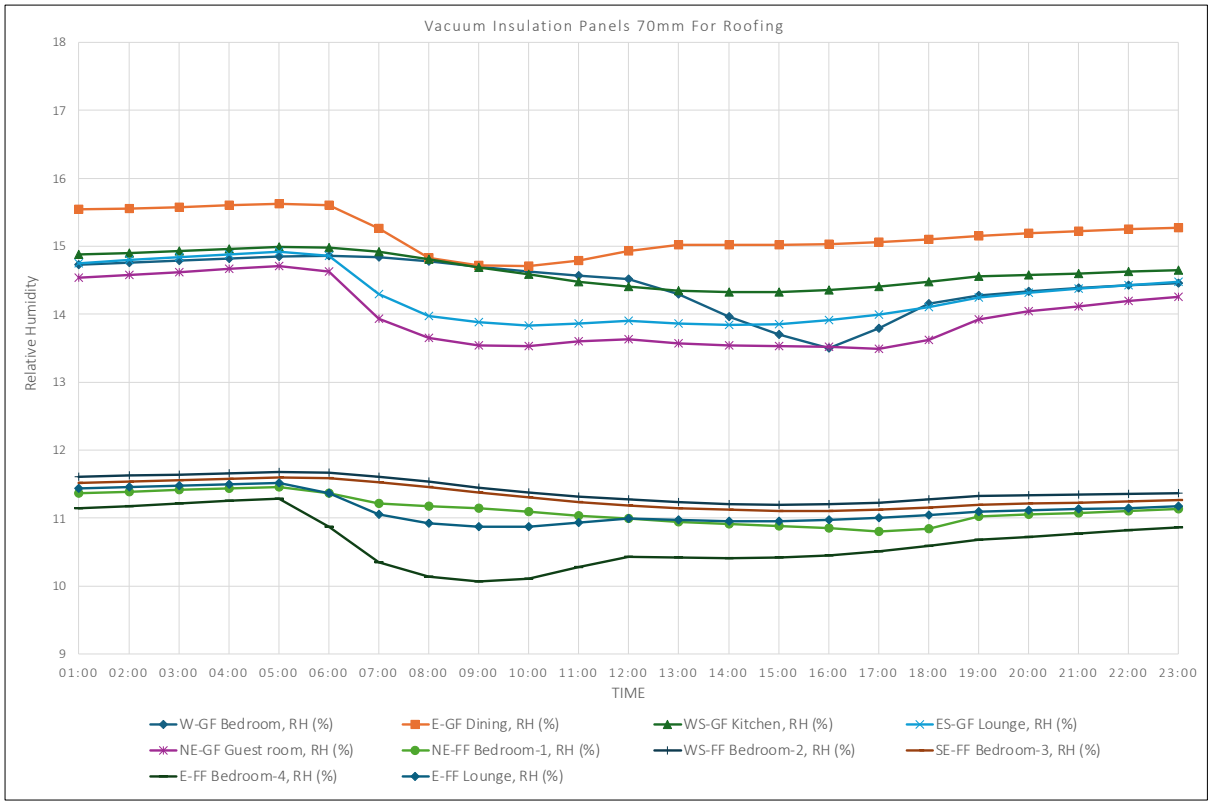


Figure A-1. 64. The free-running simulation of hourly relative humidity in the base case building zones after employing 70mm vacuum insulation panels for roofing (15th July).

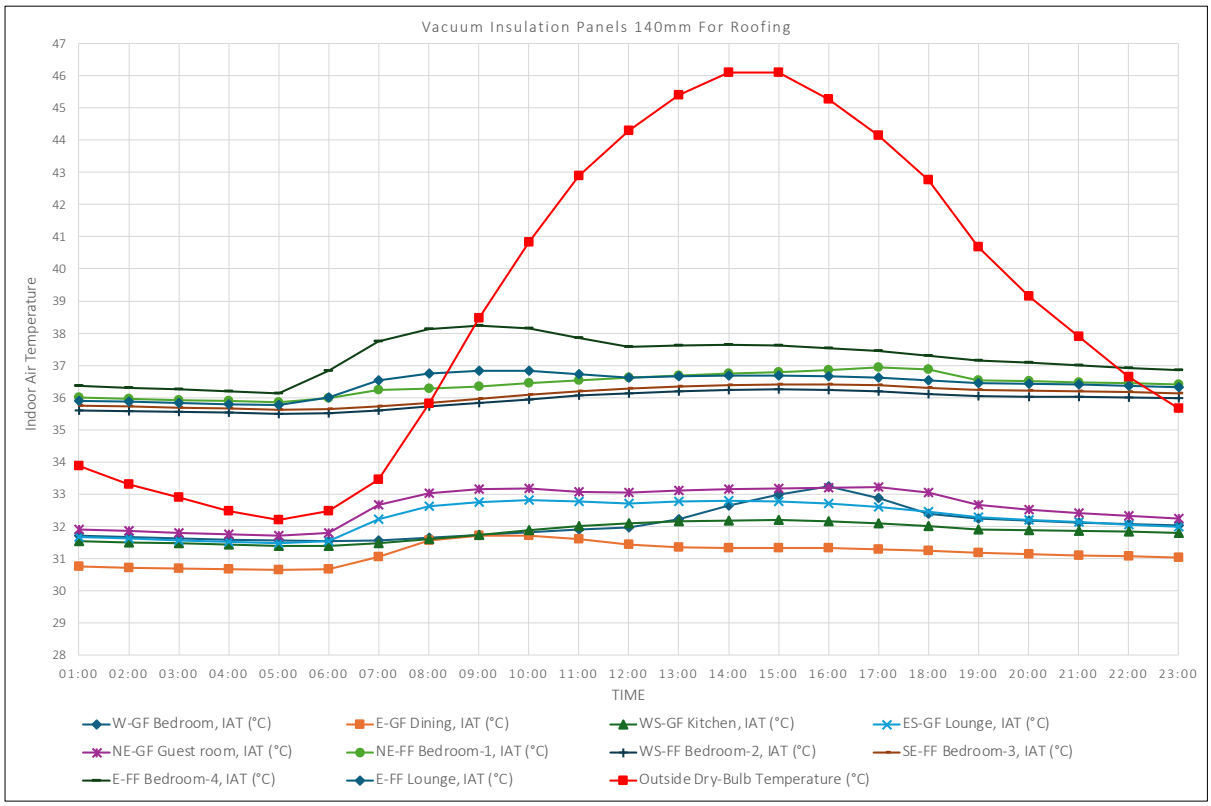


Figure A-1. 65. The free-running simulation of hourly indoor air temperature in the base case building zones after employing 140mm vacuum insulation panels for roofing (15th July).

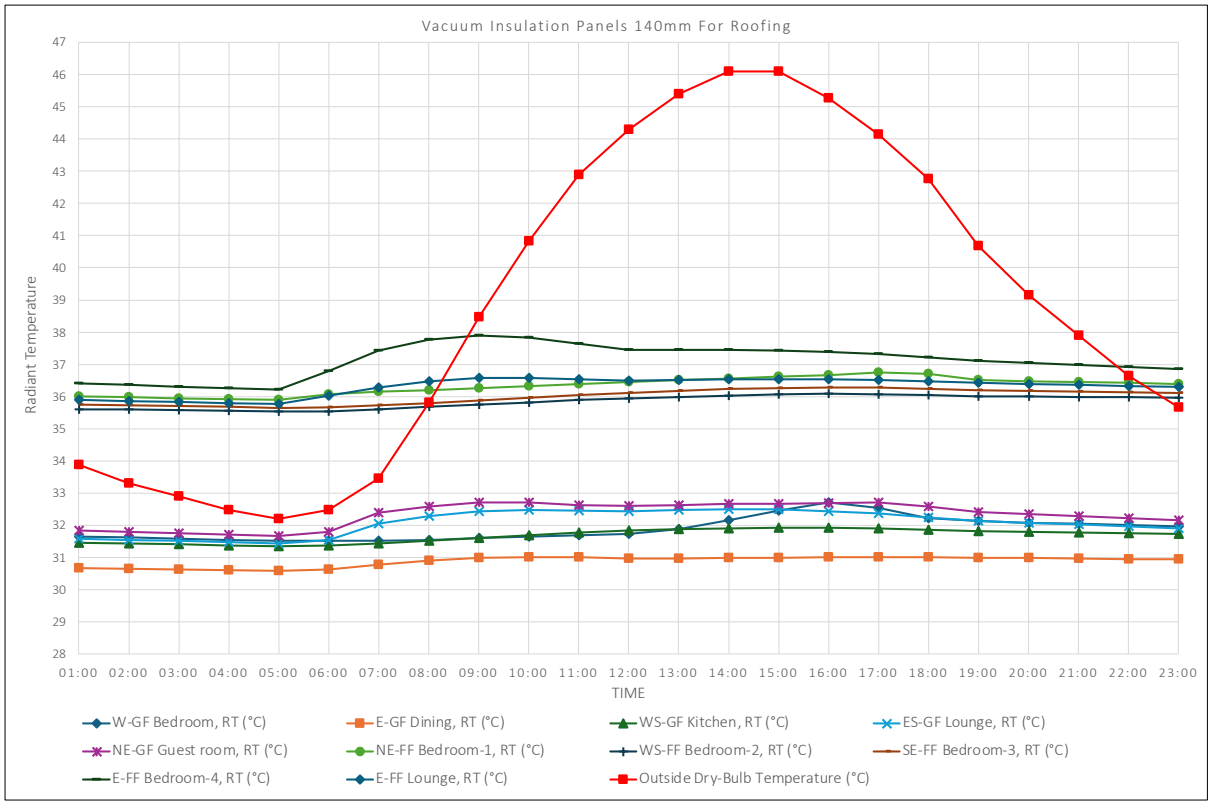


Figure A-1. 66. The free-running simulation of hourly radiant temperature in the base case building zones after employing 140mm vacuum insulation panels for roofing (15th July).

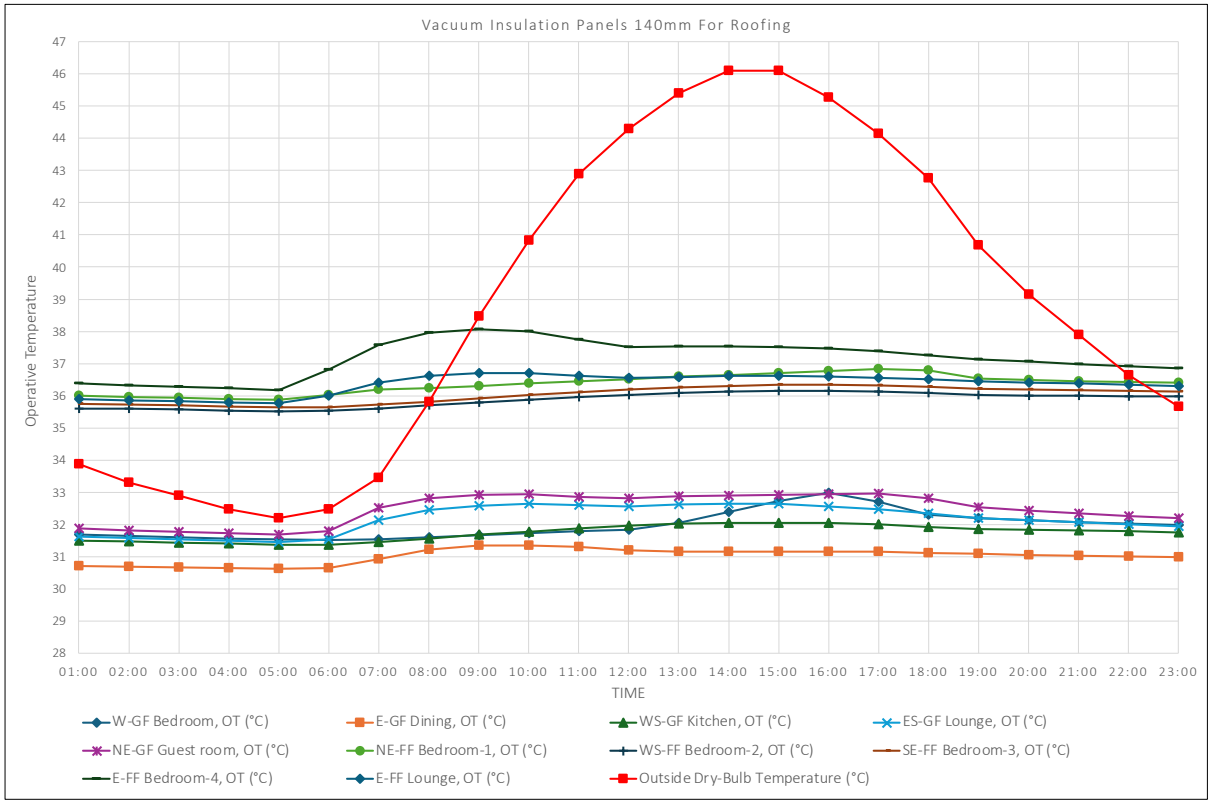


Figure A-1. 67. The free-running simulation of hourly operative temperature in the base case building zones after employing 140mm vacuum insulation panels for roofing (15th July).

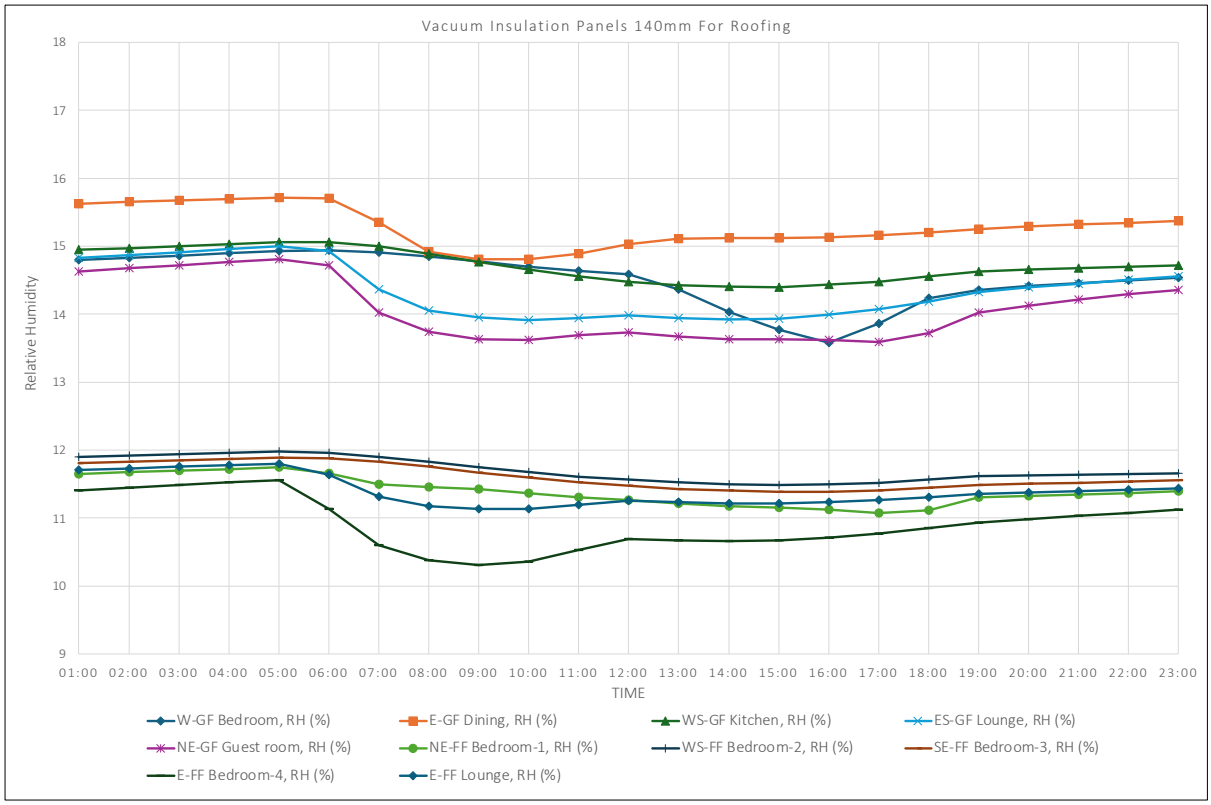


Figure A-1. 68. The free-running simulation of hourly relative humidity in the base case building zones after employing 140mm vacuum insulation panels for roofing (15th July).

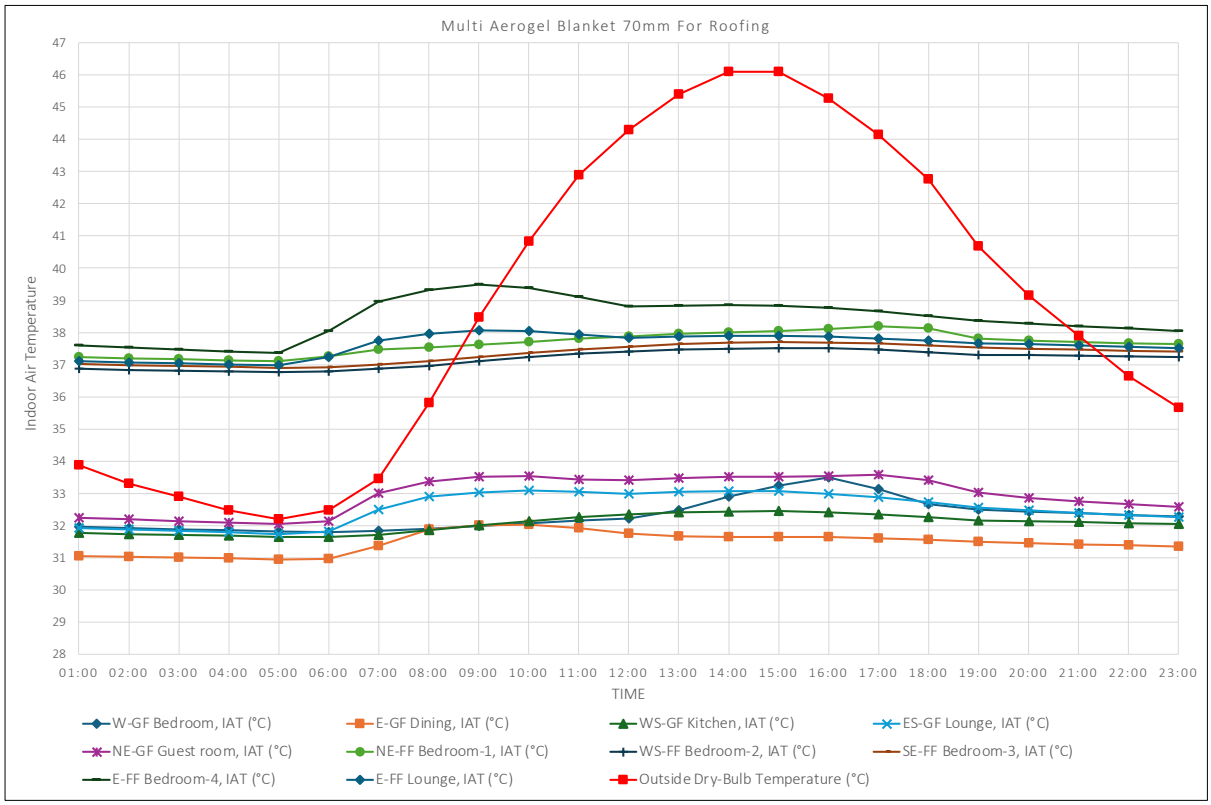


Figure A-1. 69. The free-running simulation of hourly indoor air temperature in the base case building zones after employing 70mm Multi Aerogel Blanket for roofing (15th July).

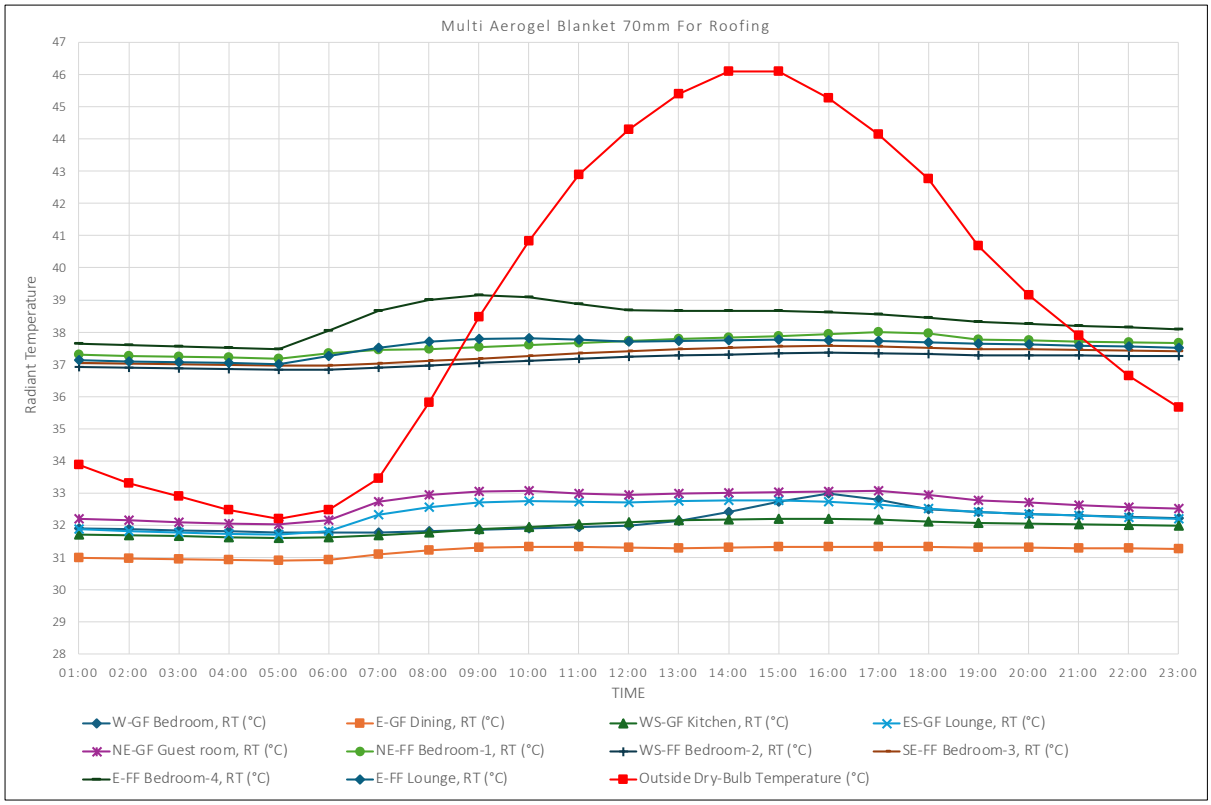


Figure A-1. 70. The free-running simulation of hourly radiant temperature in the base case building zones after employing 70mm Multi Aerogel Blanket for roofing (15th July).

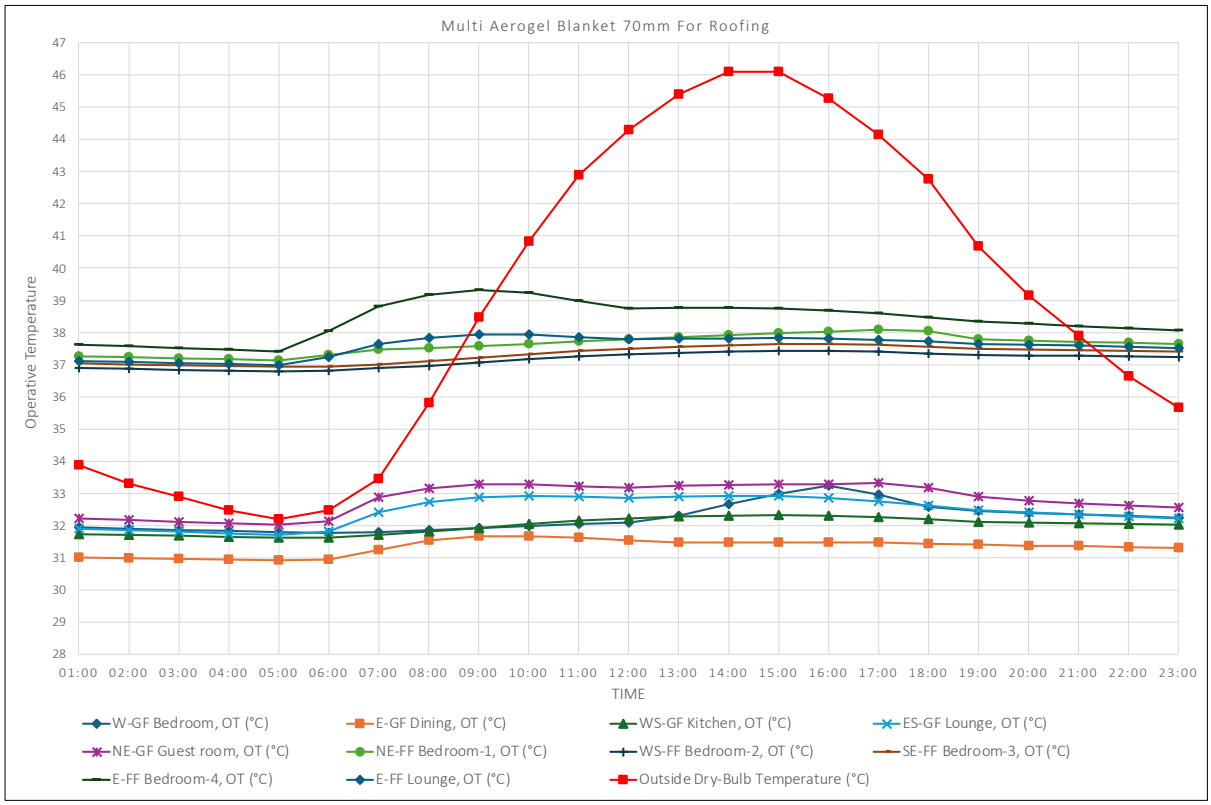


Figure A-1. 71. The free-running simulation of hourly operative temperature in the base case building zones after employing 70mm Multi Aerogel Blanket for roofing (15th July).

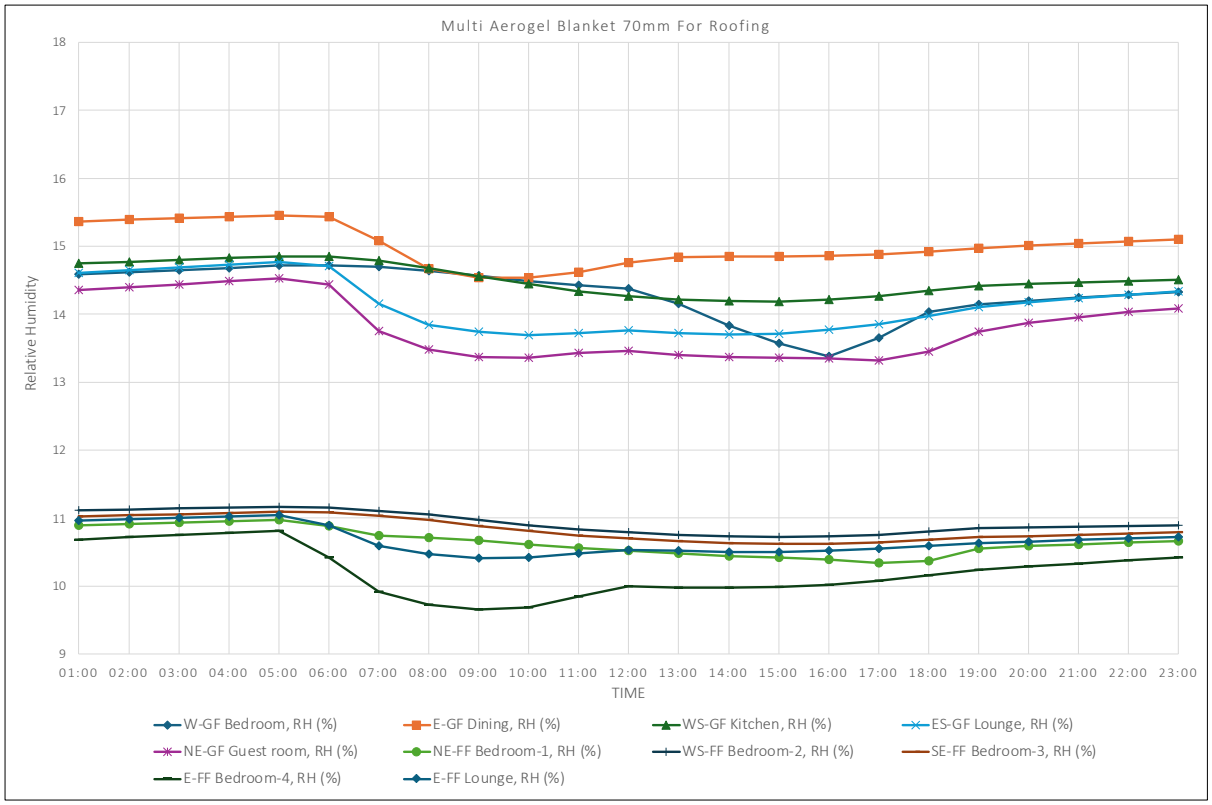


Figure A-1. 72. The free-running simulation of hourly relative humidity in the base case building zones after employing 70mm Multi Aerogel Blanket for roofing (15th July).

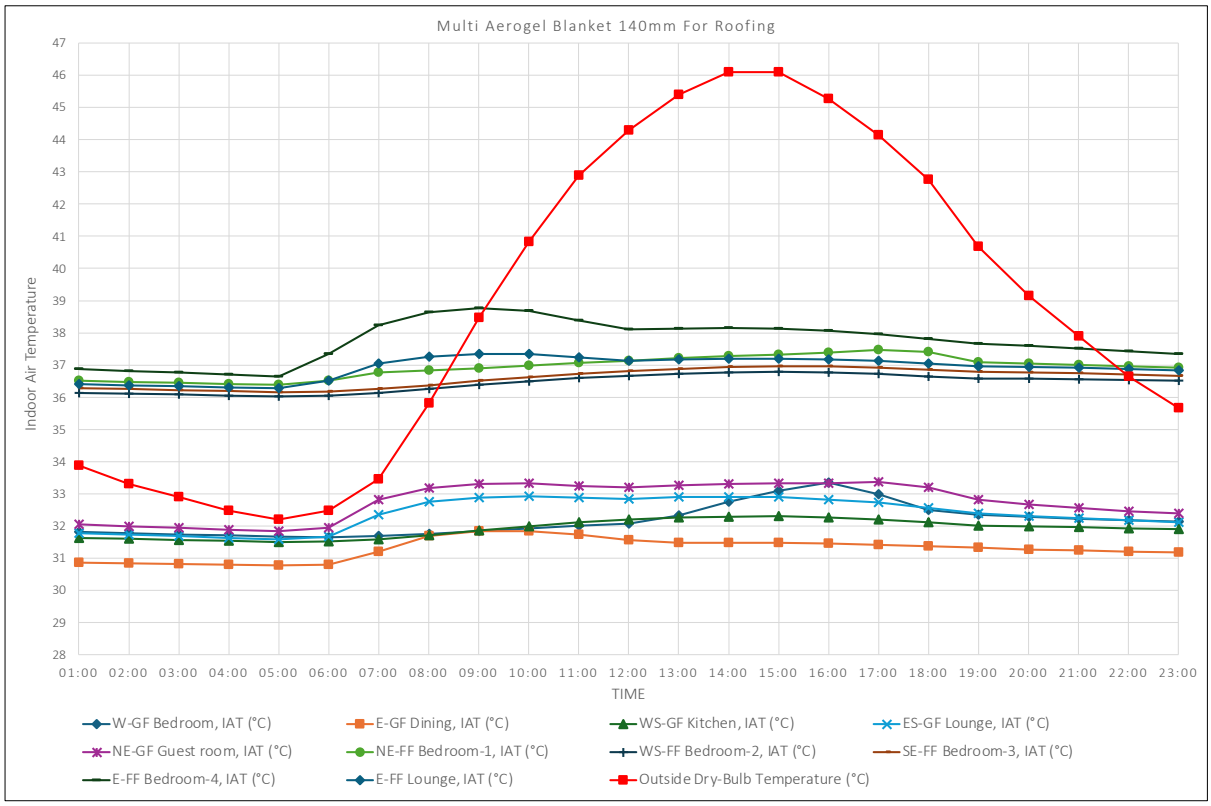


Figure A-1. 73. The free-running simulation of hourly indoor air temperature in the base case building zones after employing 140mm Multi Aerogel Blanket for roofing (15th July).

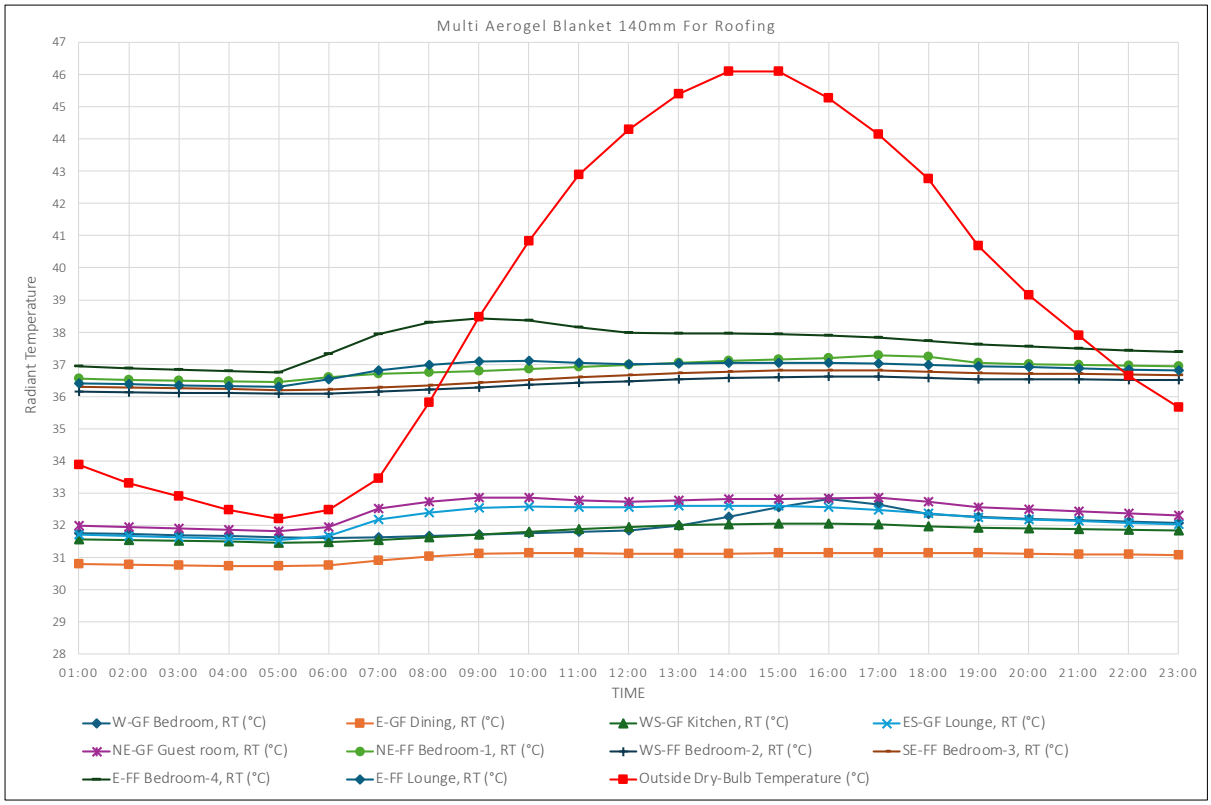


Figure A-1. 74. The free-running simulation of hourly radiant temperature in the base case building zones after employing 140mm Multi Aerogel Blanket for roofing (15th July).

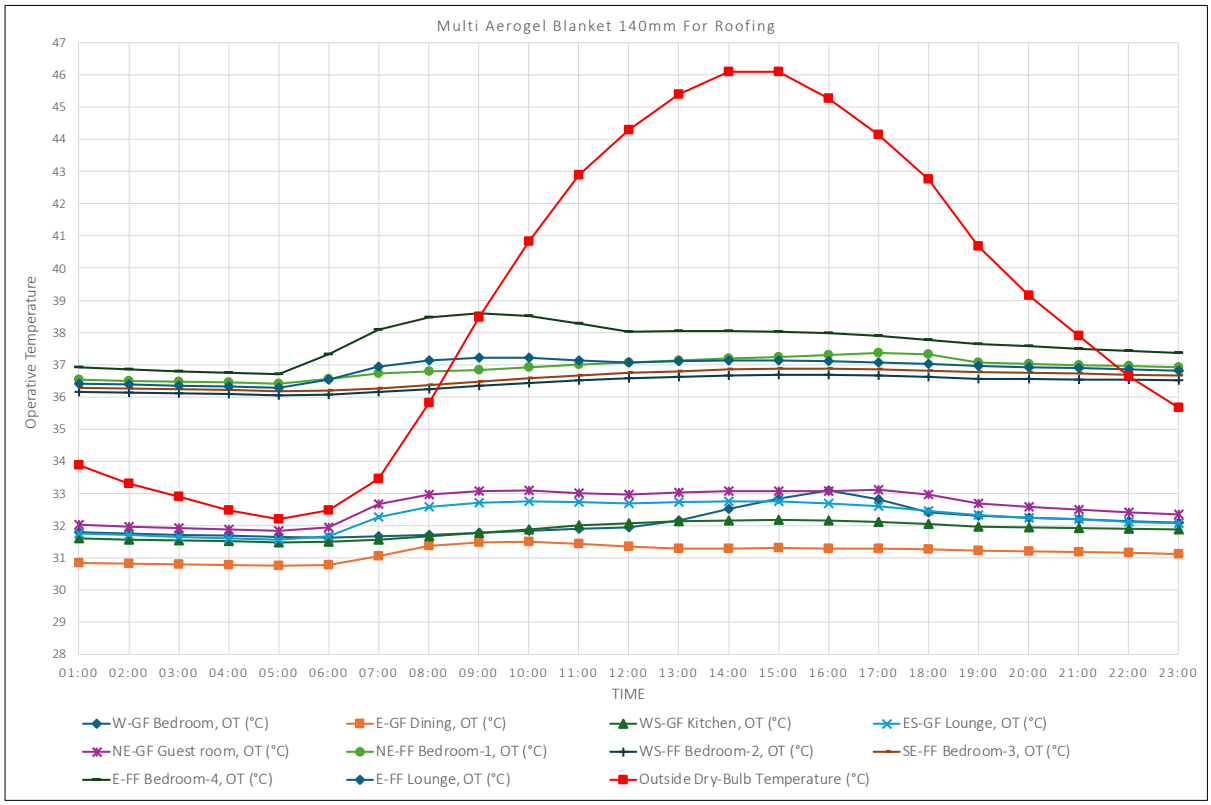


Figure A-1. 75. The free-running simulation of hourly operative temperature in the base case building zones after employing 140mm Multi Aerogel Blanket for roofing (15th July).

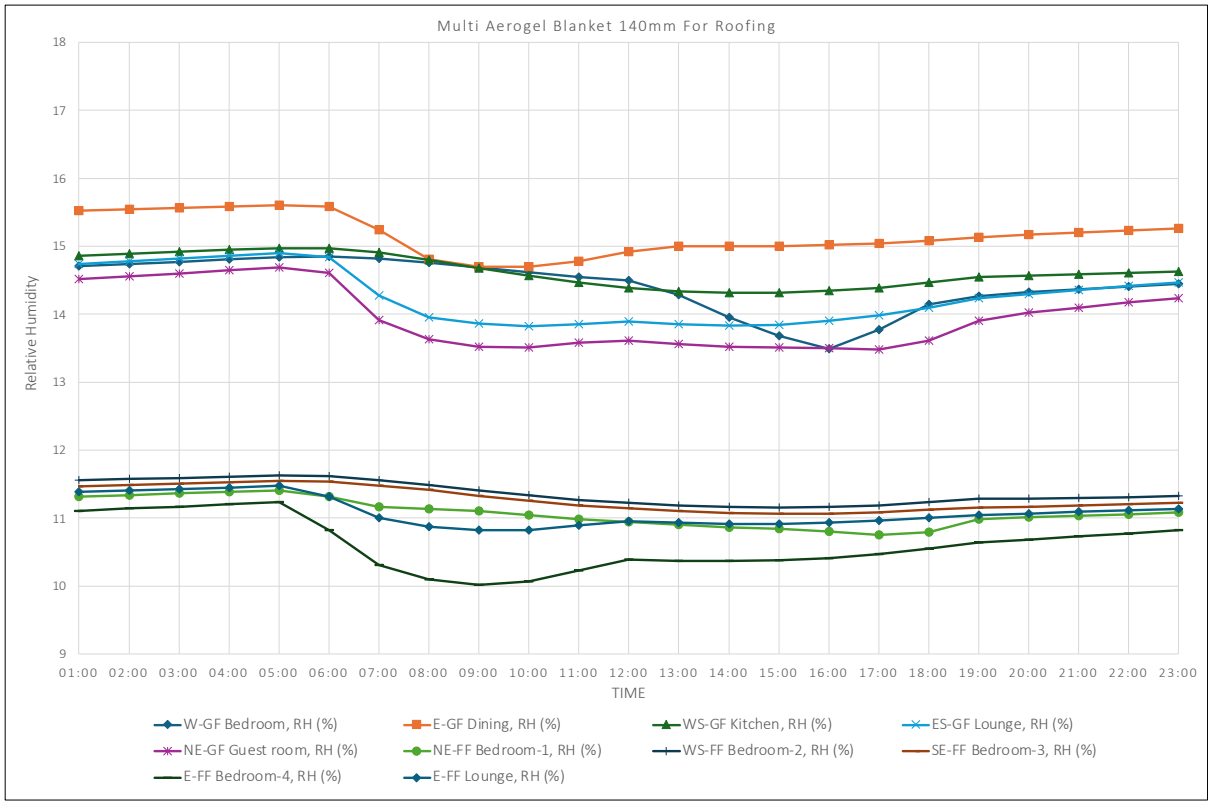


Figure A-1. 76. The free-running simulation of hourly relative humidity in the base case building zones after employing 140mm Multi Aerogel Blanket for roofing (15th July).

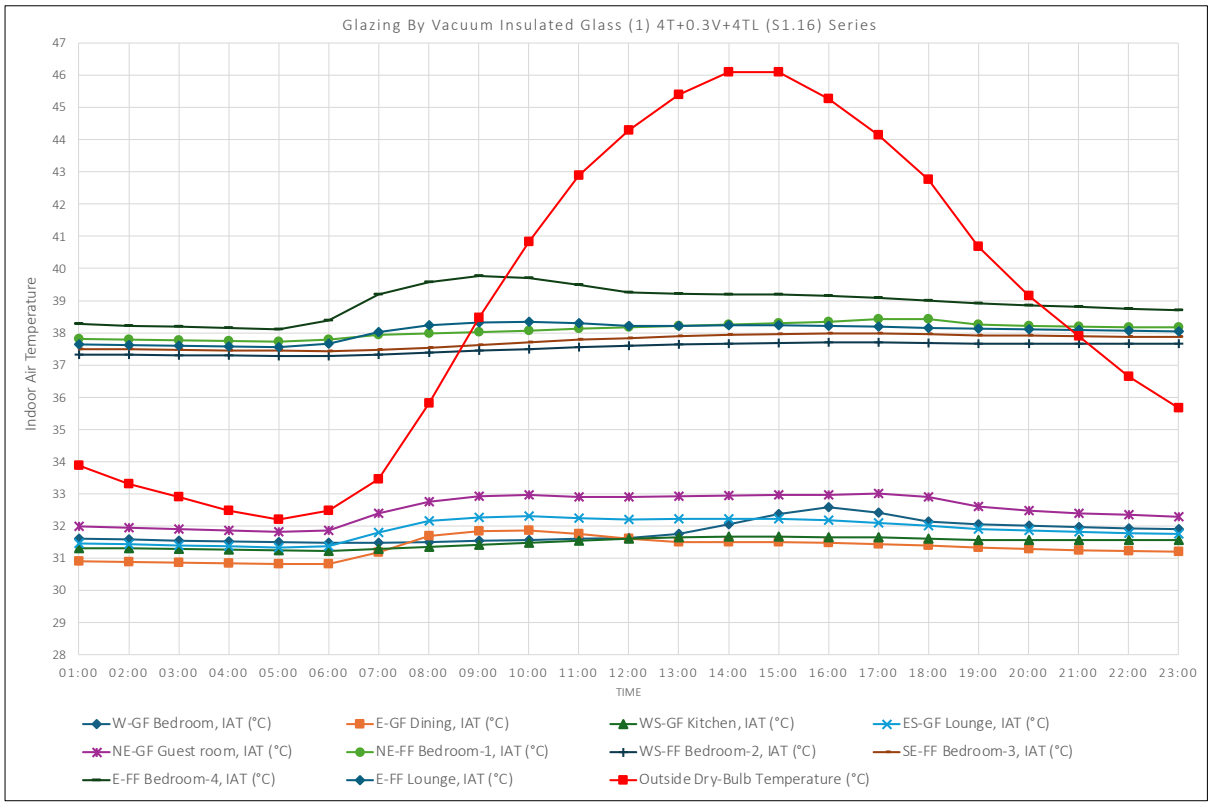


Figure A-1. 77. The free-running simulation of hourly indoor air temperature in the base case building zones after replacing the glazing by vacuum insulated glass (1) 4T+0.3V+4TL (S1.16) Series (15th July).

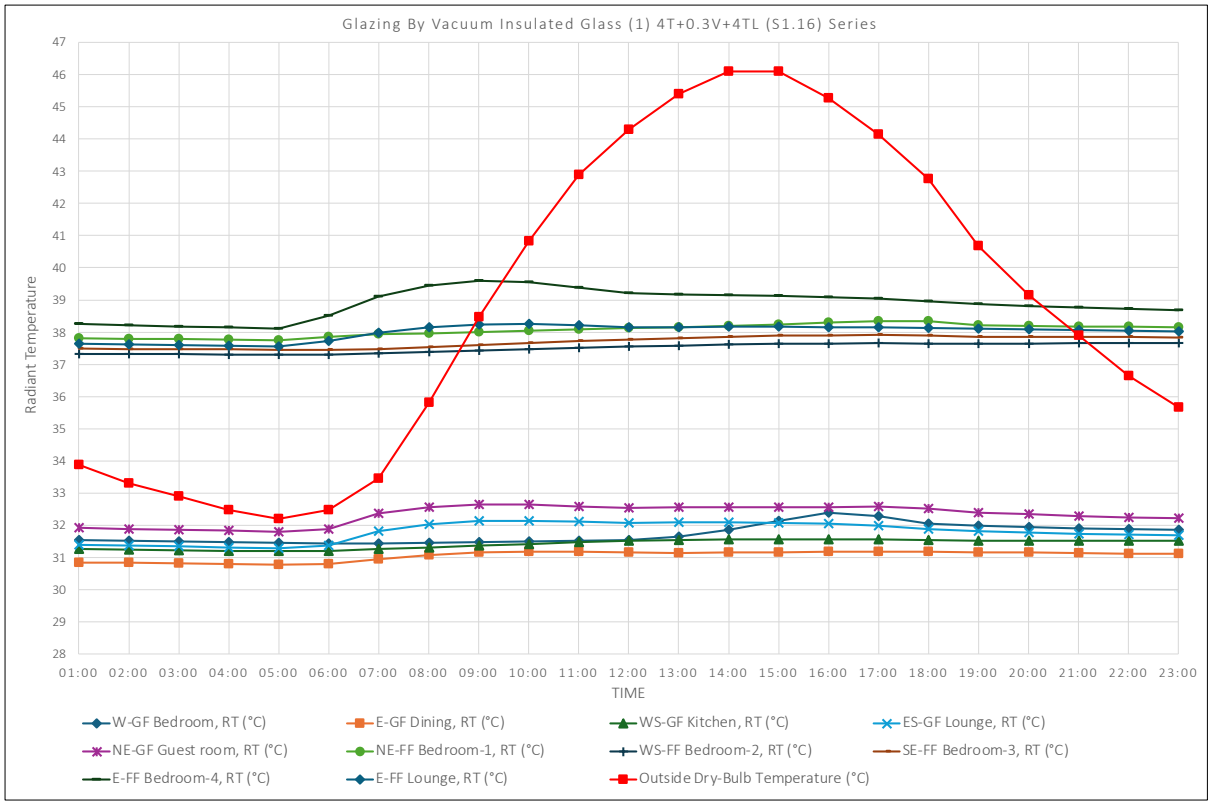


Figure A-1. 78. The free-running simulation of hourly relative temperature in the base case building zones after replacing the glazing by vacuum insulated glass (1) 4T+0.3V+4TL (S1.16) Series (15th July).

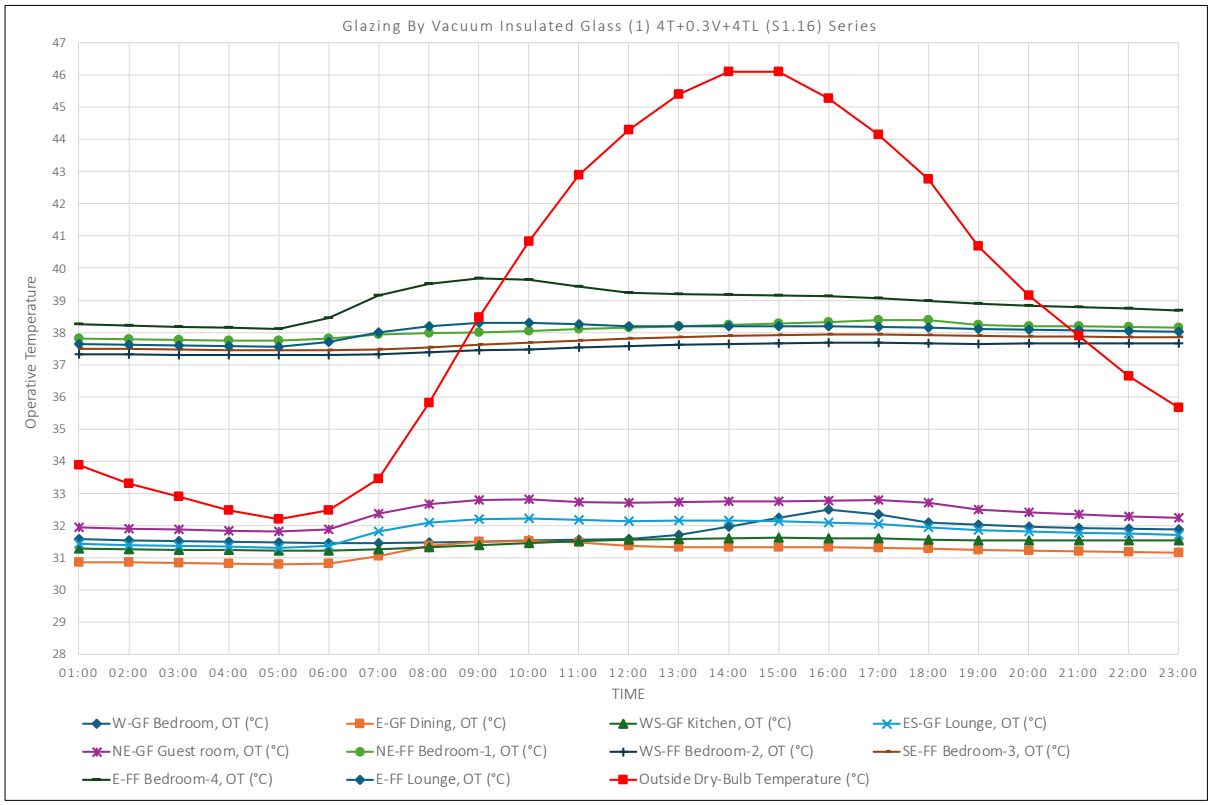


Figure A-1. 79. The free-running simulation of hourly operative temperature in the base case building zones after replacing the glazing by vacuum insulated glass (1) 4T+0.3V+4TL (S1.16) Series (15th July).

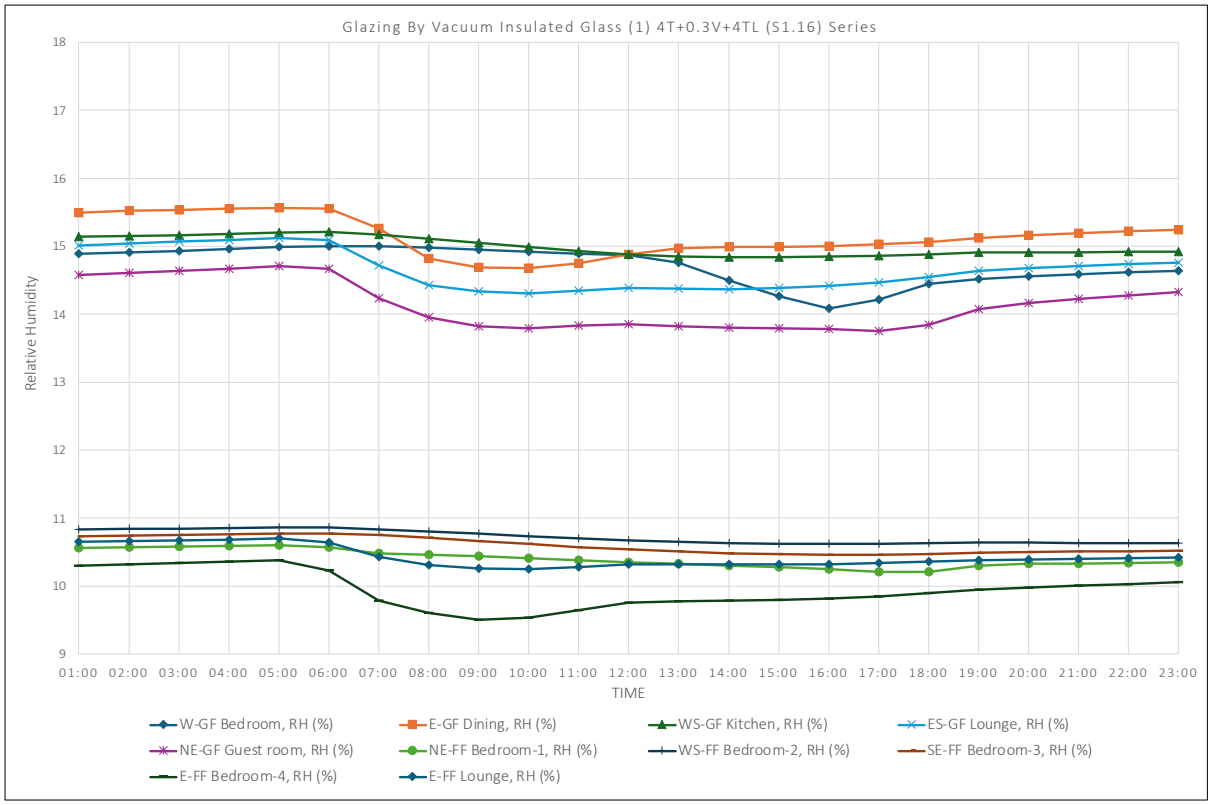


Figure A-1. 80. The free-running simulation of hourly relative humidityin the base case building zones after replacing the glazing by vacuum insulated glass (1) 4T+0.3V+4TL (S1.16) Series (15th July).

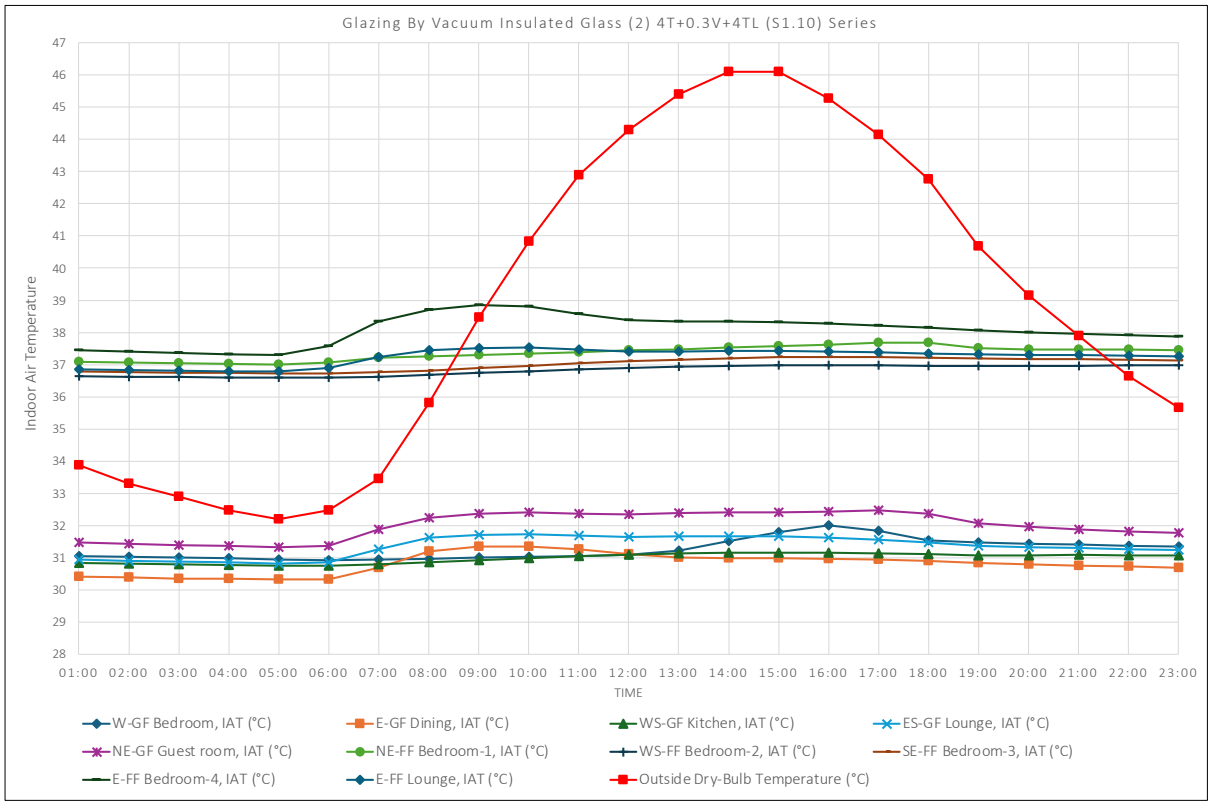


Figure A-1. 81. The free-running simulation of hourly indoor air temperature in the base case building zones after replacing the glazing by vacuum insulated glass (2) 4T+0.3V+4TL (S1.10) Series (15th July).

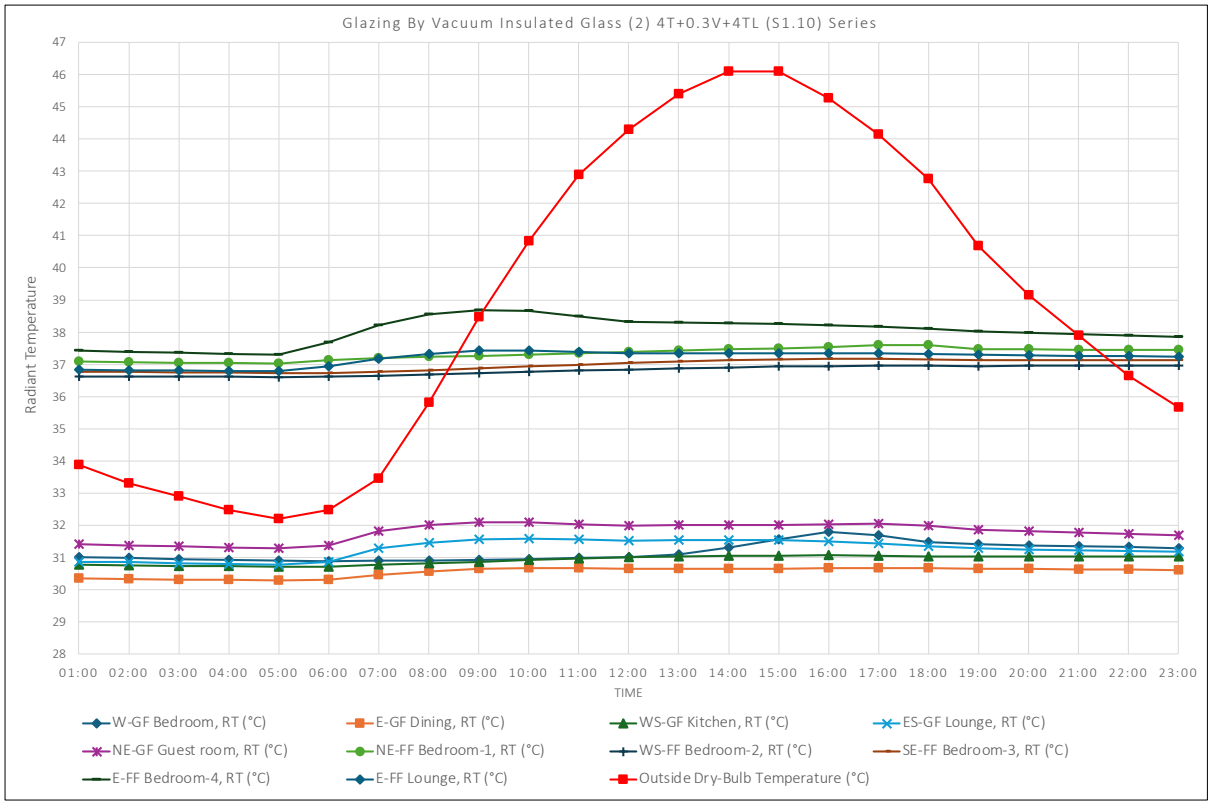


Figure A-1. 82. The free-running simulation of hourly radiant temperature in the base case building zones after replacing the glazing by vacuum insulated glass (2) 4T+0.3V+4TL (S1.10) Series (15th July).

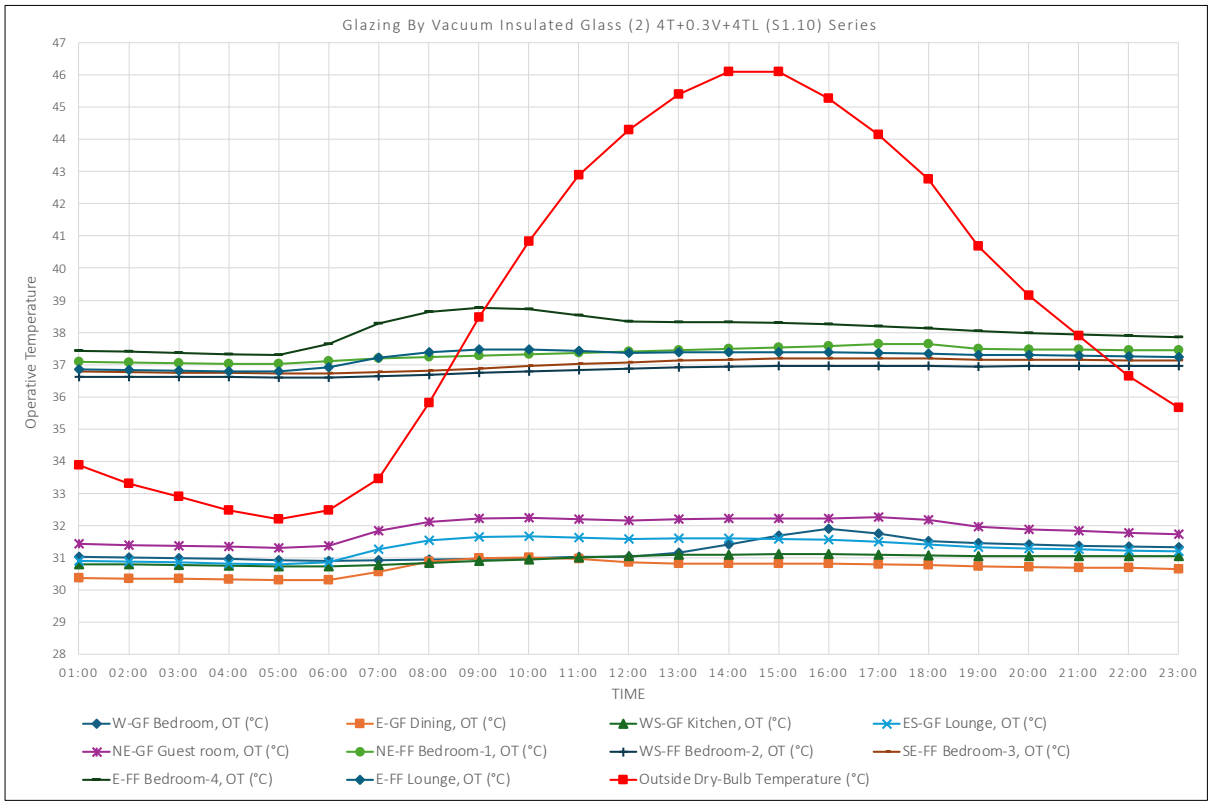


Figure A-1. 83. The free-running simulation of hourly operative temperature in the base case building zones after replacing the glazing by vacuum insulated glass (2) 4T+0.3V+4TL (S1.10) Series (15th July).

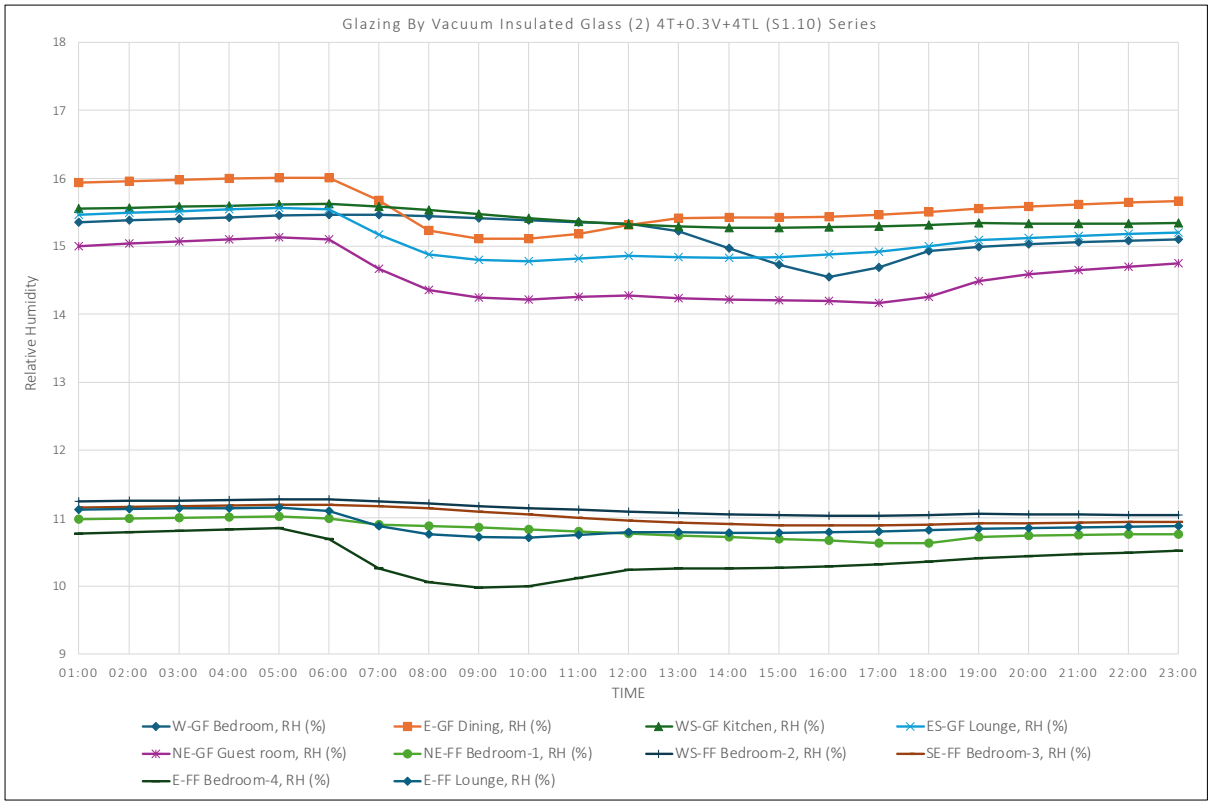


Figure A-1. 84. The free-running simulation of hourly relative humidity in the base case building zones after replacing the glazing by vacuum insulated glass (2) 4T+0.3V+4TL (S1.10) Series (15th July).

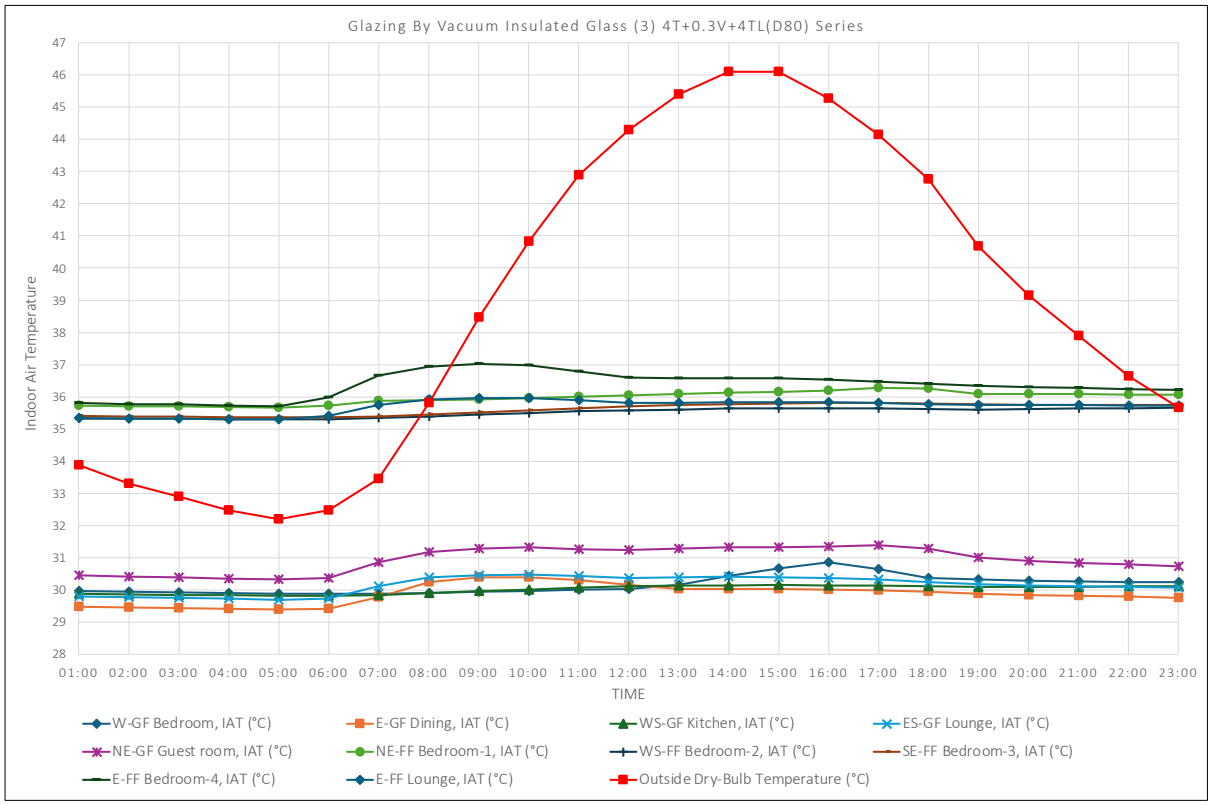


Figure A-1. 85.The free-running simulation of hourly indoor air temperature in the base case building zones after replacing the glazing by vacuum insulated glass (3) 4T+0.3V+4TL(D80) Series (15th July).

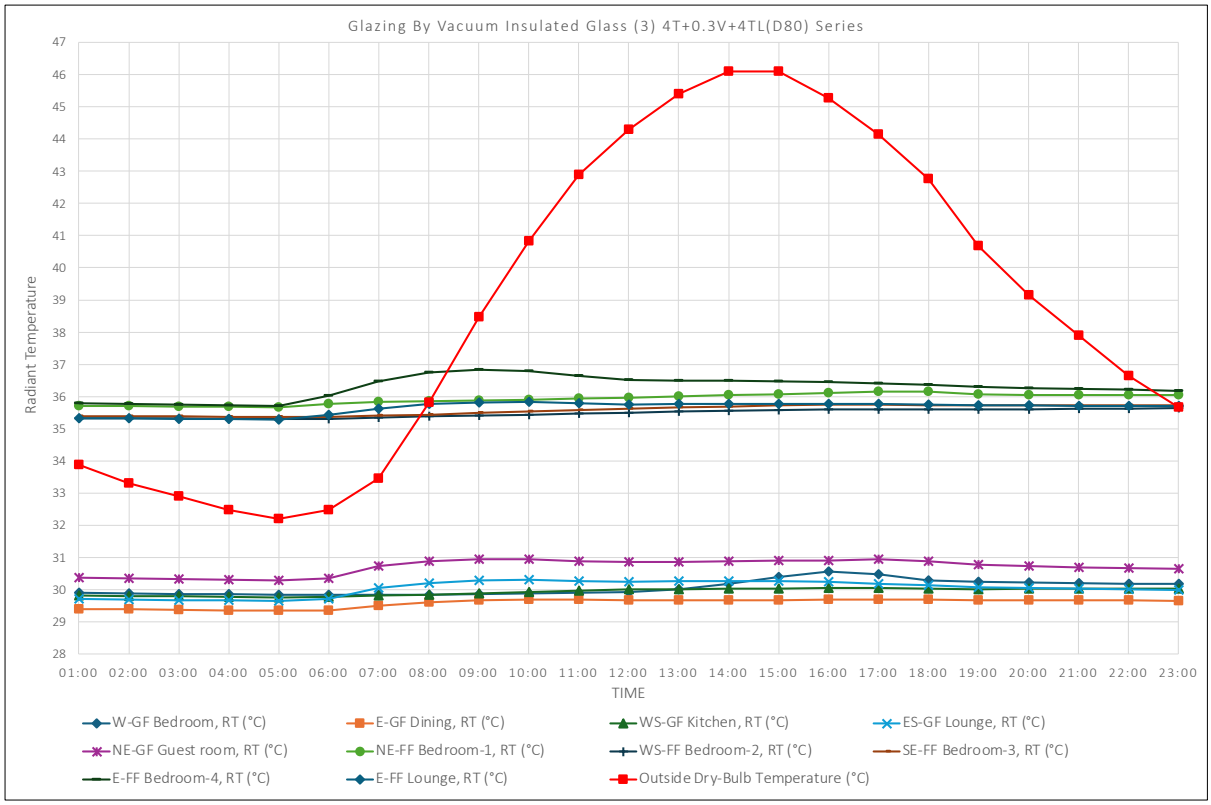


Figure A-1. 86. The free-running simulation of hourly radiant temperature in the base case building zones after replacing the glazing by vacuum insulated glass (3) 4T+0.3V+4TL(D80) Series (15th July).

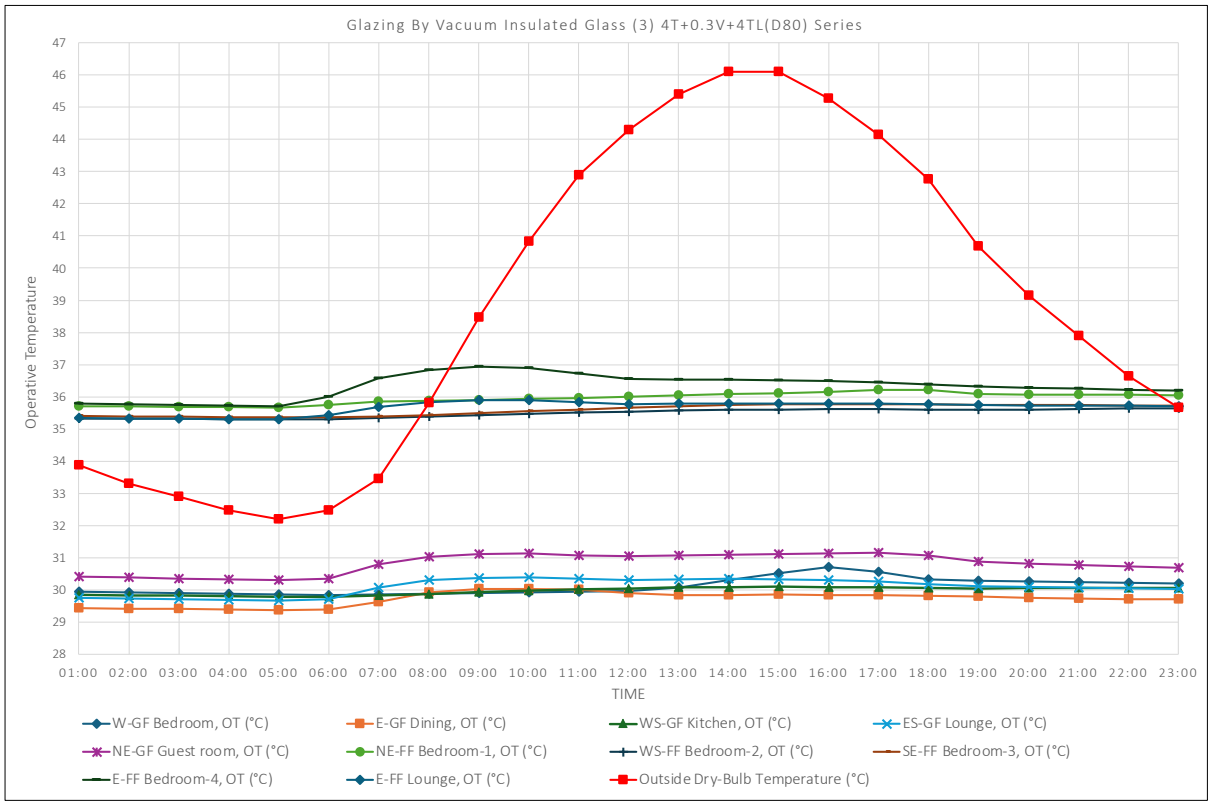


Figure A-1. 87. The free-running simulation of hourly operative temperature in the base case building zones after replacing the glazing by vacuum insulated glass (3) 4T+0.3V+4TL(D80) Series (15th July).

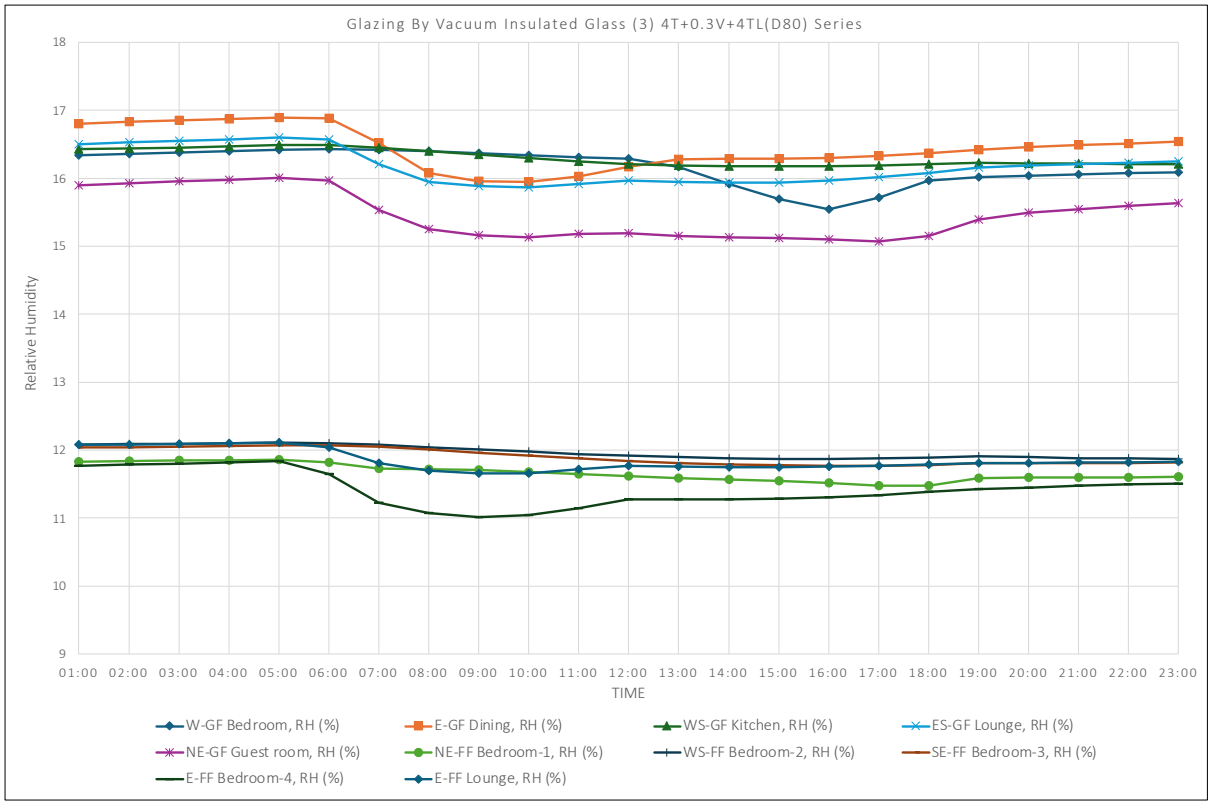


Figure A-1. 88. The free-running simulation of hourly relative humidity in the base case building zones after replacing the glazing by vacuum insulated glass (3) 4T+0.3V+4TL(D80) Series (15th July).

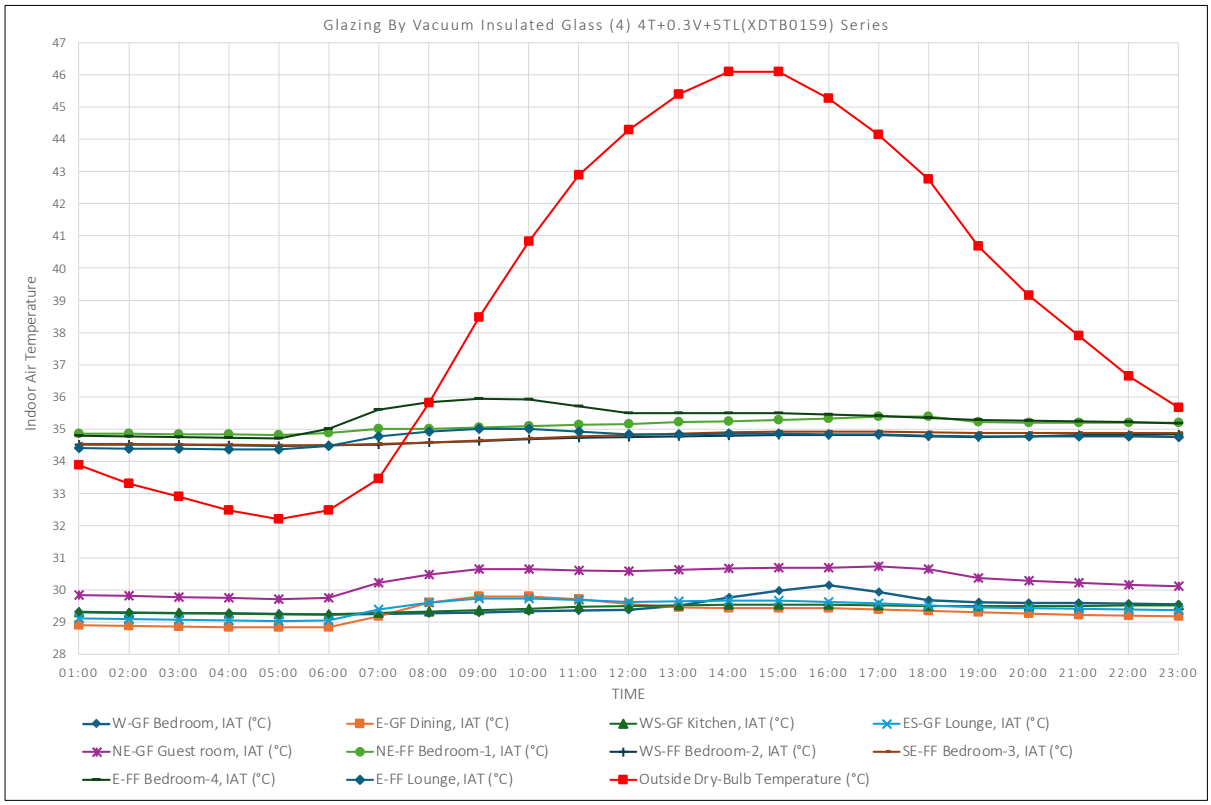


Figure A-1. 89. The free-running simulation of hourly indoor air temperature in the base case building zones after replacing the glazing by vacuum insulated glass (4) 4T+0.3V+5TL(XDTB0159) Series (15th July).

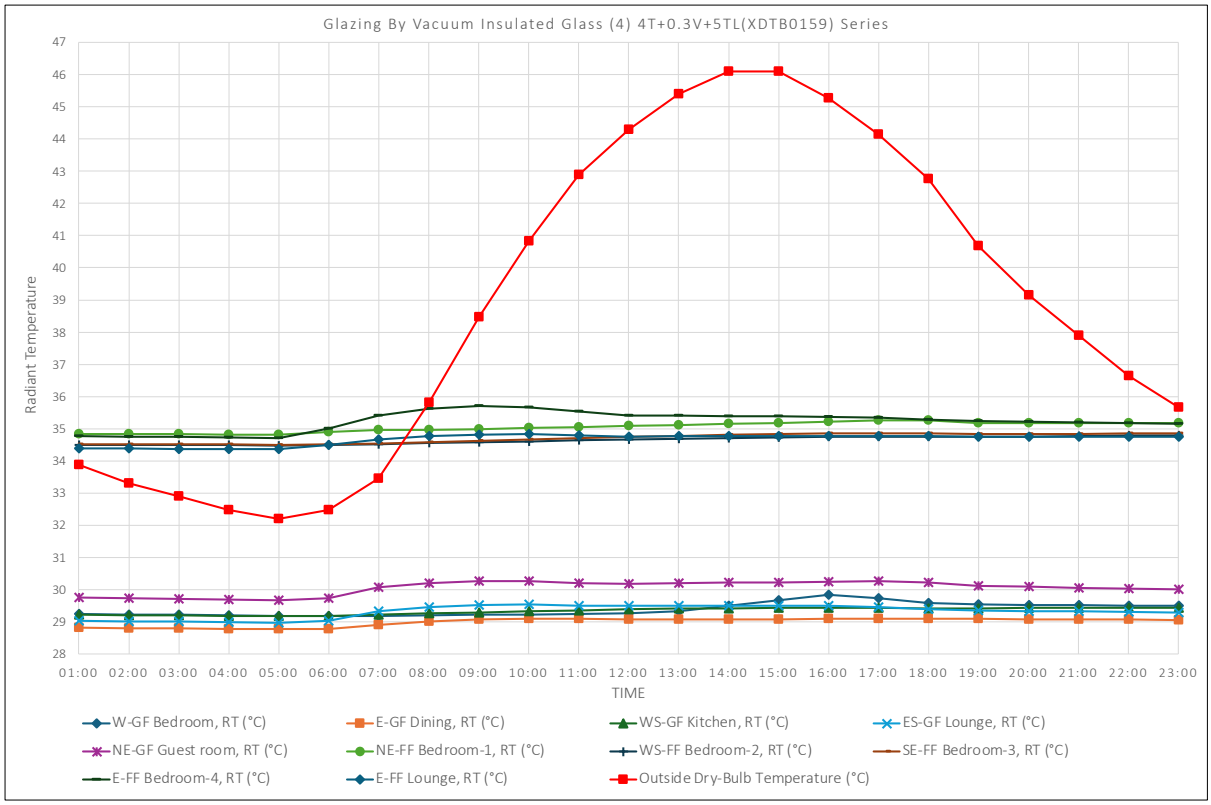


Figure A-1. 90. The free-running simulation of hourly radiant temperature in the base case building zones after replacing the glazing by vacuum insulated glass (4) 4T+0.3V+5TL(XDTB0159) Series (15th July).

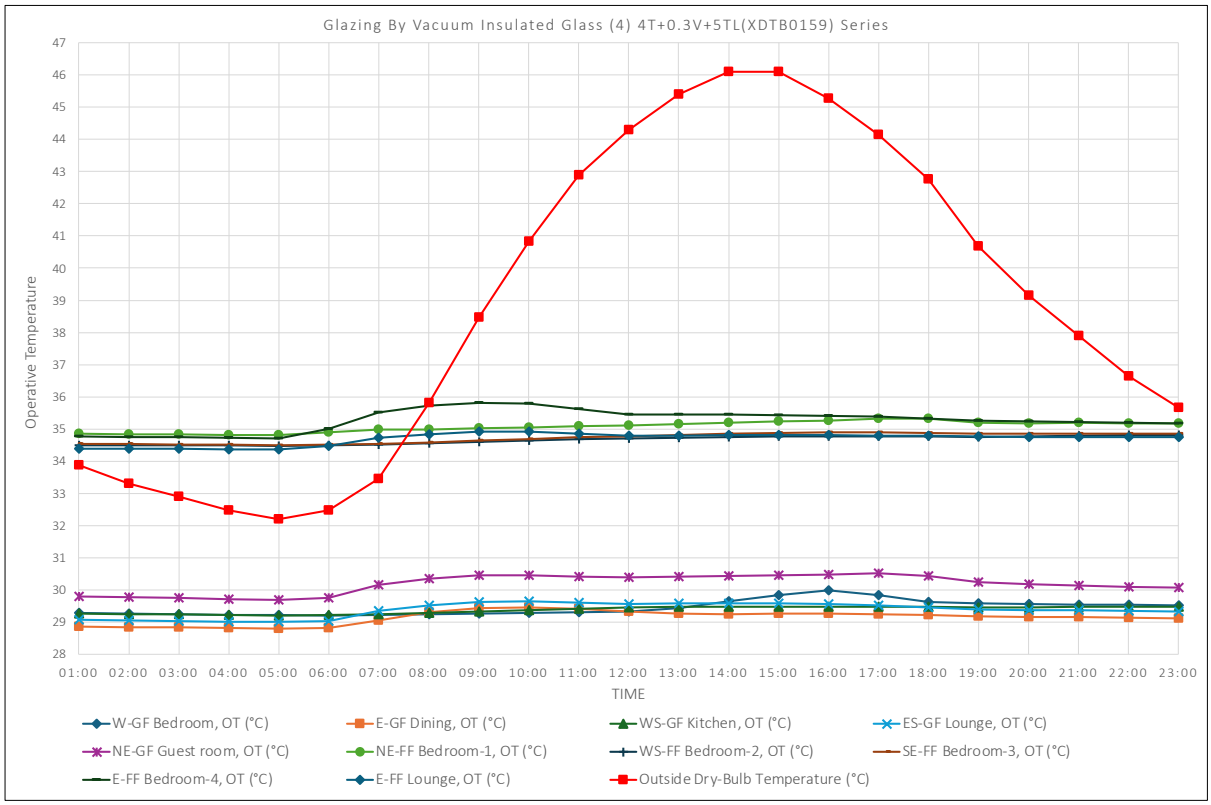


Figure A-1. 91. The free-running simulation of hourly operative temperature in the base case building zones after replacing the glazing by vacuum insulated glass (4) 4T+0.3V+5TL(XDTB0159) Series (15th July).

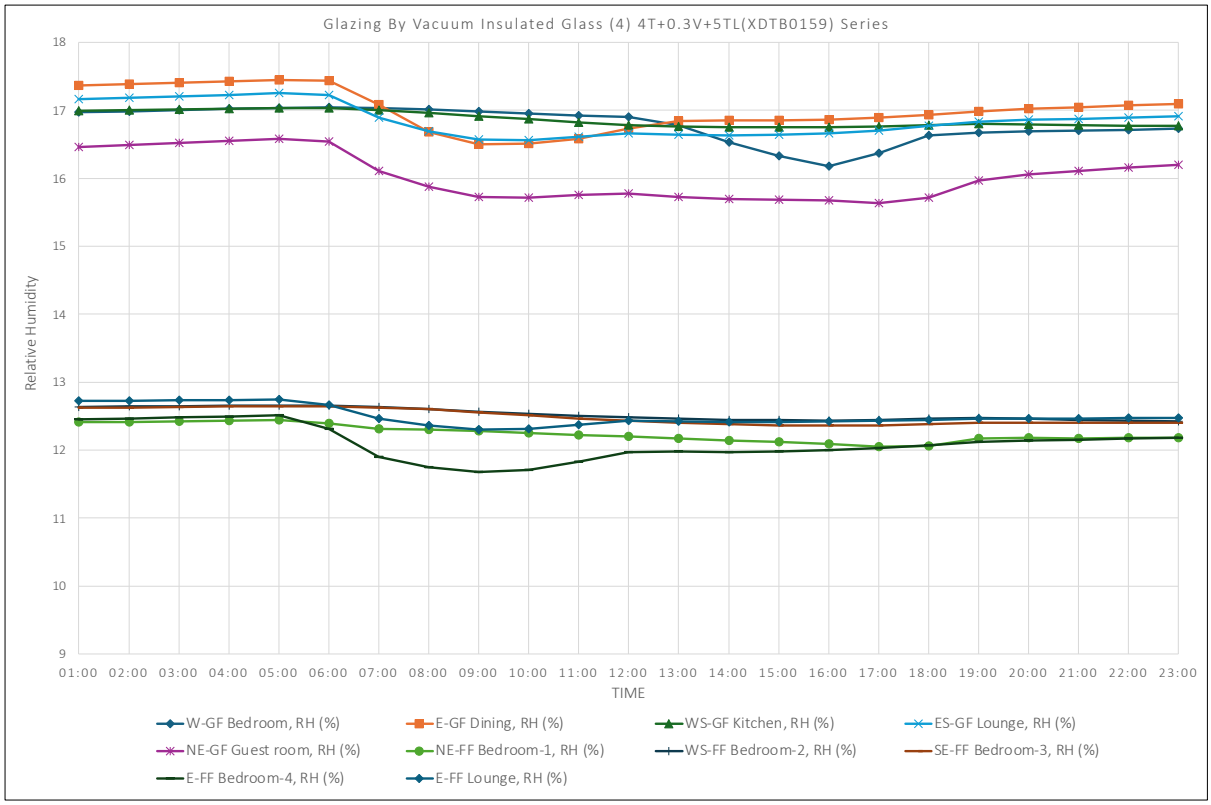


Figure A-1. 92. The free-running simulation of hourly relative humidity in the base case building zones after replacing the glazing by vacuum insulated glass (4) 4T+0.3V+5TL(XDTB0159) Series (15th July).

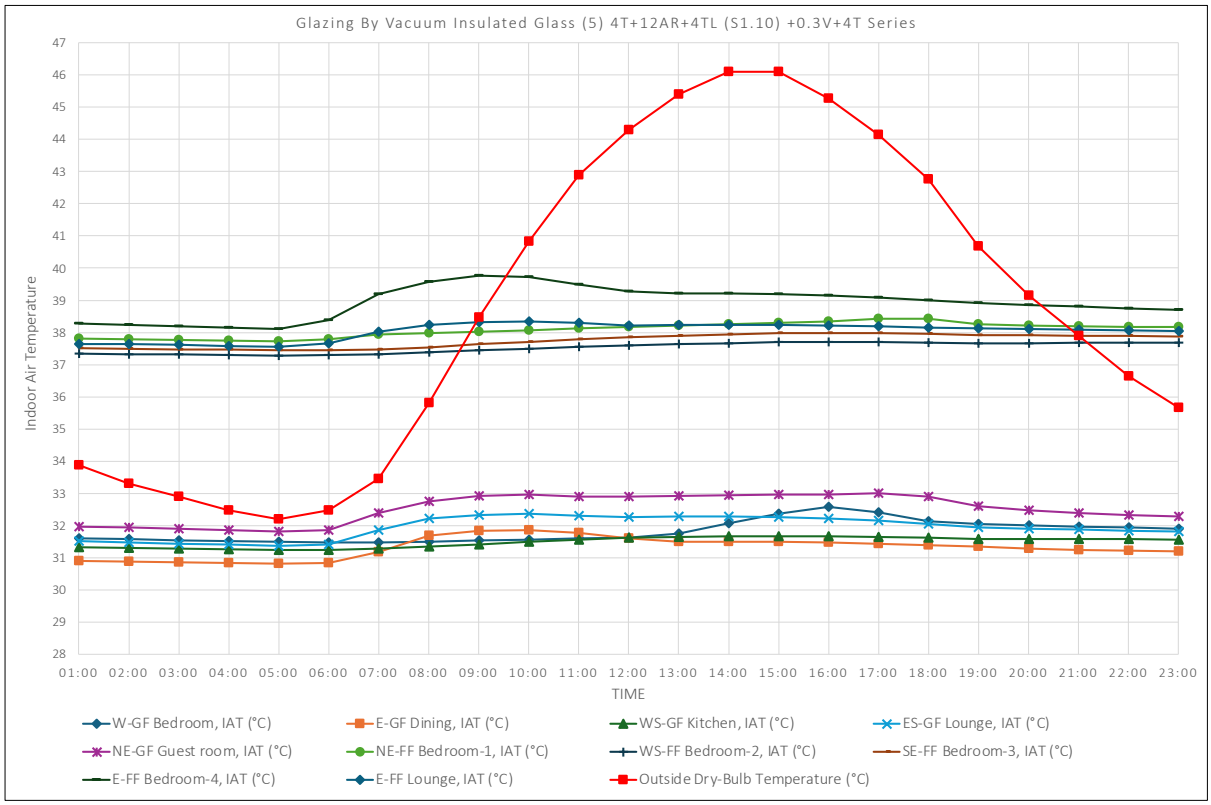


Figure A-1. 93. The free-running simulation of hourly indoor air temperature in the base case building zones after replacing the glazing by vacuum insulated glass (5) 4T+12AR+4TL (S1.10) +0.3V+4T Series (15th July).

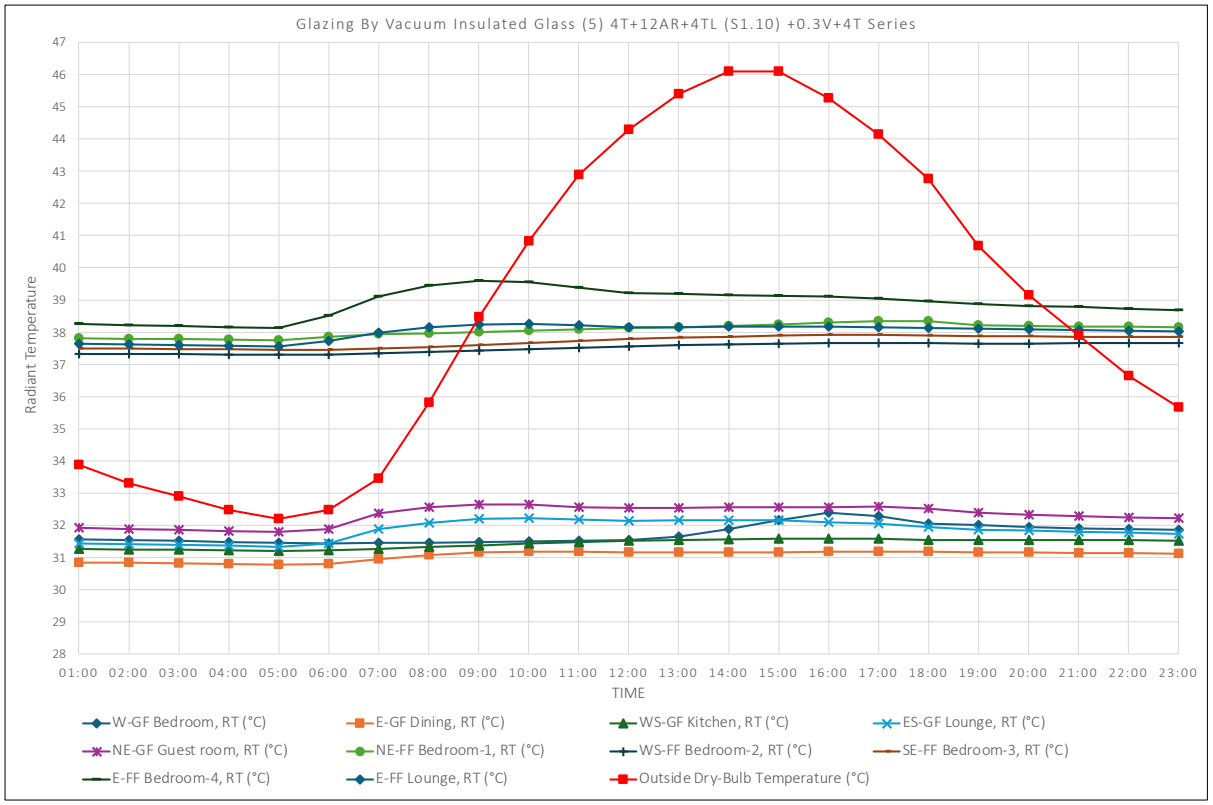


Figure A-1. 94. The free-running simulation of hourly radiant temperature in the base case building zones after replacing the glazing by vacuum insulated glass (5) 4T+12AR+4TL (S1.10) +0.3V+4T Series (15th July).

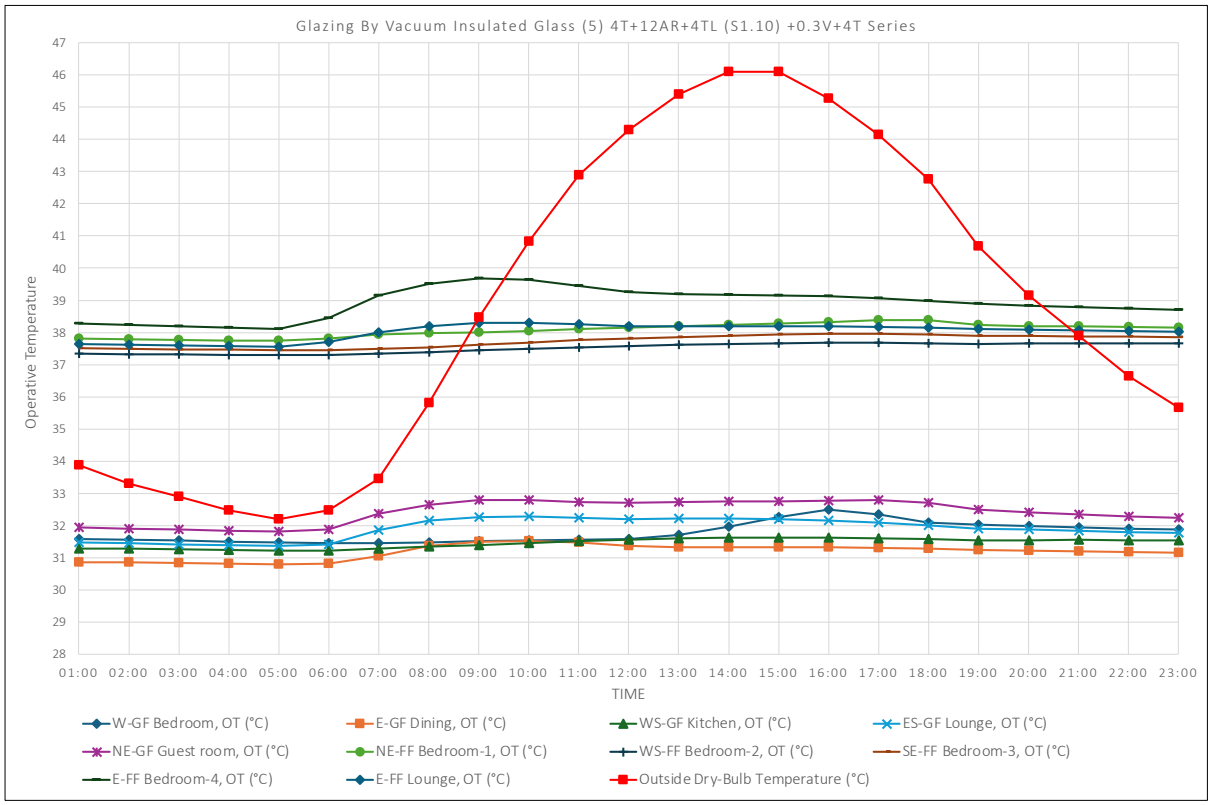


Figure A-1. 95. The free-running simulation of hourly operative temperature in the base case building zones after replacing the glazing by vacuum insulated glass (5) 4T+12AR+4TL (S1.10) +0.3V+4T Series (15th July).

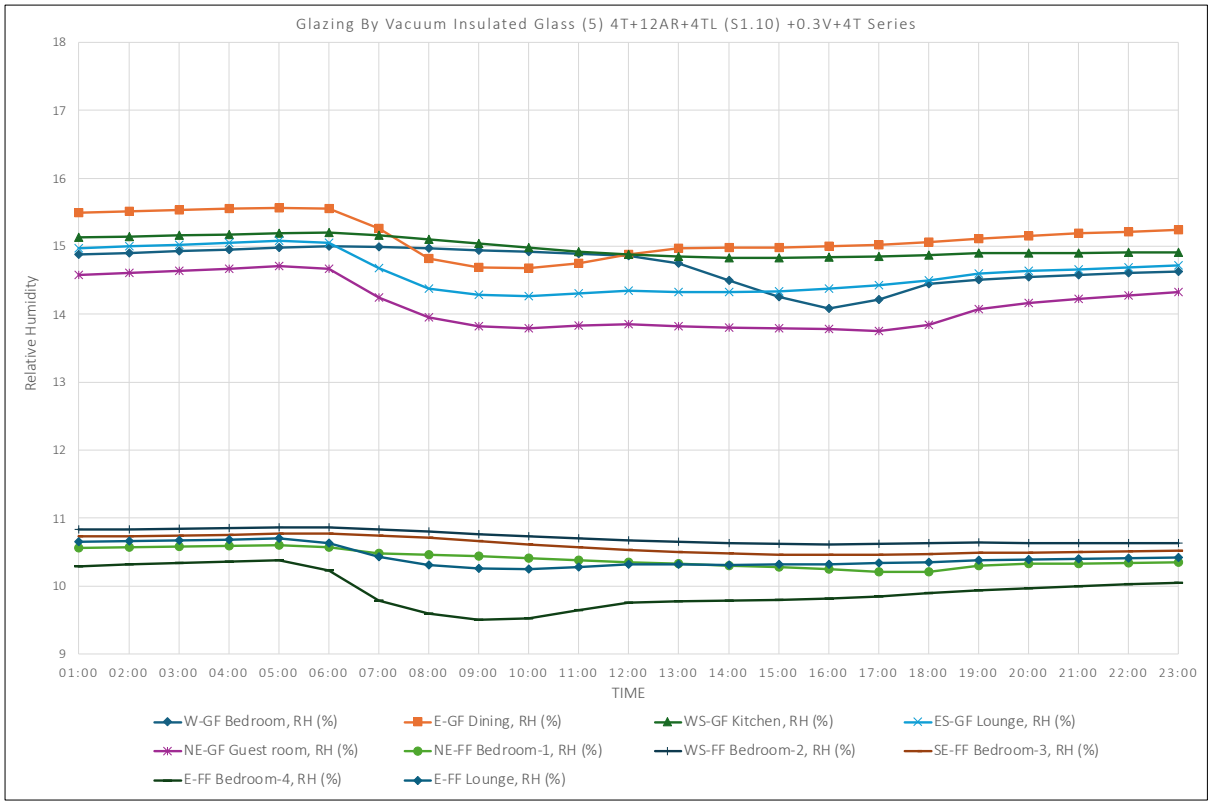


Figure A-1. 96. The free-running simulation of hourly relative humidity in the base case building zones after replacing the glazing by vacuum insulated glass (5) 4T+12AR+4TL (S1.10) +0.3V+4T Series (15th July).

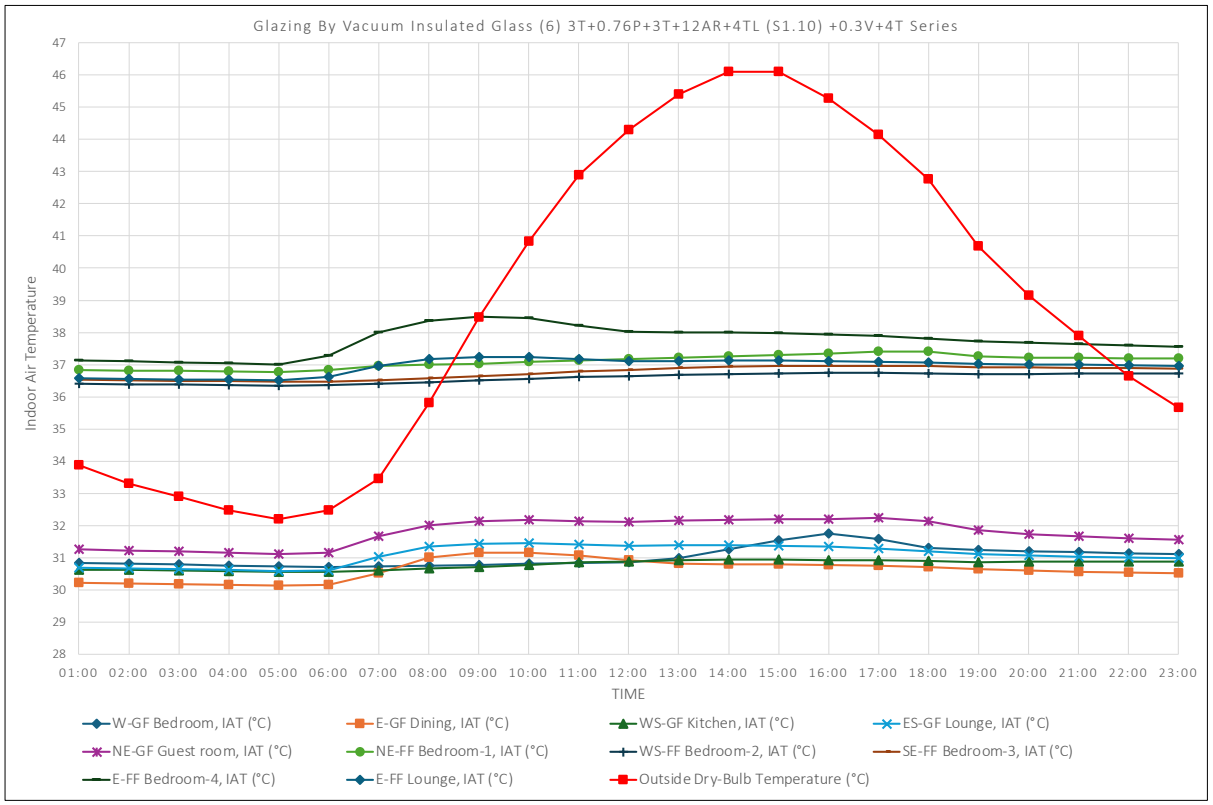


Figure A-1. 97. The free-running simulation of hourly indoor air temperature in the base case building zones after replacing the glazing by vacuum insulated glass (6) 3T+0.76P+3T+12AR+4TL (S1.10) +0.3V+4T Series (15th July).

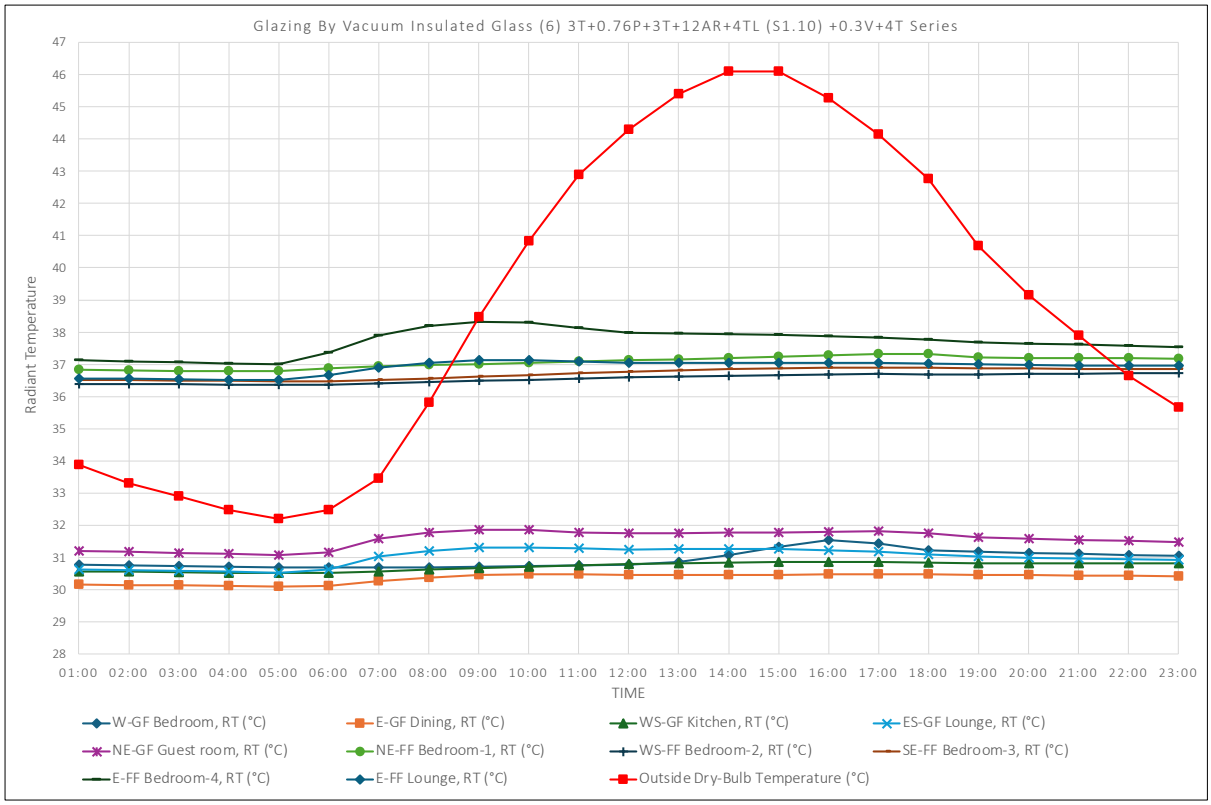


Figure A-1. 98. The free-running simulation of hourly radiant temperature in the base case building zones after replacing the glazing by vacuum insulated glass (6) 3T+0.76P+3T+12AR+4TL (S1.10) +0.3V+4T Series (15th July).

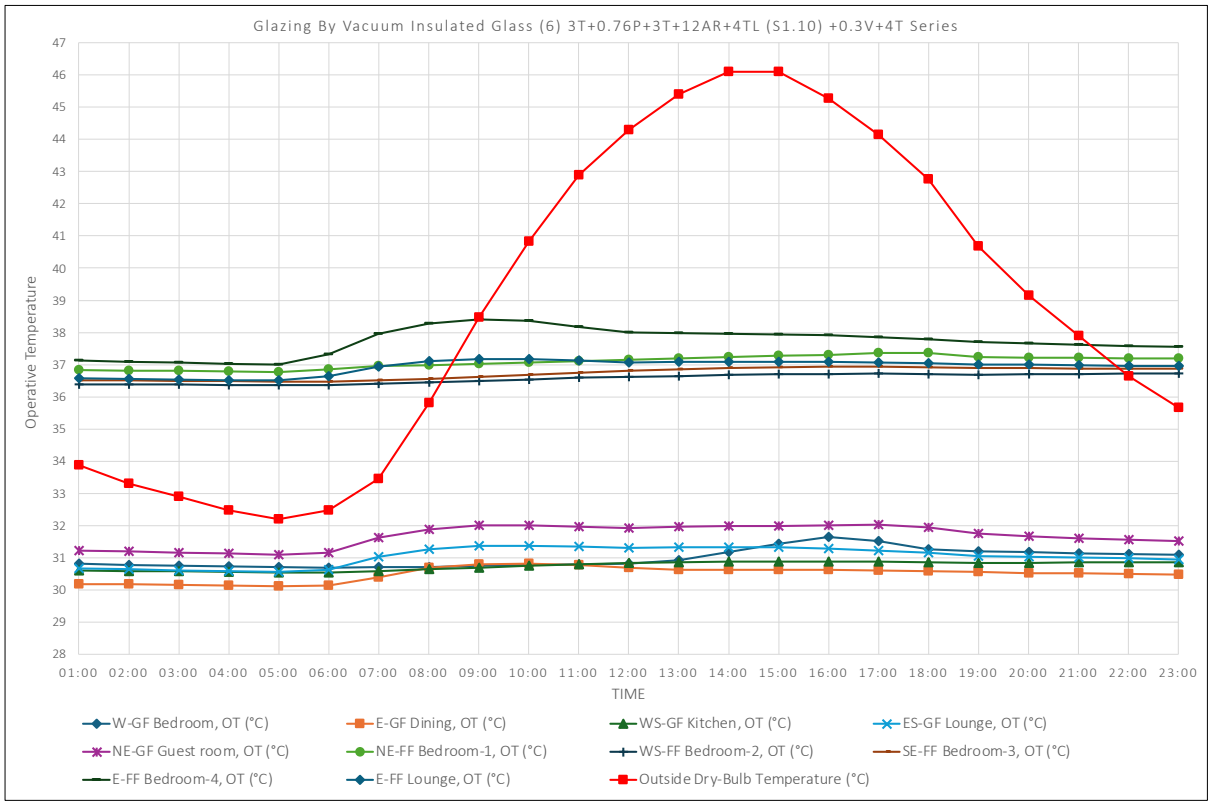


Figure A-1. 99. The free-running simulation of hourly operative temperature in the base case building zones after replacing the glazing by vacuum insulated glass (6) 3T+0.76P+3T+12AR+4TL (S1.10) +0.3V+4T Series (15th July).

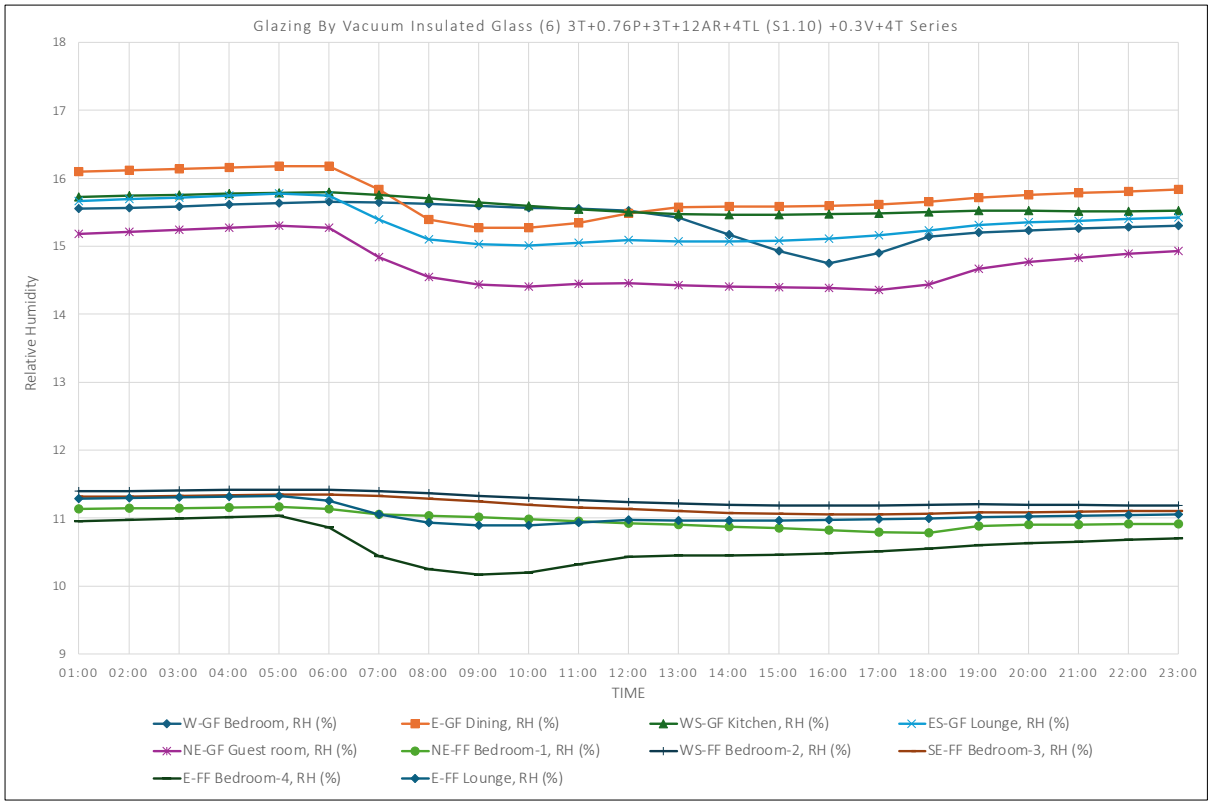


Figure A-1. 100. The free-running simulation of hourly relative humidity in the base case building zones after replacing the glazing by vacuum insulated glass (6) 3T+0.76P+3T+12AR+4TL (S1.10) +0.3V+4T Series (15th July).

Appendix 2: An analysis combining all parameters evaluated during the free-running simulation of indoor thermal environments, based on room uses.

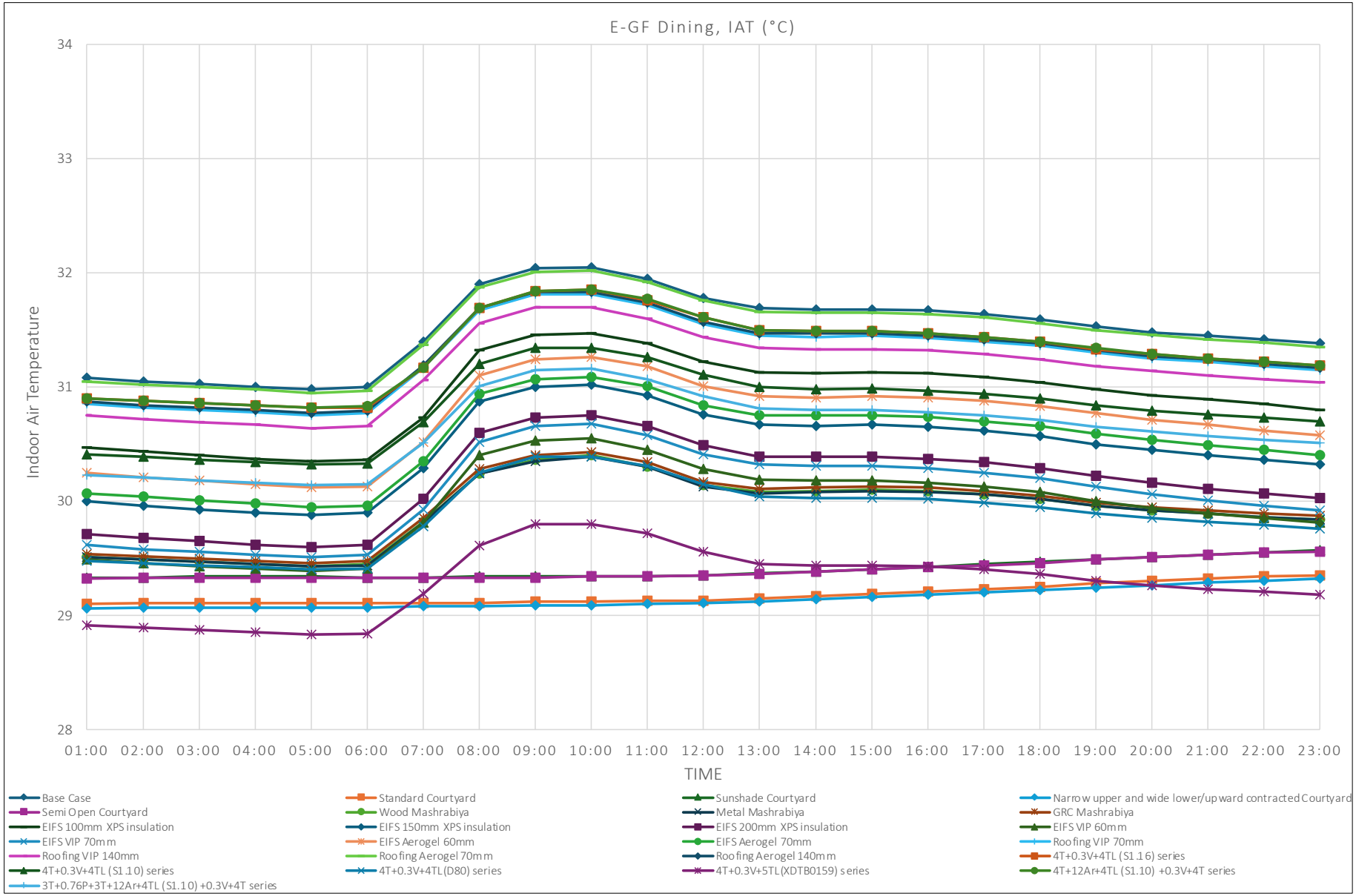


Figure A-2 1. The IAT free-running simulation of combined parameters for the E-GF dining room (15th July).

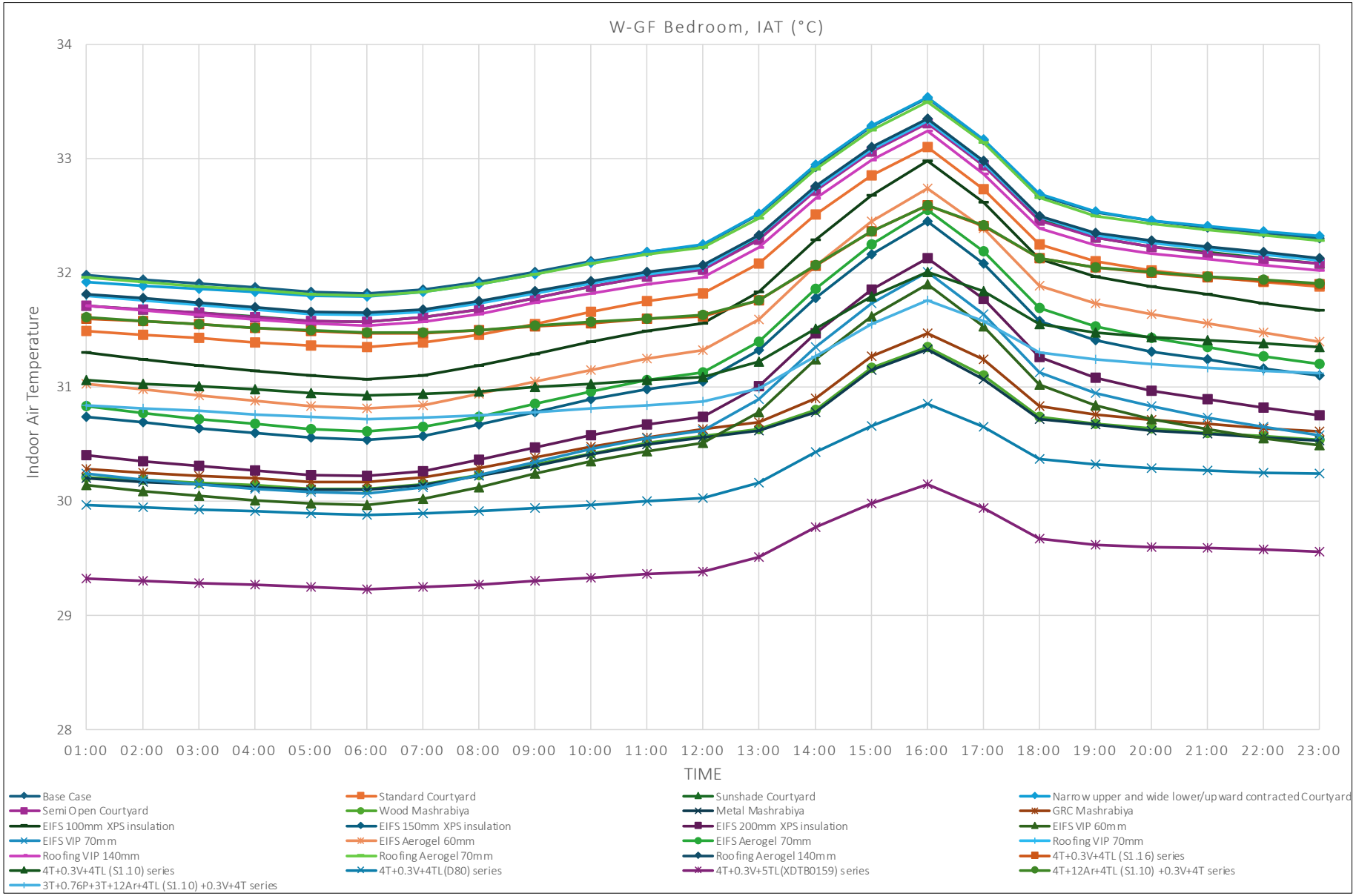


Figure A-2 2. The IAT free-running simulation of combined parameters for the W-GF Bedroom (15th July).

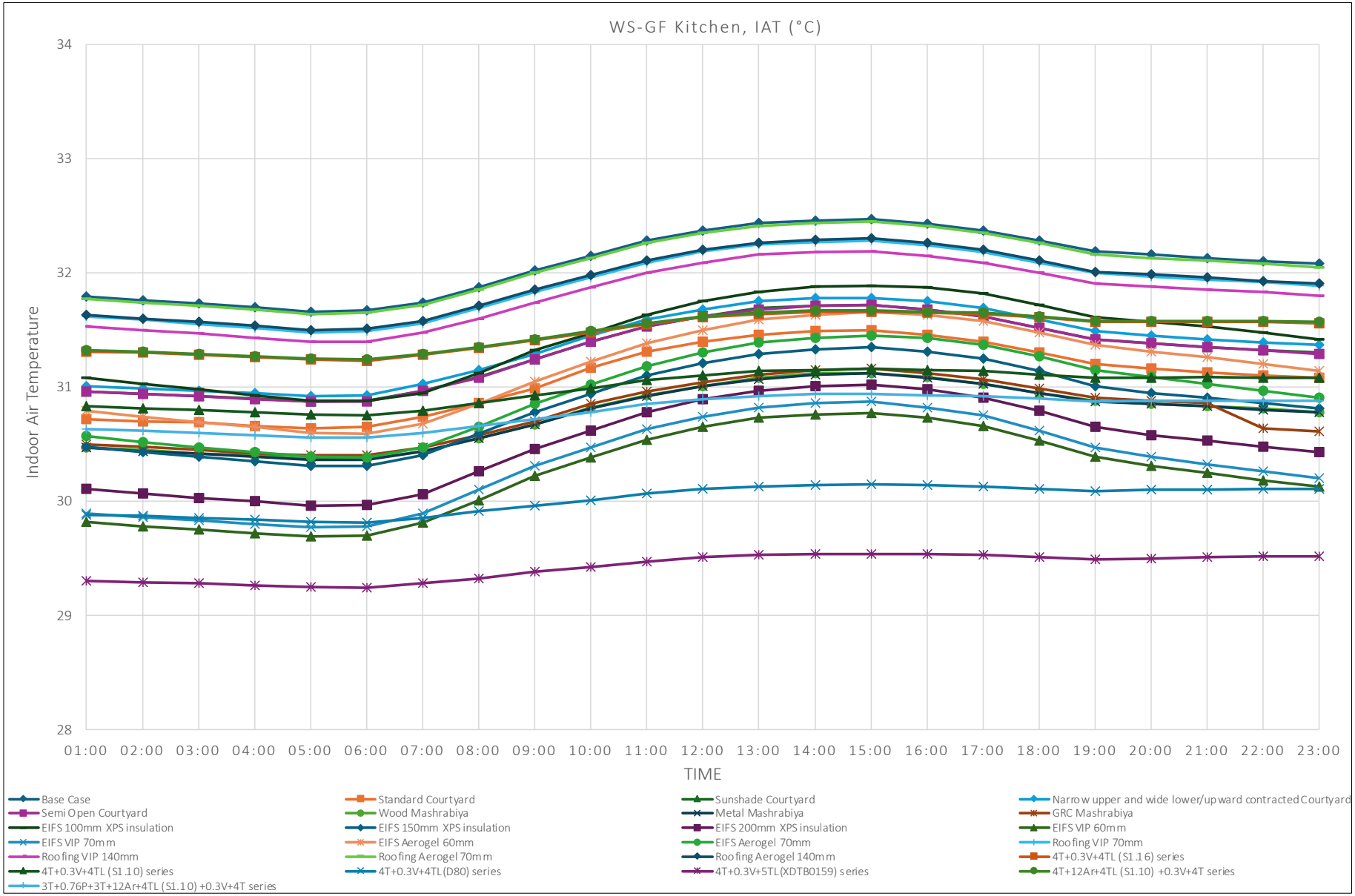


Figure A-2 3. The IAT free-running simulation of combined parameters for the WS-GF Kitchen (15th July).

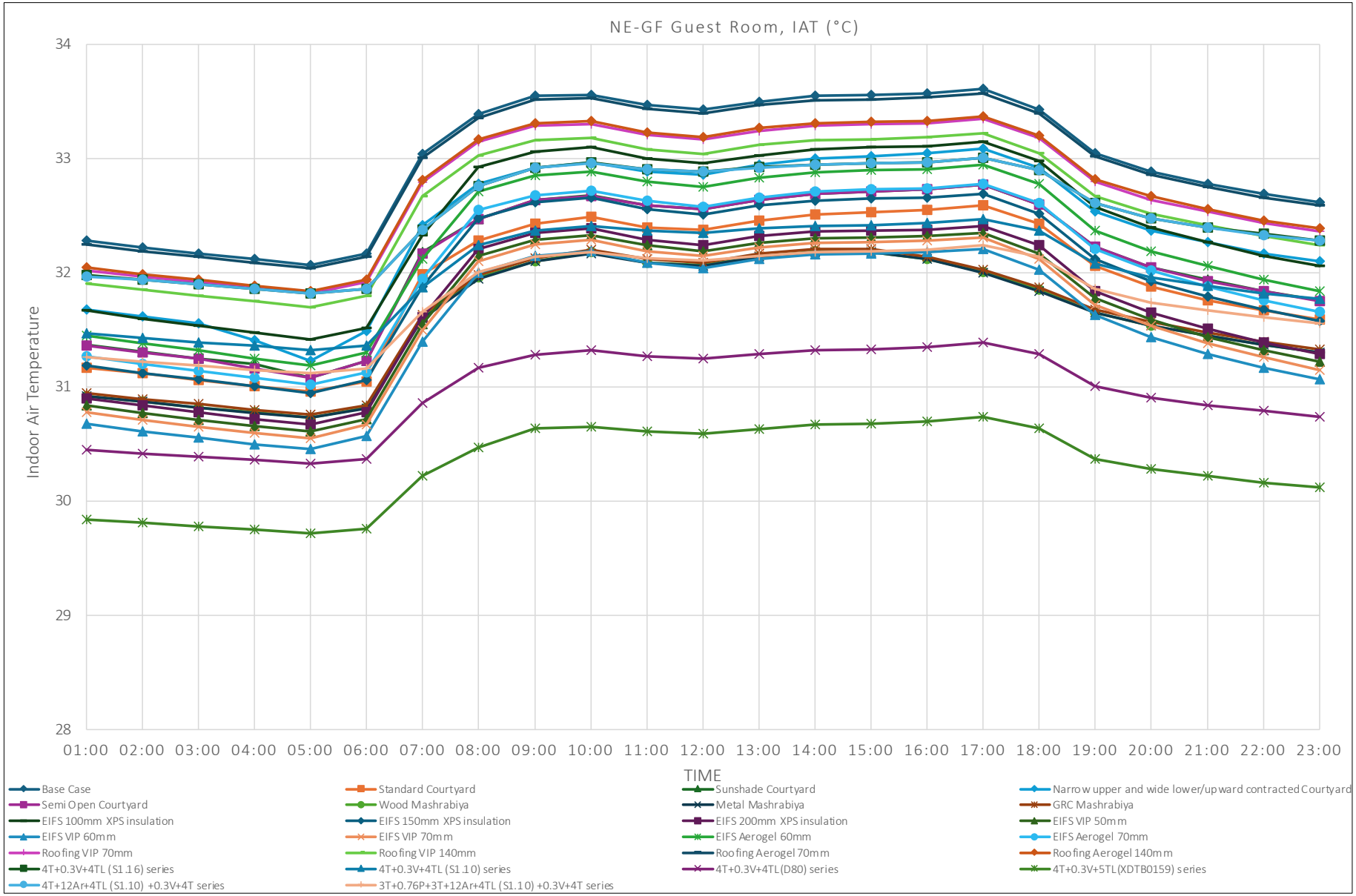


Figure A-2 4. The IAT free-running simulation of combined parameters for the NE-GF Guest Room (15th July)

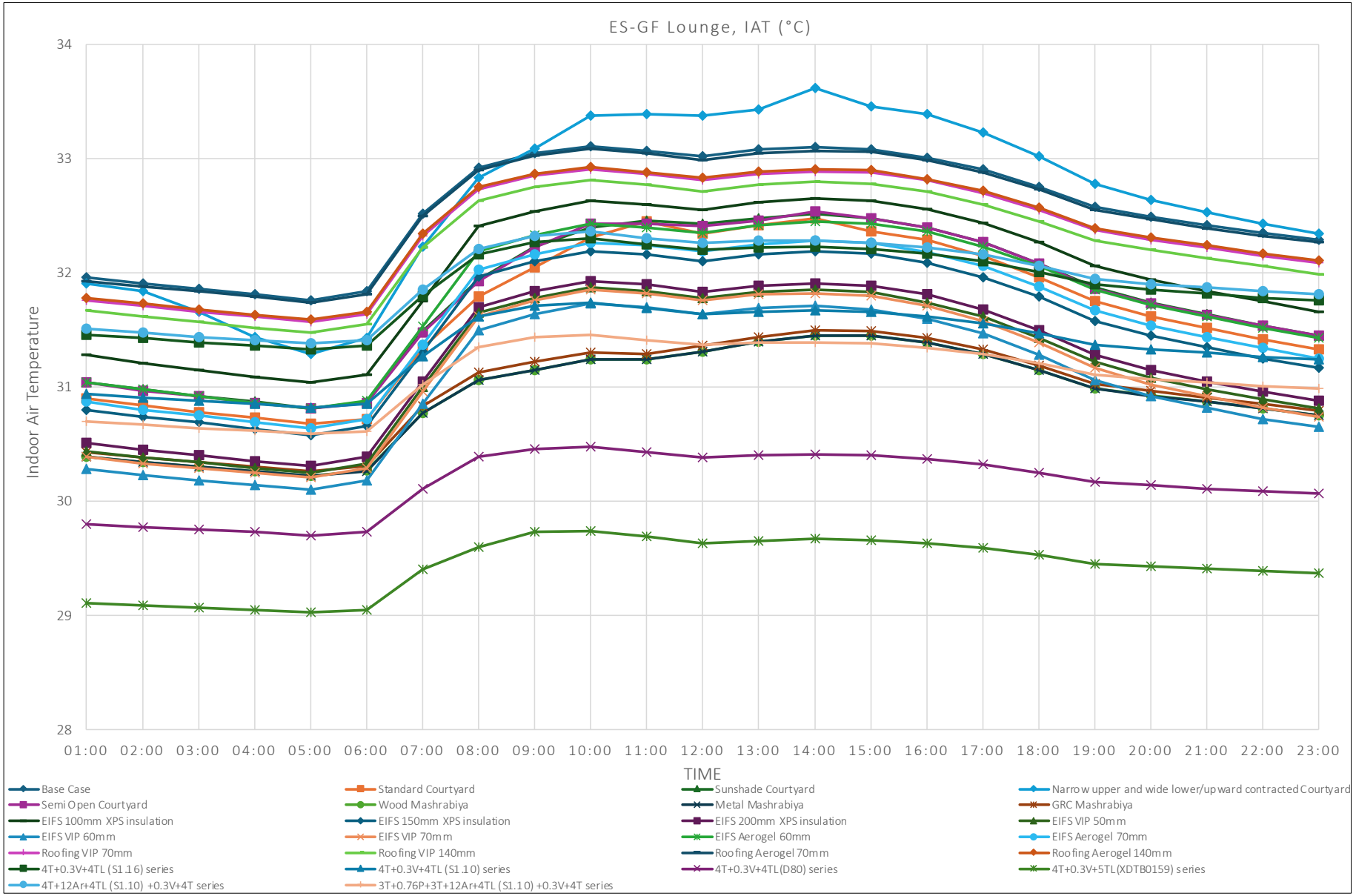


Figure A-2 5. The IAT free-running simulation of combined parameters for the ES-GF Lounge (15th July)

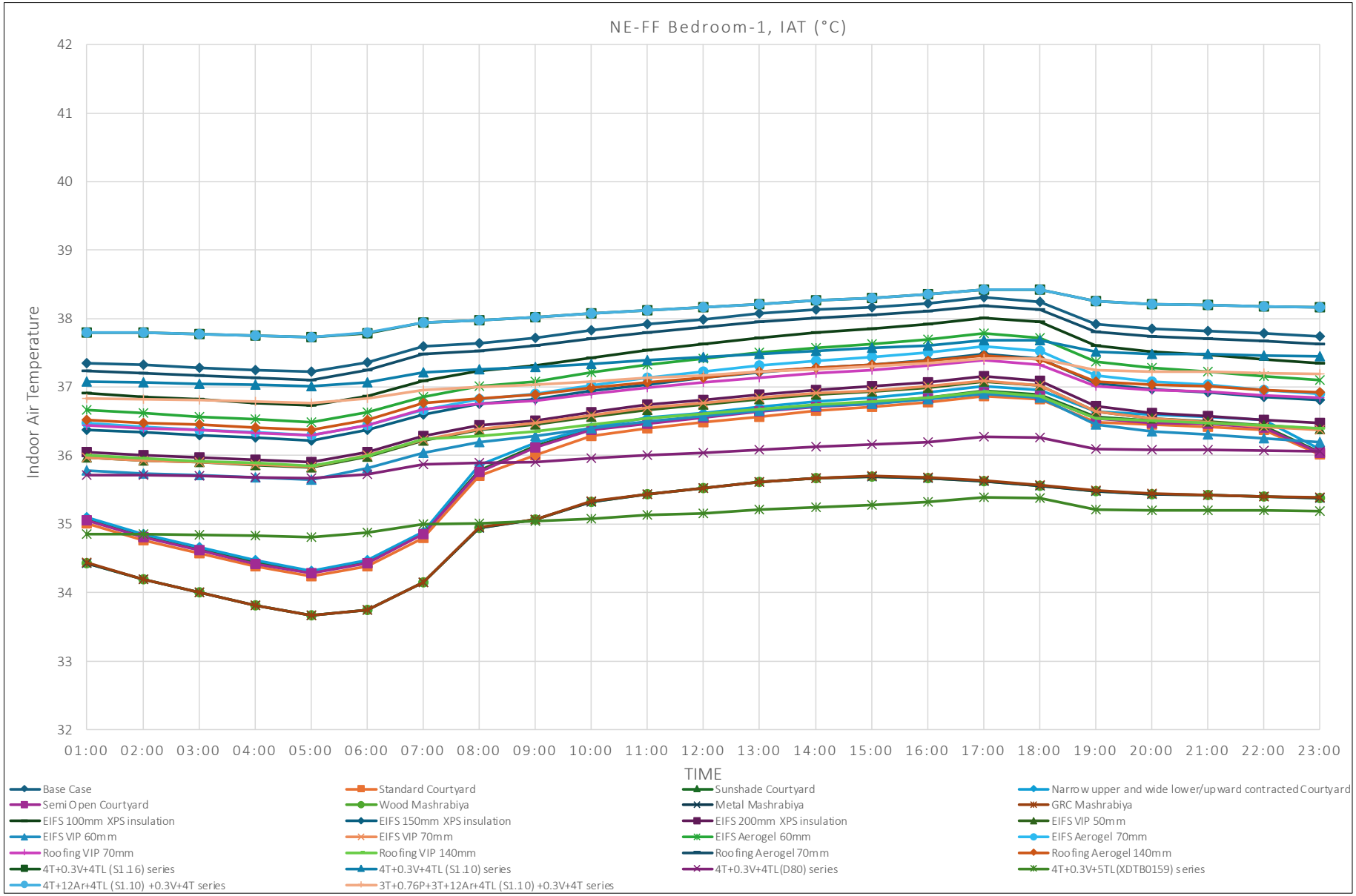


Figure A-2 6. The IAT free-running simulation of combined parameters for the NE-FF Bedroom-1 (15th July)

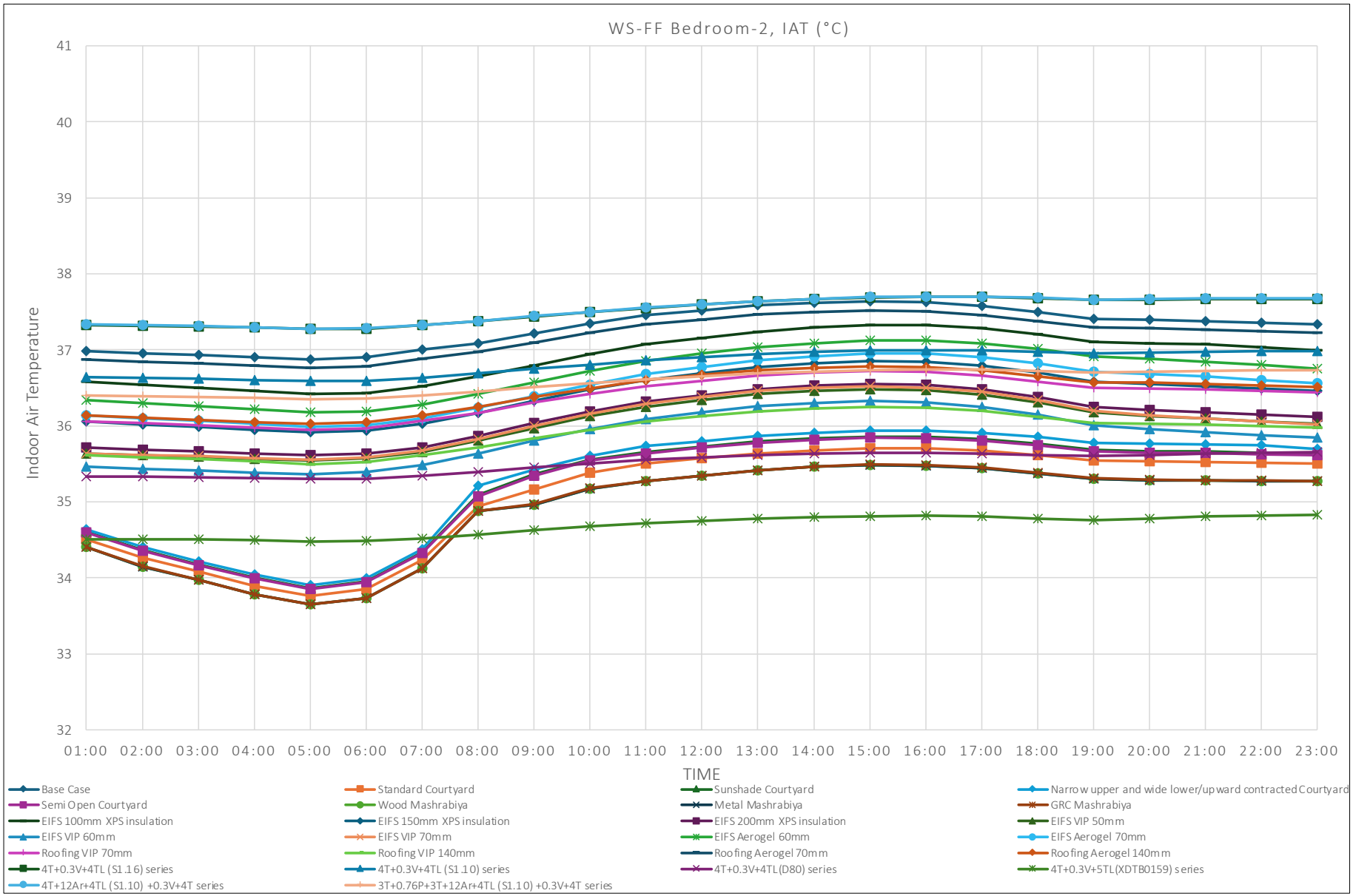


Figure A-2 7. The IAT free-running simulation of combined parameters for the WS-FF Bedroom-2 (15th July)

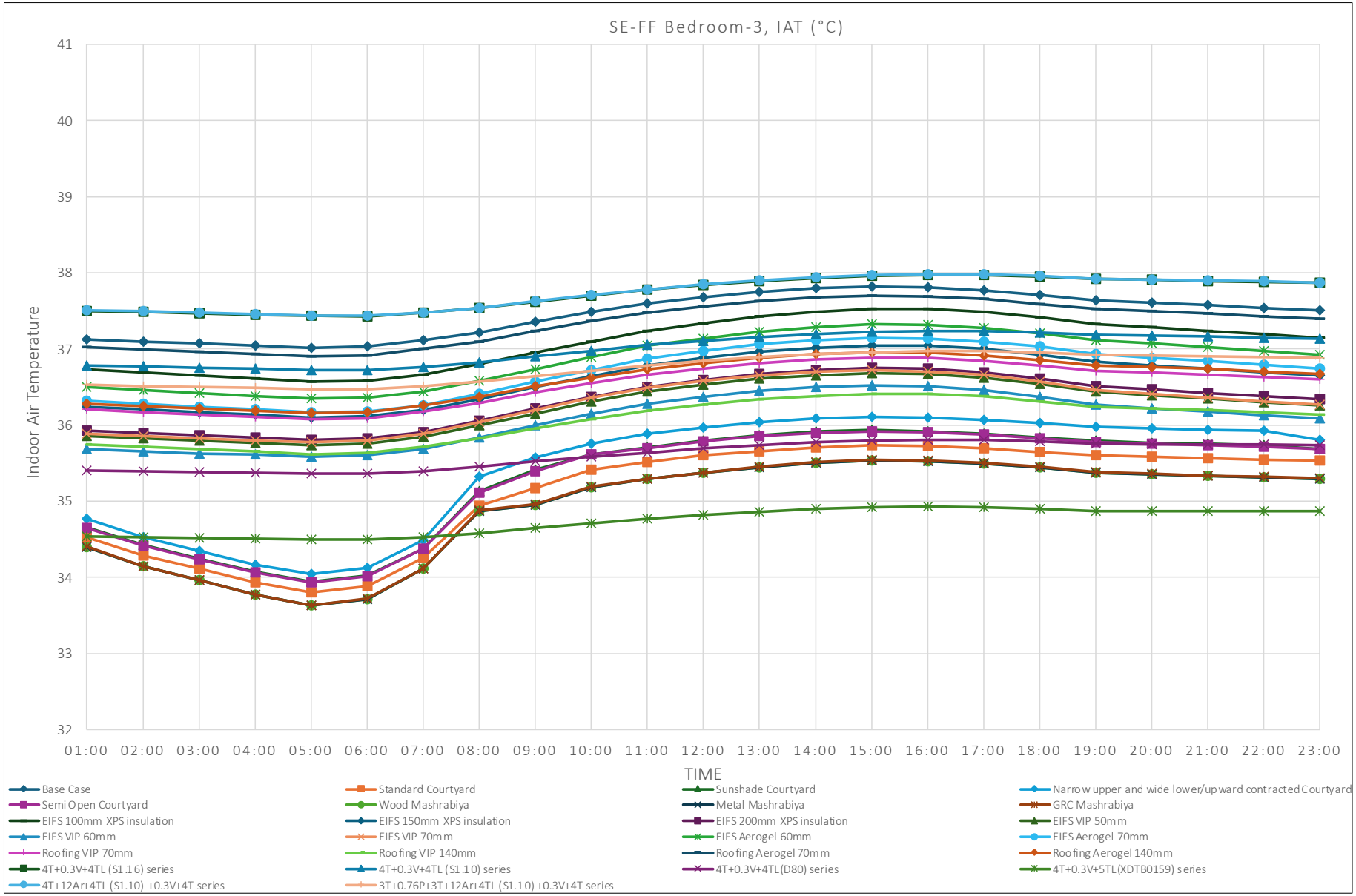


Figure A-2 8. The IAT free-running simulation of combined parameters for the SE-FF Bedroom-3 (15th July)

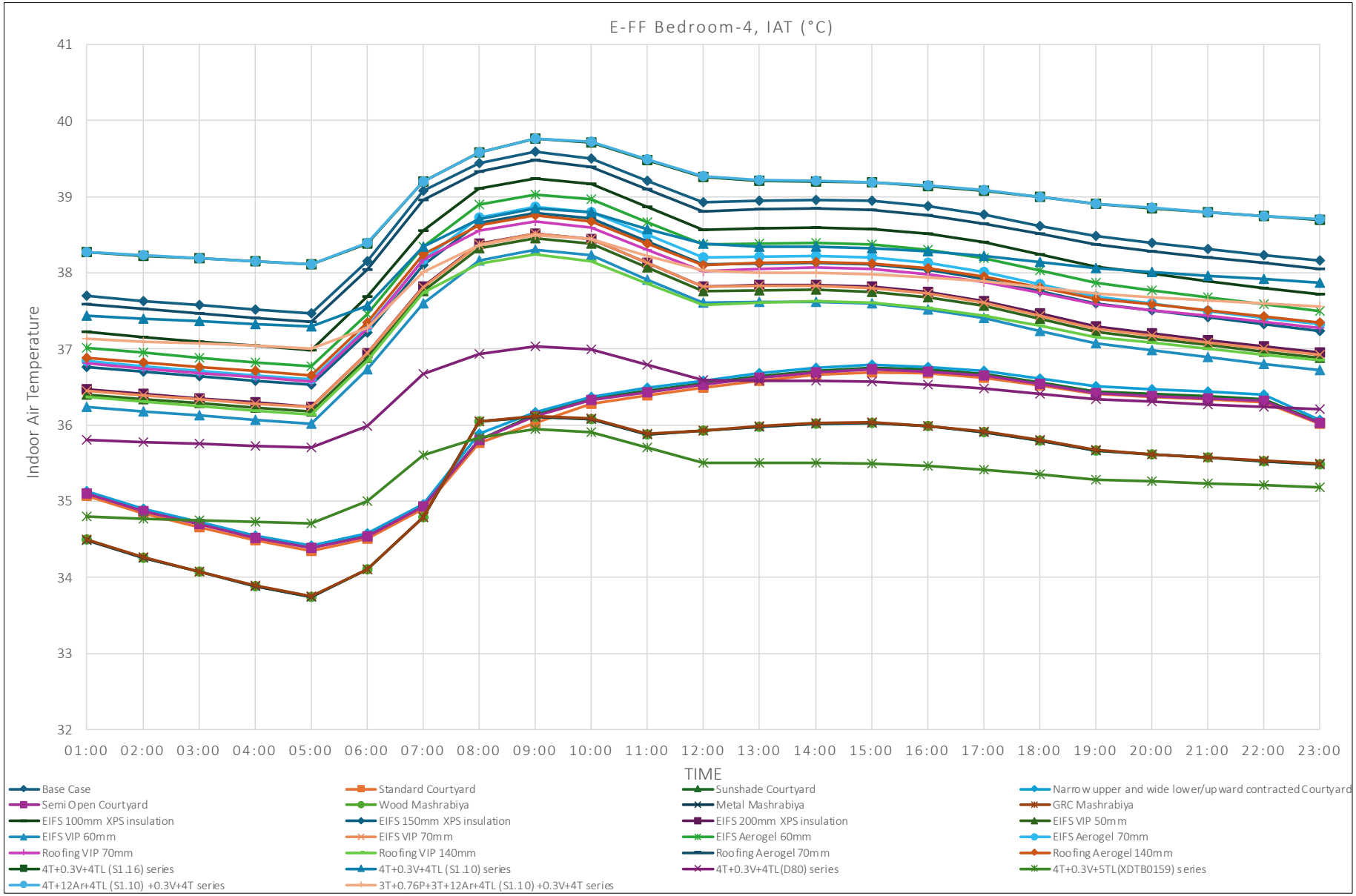


Figure A-2 9. The IAT free-running simulation of combined parameters for the E-FF Bedroom-4 (15th July)

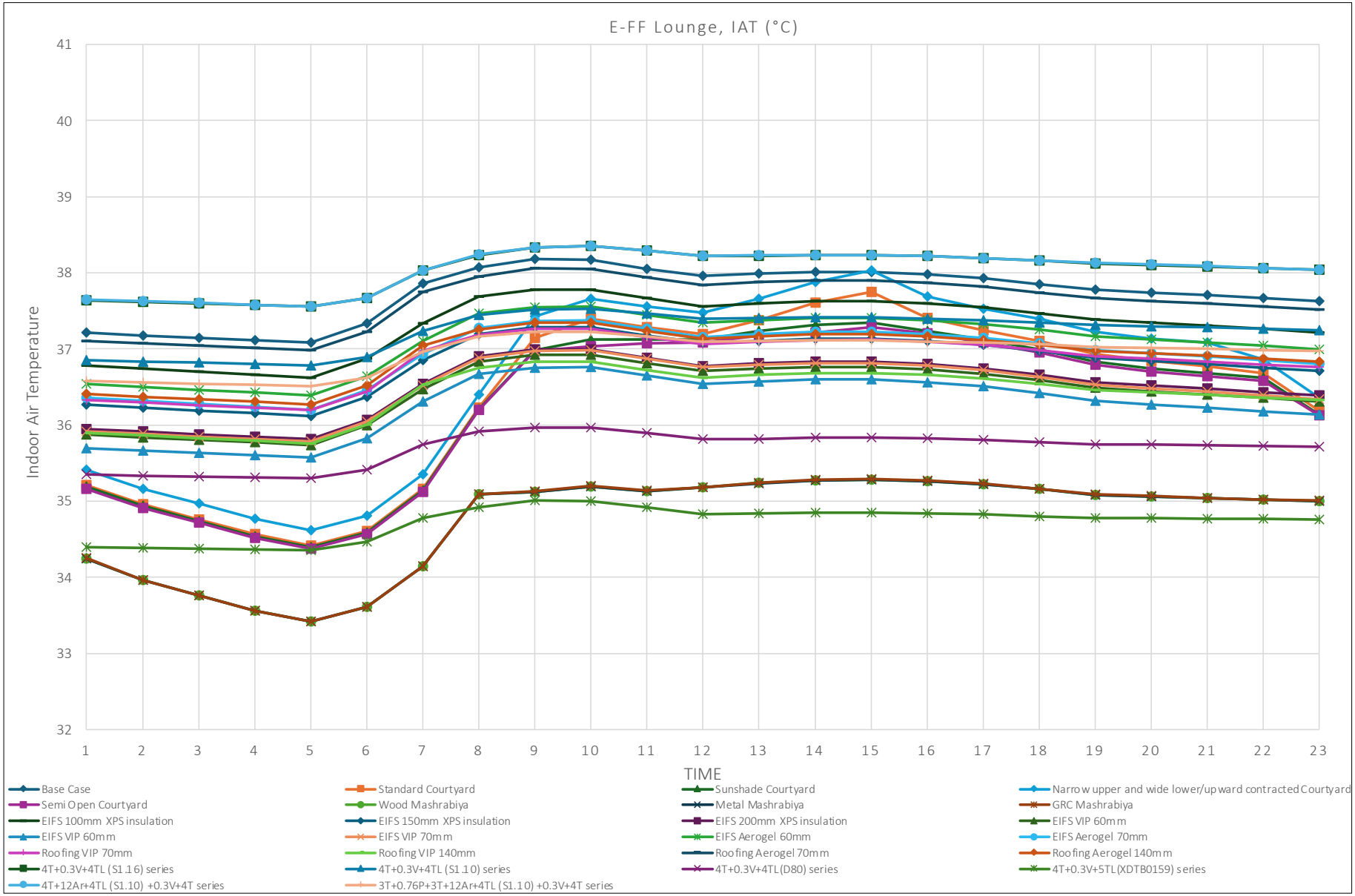


Figure A-2 10. The IAT free-running simulation of combined parameters for the E-FF Lounge (15th July)

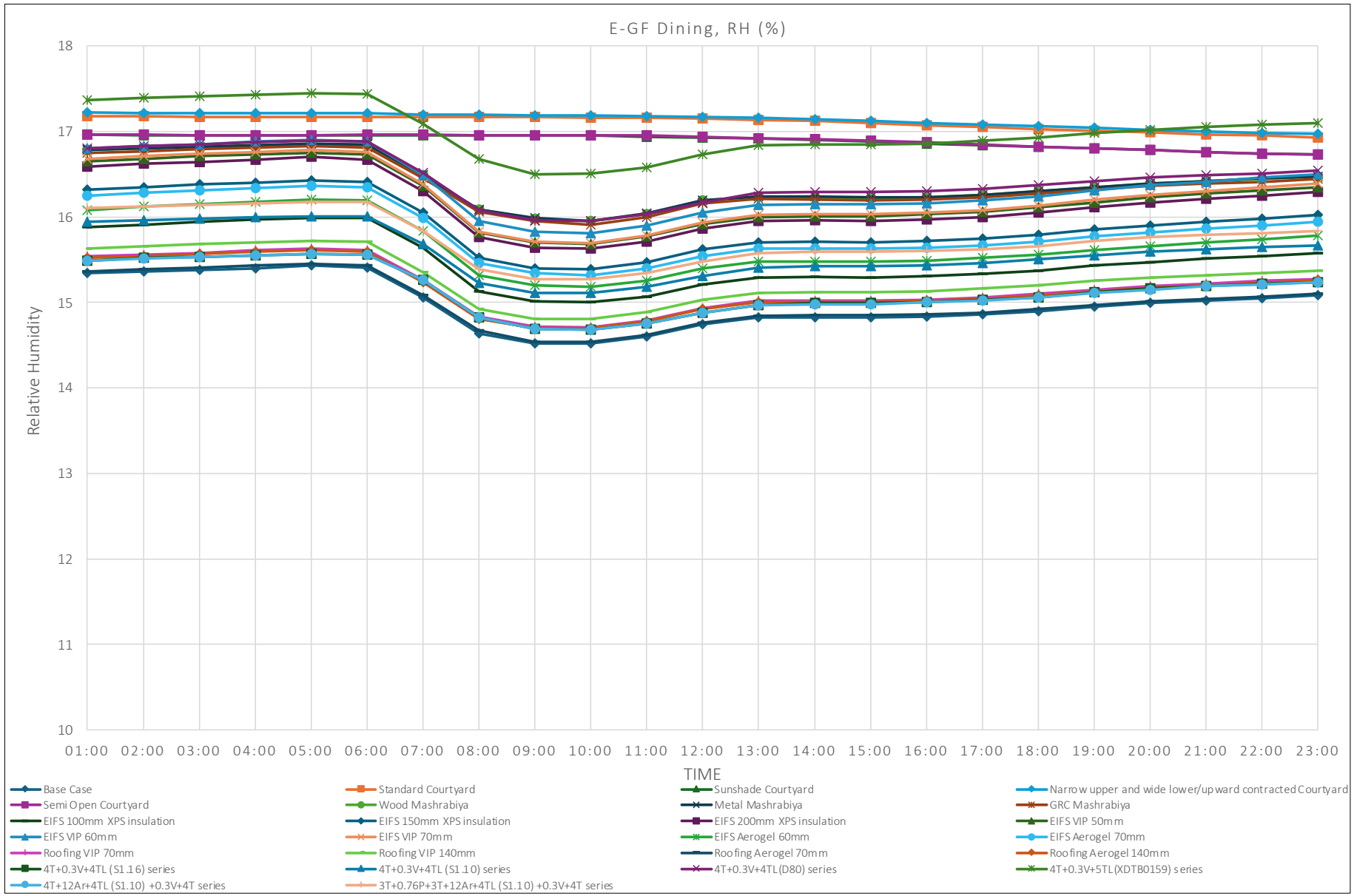


Figure A-2 11. The RH free-running simulation of combined parameters for the E-GF dining room (15th July)

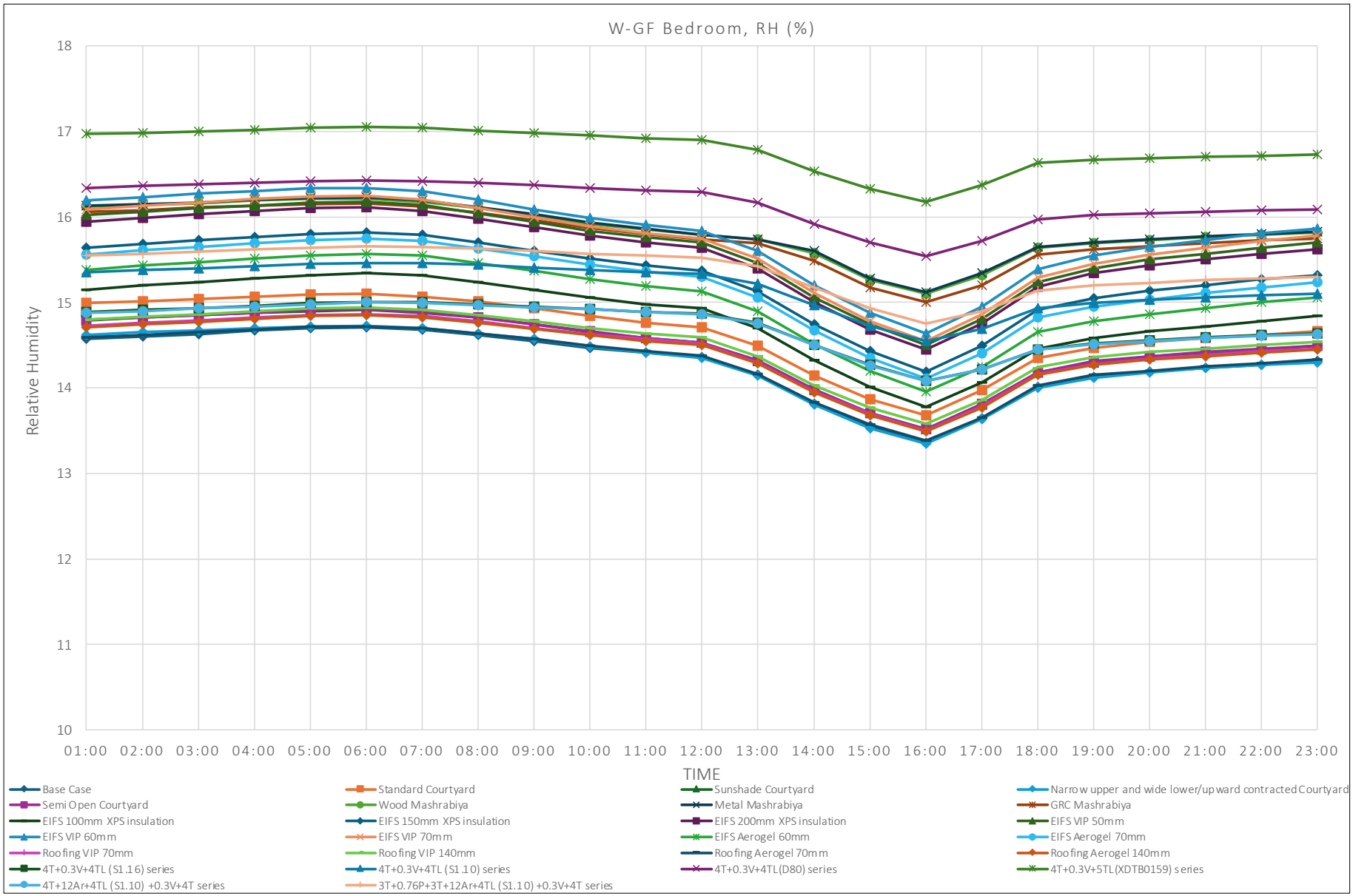


Figure A-2 12. The RH free-running simulation of combined parameters for the W-GF Bedroom (15th July)

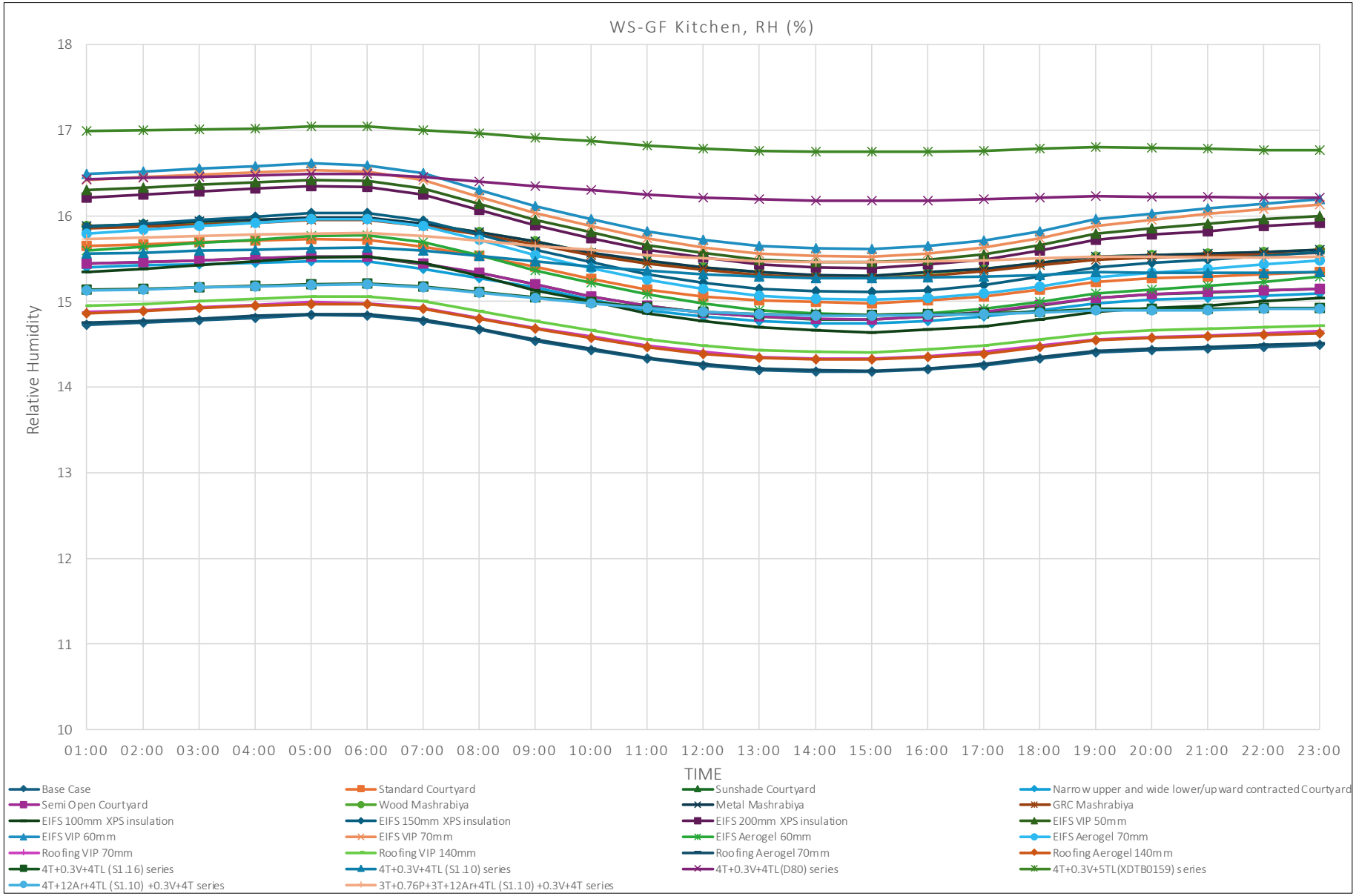


Figure A-2 13. The RH free-running simulation of combined parameters for the WS-GF Kitchen (15th July)

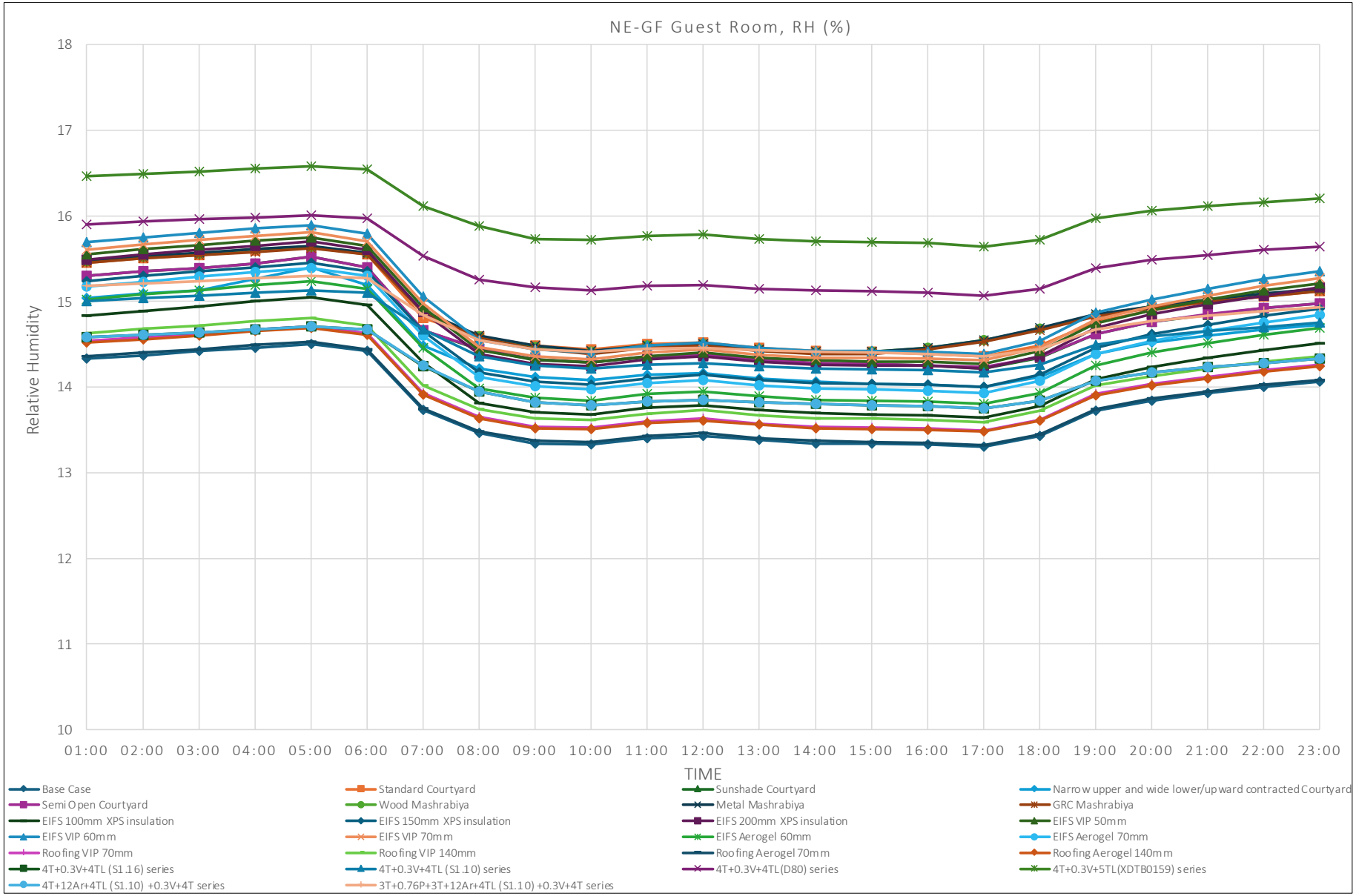


Figure A-2 14. The RH free-running simulation of combined parameters for the NE-GF Guest Room (15th July)

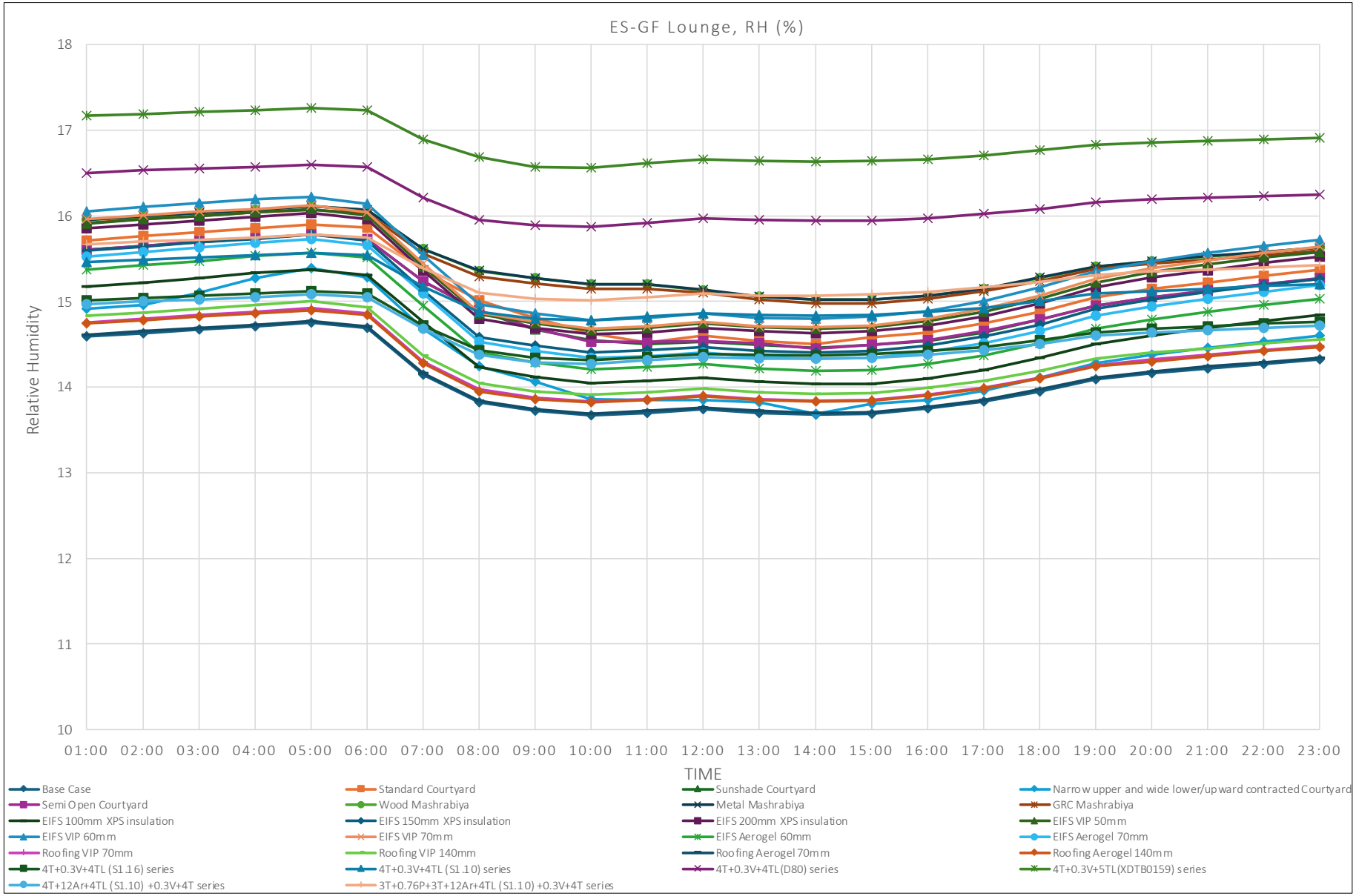


Figure A-2 15. The RH free-running simulation of combined parameters for the E ES-GF Lounge (15th July)

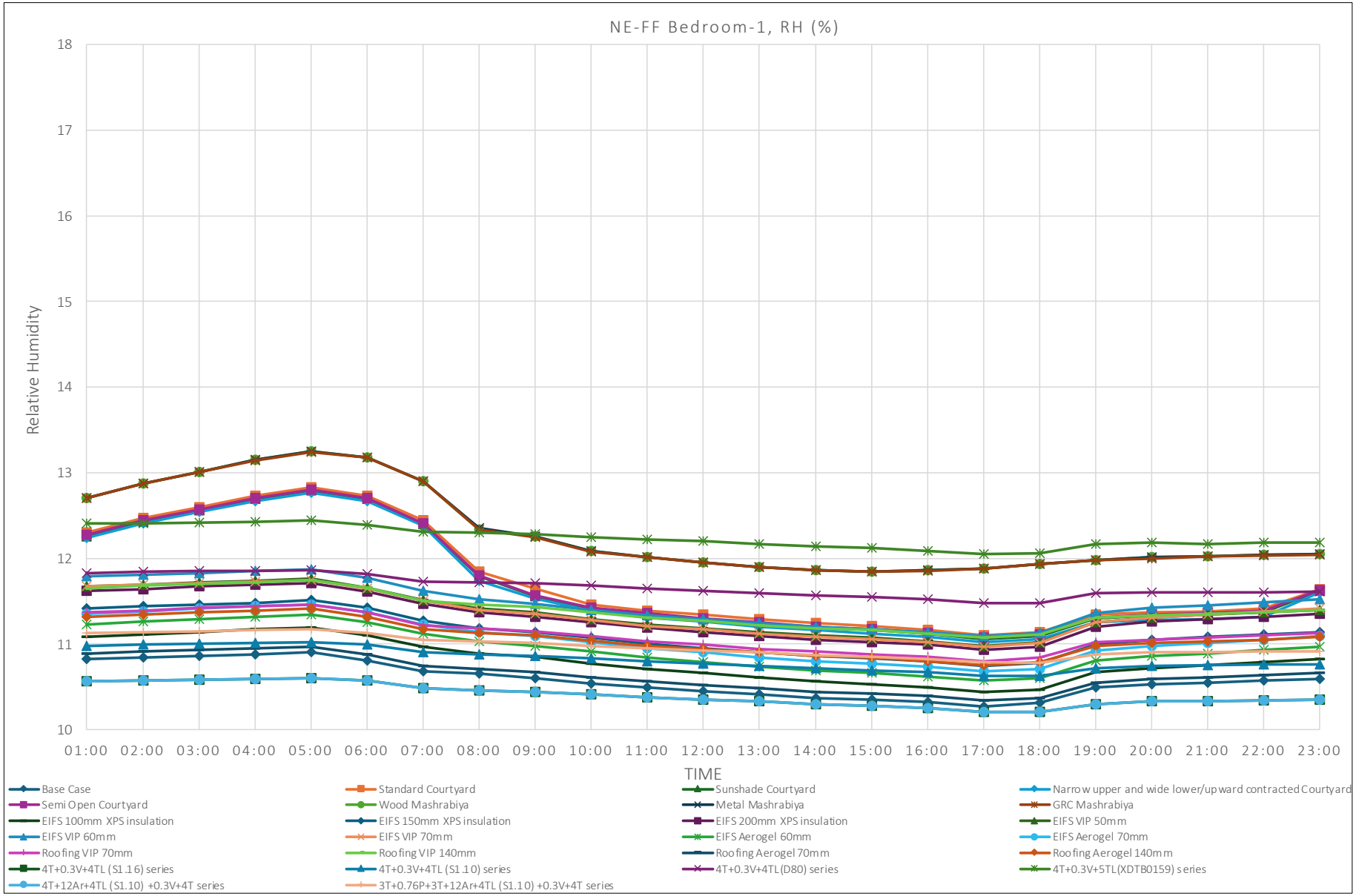


Figure A-2 16. The RH free-running simulation of combined parameters for the NE-FF Bedroom-1 (15th July)

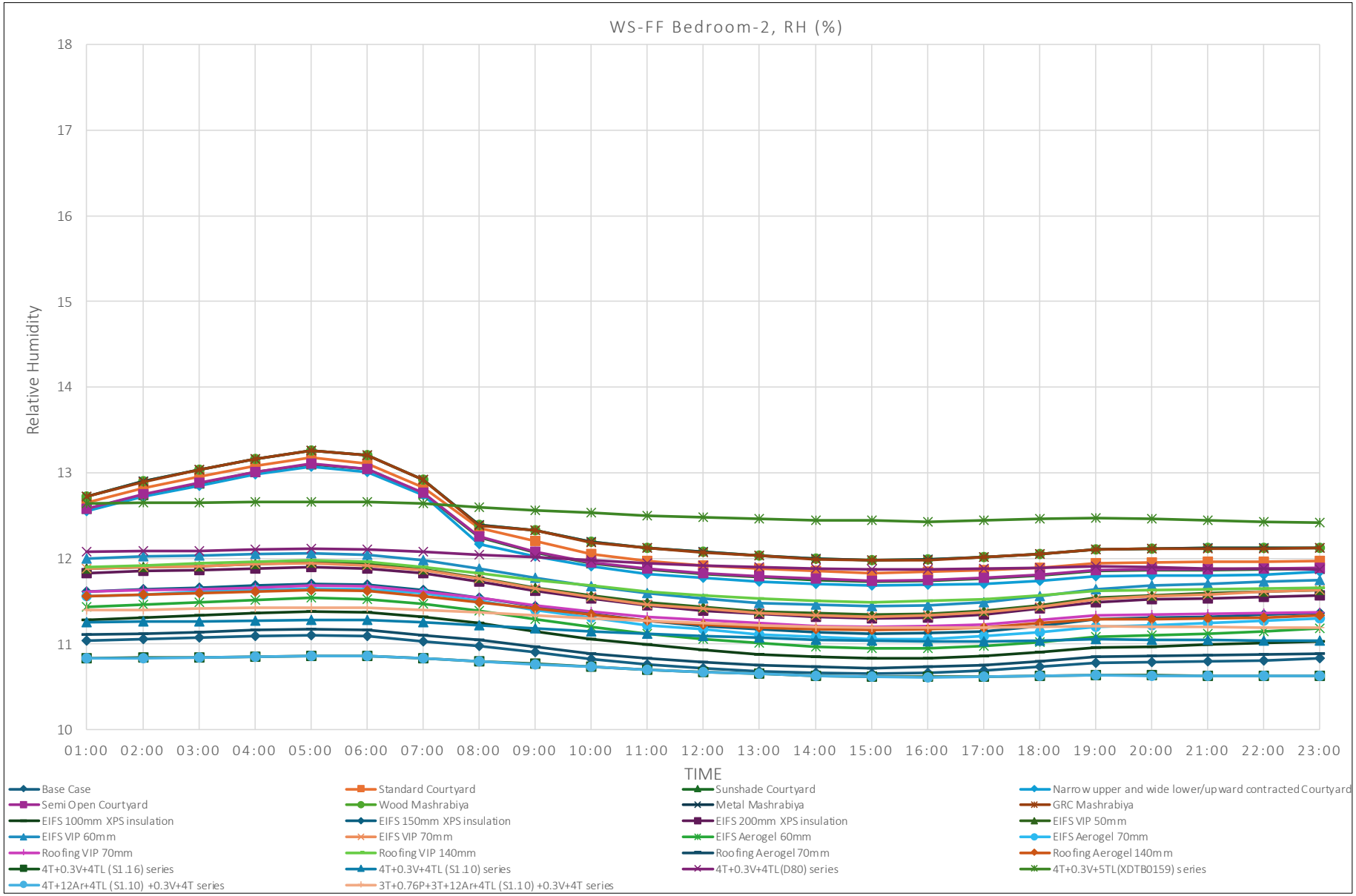


Figure A-2 17. The RH free-running simulation of combined parameters for the WS-FF Bedroom-2 (15th July)

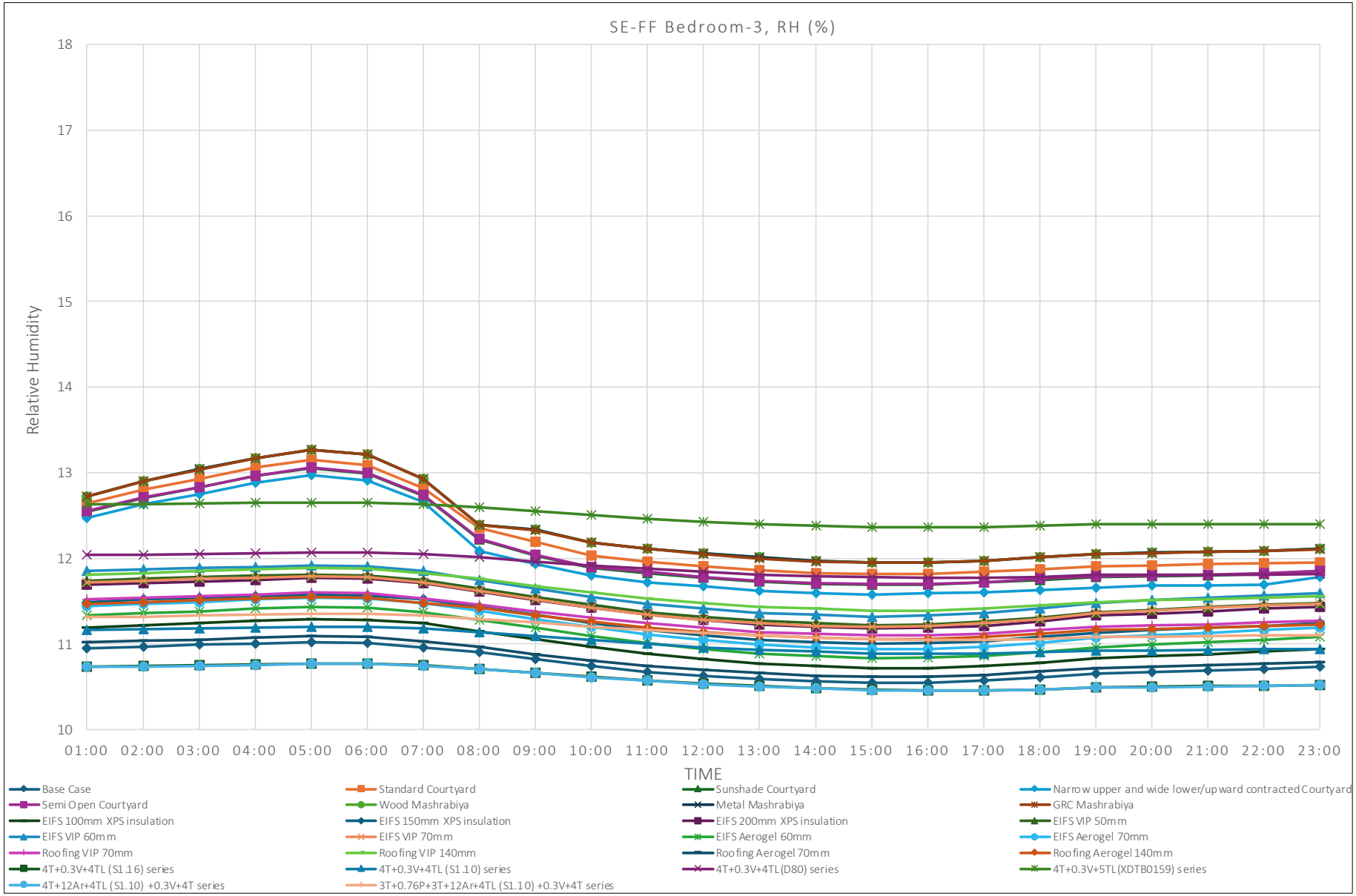


Figure A-2 18. The RH free-running simulation of combined parameters for the SE-FF Bedroom-3 (15th July)

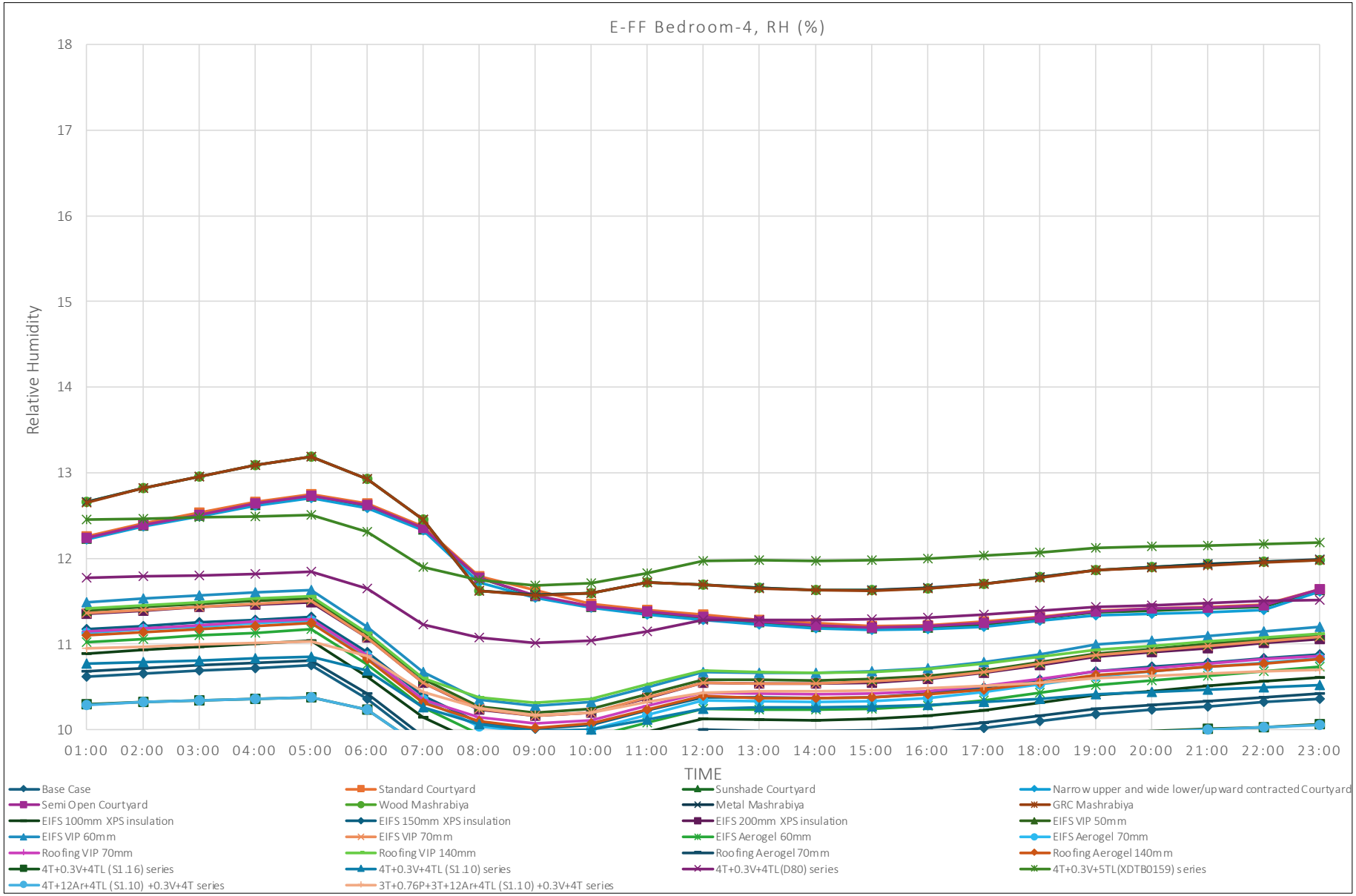


Figure A-2 19. The RH free-running simulation of combined parameters for the E-FF Bedroom-4 (15th July)

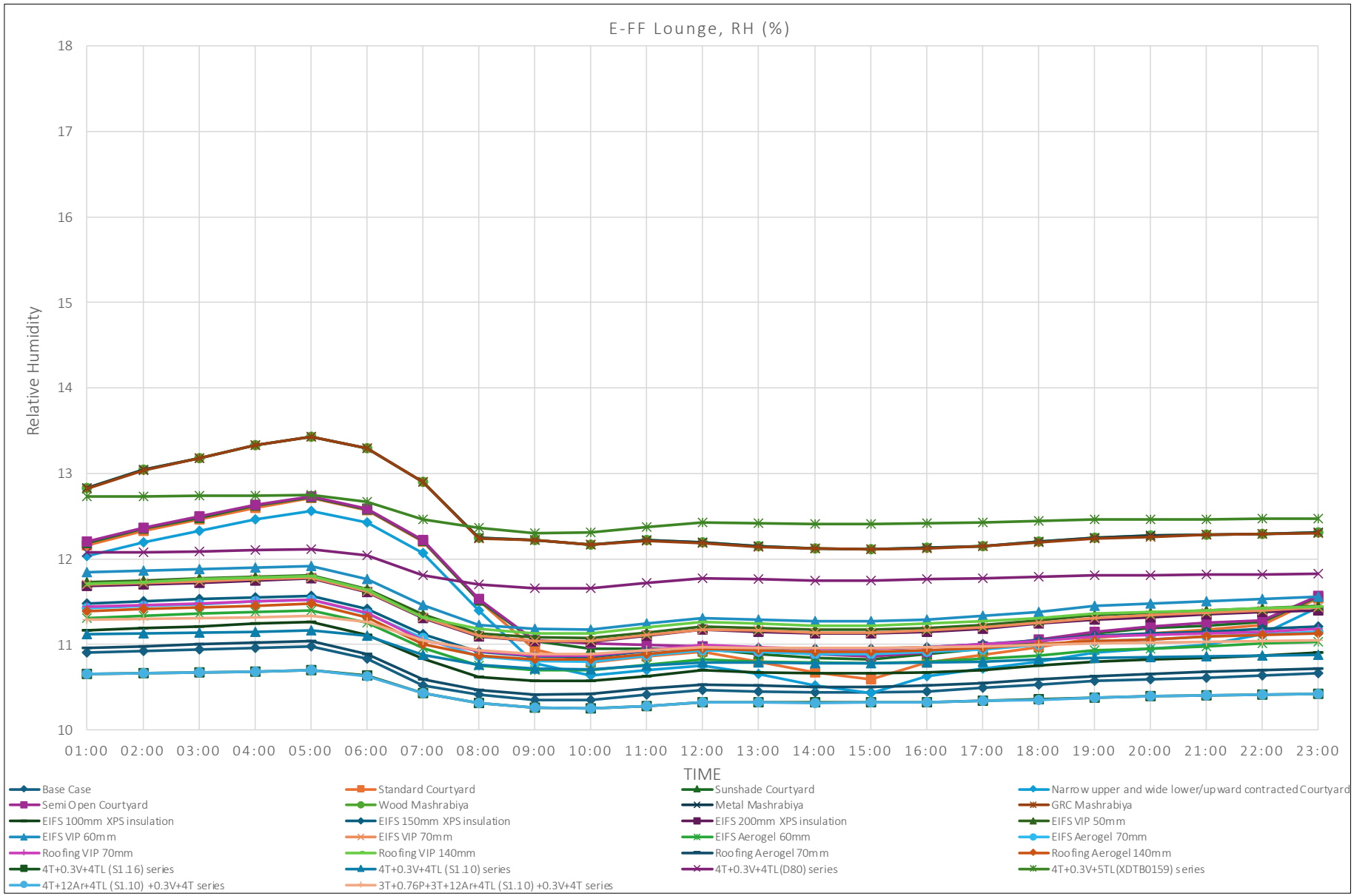


Figure A-2 20. The RH free-running simulation of combined parameters for the E-FF Lounge (15th July)

Appendix 3: A Comparative Analysis of Free-Running Simulations of Hourly Indoor Air, Radiant, Operative Temperatures, and Relative Humidity in Building Zones for the Base Case and After Applying Green Engineering Solutions.

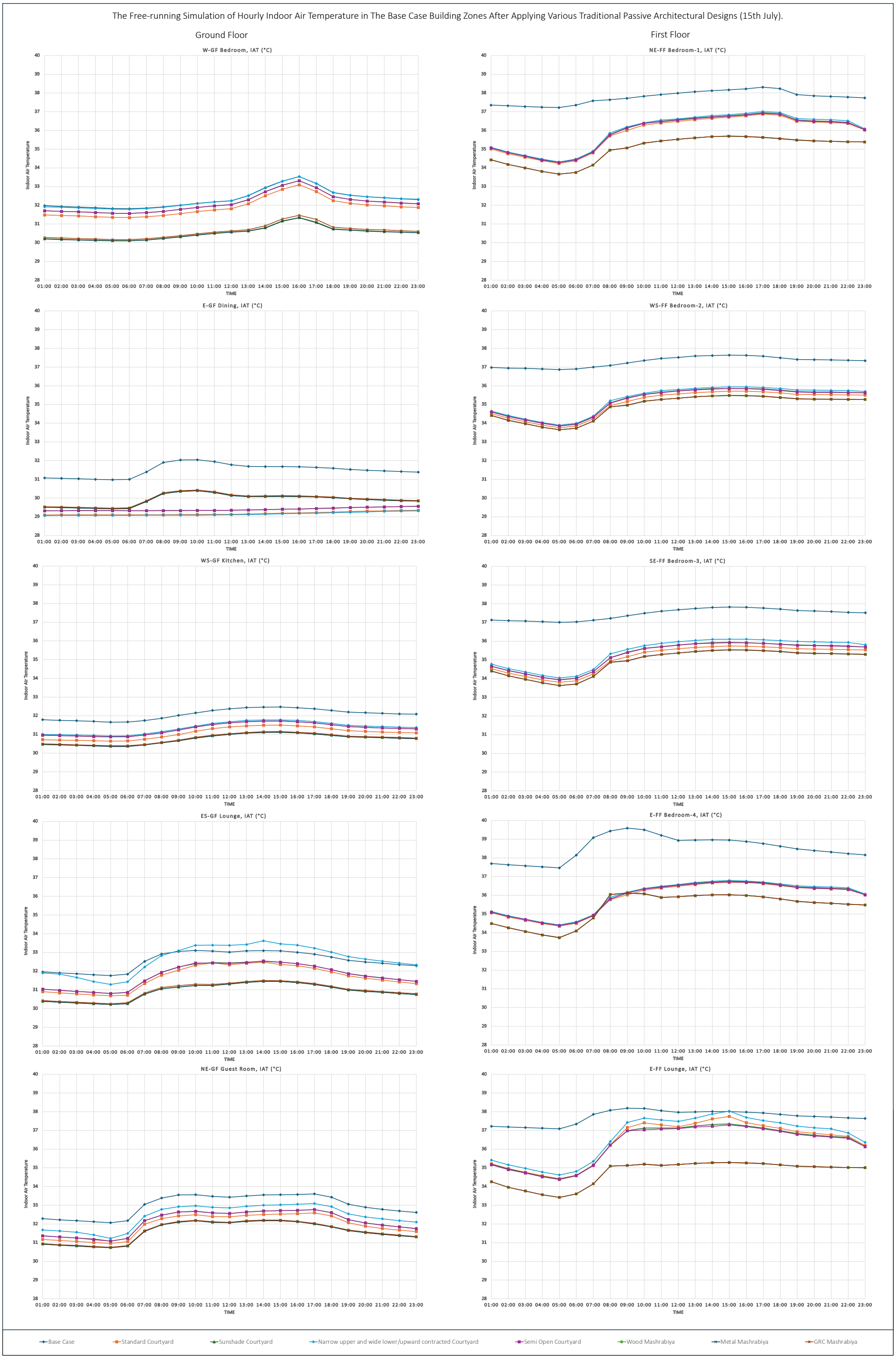
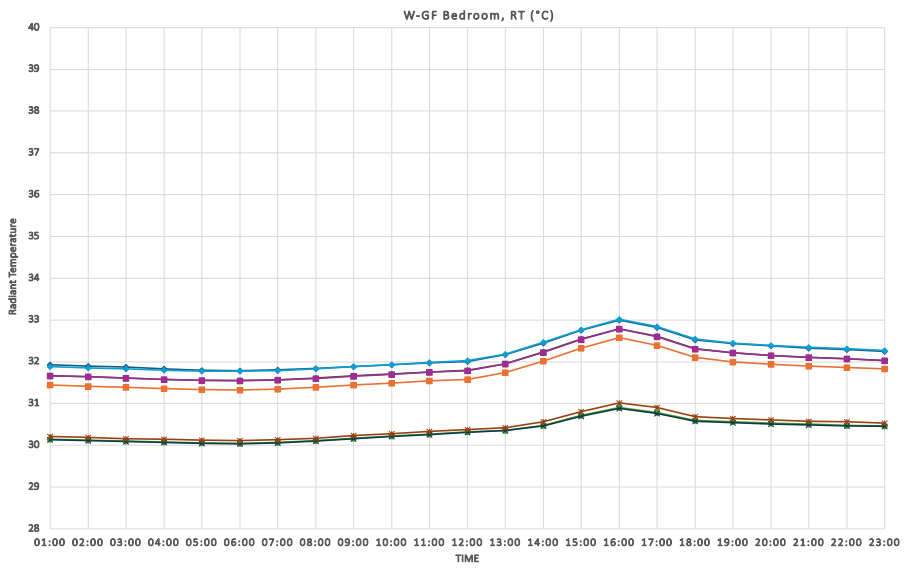


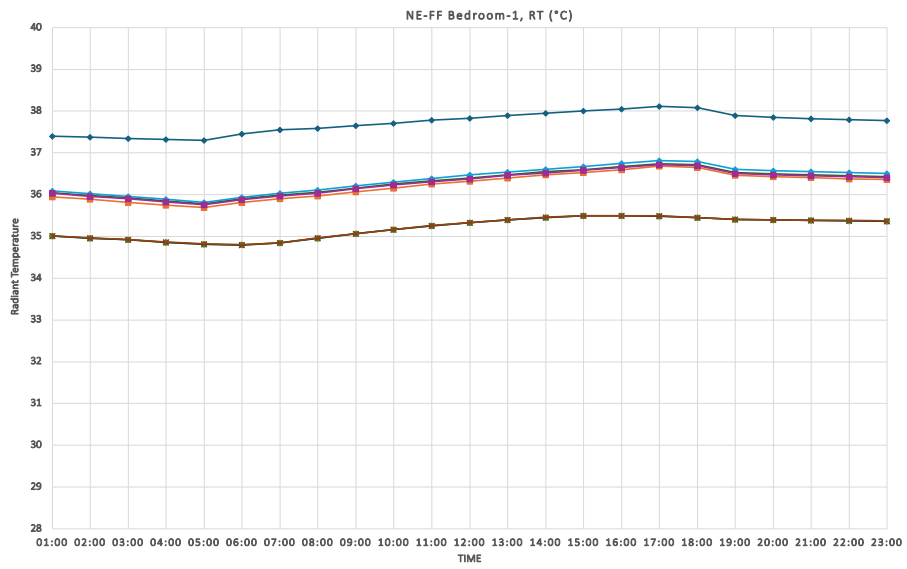
Figure A-3. 1. The Free-Running Simulation of Hourly IATs in The Base Case Building Zones After Applying Various Traditional Passive Architectural Designs (15th July)

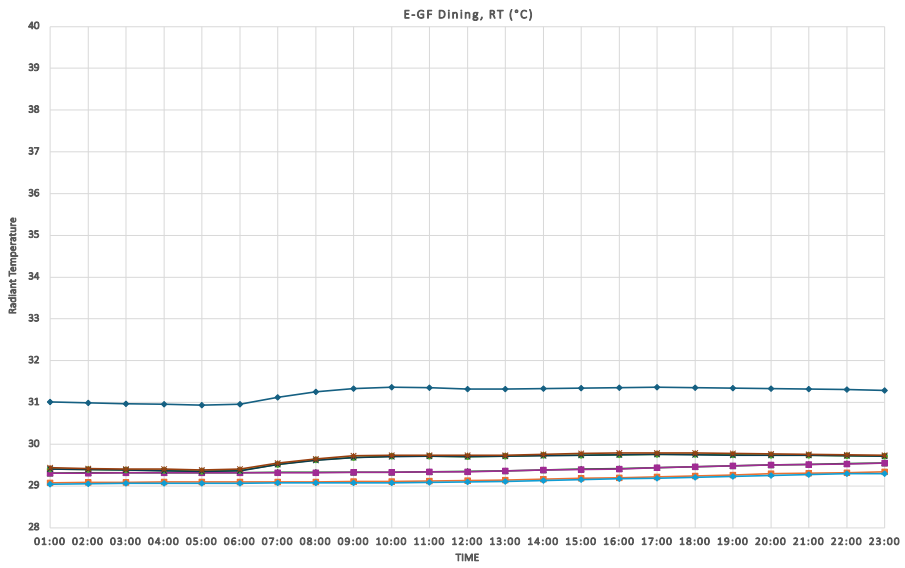
The Free-running Simulation of Hourly Radiant Temperature in The Base Case Building Zones After Applying Various Traditional Passive Architectural Designs (15th July).

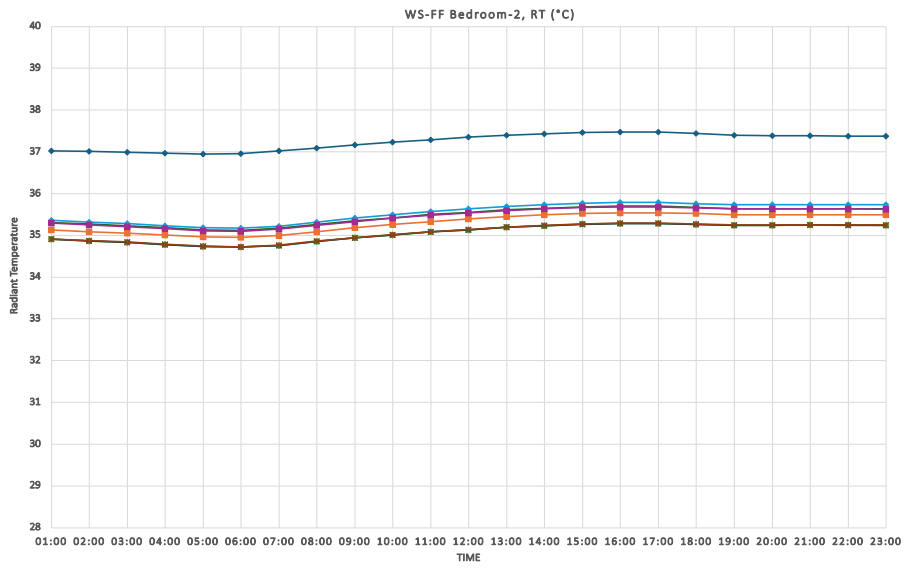
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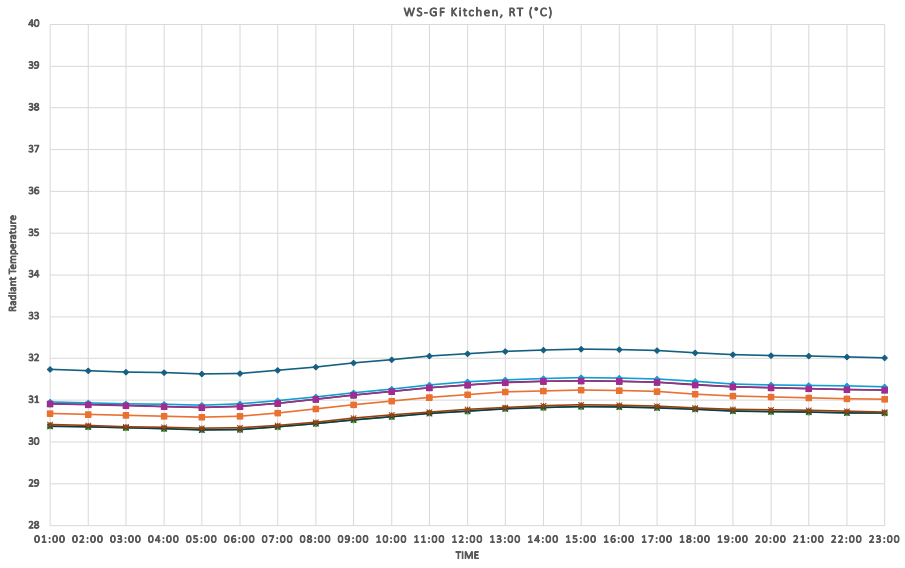


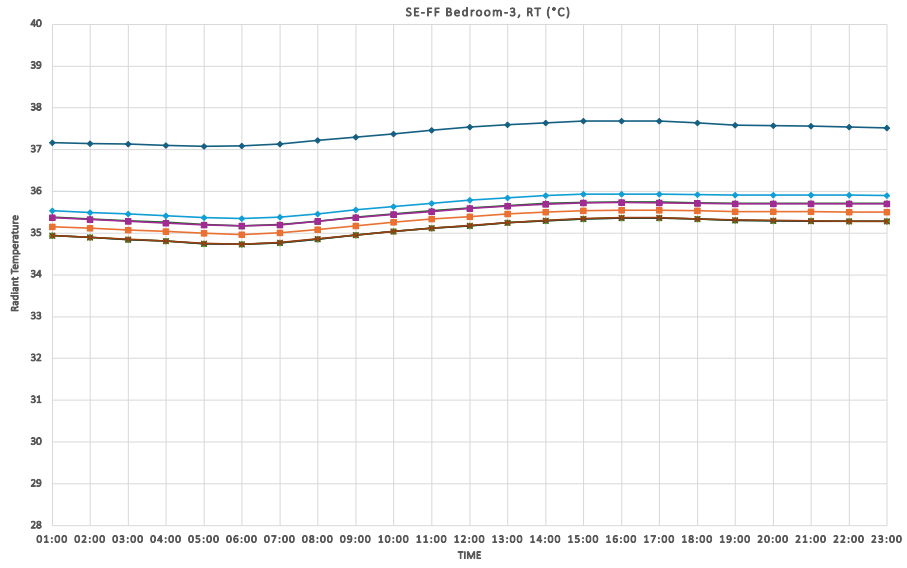
First Floor

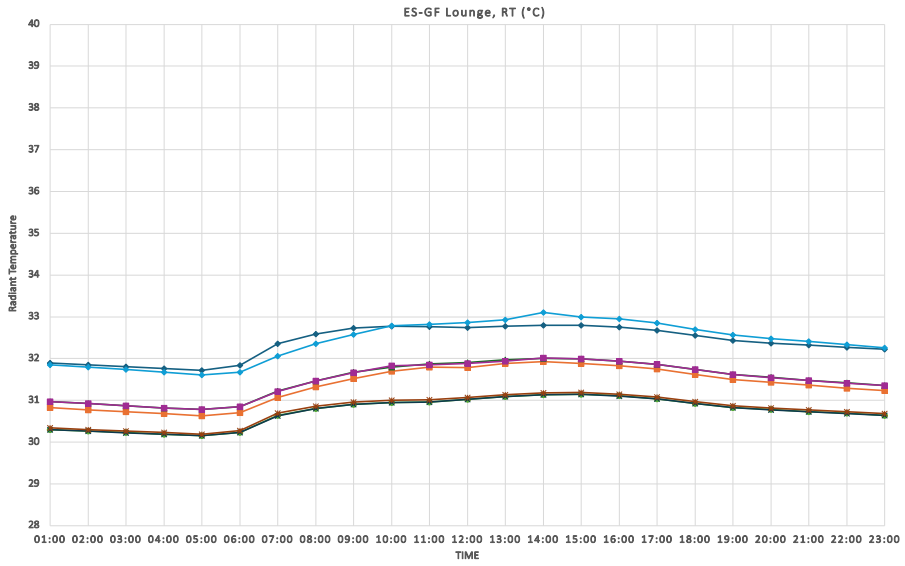


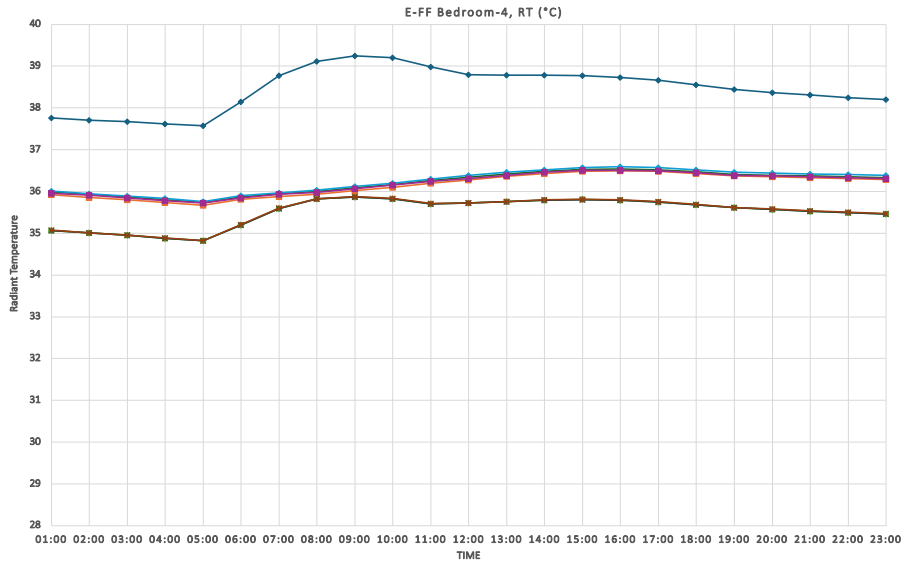


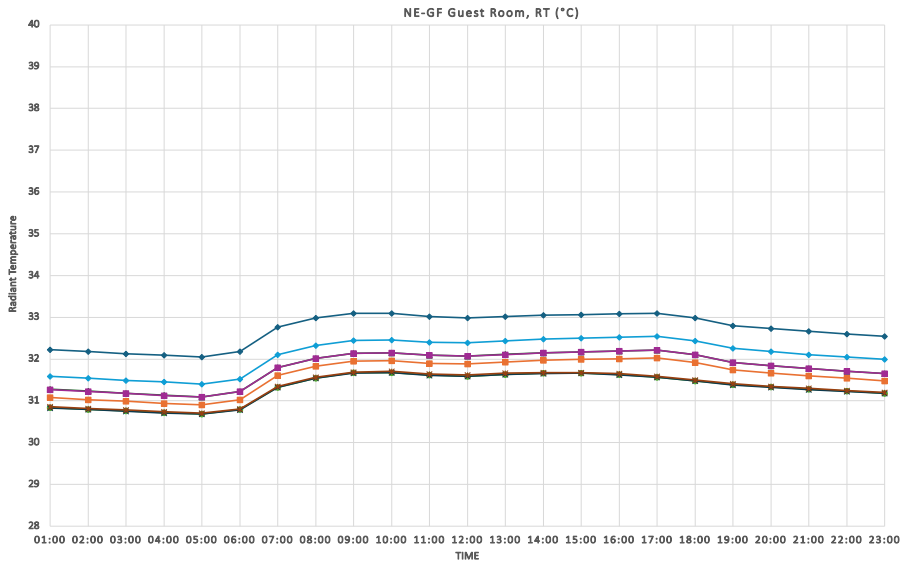












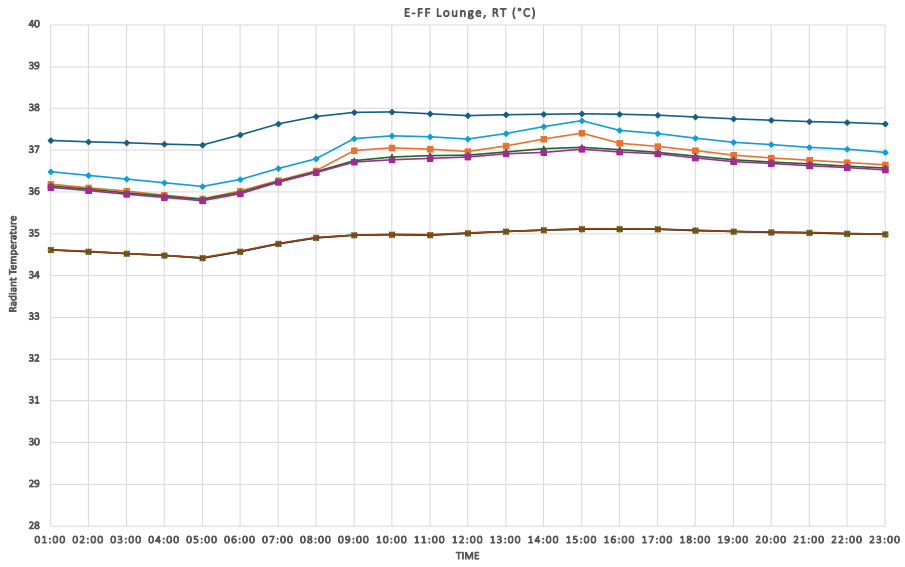
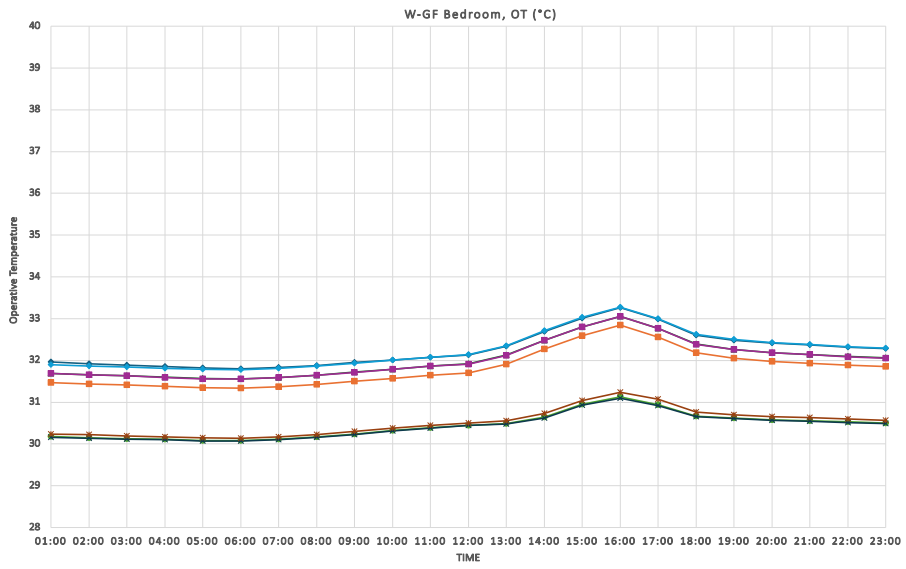




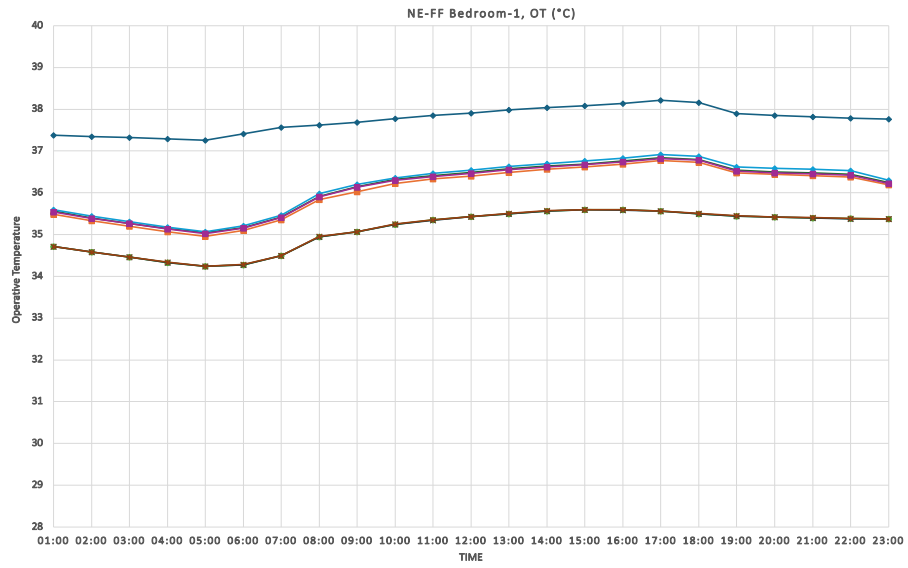
Figure A-3. 2. The Free-Running Simulation of Hourly RTs in The Base Case Building Zones After Applying Various Traditional Passive Architectural Designs (15th July).

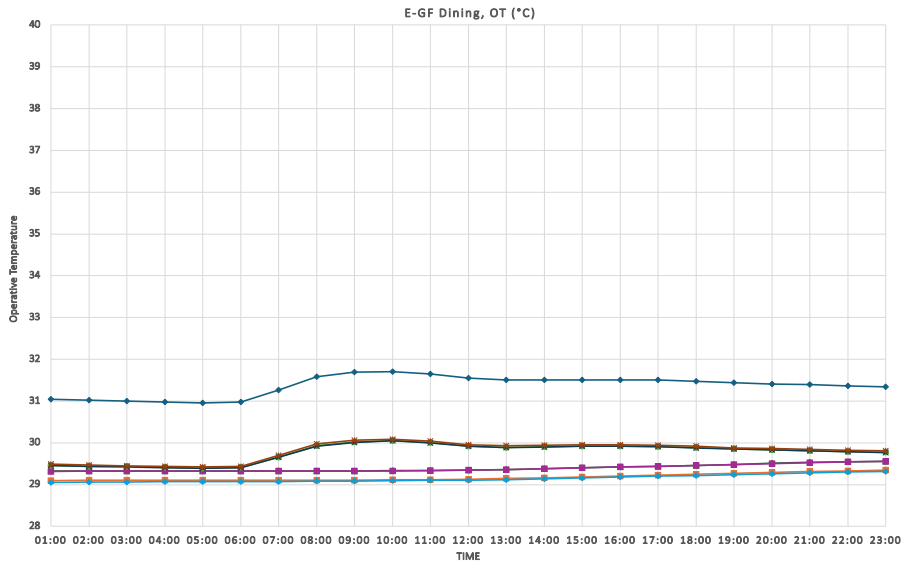
The Free-running Simulation of Hourly Operative Temperature in The Base Case Building Zones After Applying Various Traditional Passive Architectural Designs (15th July).

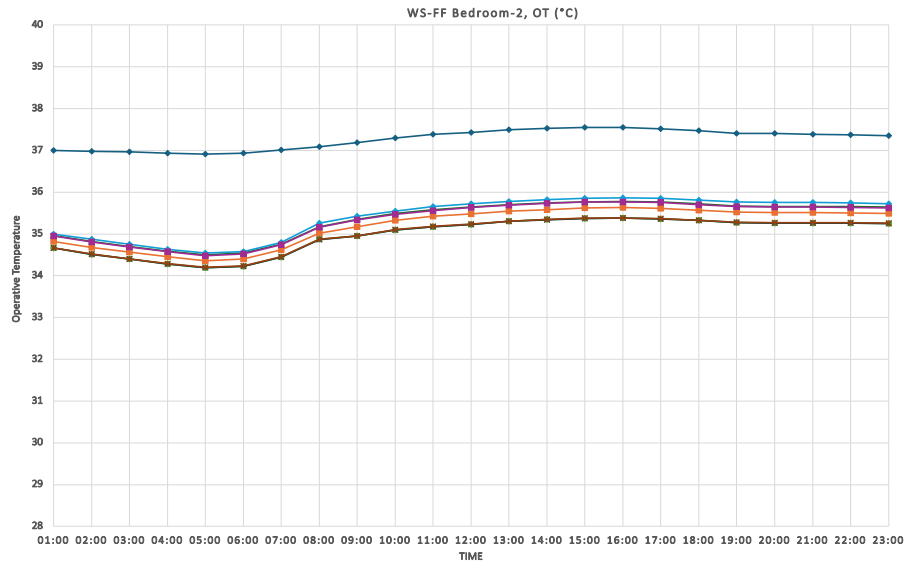
Ground Floor

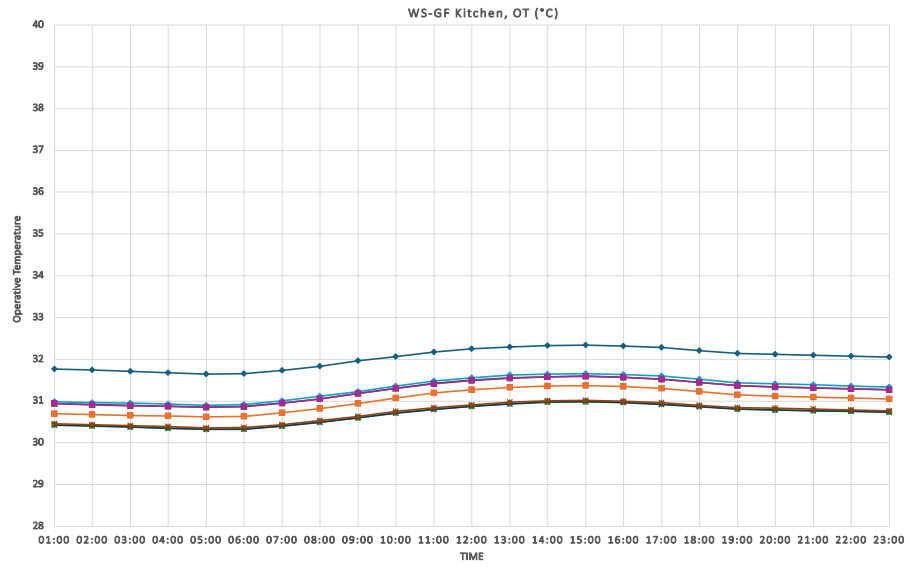


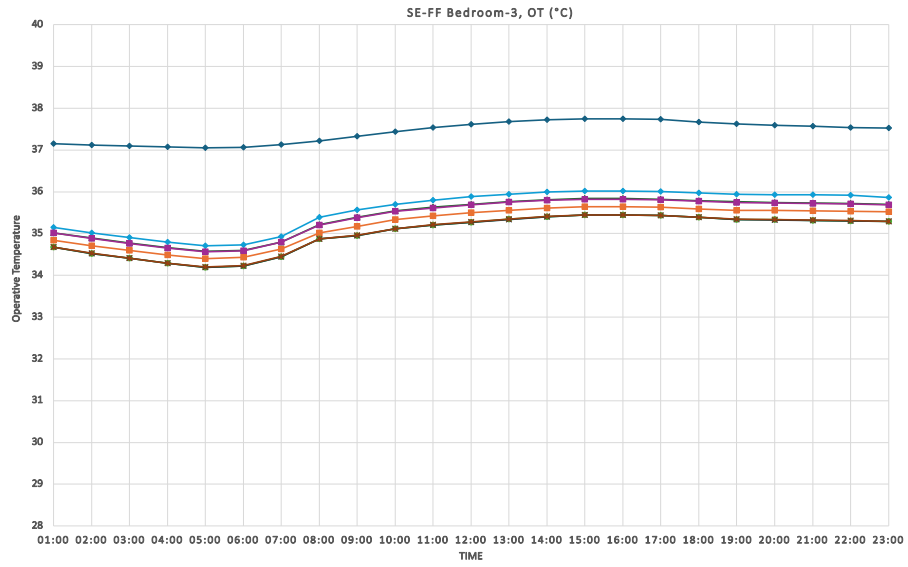
First Floor

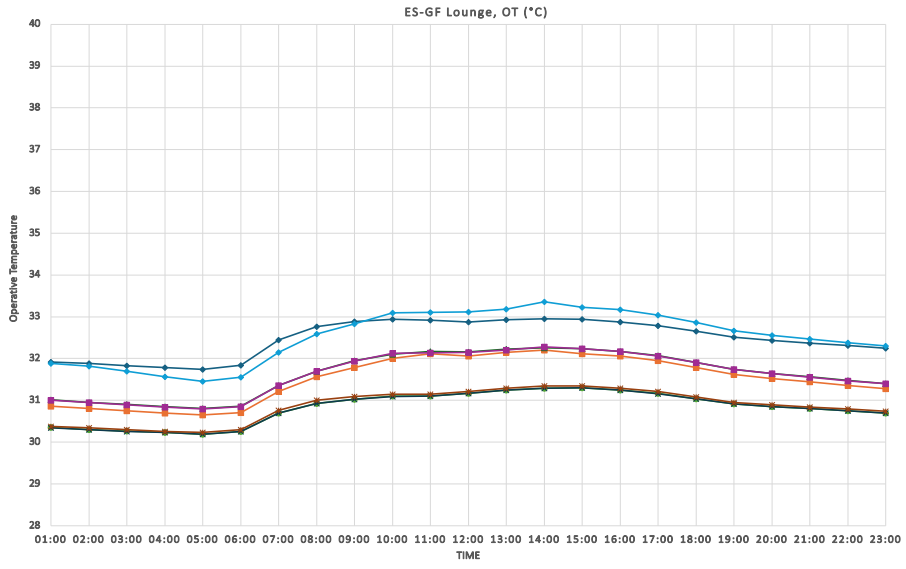


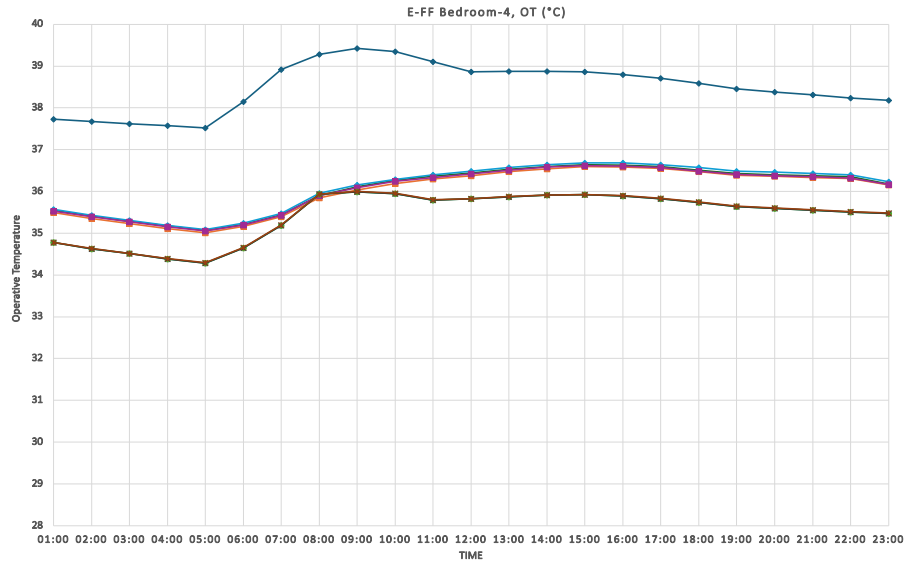


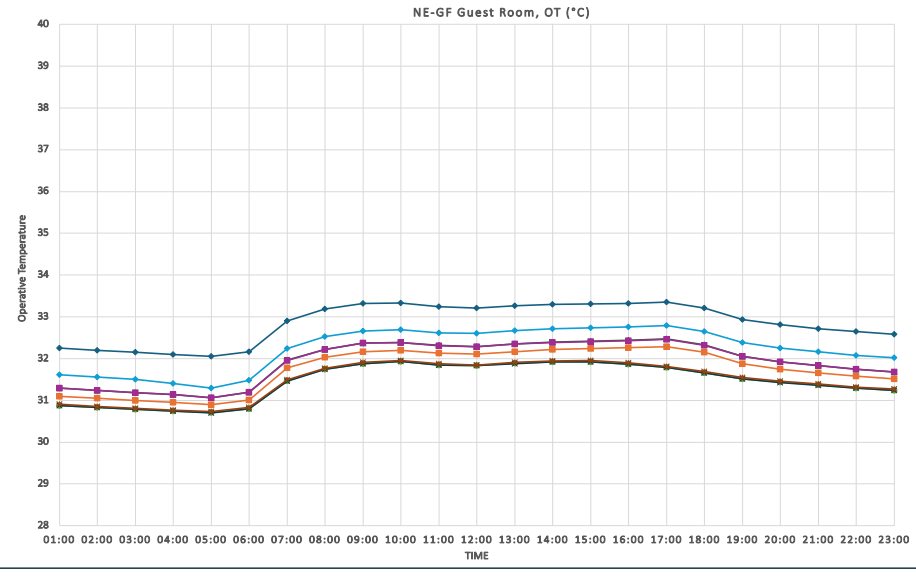












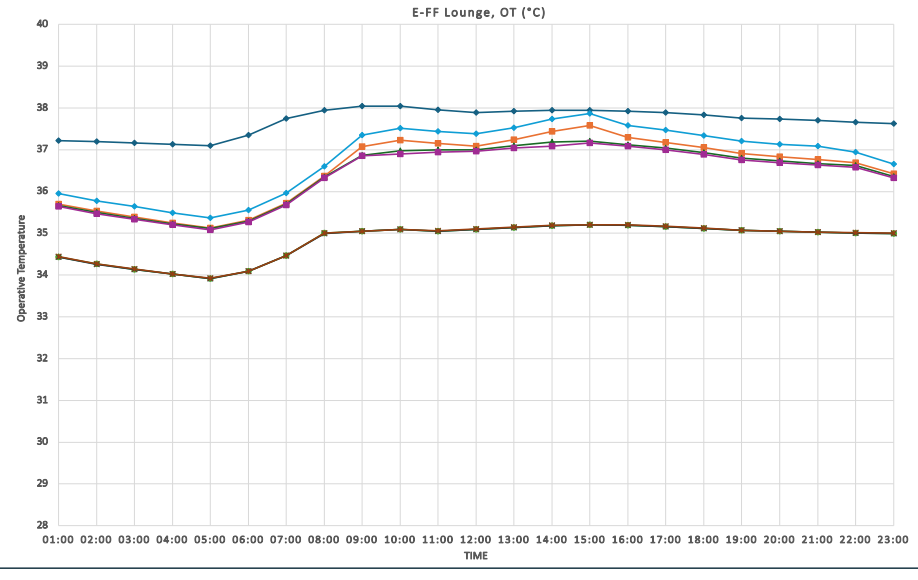


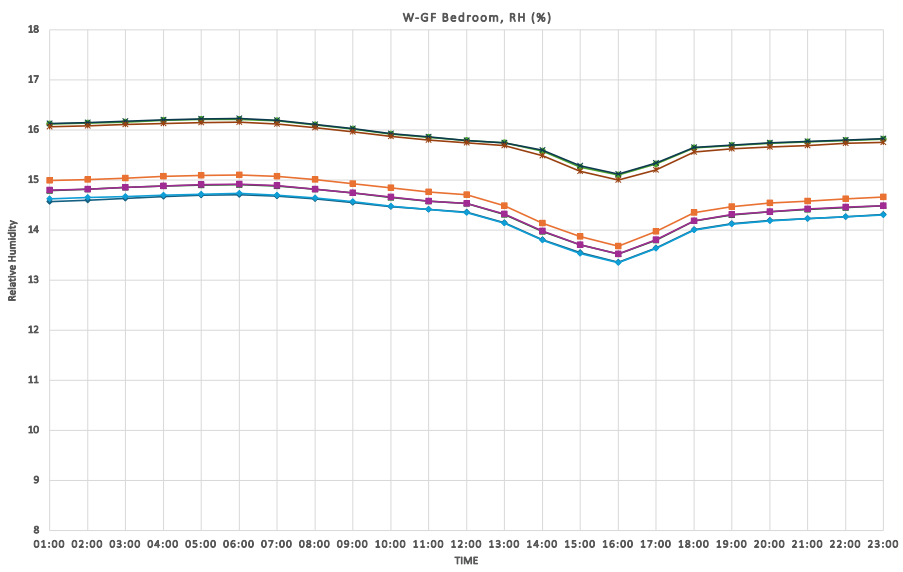


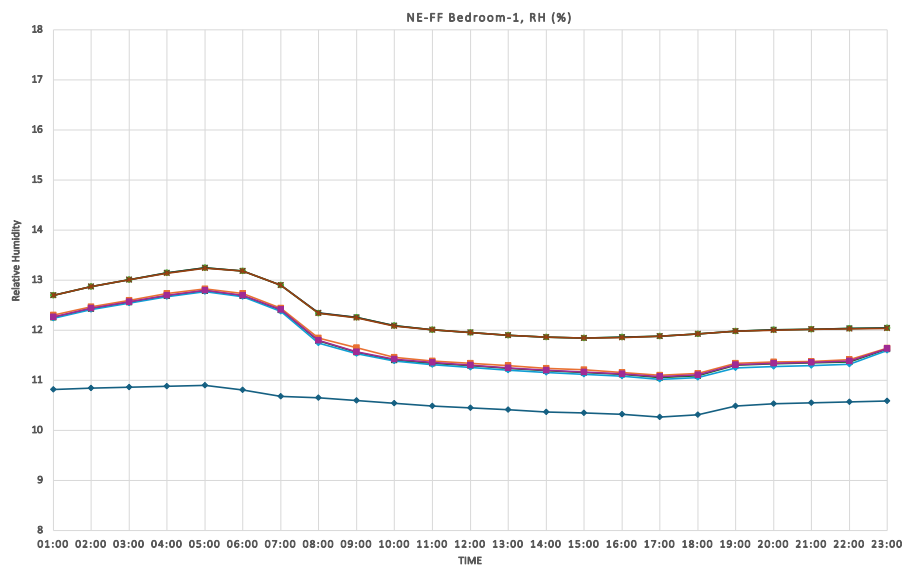
Figure A-3. 3. The Free-Running Simulation of Hourly OTs in The Base Case Building Zones After Applying Various Traditional Passive Architectural Designs (15th July).

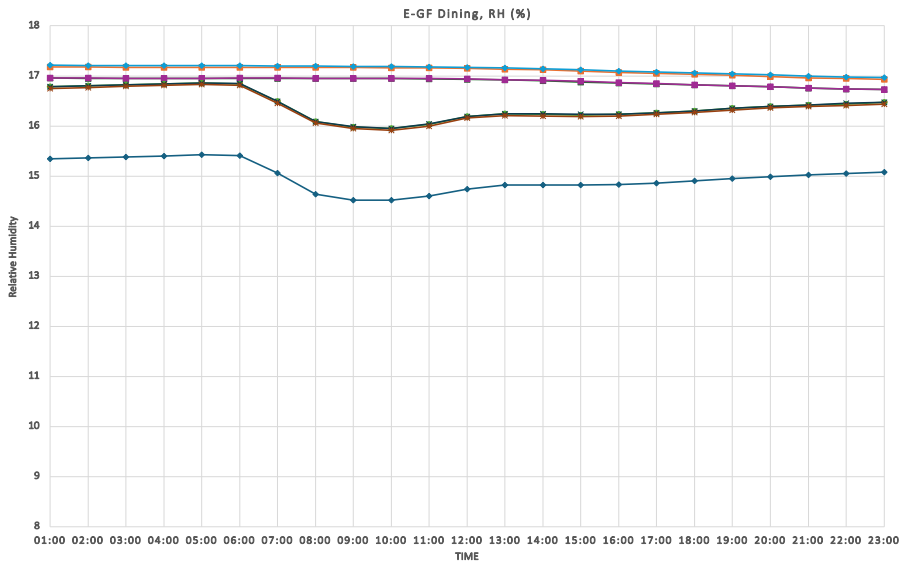
The Free-running Simulation of Hourly Relative Humidity in The Base Case Building Zones After Applying Various Traditional Passive Architectural Designs (15th July).

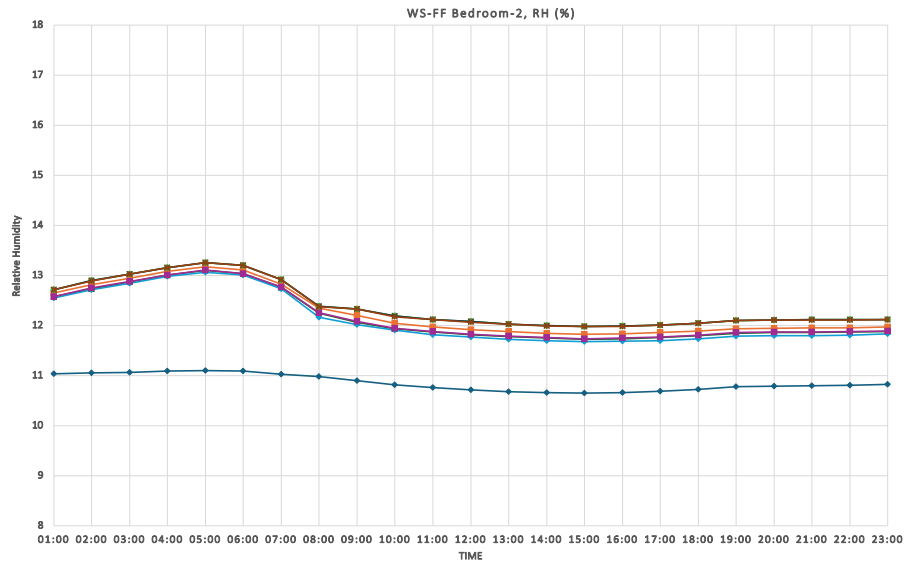
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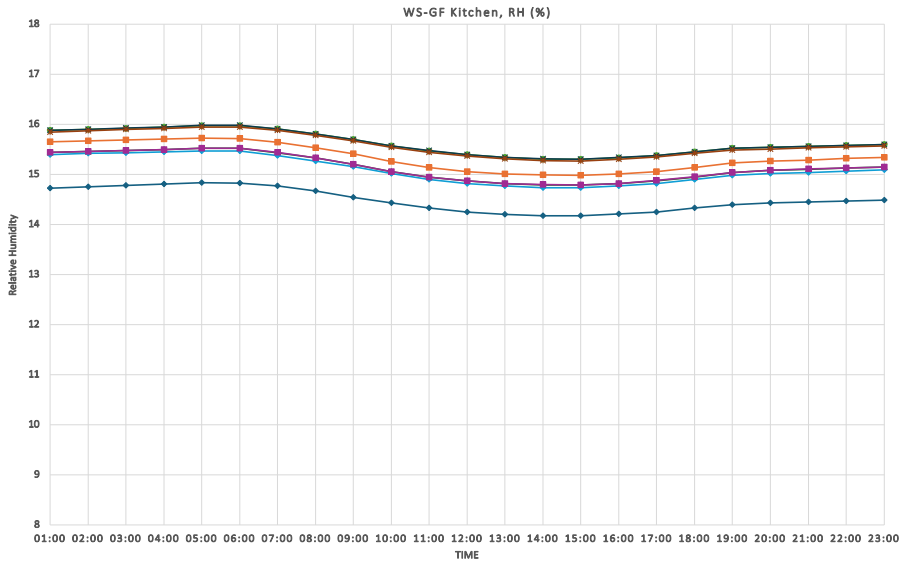
First Floor

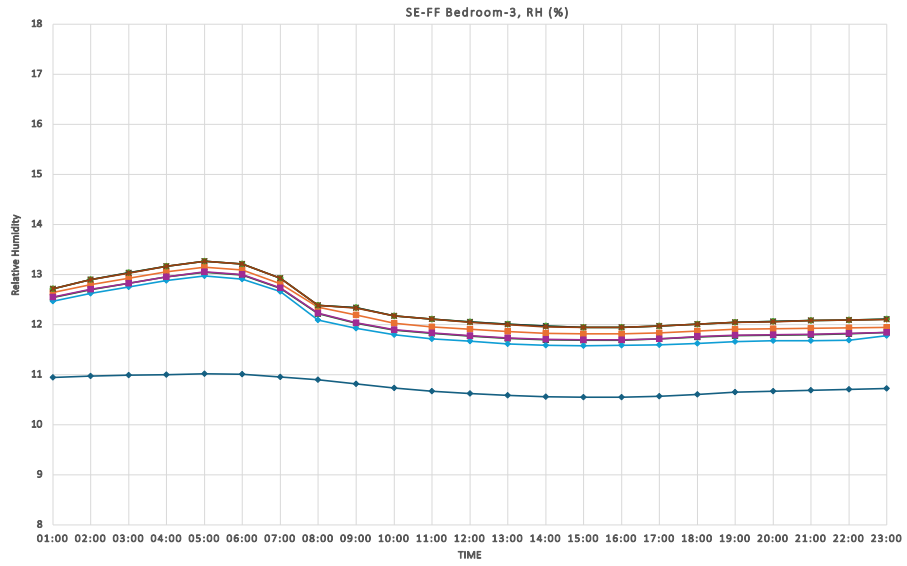


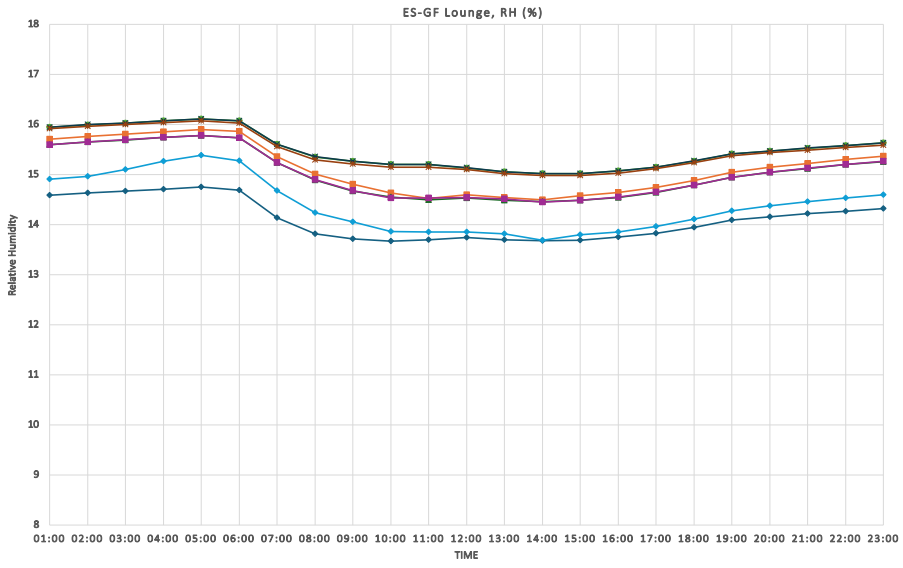


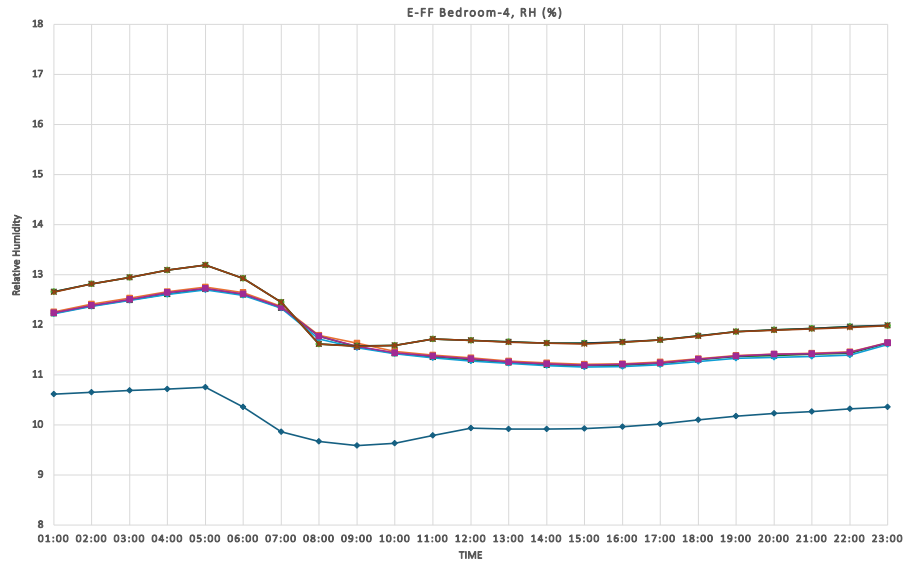


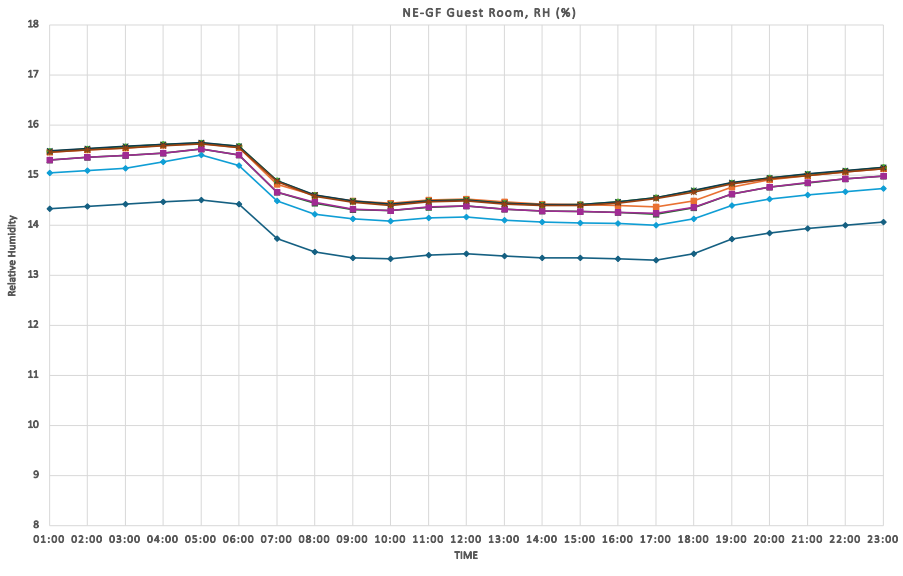


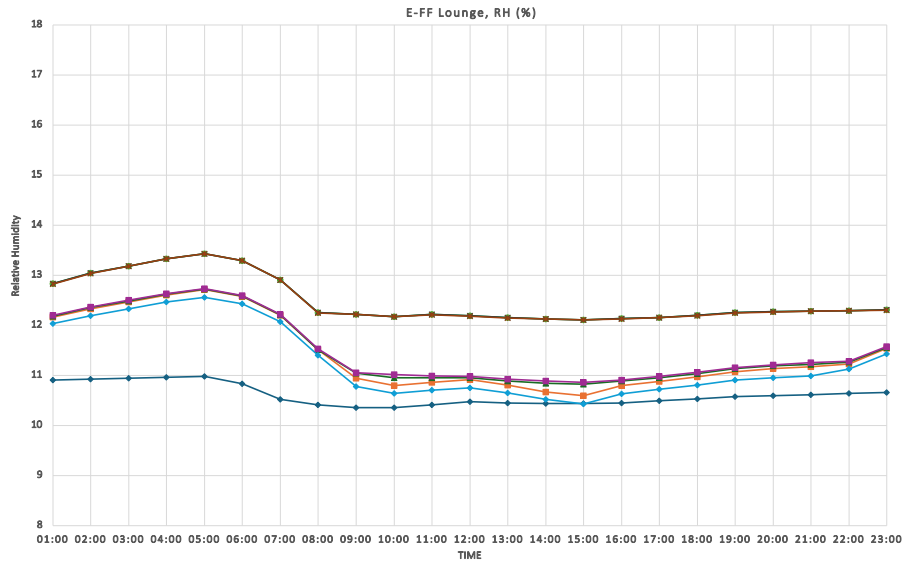












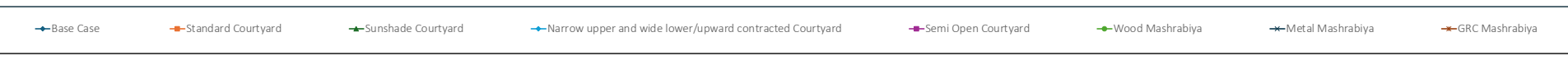
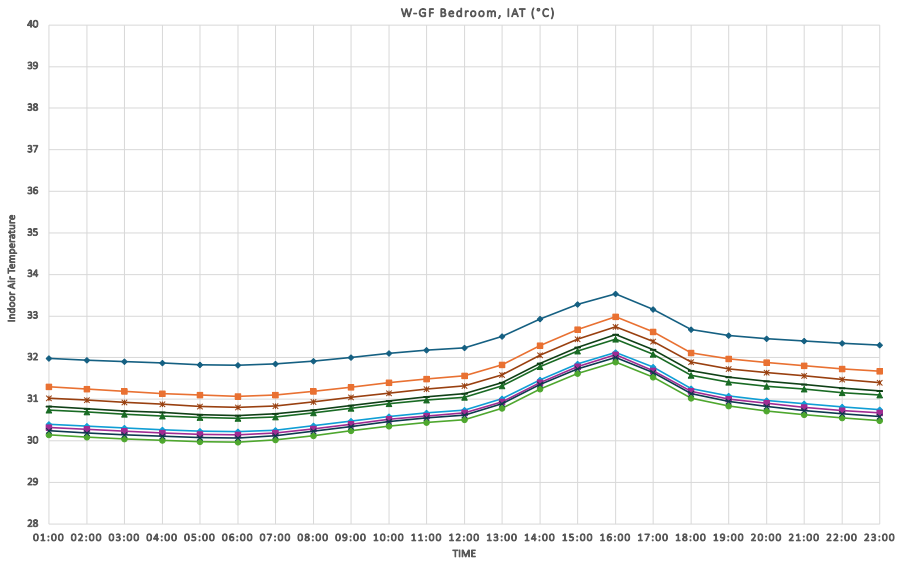


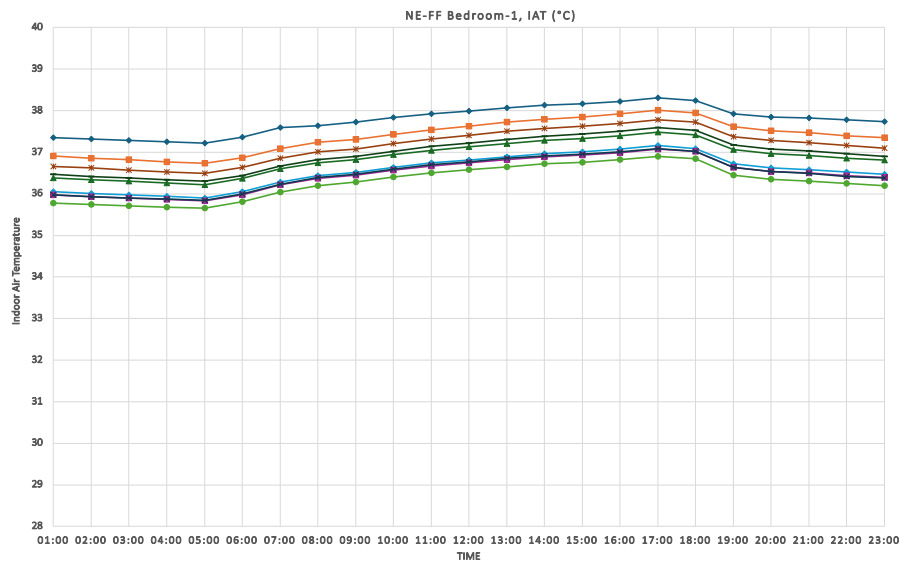
Figure A-3. 4. The Free-Running Simulation of Hourly RH in The Base Case Building Zones After Applying Various Traditional Passive Architectural Designs (15th July).

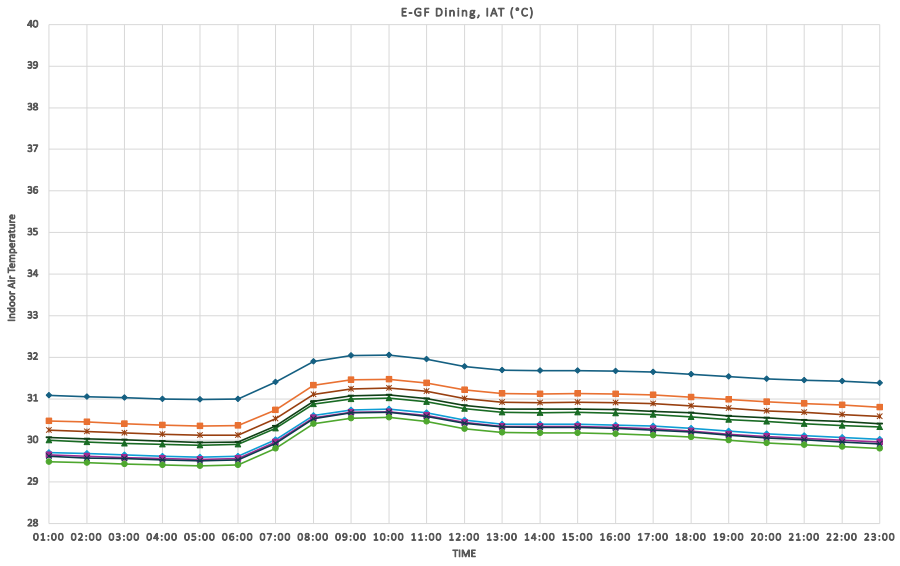
The Free-running Simulation of Hourly Indoor Air Temperature in The Base Case Building Zones After Applying Various Wall Energy Efficiency Measures (Exterior insulation and finish system (EIFS)) (15th July).

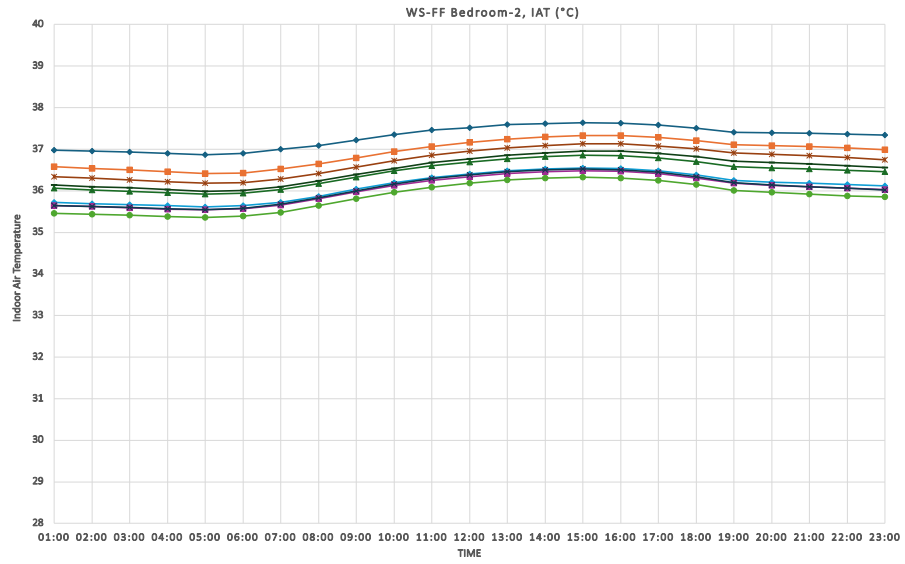
Ground Floor

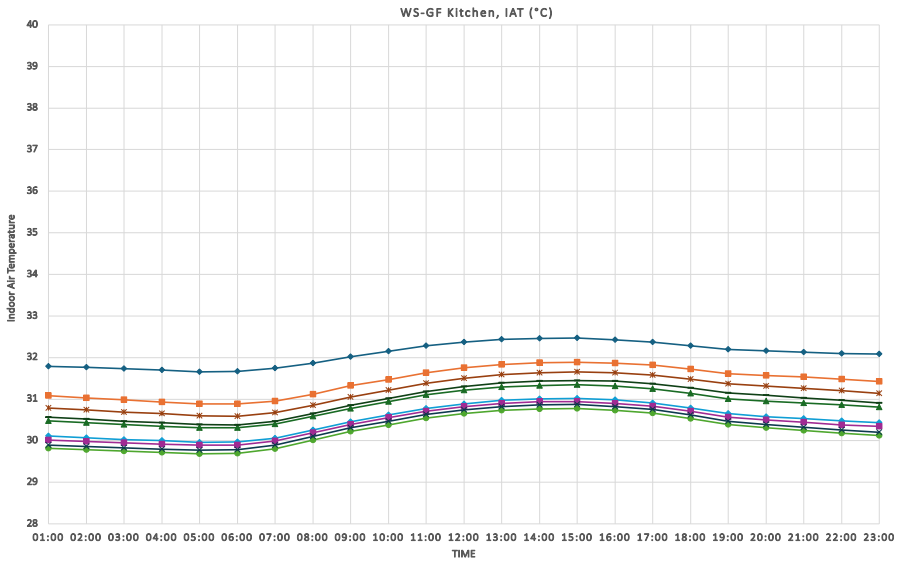


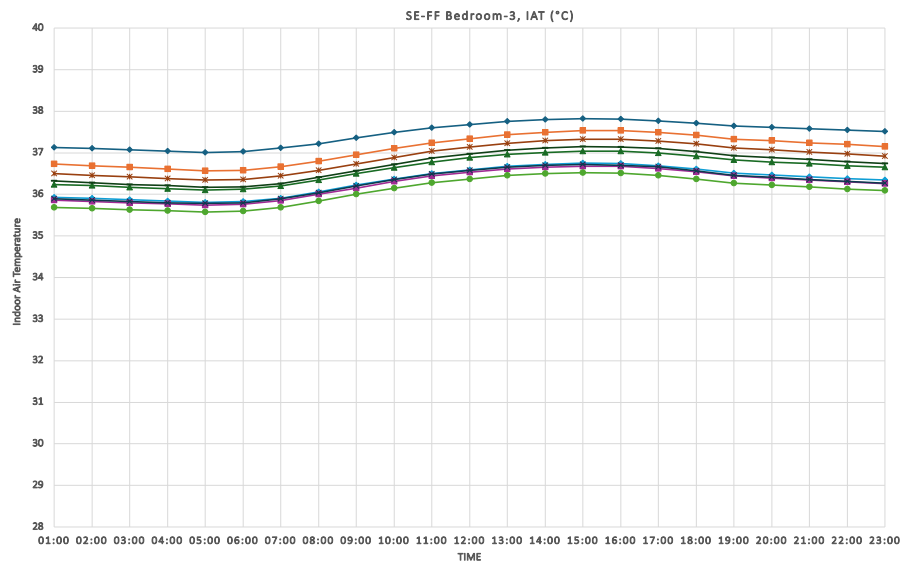
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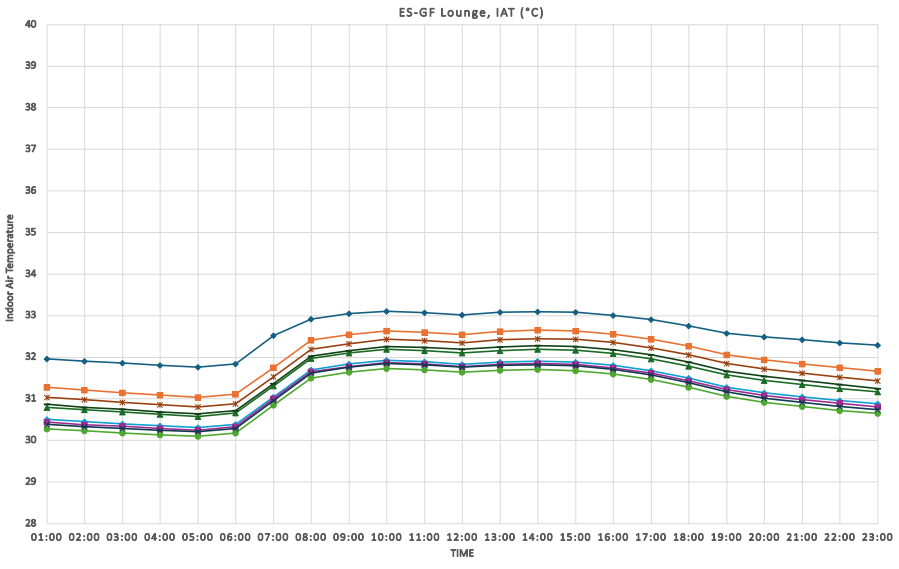


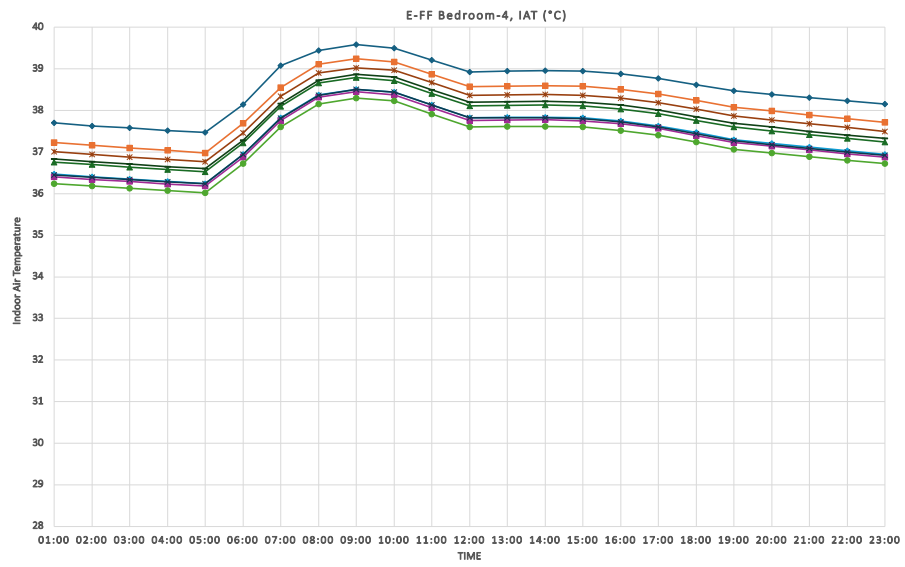


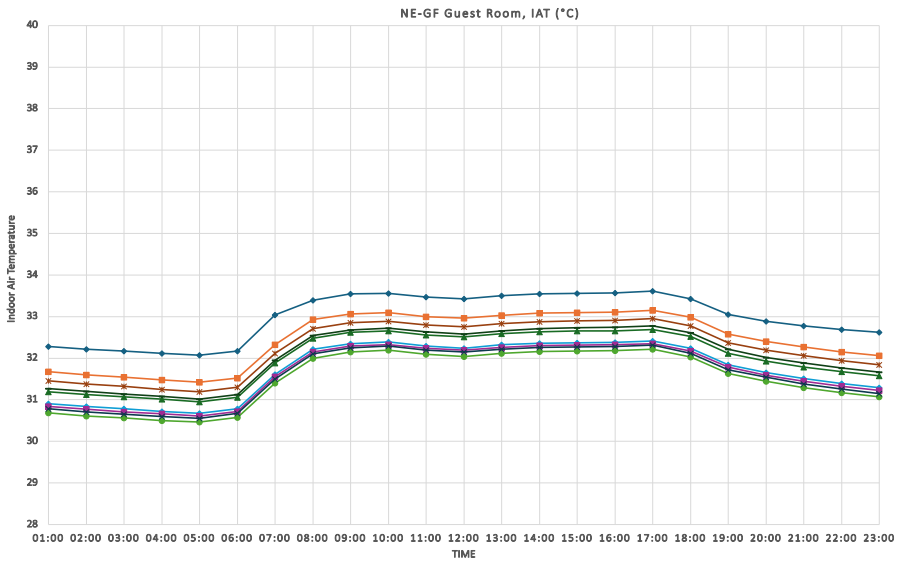


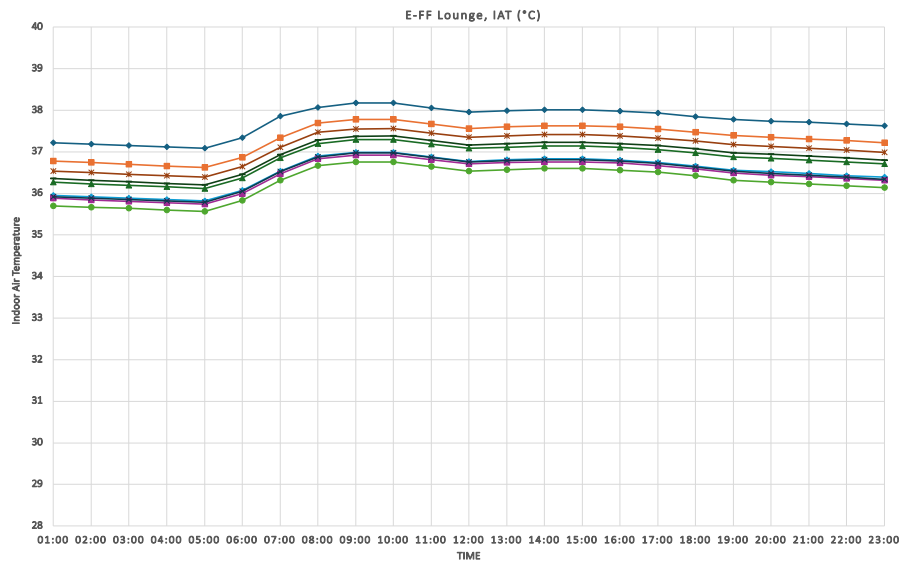












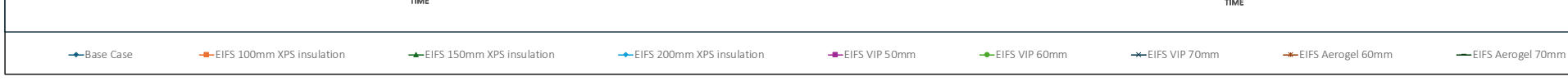
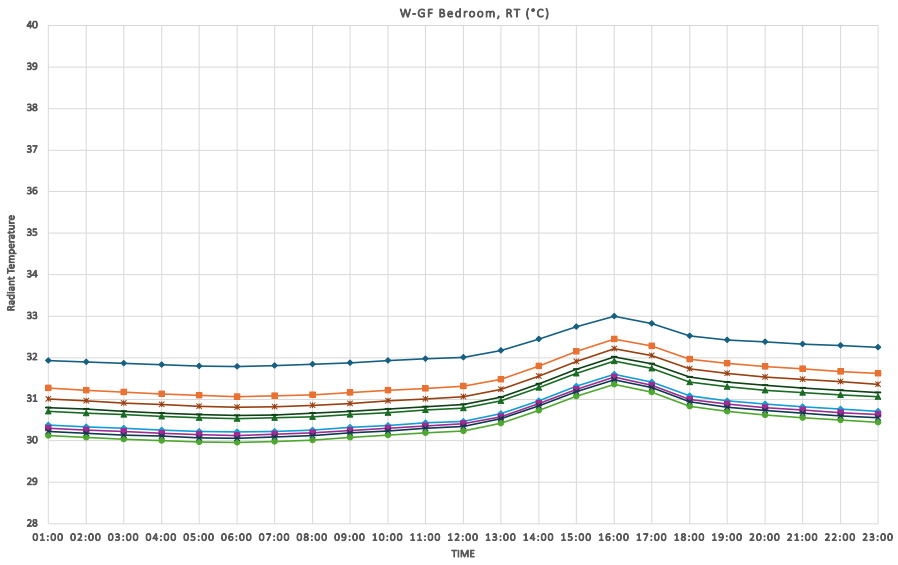


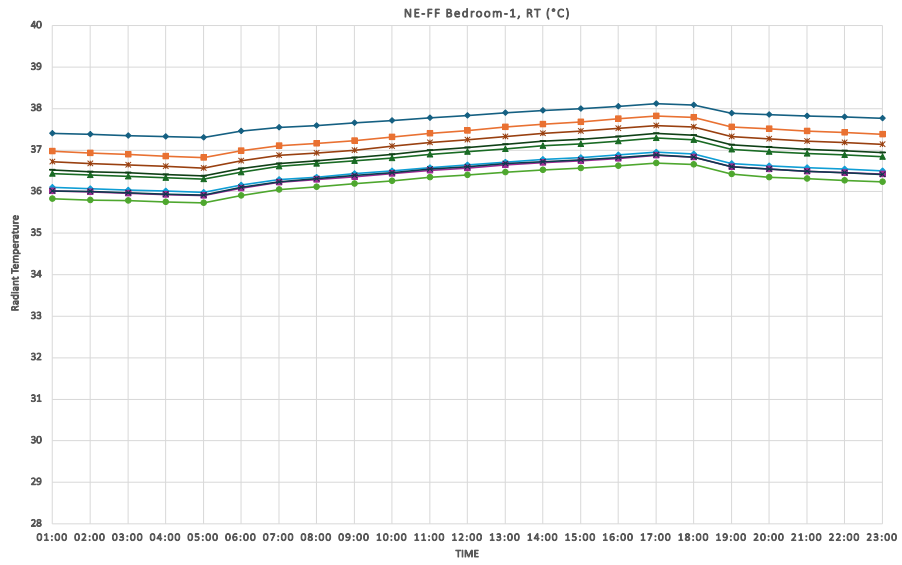
Figure A-3. 5 The Free-Running Simulation of Hourly IATs in The Base Case Building Zones After Applying Various Wall Energy Efficiency Measures (Exterior insulation and finish system (EIFS) (15th July).

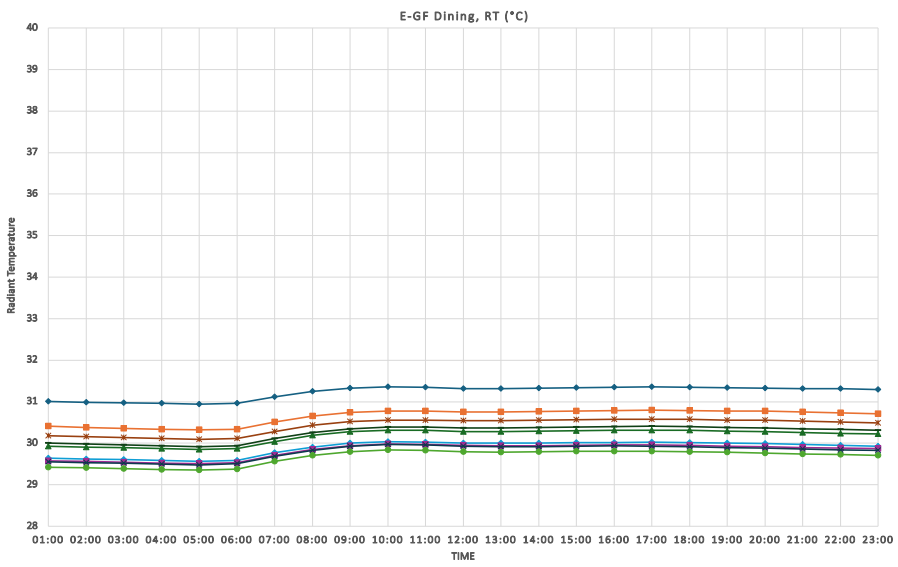
The Free-running Simulation of Hourly Radiant Temperature in The Base Case Building Zones After Applying Various Wall Energy Efficiency Measures (Exterior insulation and finish system (EIFS)) (15th July).

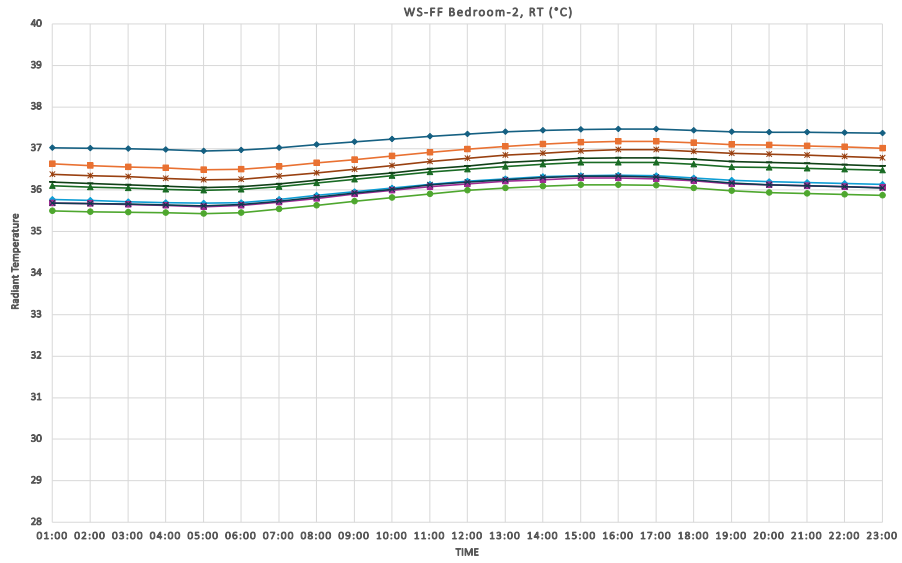
Ground Floor

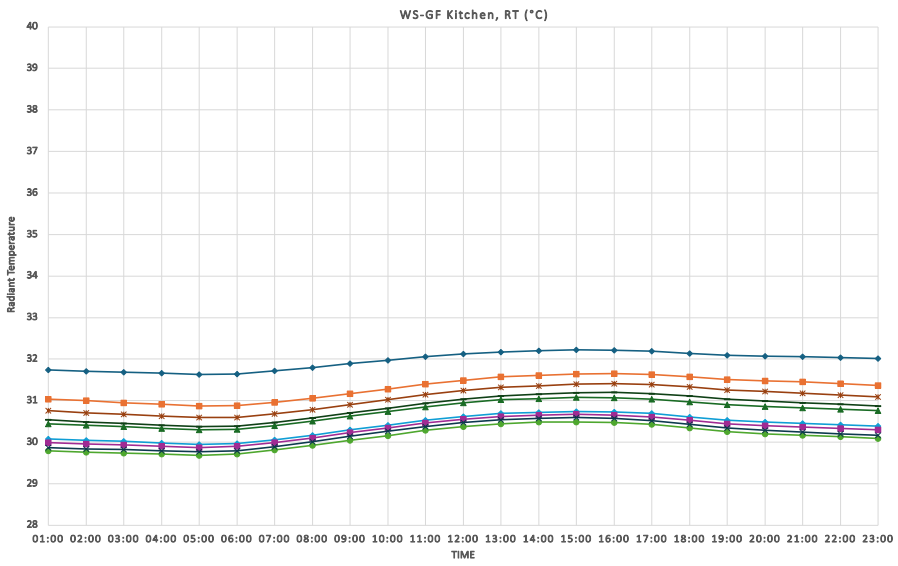


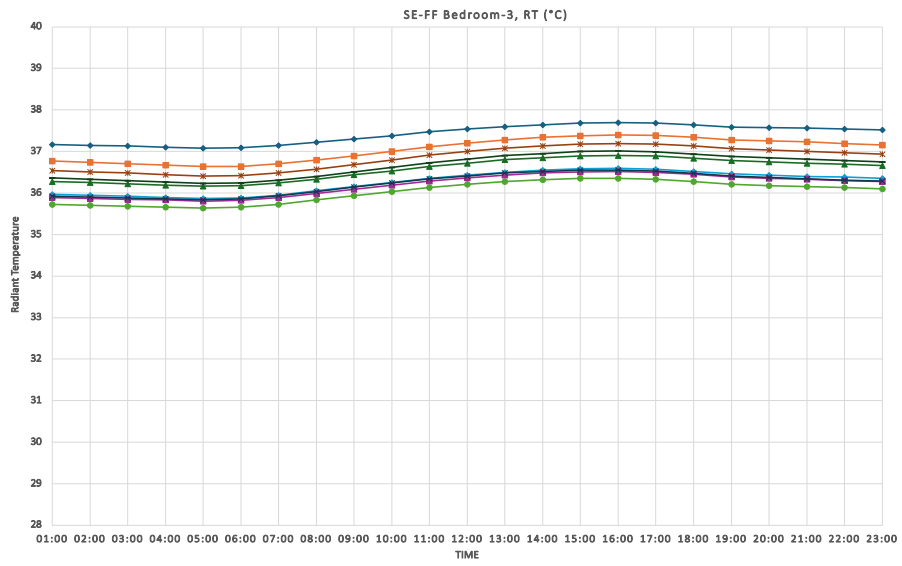
First Floor

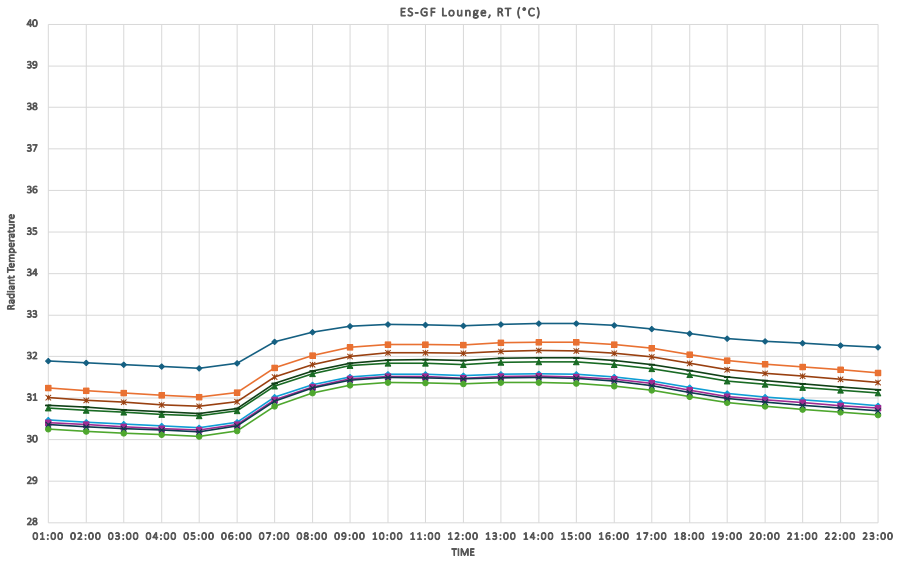


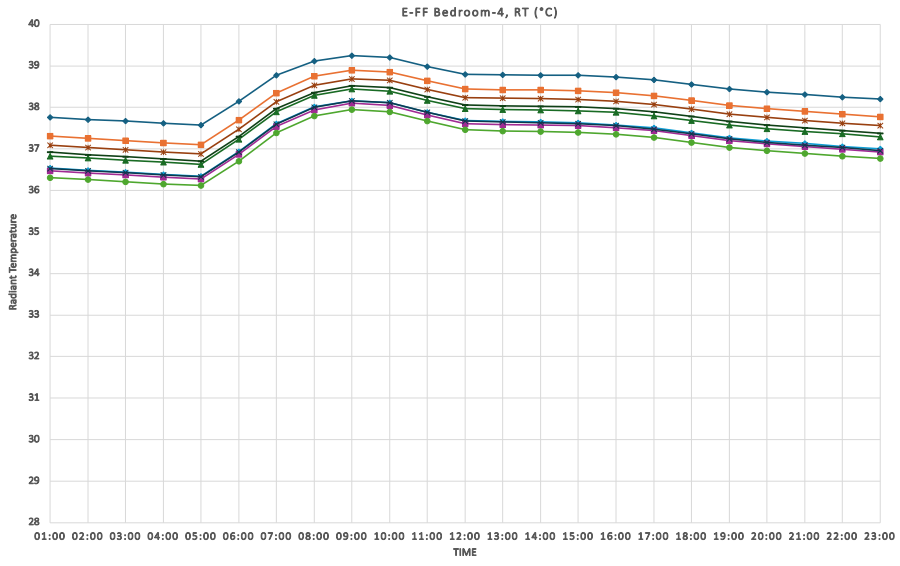


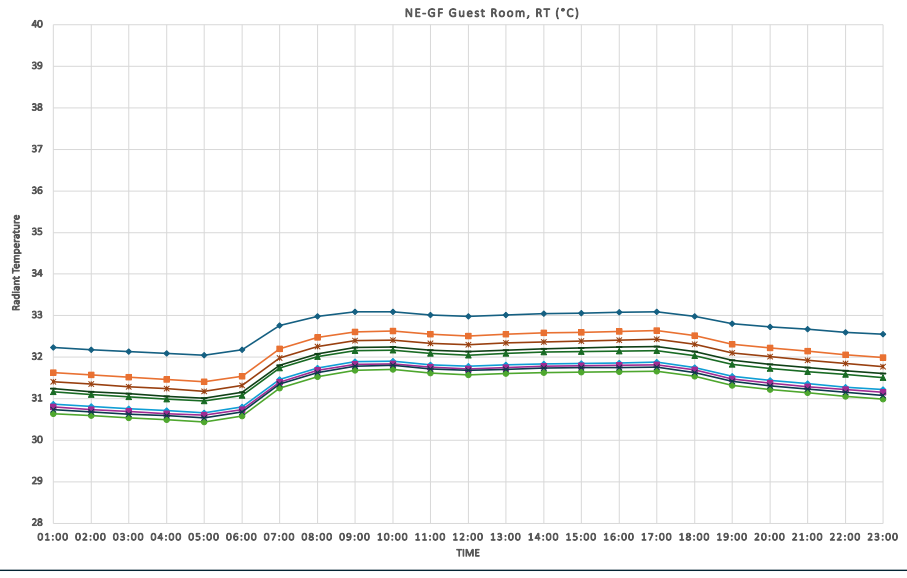












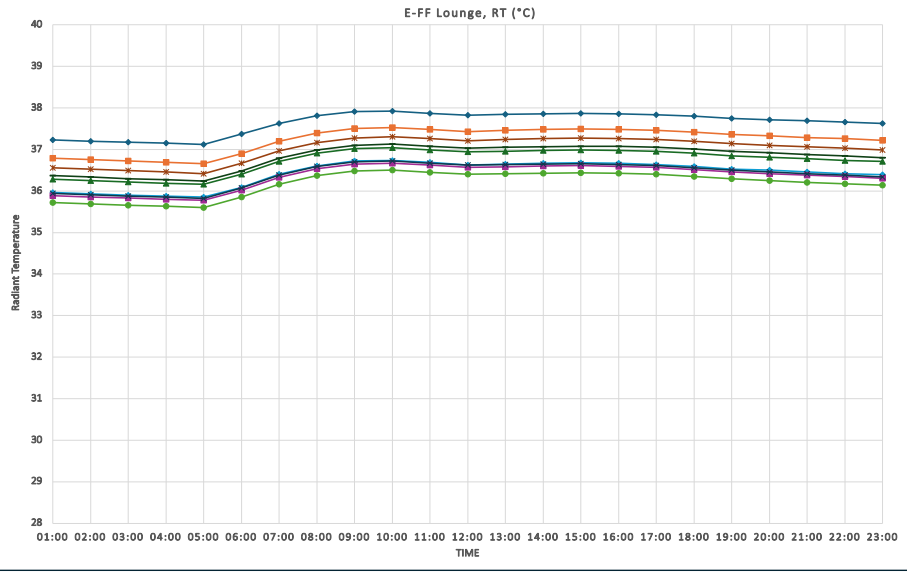
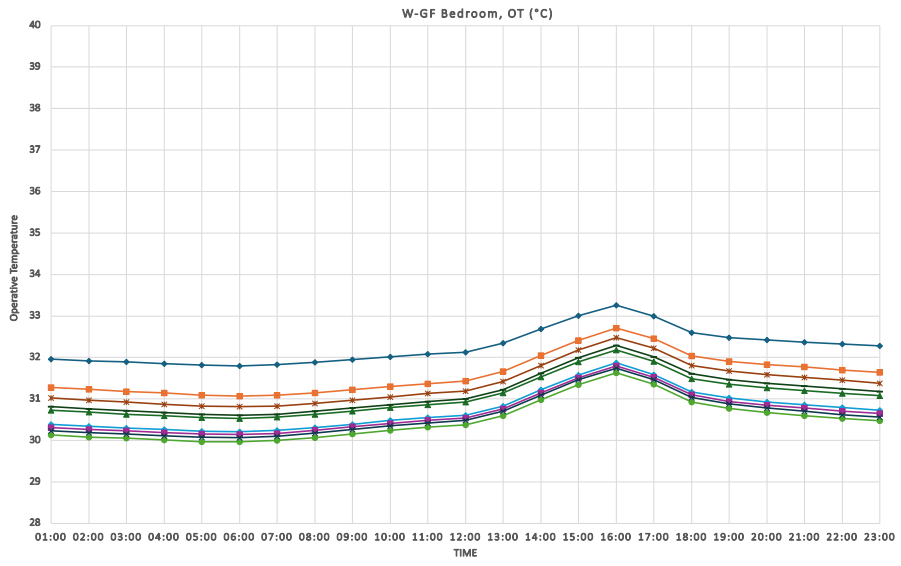




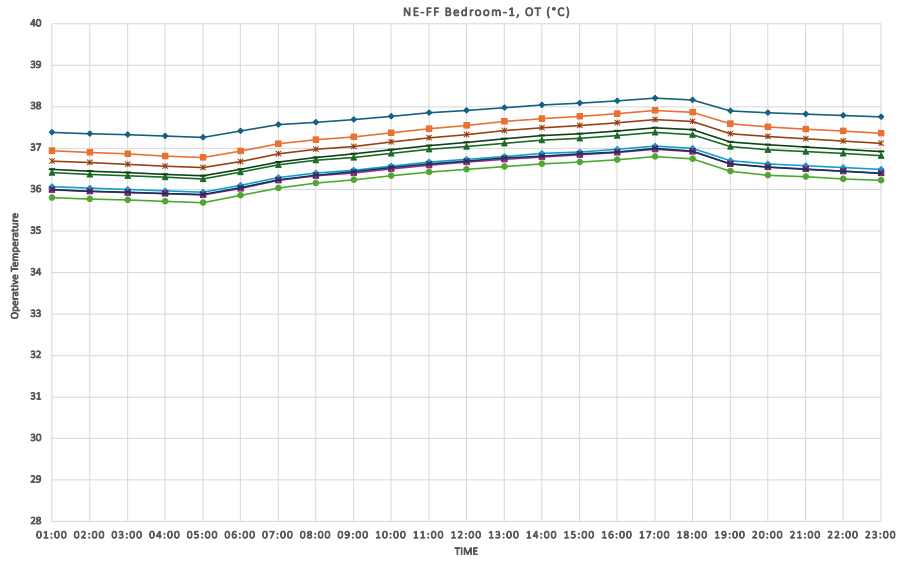
Figure A-3. 6. The Free-Running Simulation of Hourly RTs in The Base Case Building Zones After Applying Various Wall Energy Efficiency Measures (Exterior insulation and finish system (EIFS) (15th July).

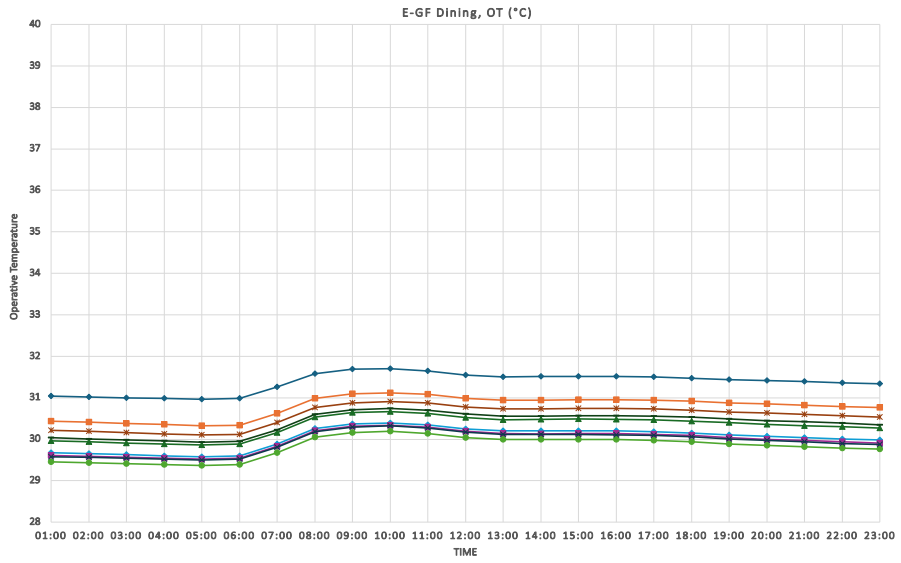
The Free-running Simulation of Hourly Operative Temperature in The Base Case Building Zones After Applying Various Wall Energy Efficiency Measures (Exterior insulation and finish system (EIFS)) (15th July).

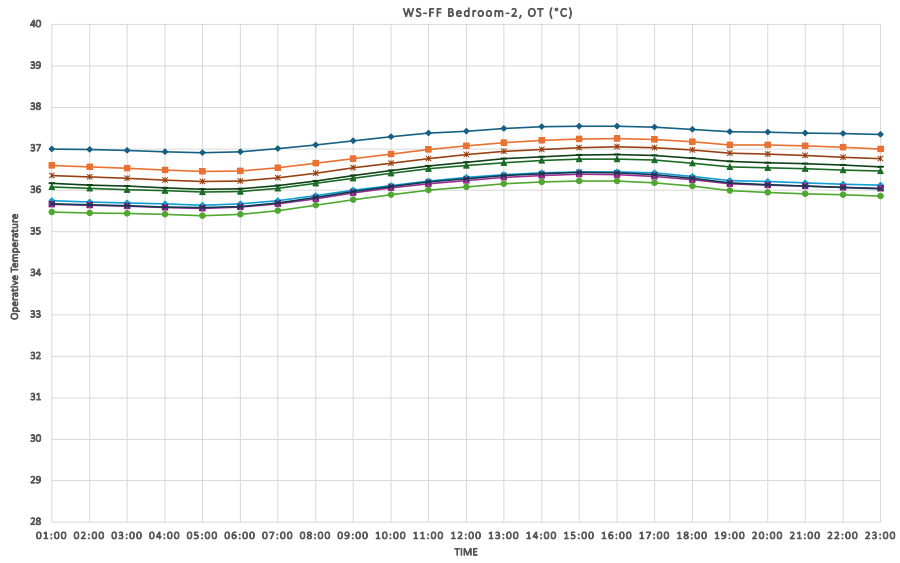
Ground Floor

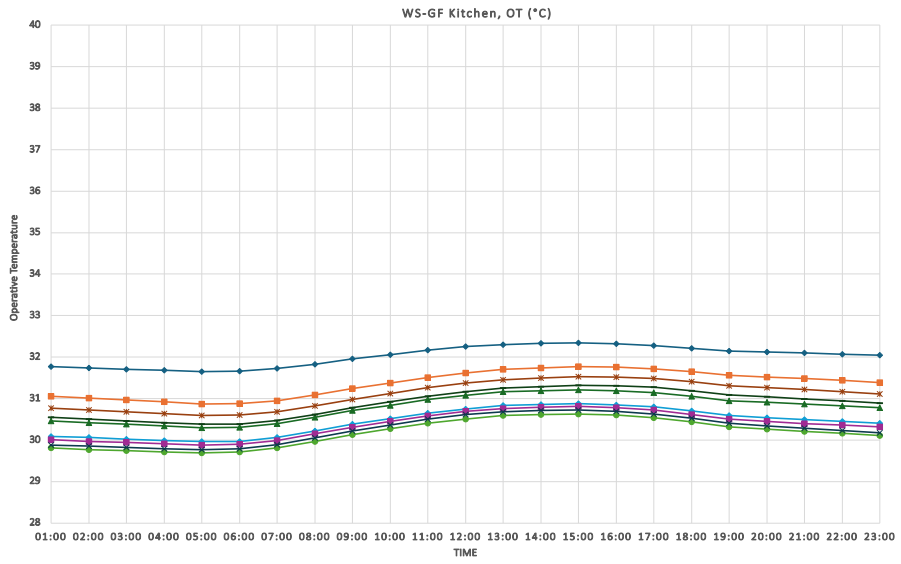


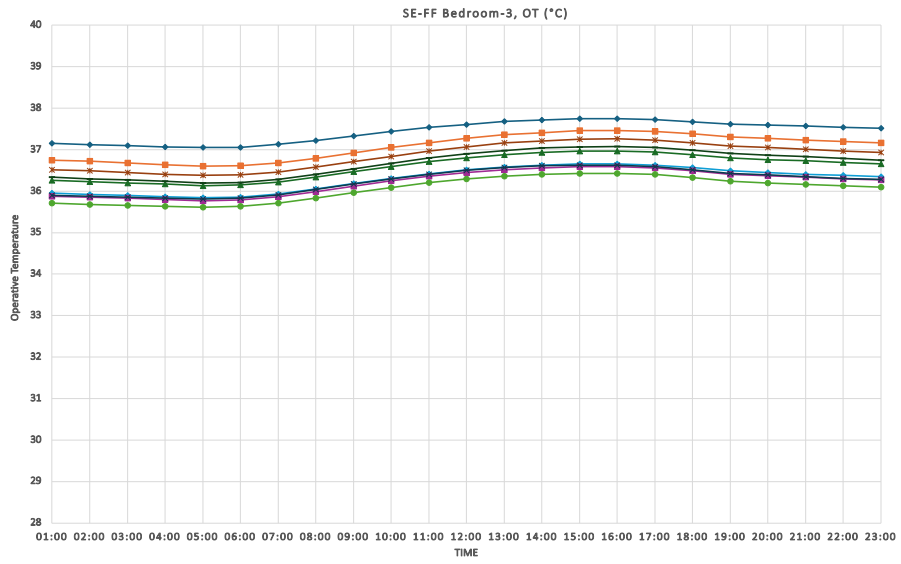
First Floor

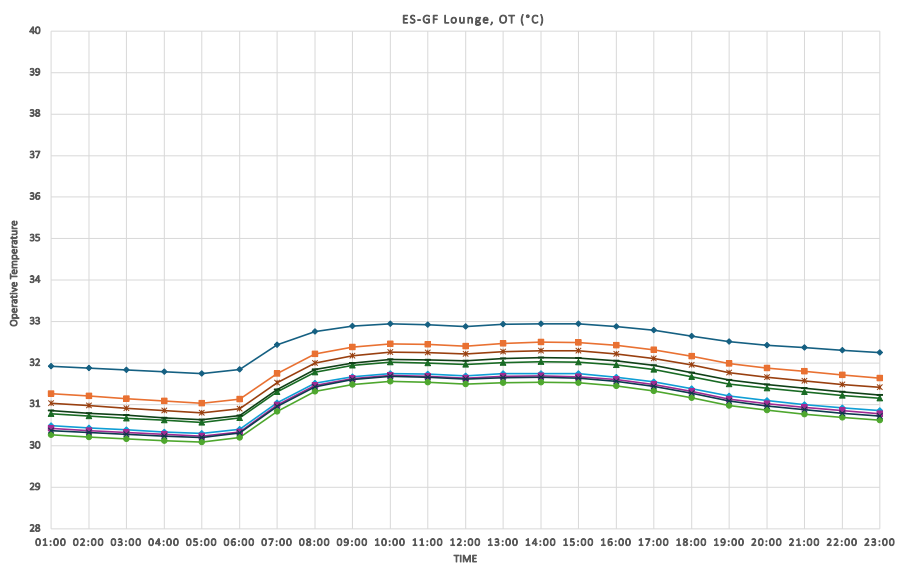


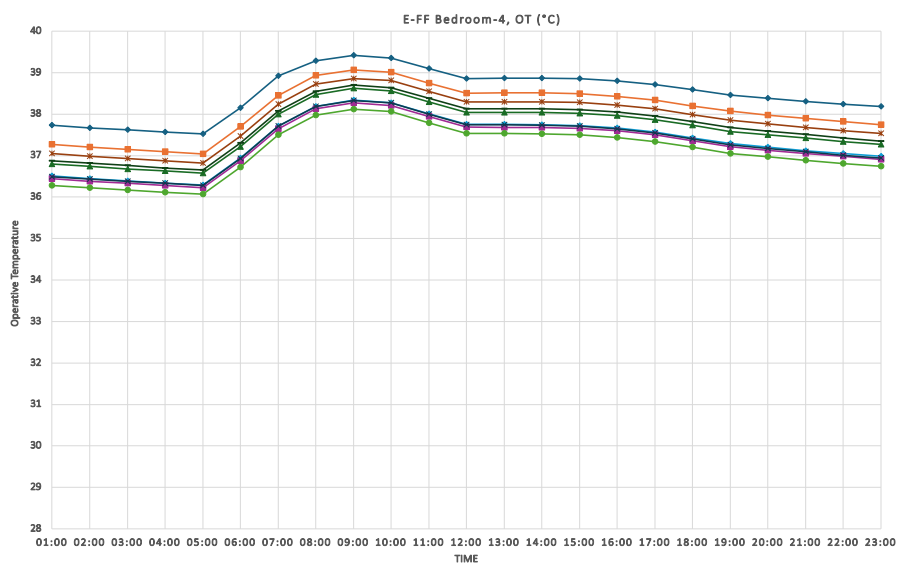


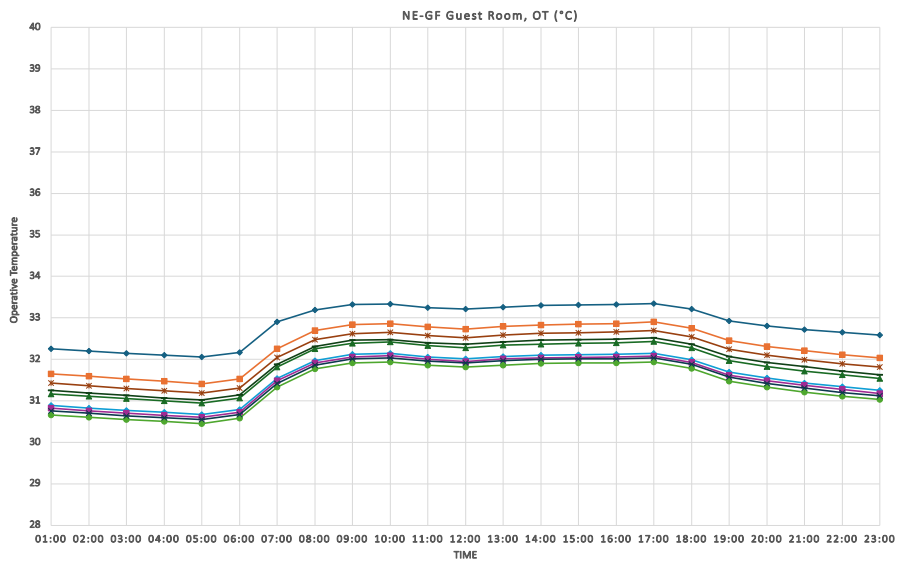












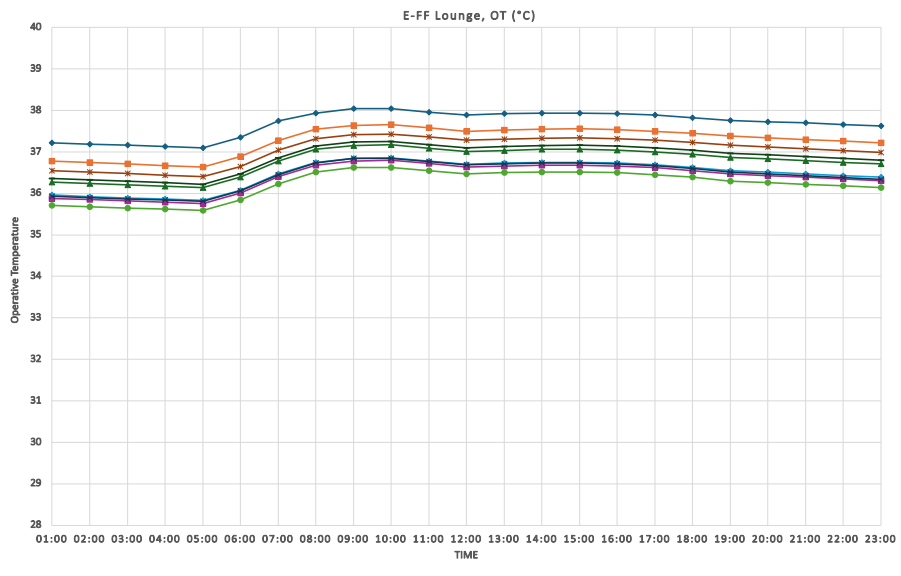




Figure A-3. 7 The Free-Running Simulation of Hourly OTs in The Base Case Building Zones After Applying Various Wall Energy Efficiency Measures (Exterior insulation and finish system (EIFS) (15th July).

The Free-running Simulation of Hourly Relative Humidity in The Base Case Building Zones After Applying Various Wall Energy Efficiency Measures (Exterior insulation and finish system (EIFS)) (15th July).

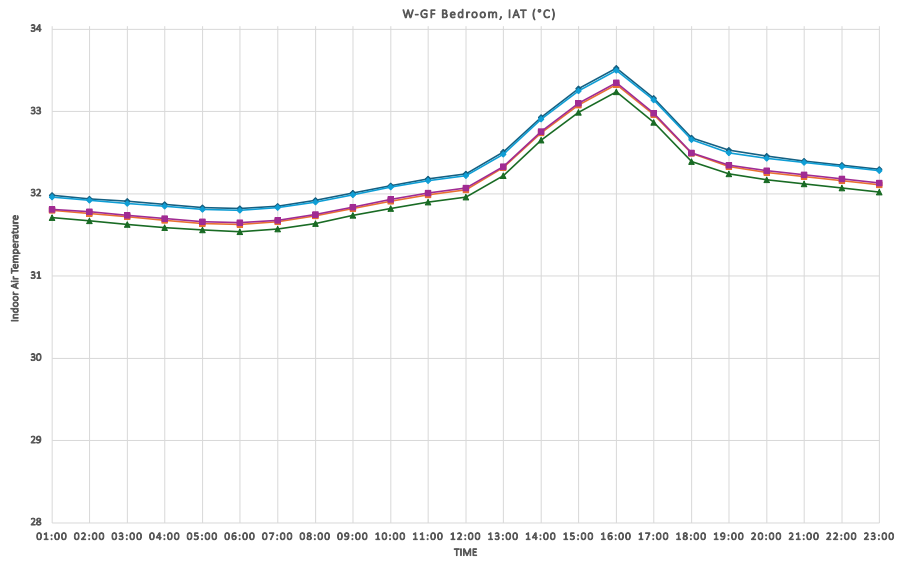
Ground Floor

First Floor

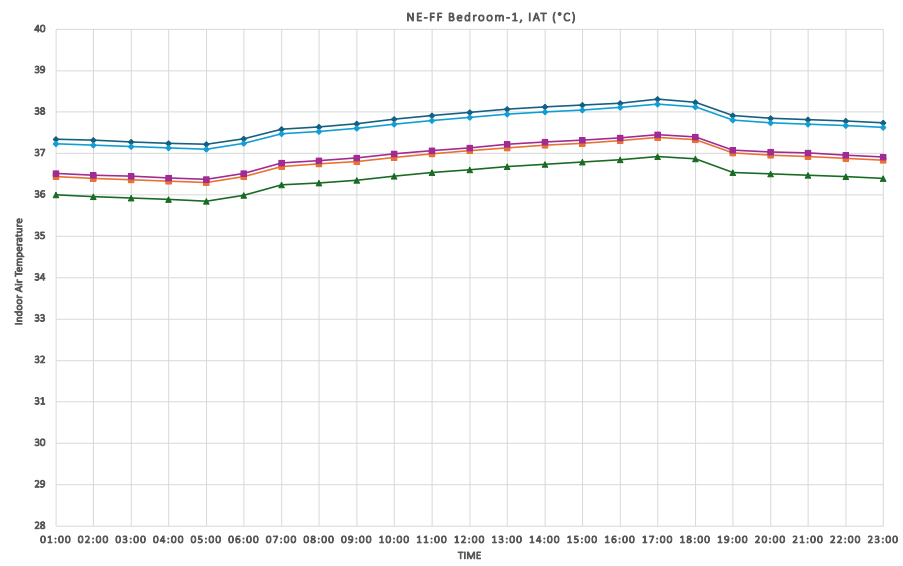
Figure A-3. 8. The Free-Running Simulation of Hourly RH in The Base Case Building Zones After Applying Various Wall Energy Efficiency Measures (Exterior insulation and finish system (EIFS) (15th July).

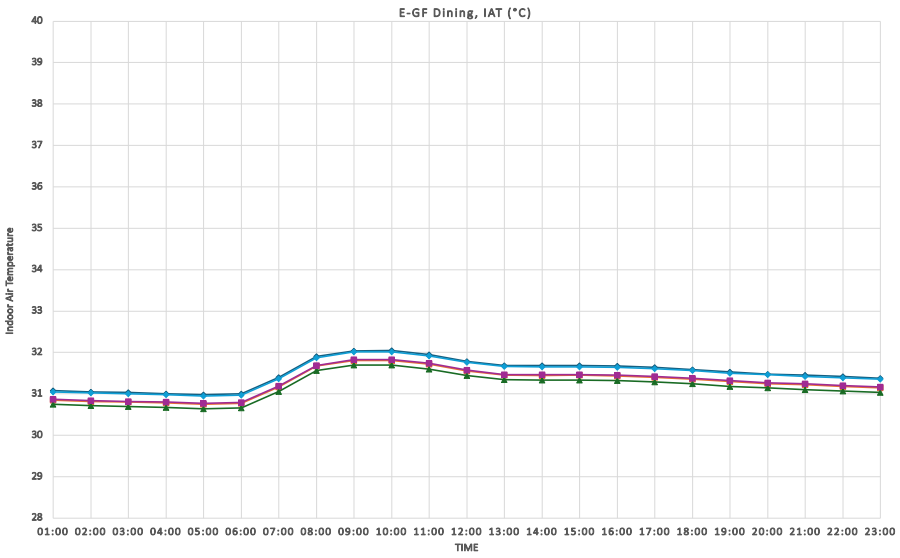
The Free-running Simulation of Hourly Indoor Air Temperature in The Base Case Building Zones After Applying Various Energy Efficiency Measures for Roofing by Advanced Insulation. (15th July).

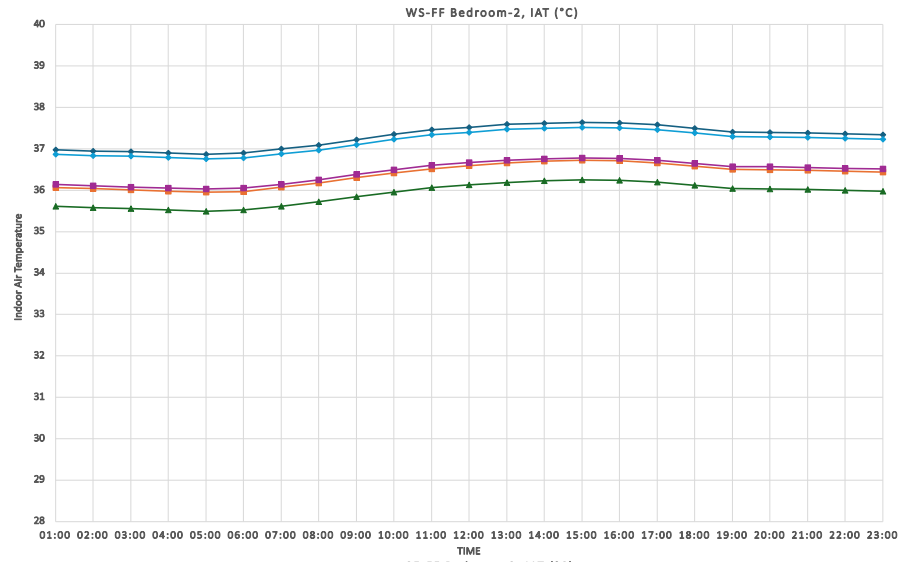
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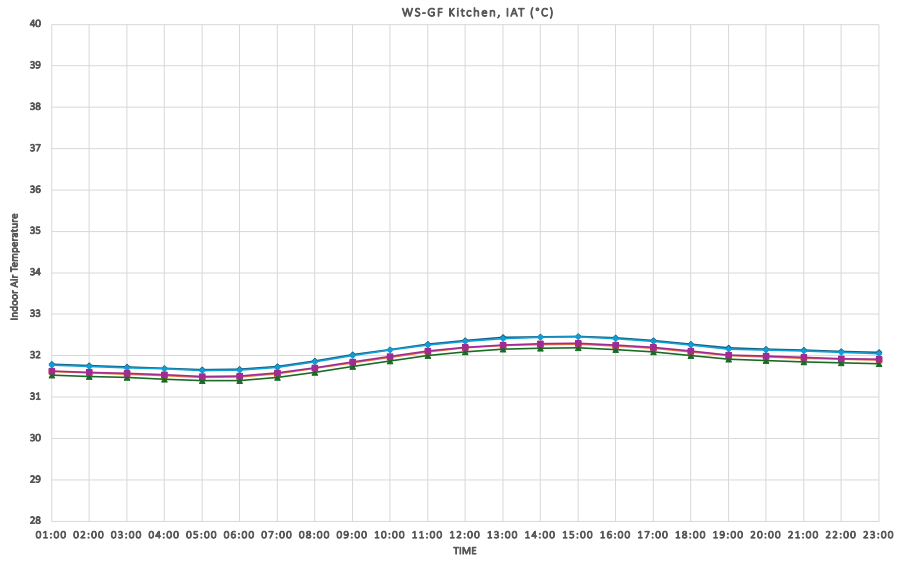


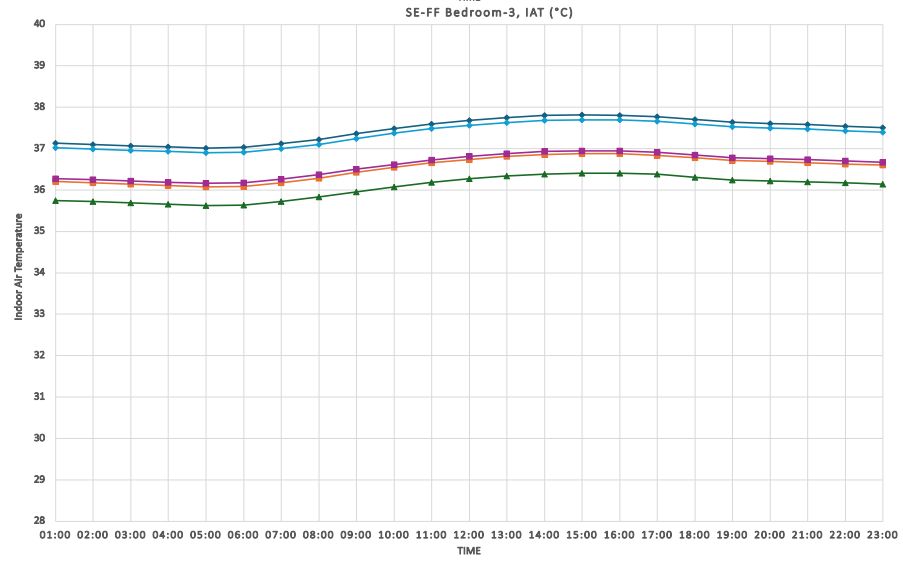
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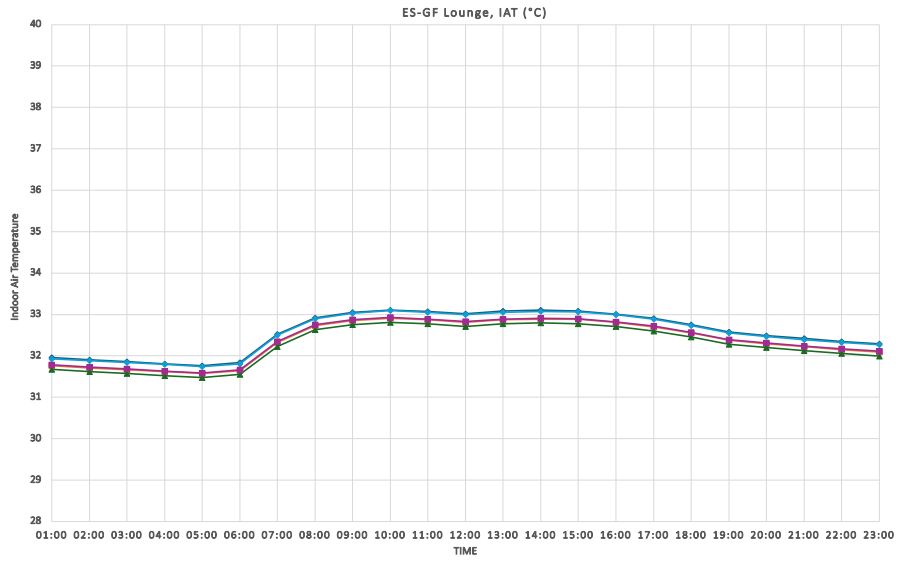


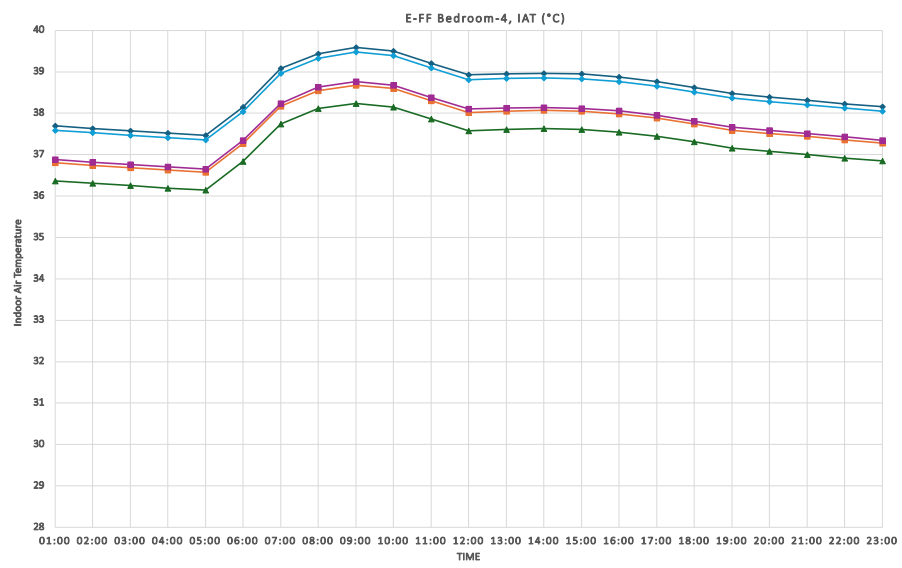


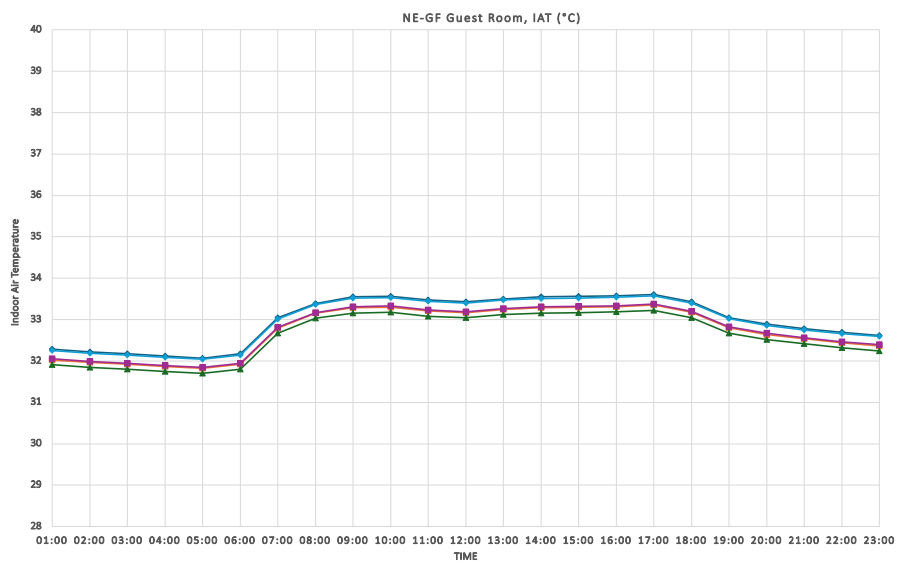


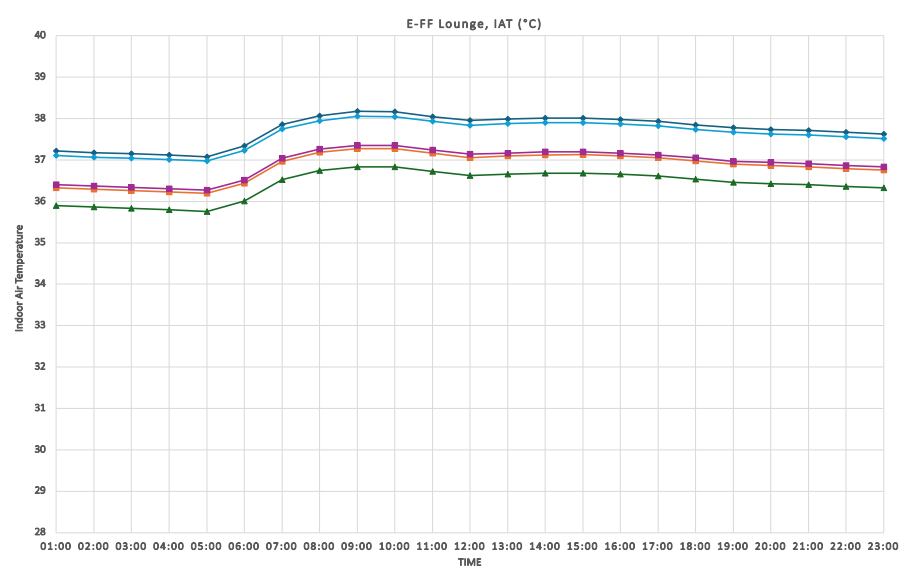










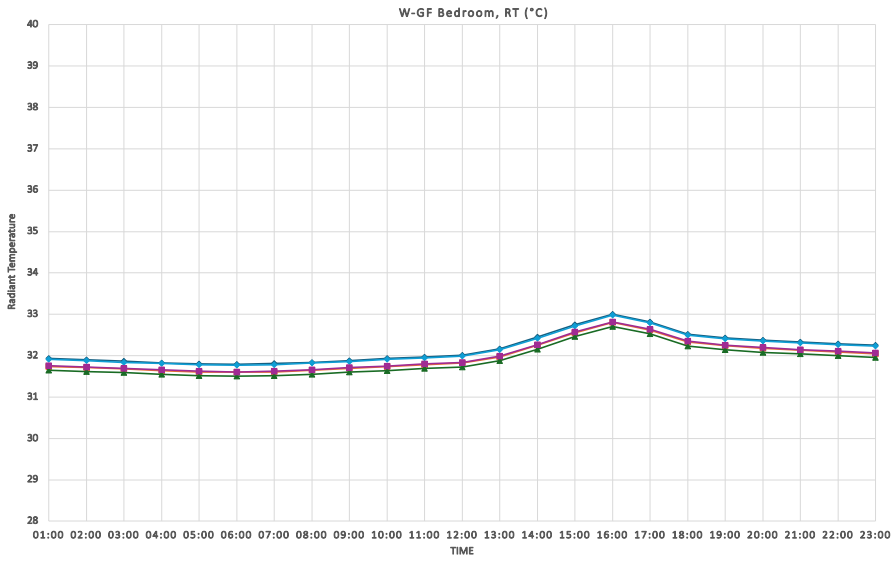


Base Case | Roofing VIP 70mm | Roofing VIP 140mm | Roofing Aerogel 70mm | Roofing Aerogel 140mm

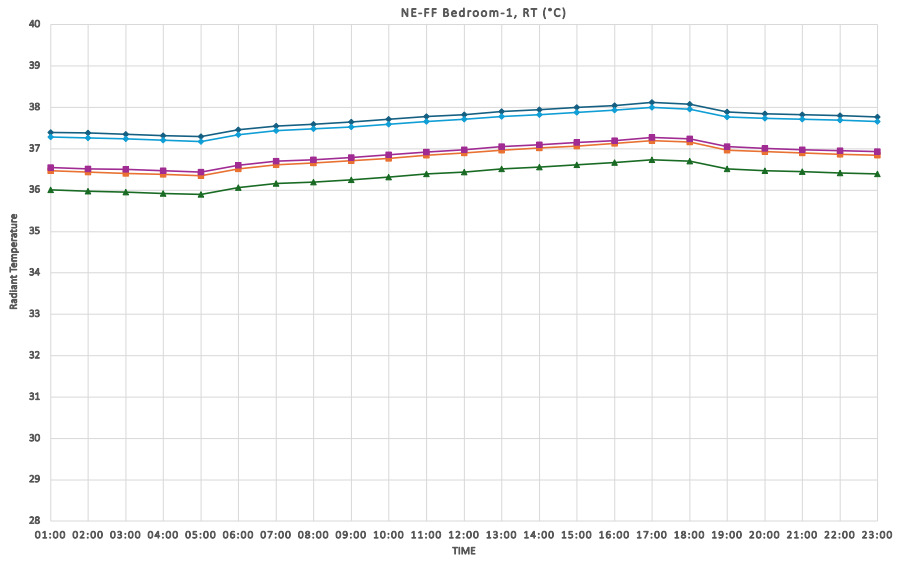
Figure A-3. 9. The Free-Running Simulation of Hourly IATs in The Base Case Building Zones After Applying Various Energy Efficiency Measures for Roofing by Advanced Insulation. (15th July).

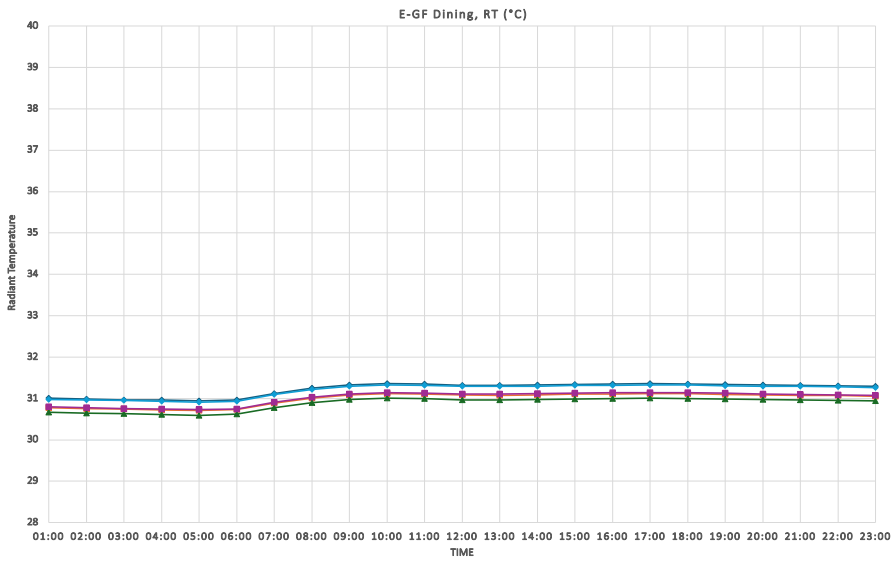
The Free-running Simulation of Hourly Radiant Temperature in The Base Case Building Zones After Applying Various Energy Efficiency Measures for Roofing by Advanced Insulation. (15th July).

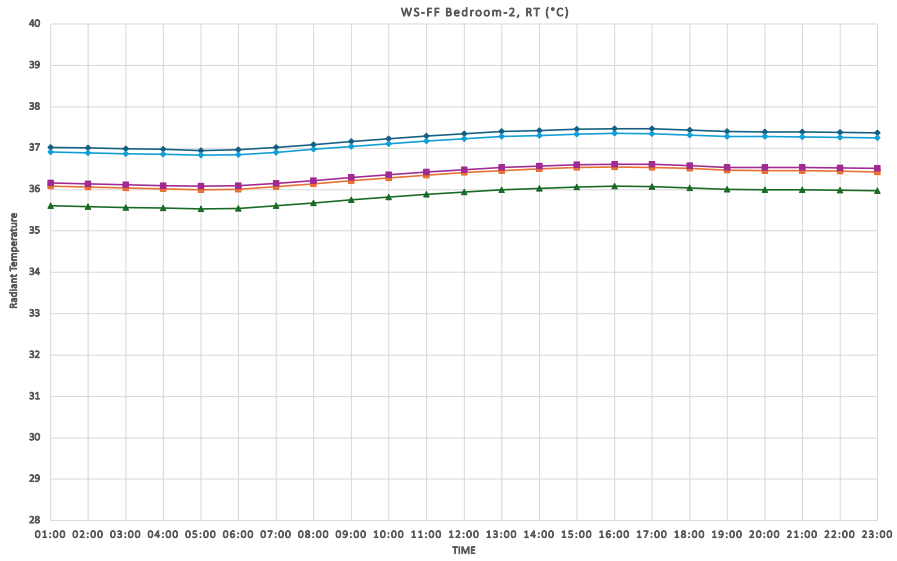
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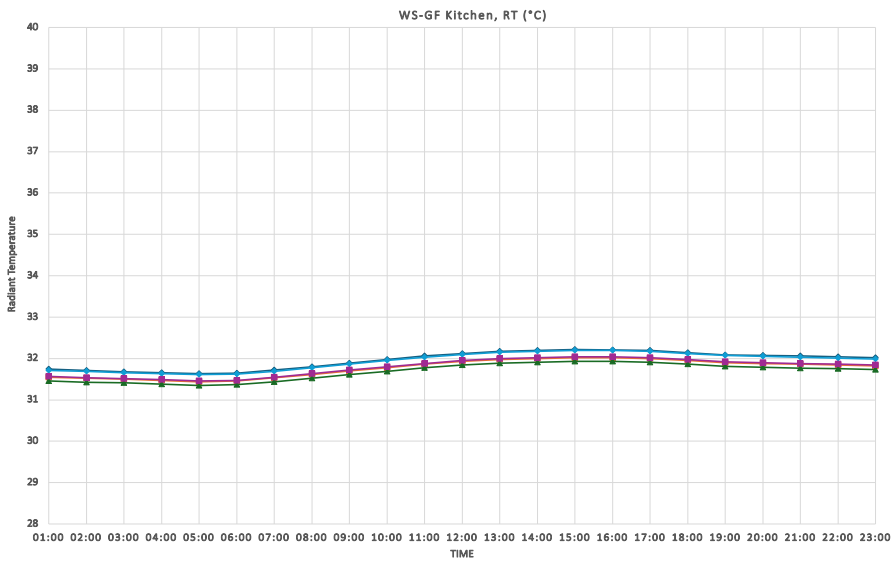


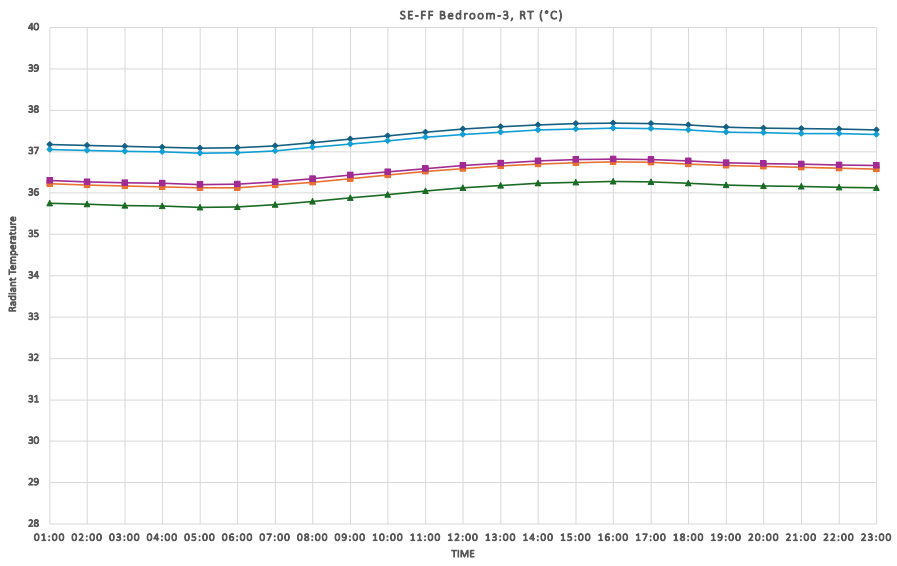
First Floor

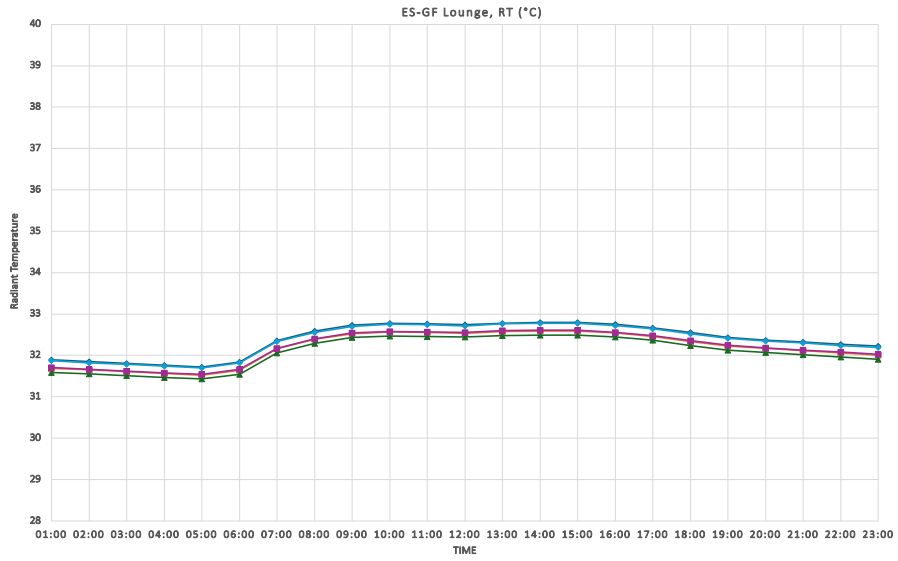


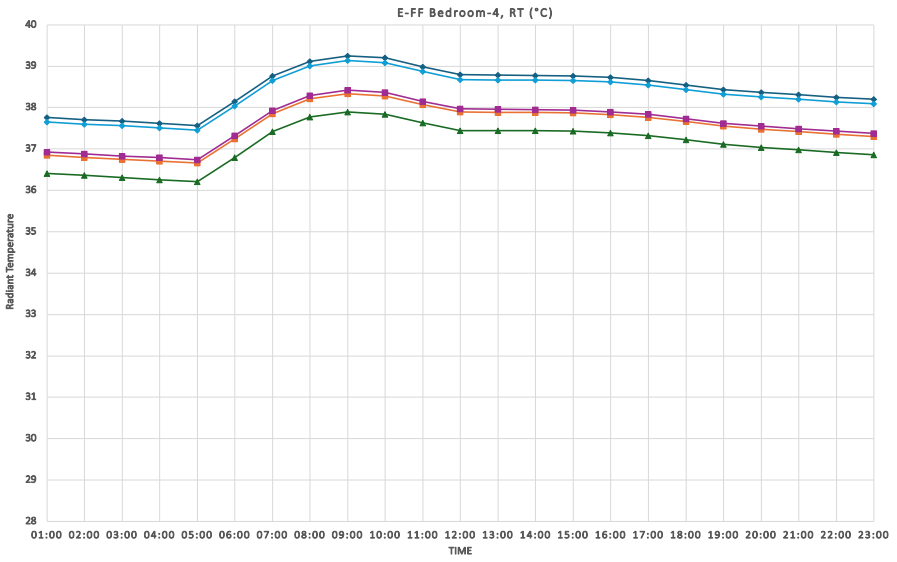


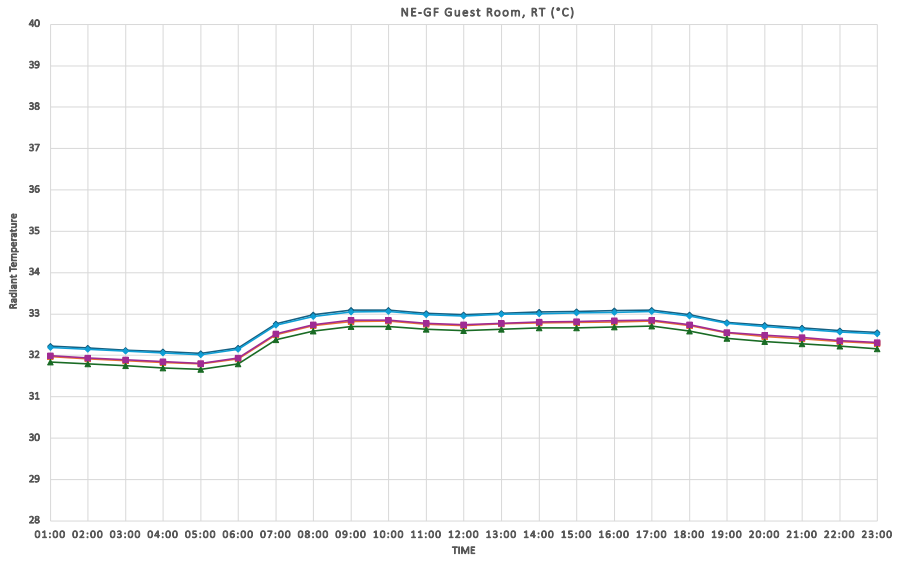












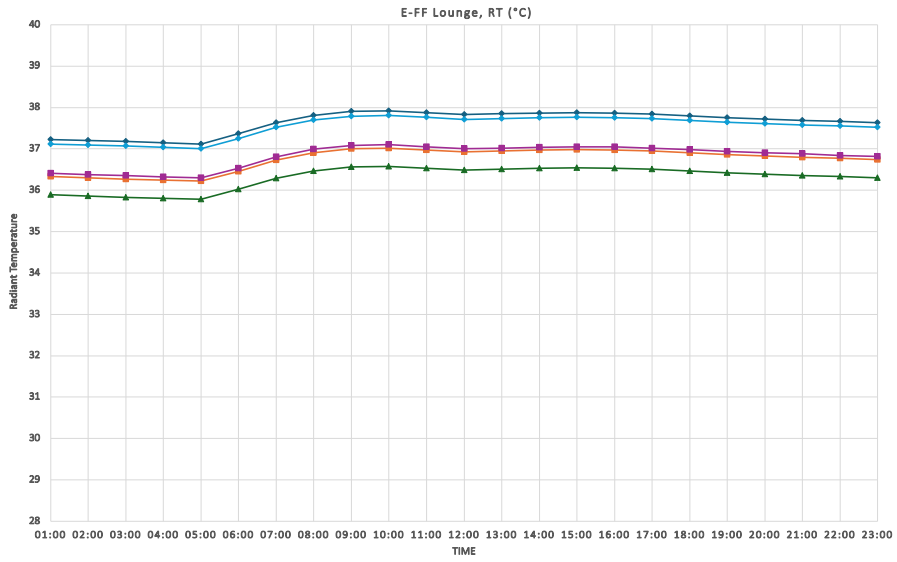


Figure A-3. 10. The Free-Running Simulation of Hourly RTs in The Base Case Building Zones After Applying Various Energy Efficiency Measures for Roofing by Advanced Insulation. (15th July).

The Free-running Simulation of Hourly Operative Temperature in The Base Case Building Zones After Applying Various Energy Efficiency Measures for Roofing by Advanced Insulation. (15th July).

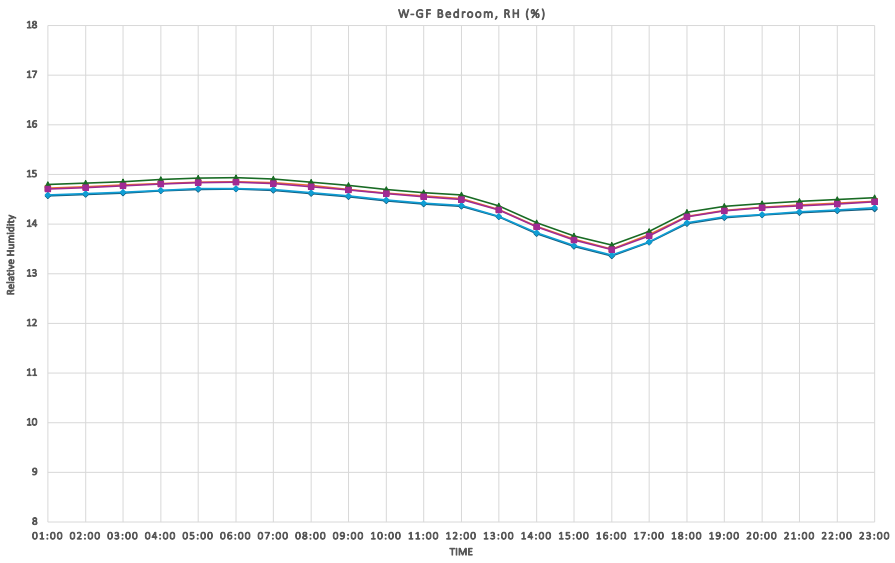
Ground Floor

First Floor

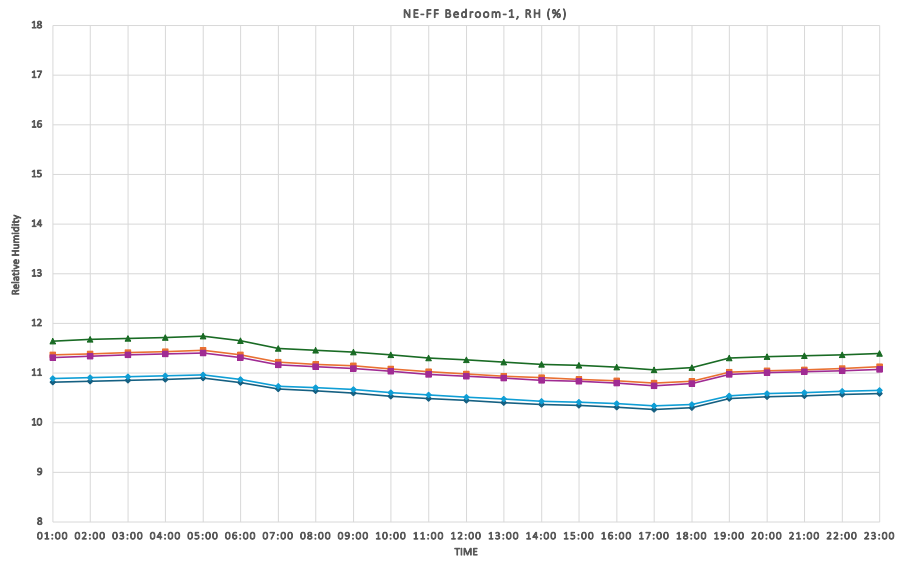
Figure A-3. 11. The Free-Running Simulation of Hourly OTs in The Base Case Building Zones After Applying Various Energy Efficiency Measures for Roofing by Advanced Insulation. (15th July).

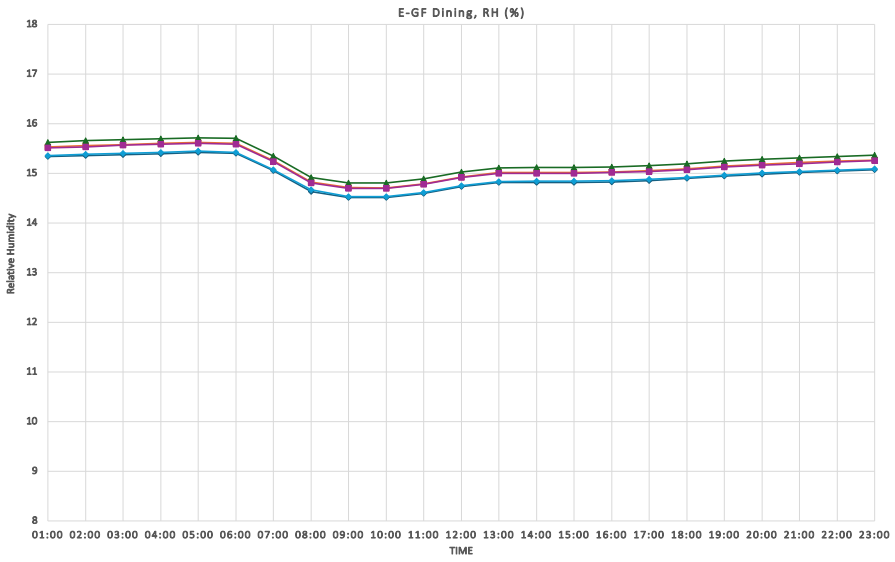
The Free-running Simulation of Hourly Relative Humidity in The Base Case Building Zones After Applying Various Energy Efficiency Measures for Roofing by Advanced Insulation. (15th July).

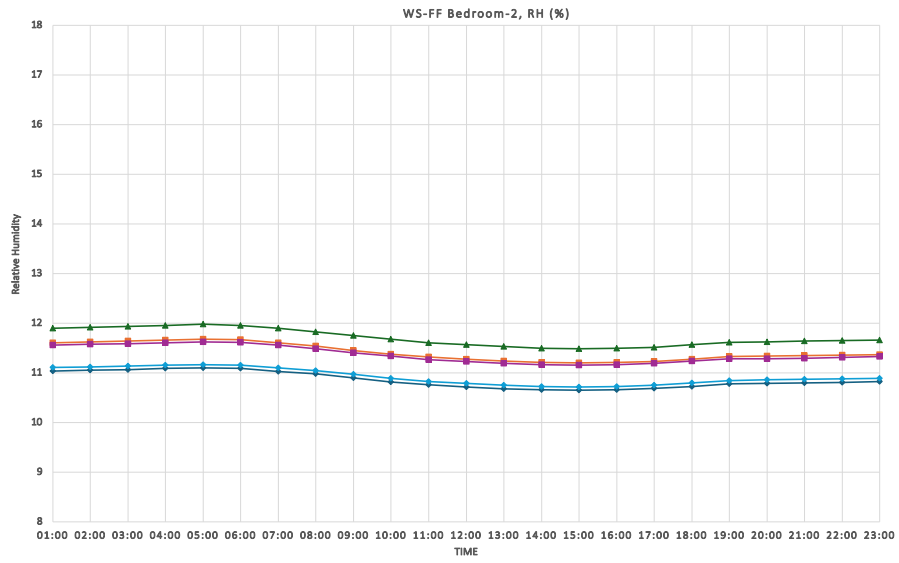
Ground Floor

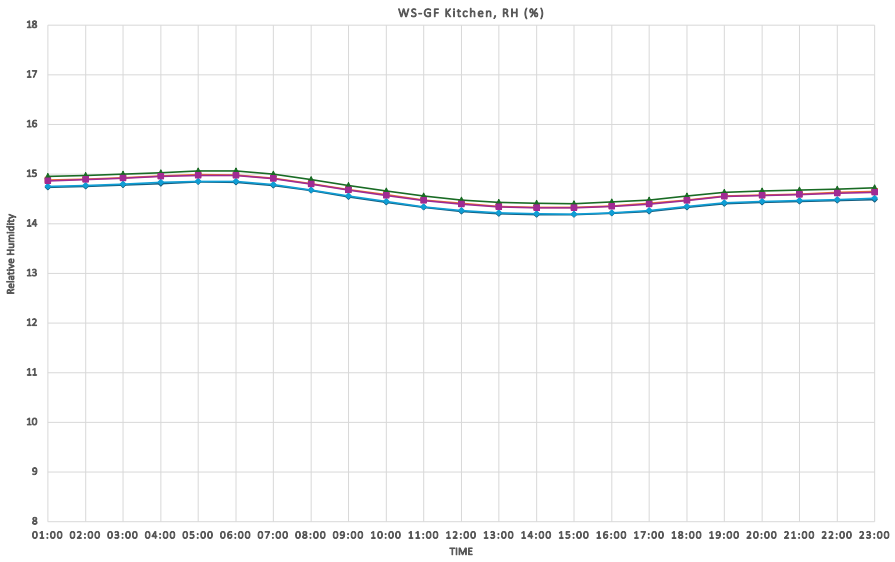


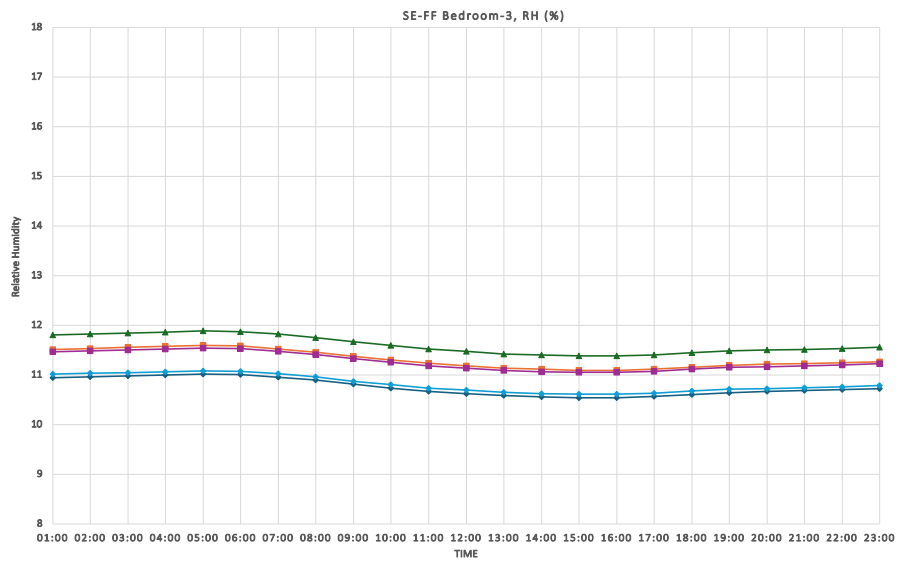
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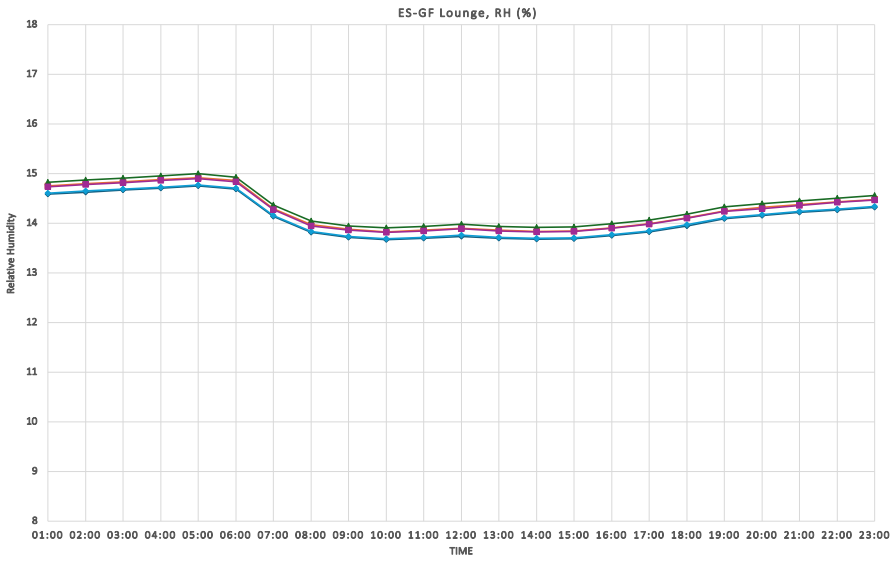


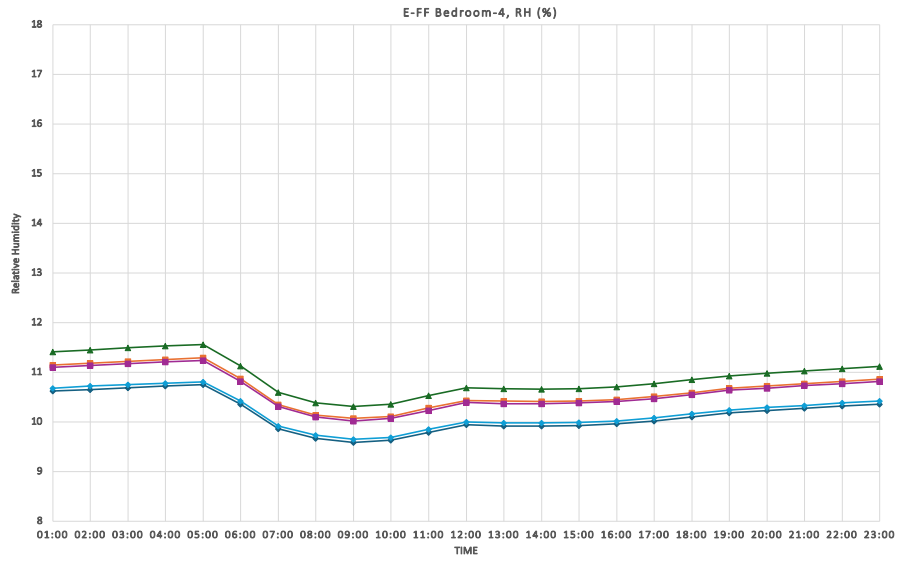


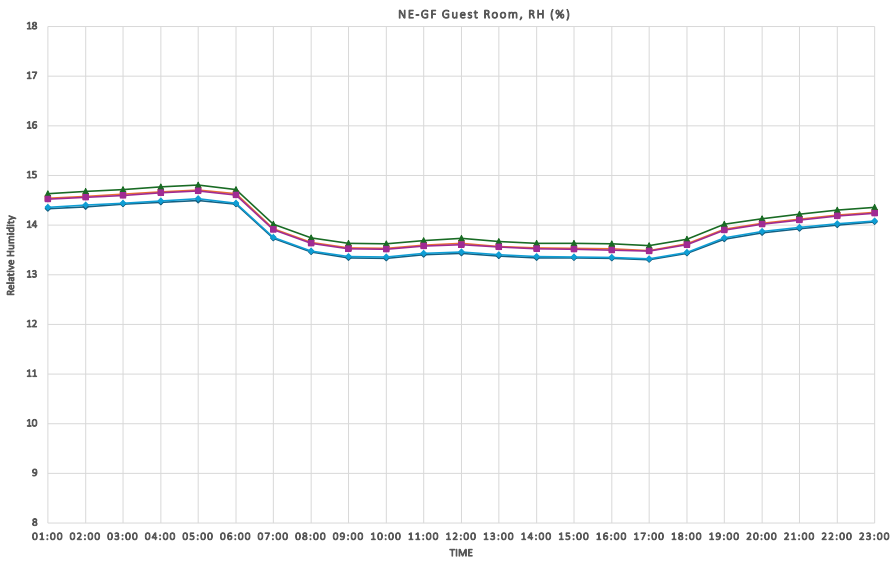












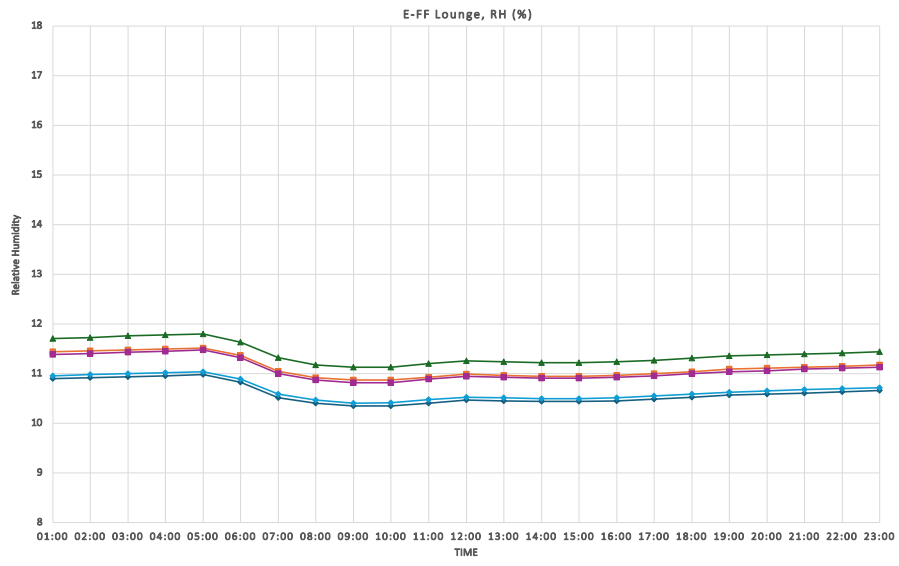
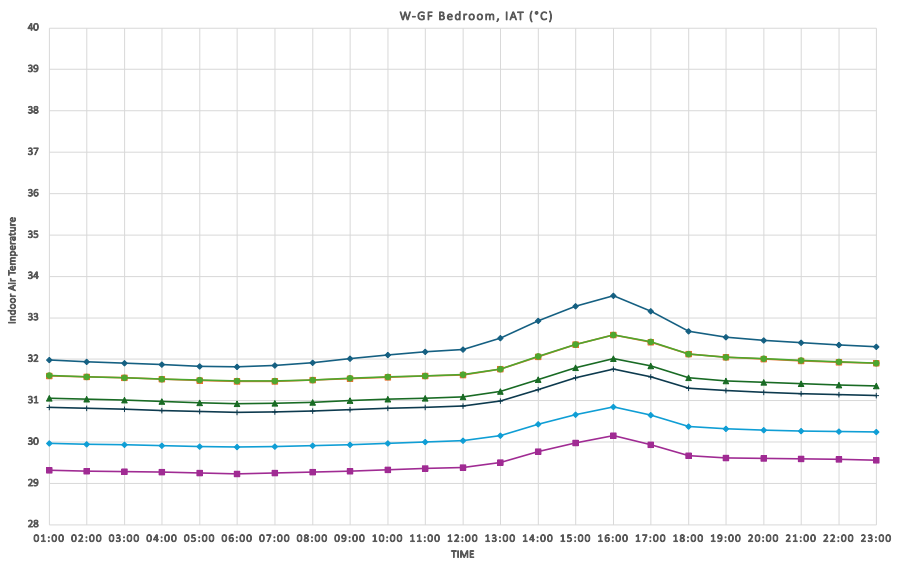


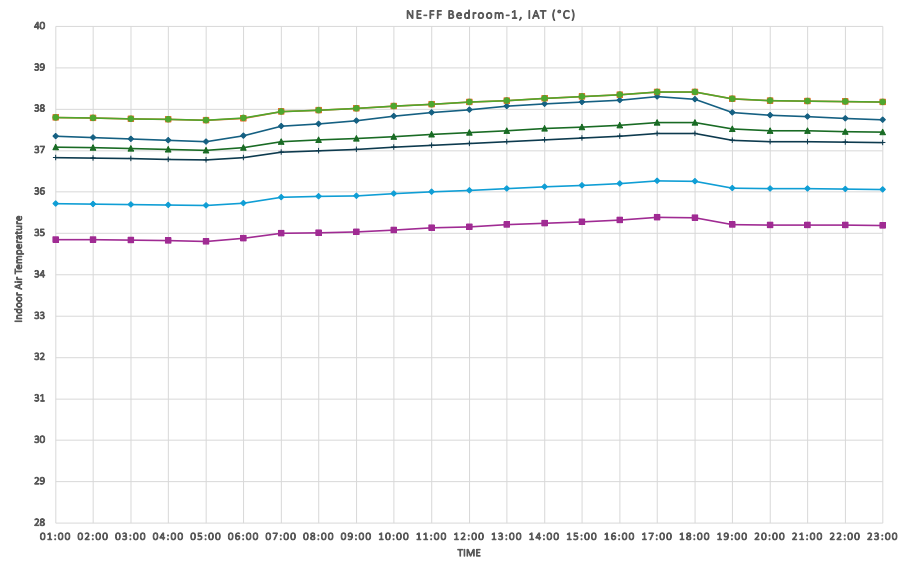
Figure A-3. 12. The Free-Running Simulation of Hourly RH in The Base Case Building Zones After Applying Various Energy Efficiency Measures for Roofing by Advanced Insulation. (15th July).

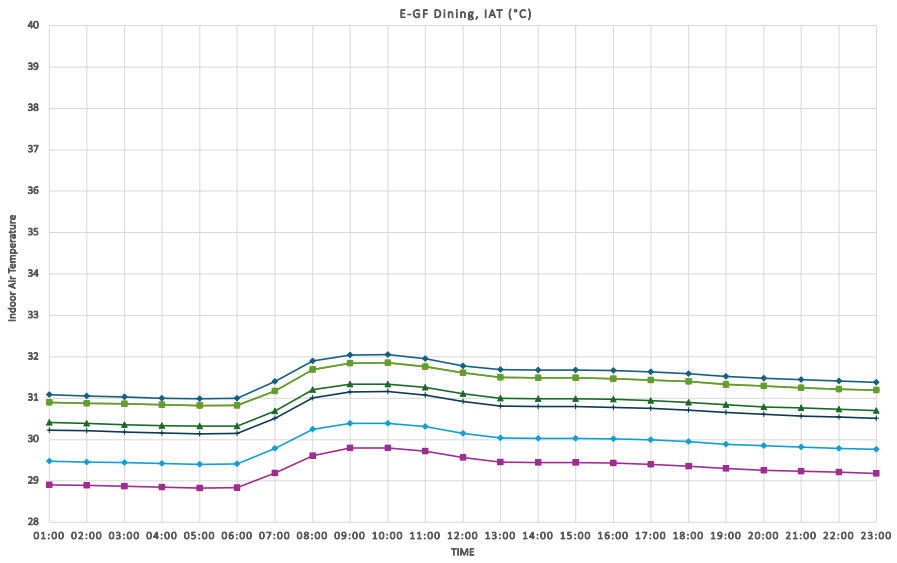
The Free-running Simulation of Hourly Indoor Air Temperature in The Base Case Building Zones After Applying Various Energy Efficiency Measures for Glazing by Vacuum Insulated Glass Product series. (15th July).

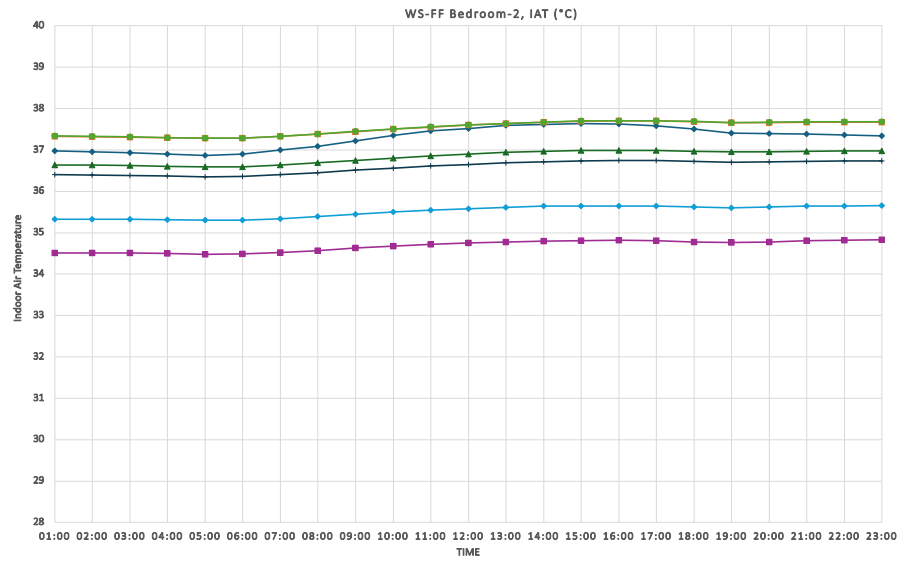
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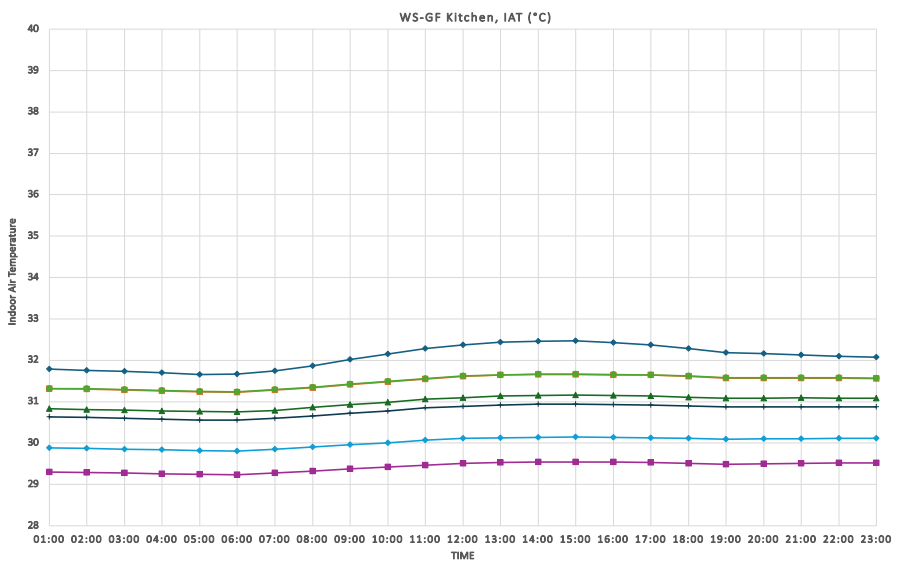


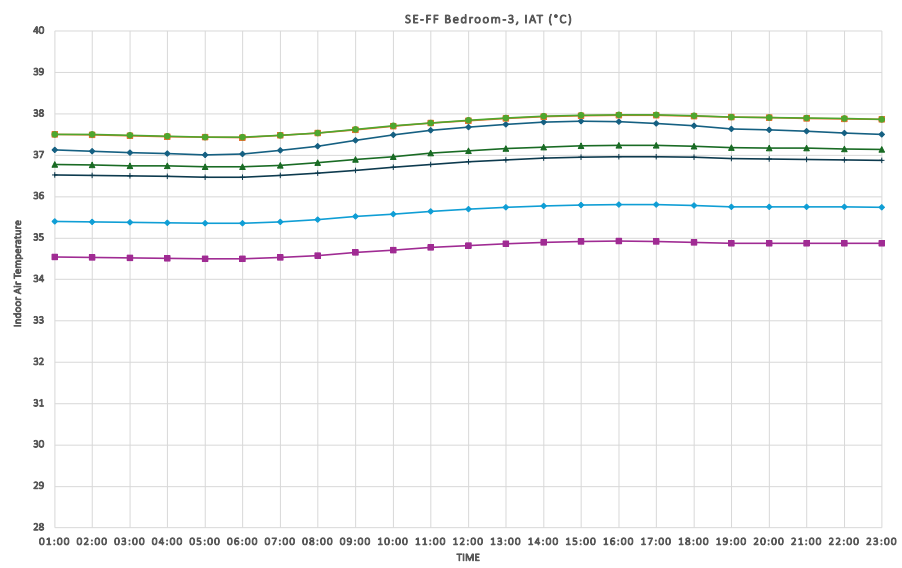
First Floor

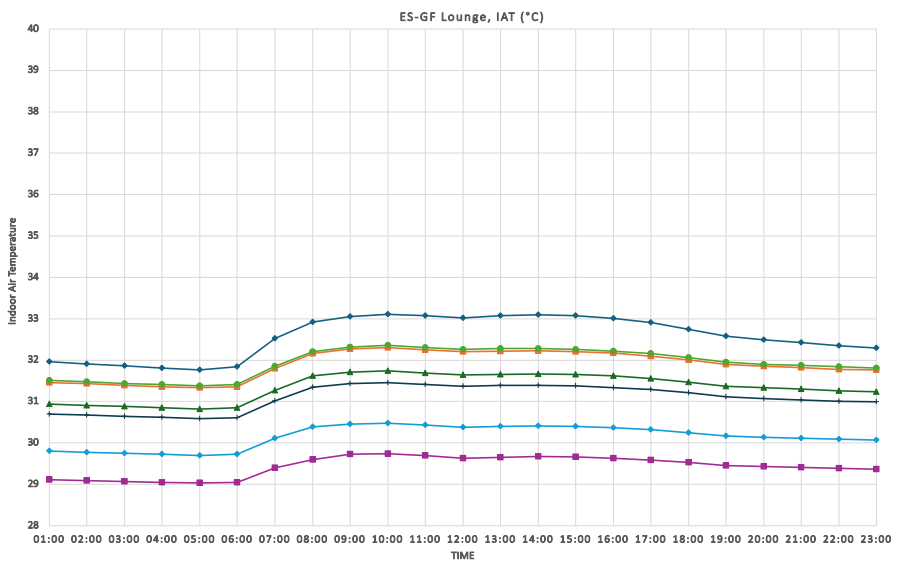


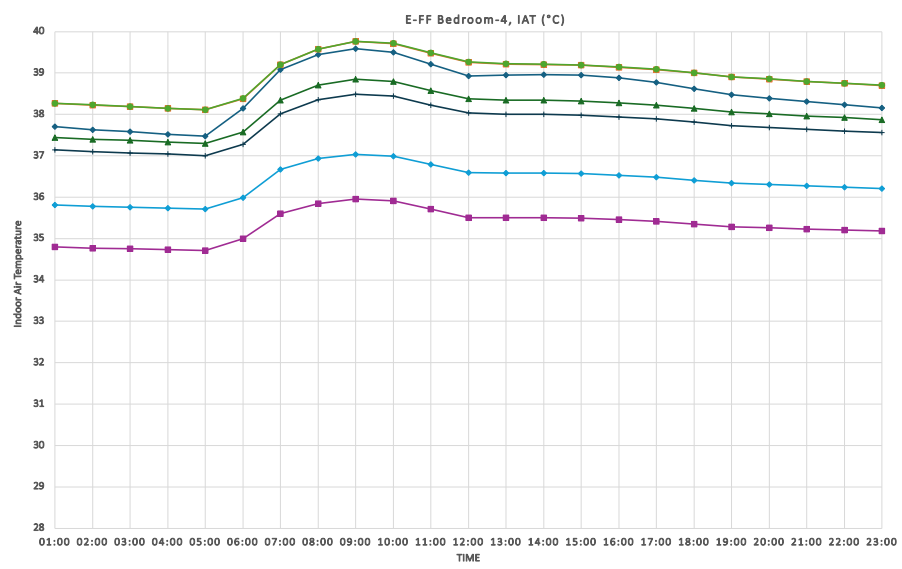


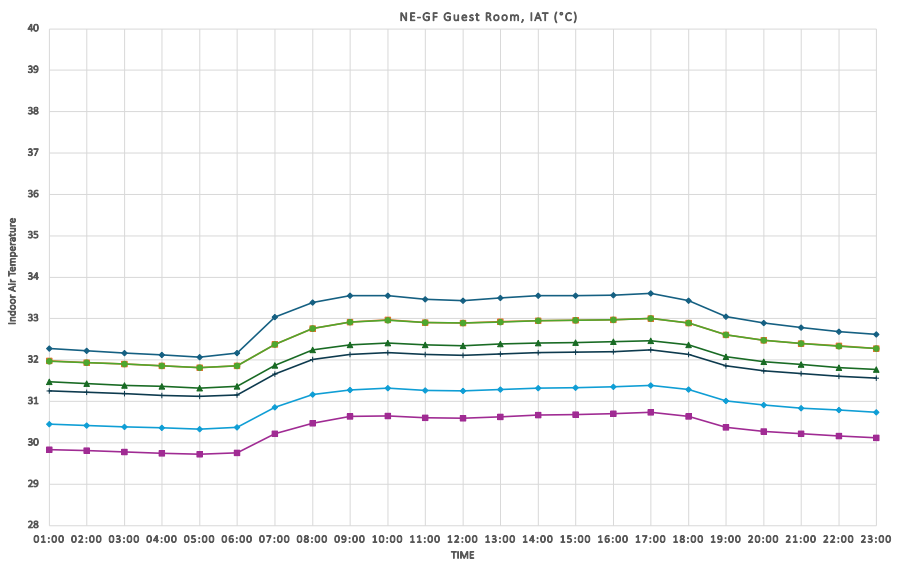


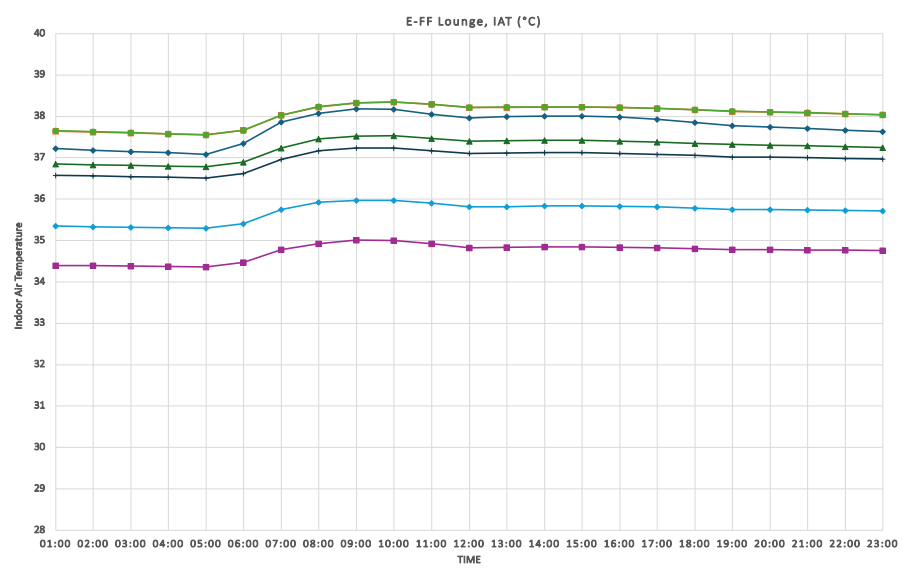










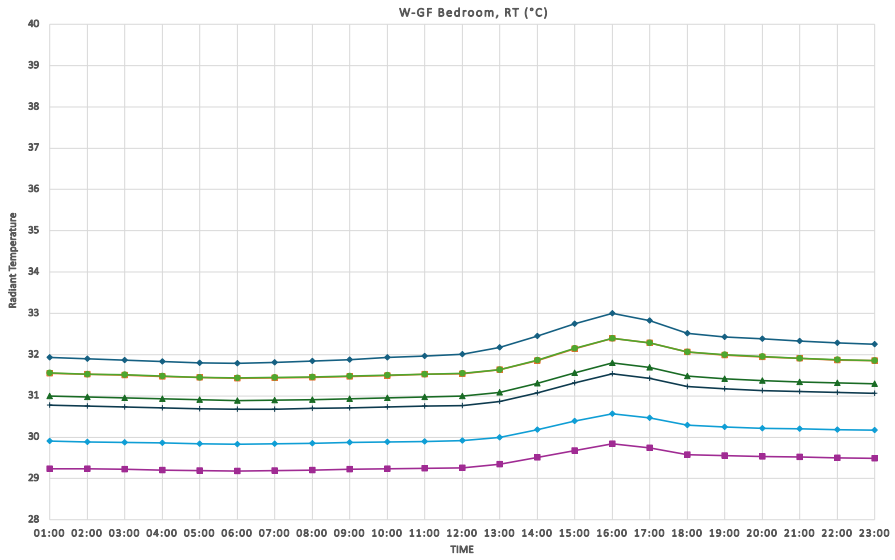


Base Case | 4T+0.3V+4TL (S1.16) series | 4T+0.3V+4TL (S1.10) series | 4T+0.3V+4TL(D80) series | 4T+0.3V+5TL(XDTB0159) series | 4T+12Ar+4TL (S1.10) +0.3V+4T series | 3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series

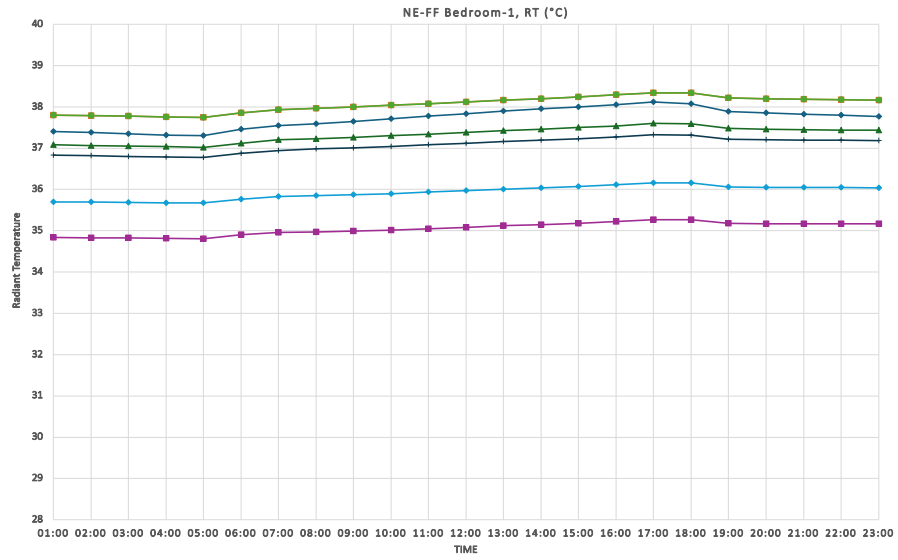
Figure A-3. 13. The Free-Running Simulation of Hourly IATs in The Base Case Building Zones After Applying Various Energy Efficiency Measures for Glazing by Vacuum Insulated Glass Product series. (15th July).

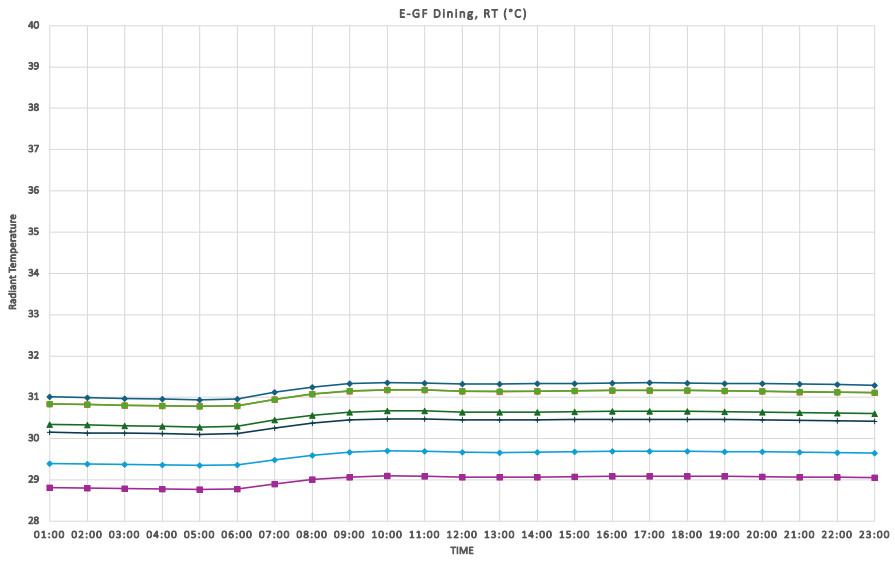
The Free-running Simulation of Hourly Radiant Temperature in The Base Case Building Zones After Applying Various Energy Efficiency Measures for Glazing by Vacuum Insulated Glass Product series. (15th July).

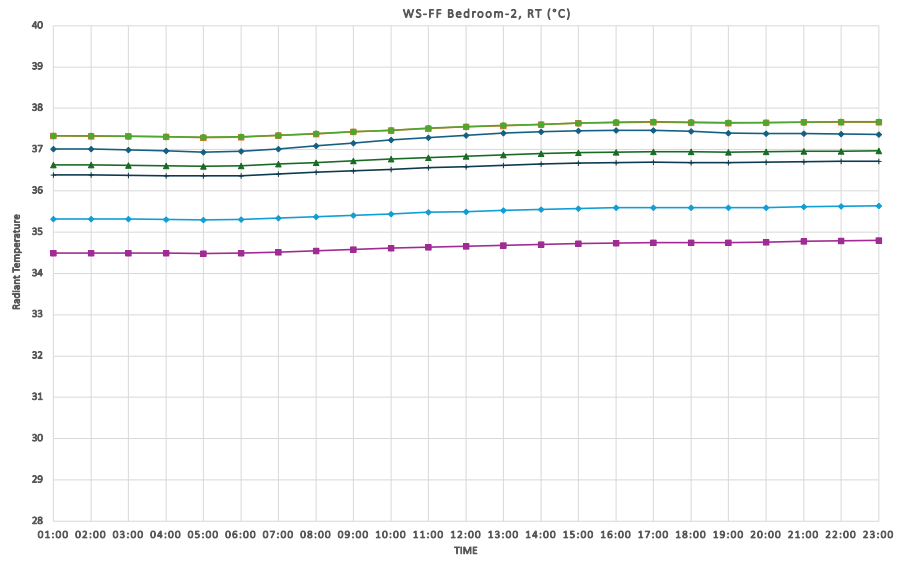
Ground Floor

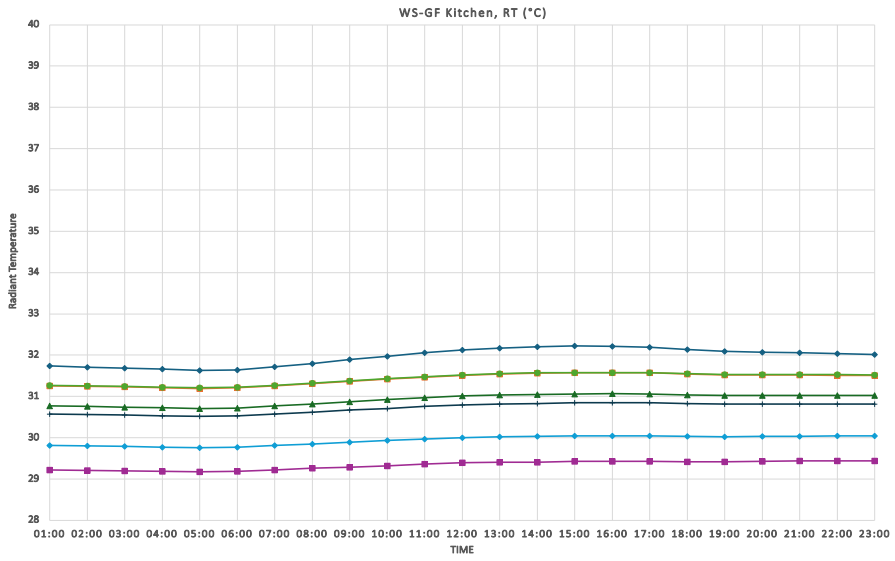


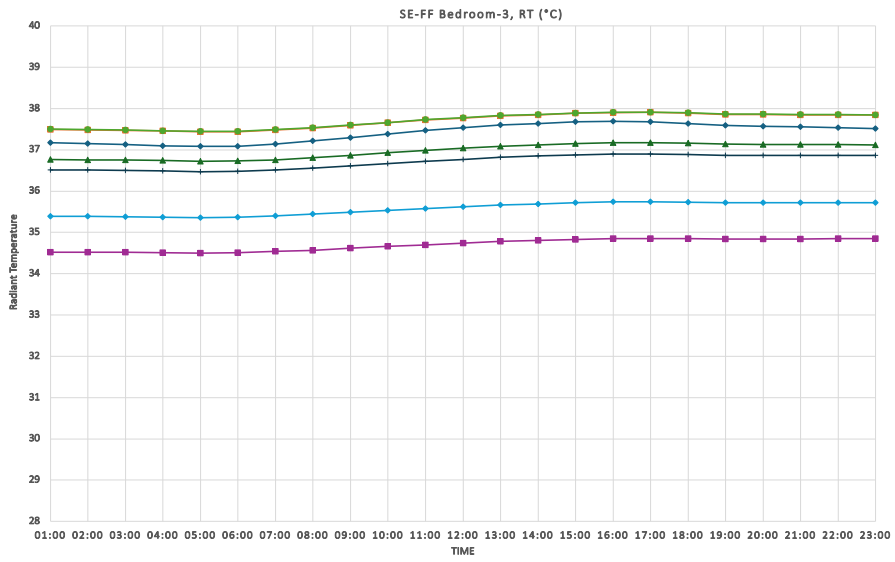
First Floor

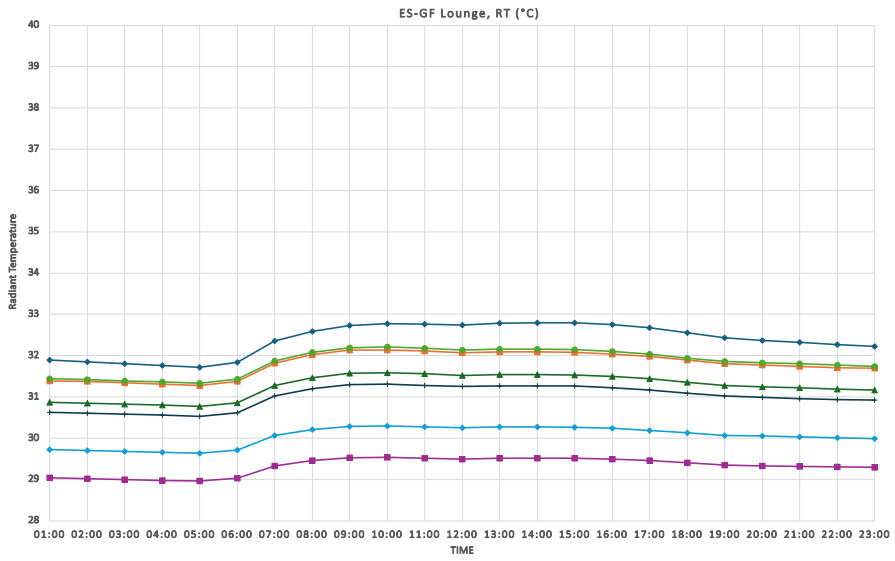


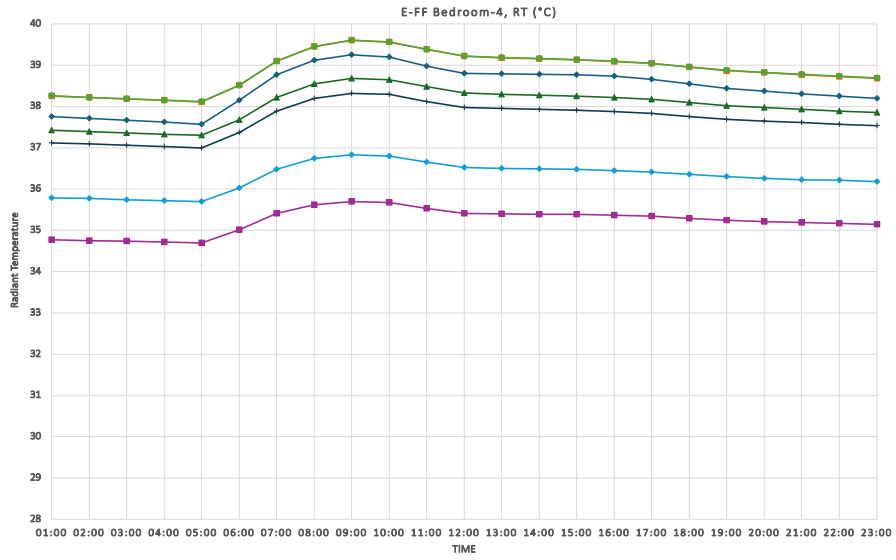


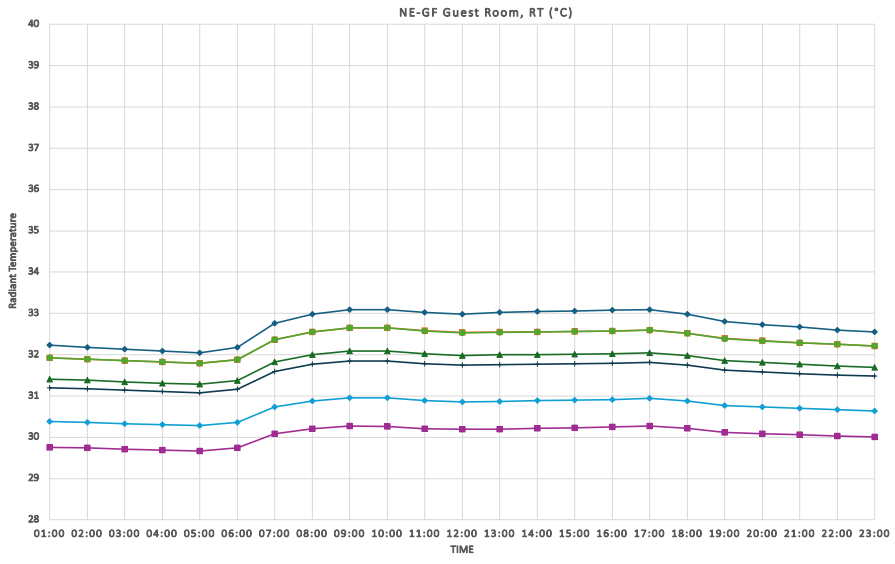












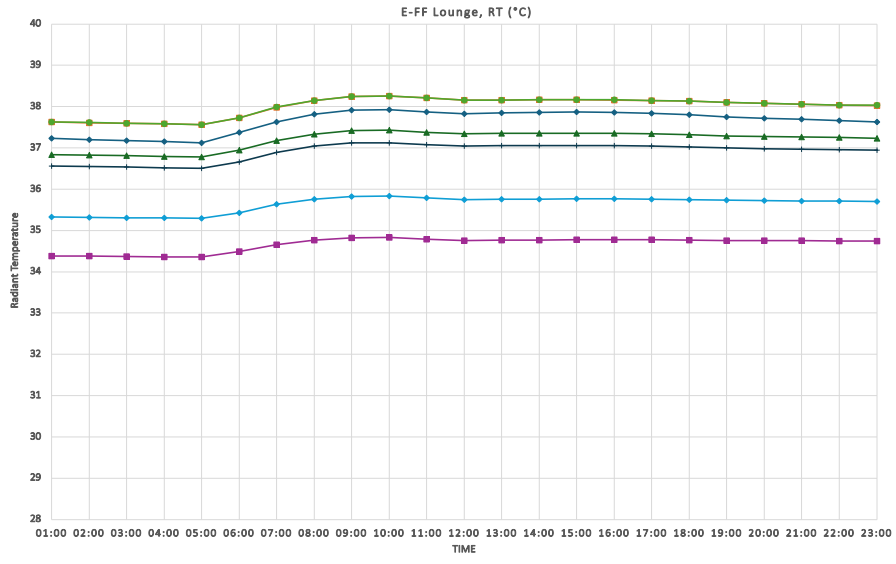
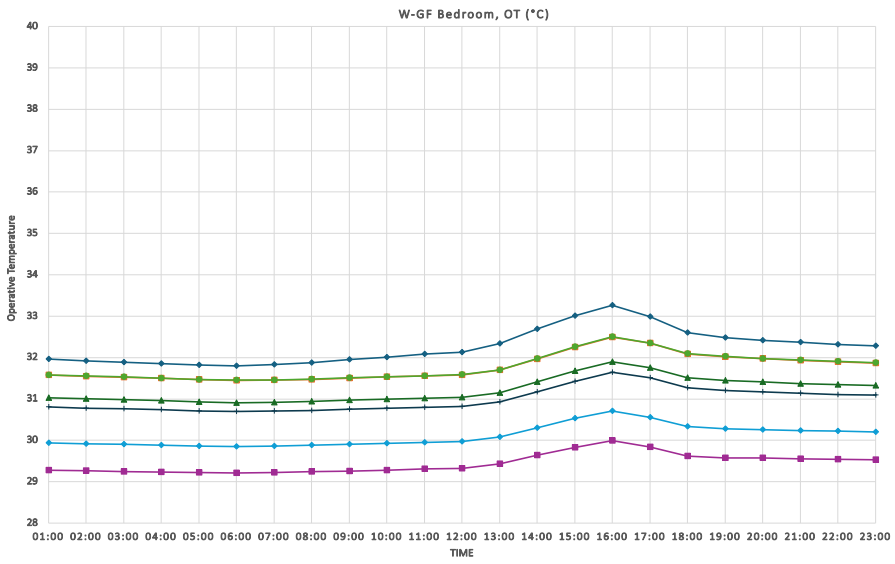




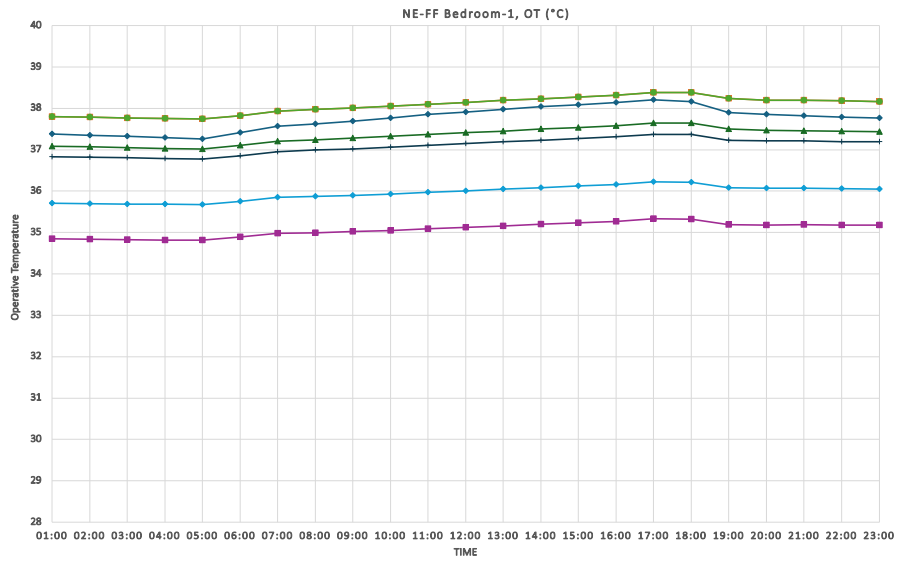
Figure A-3. 14. The Free-Running Simulation of Hourly RTs in The Base Case Building Zones After Applying Various Energy Efficiency Measures for Glazing by Vacuum Insulated Glass Product series. (15th July).

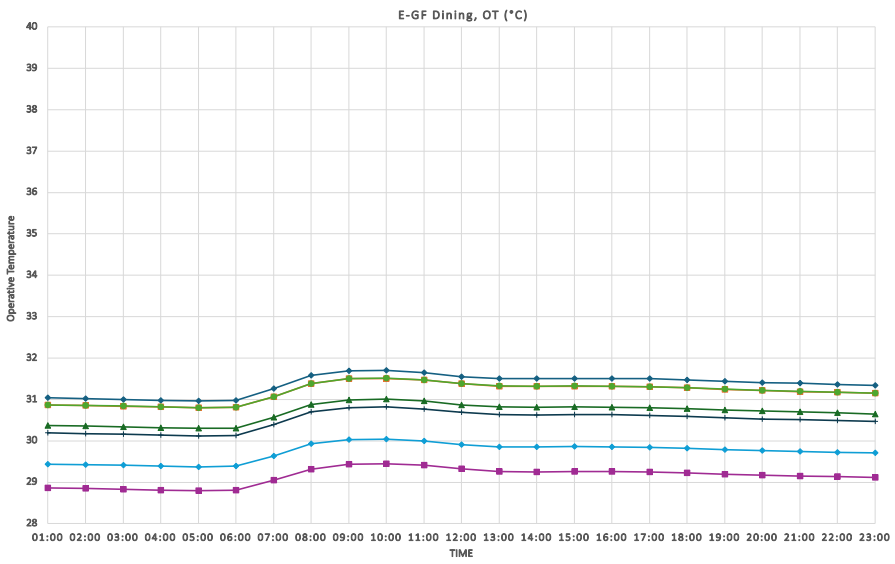
The Free-running Simulation of Hourly Operative Temperature in The Base Case Building Zones After Applying Various Energy Efficiency Measures for Glazing by Vacuum Insulated Glass Product series. (15th July).

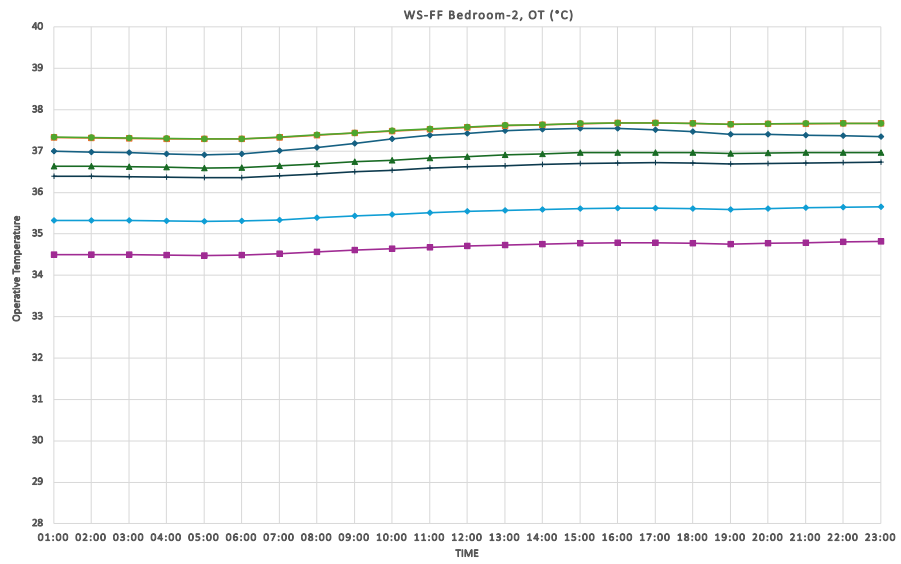
Ground Floor

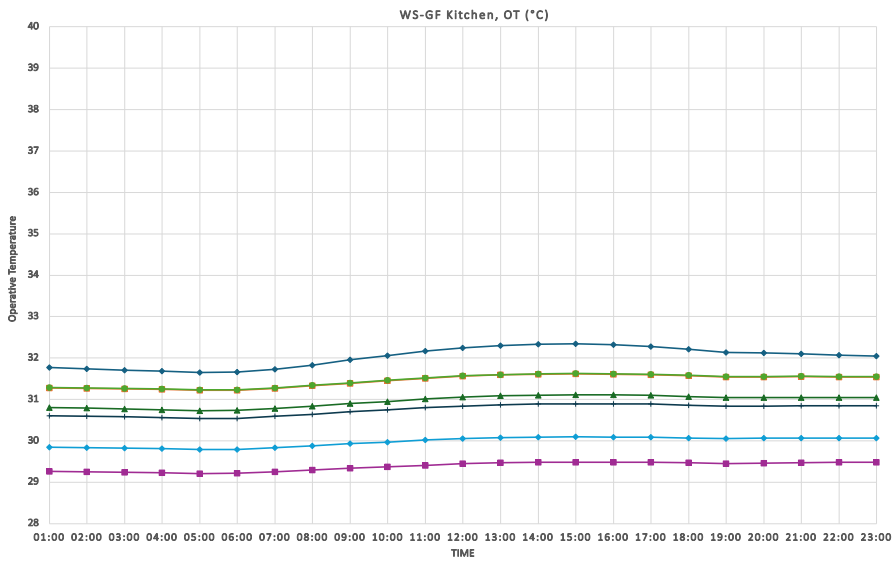


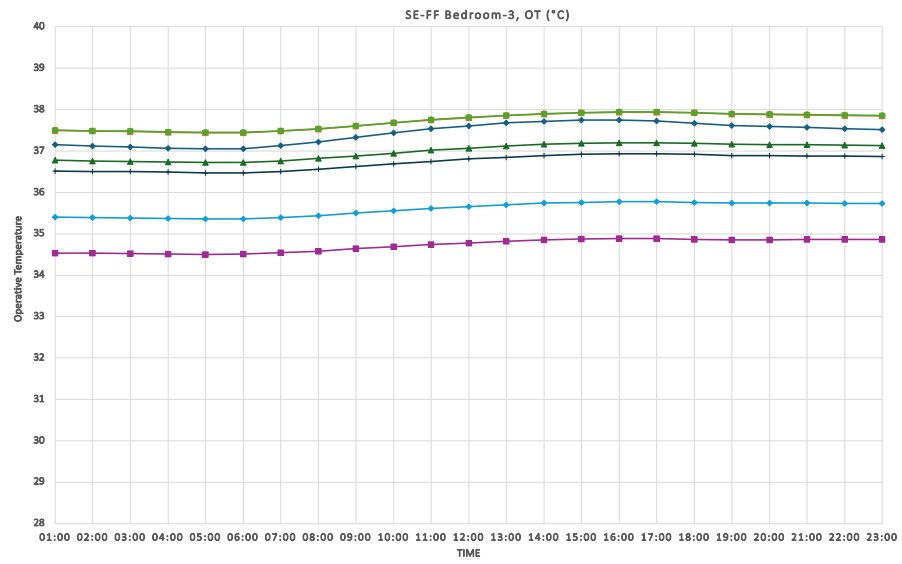
First Floor

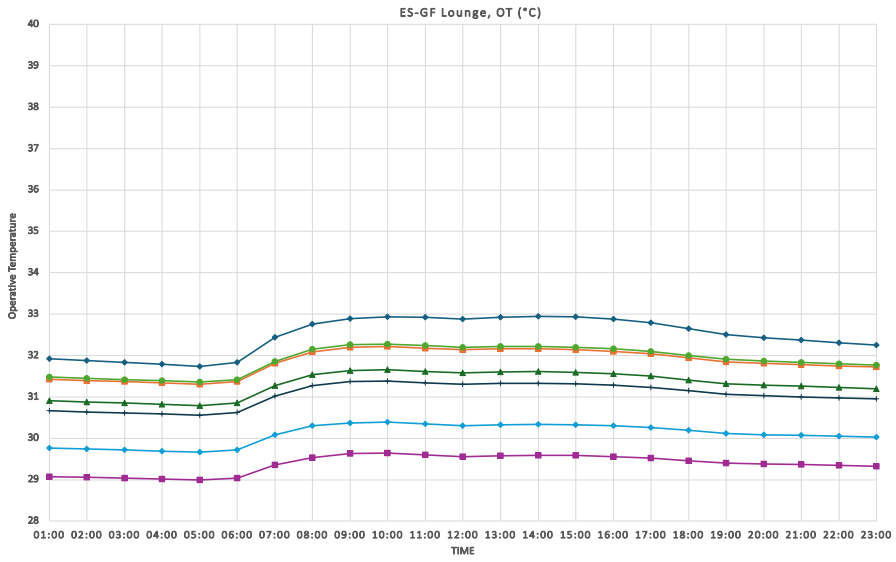


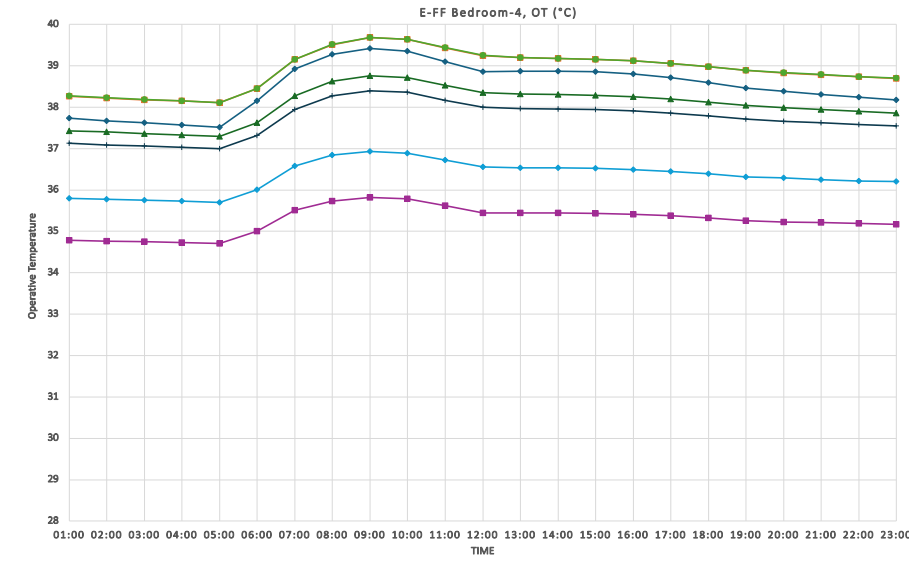


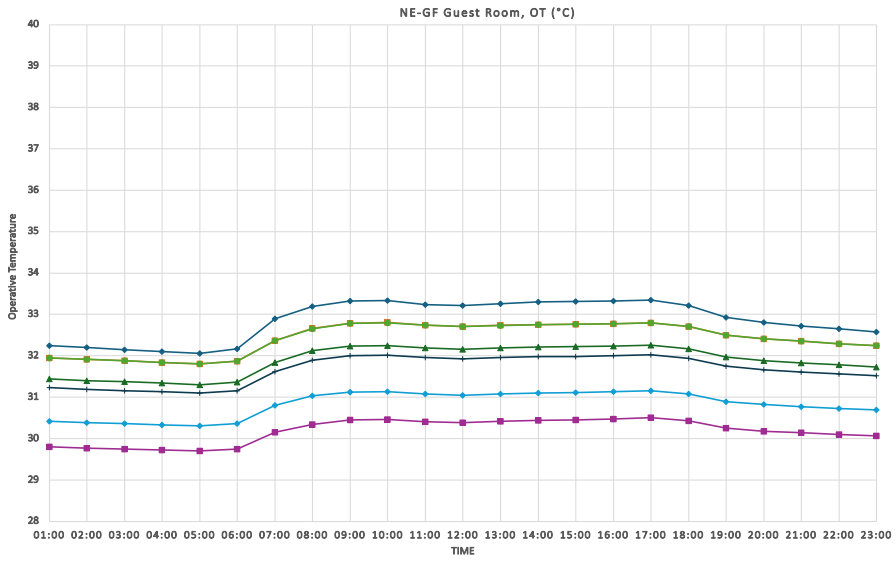












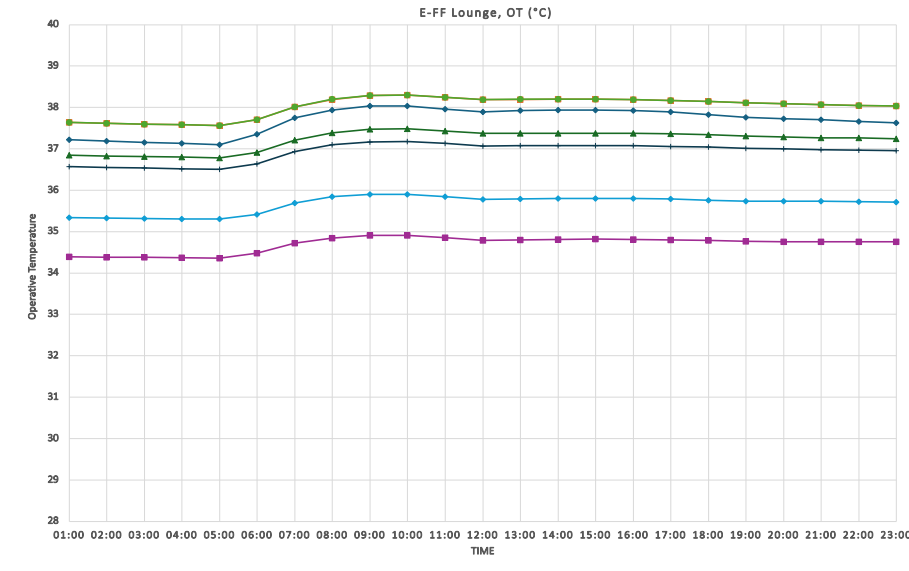
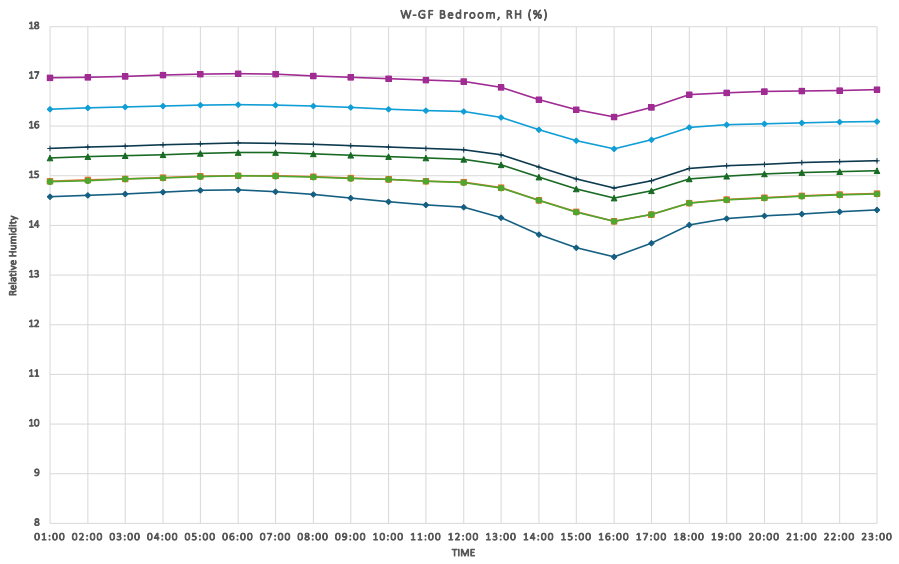




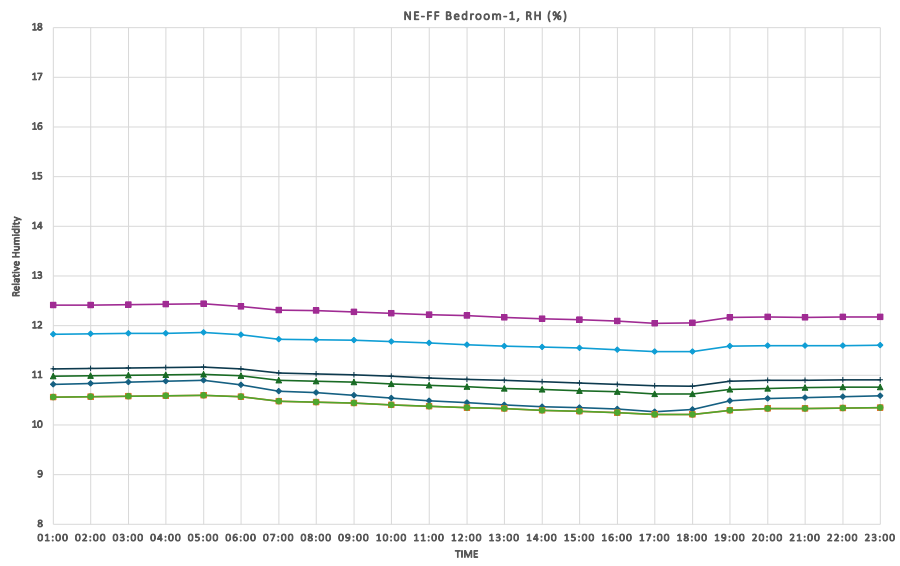
Figure A-3. 15. The Free-Running Simulation of Hourly OTs in The Base Case Building Zones After Applying Various Energy Efficiency Measures for Glazing by Vacuum Insulated Glass Product series. (15th July).

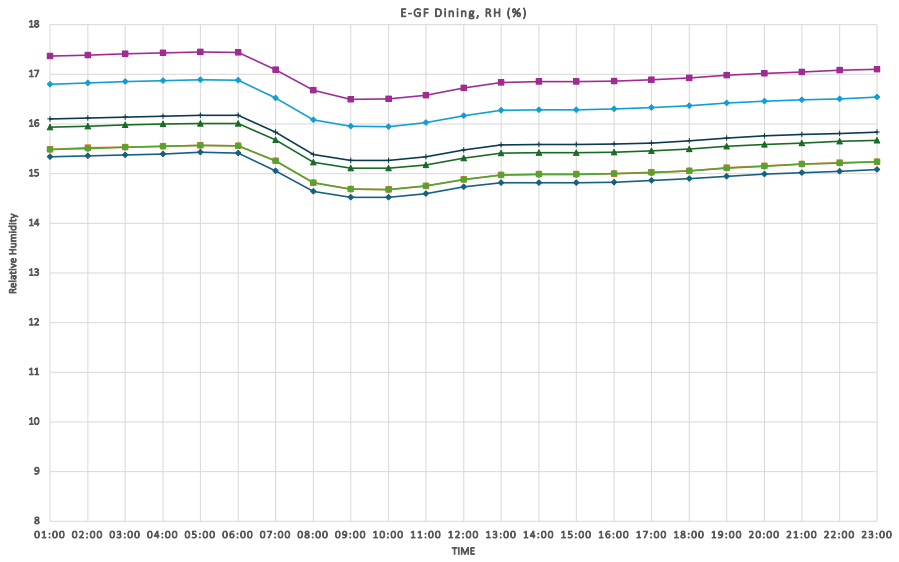
The Free-running Simulation of Hourly Relative Humidity in The Base Case Building Zones After Applying Various Energy Efficiency Measures for Glazing by Vacuum Insulated Glass Product series. (15th July).

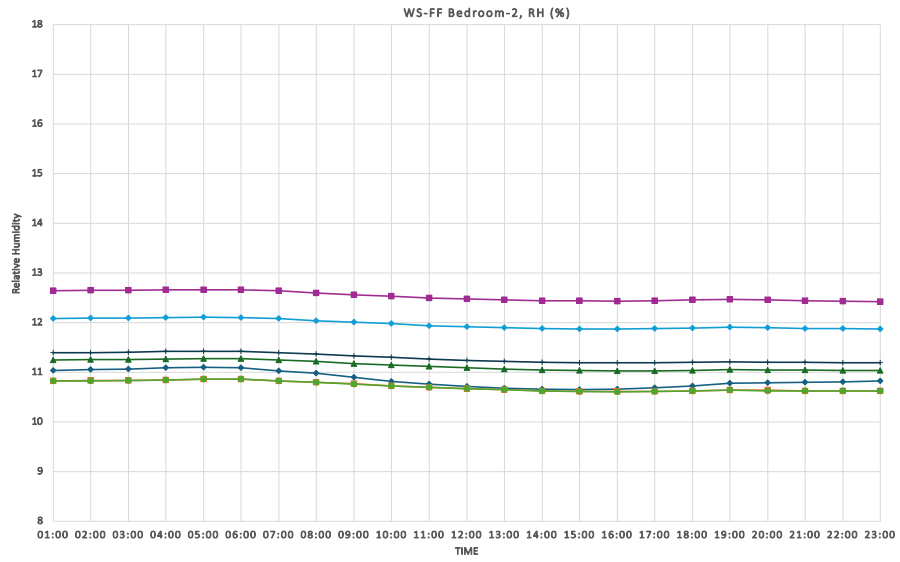
Ground Floor

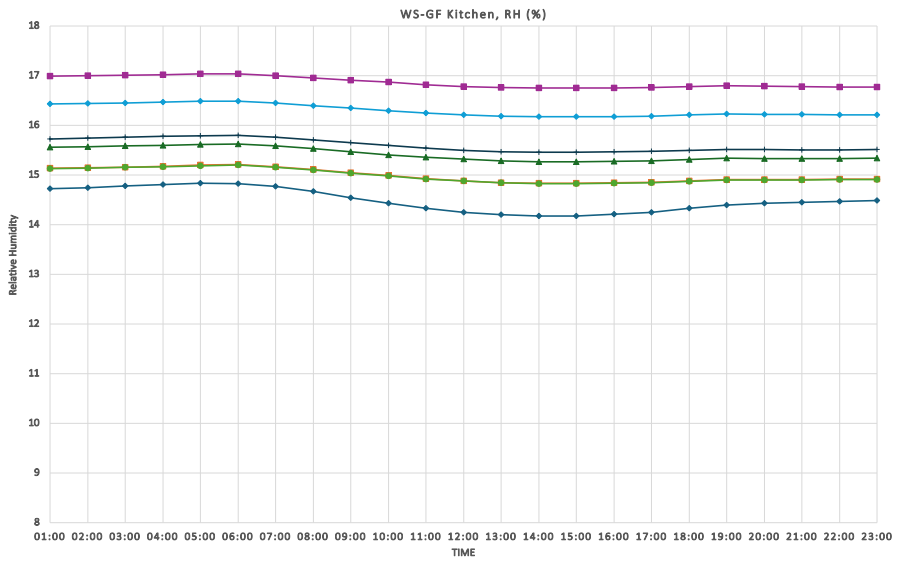


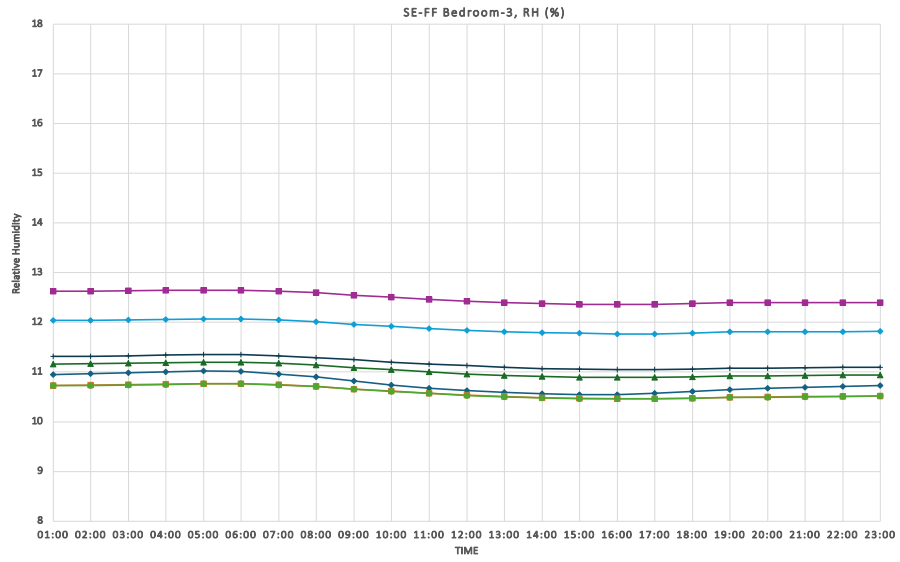
First Floor

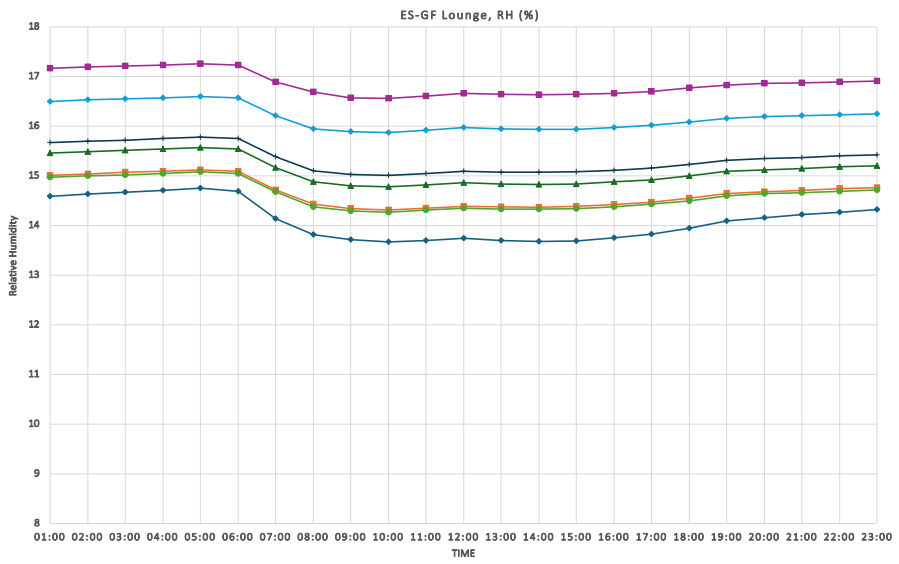


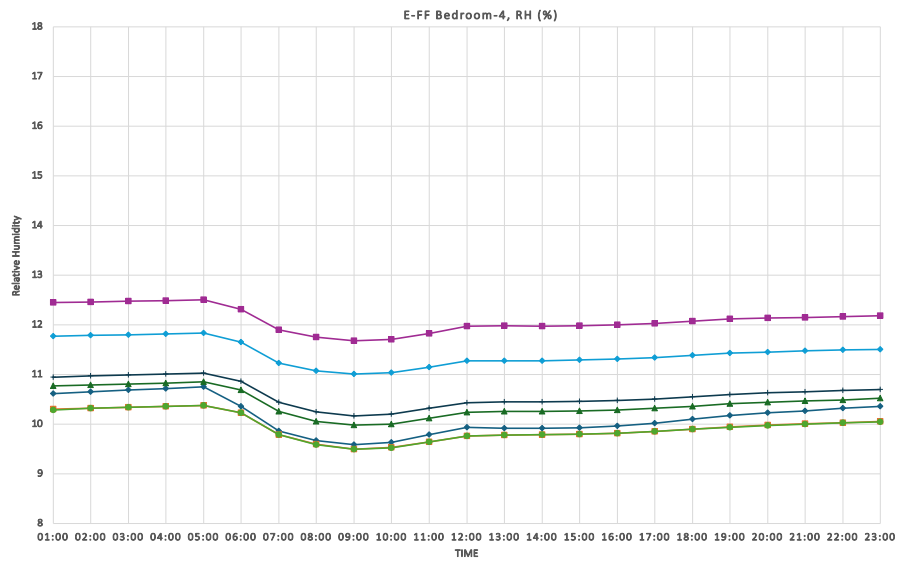


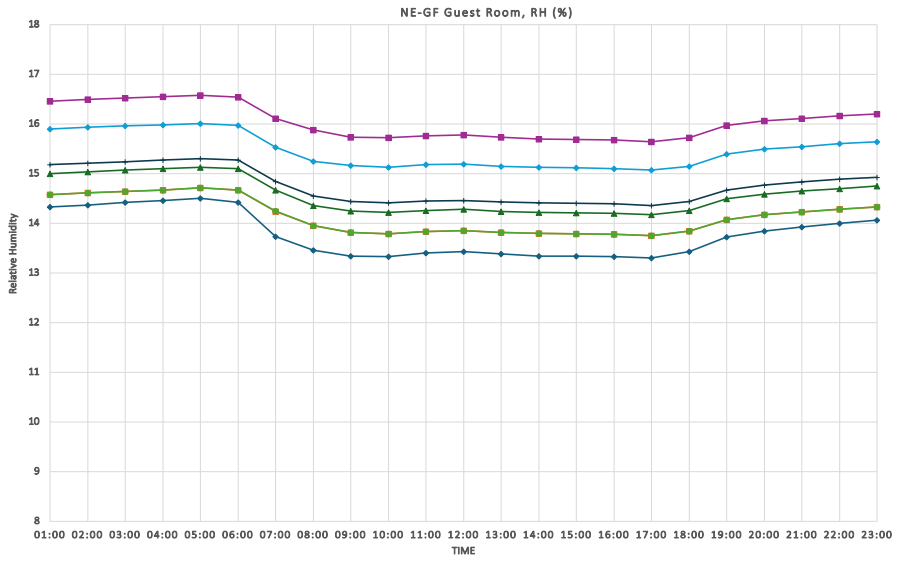


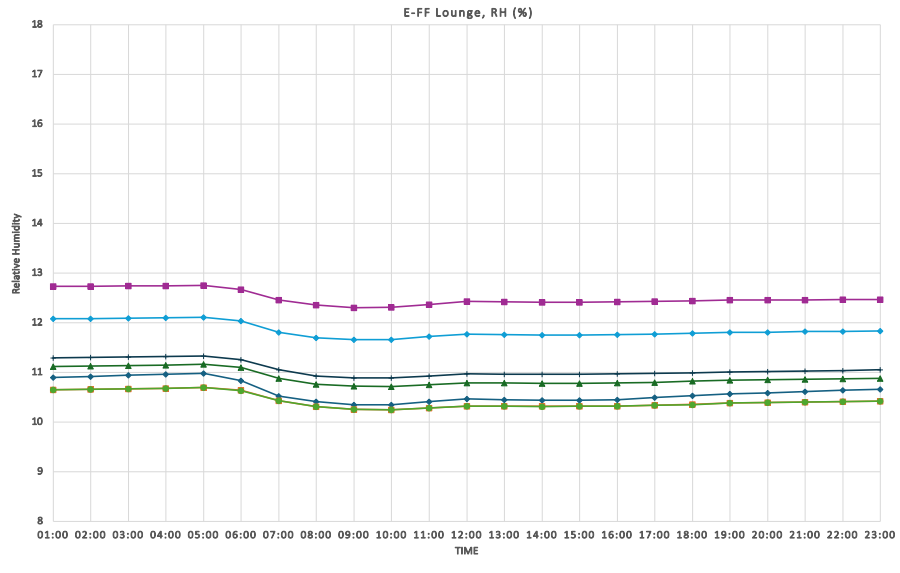












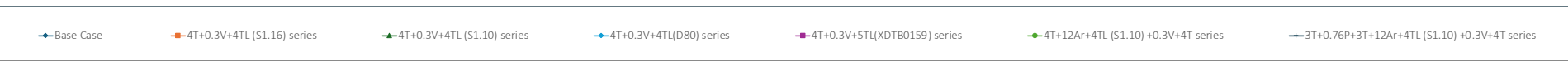


Figure A-3. 16. The Free-Running Simulation of Hourly RH in The Base Case Building Zones After Applying Various Energy Efficiency Measures for Glazing by Vacuum Insulated Glass Product series. (15th July).

Appendix 4: Detailed Parameters and Outcomes of Optimal Strategic Solutions Evaluated and Implemented Across the Climate Zones of Saudi Arabia.

Table A4- 1.Details of Parameters and Variables for Optimal Strategic Solutions Evaluated in the Optimisation Analysis.

Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Construction	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
38	1	Optimal Strategics	Base Case	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	20432.50	1474.65
44	2	Optimal Strategics	Base Case	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	19076.13	1580.58
138	9	Optimal Strategics	Base Case	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	22363.34	1384.52
42	1	Optimal Strategics	Standard Courtyard	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17738.18	585.29
112	7	Optimal Strategics	Standard Courtyard	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16700.93	598.90
65	3	Optimal Strategics	Semi-open Courtyard	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16378.88	581.13
71	3	Optimal Strategics	Semi-open Courtyard	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17343.49	564.84
62	3	Optimal Strategics	Sunshade Courtyard	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17412.61	561.76
103	7	Optimal Strategics	Sunshade Courtyard	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16441.76	584.41
61	2	Optimal Strategics	Upward Contracted Courtyard	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18376.75	706.61
135	9	Optimal Strategics	Upward Contracted Courtyard	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17319.33	709.14
21	0	Optimal Strategics	Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	19082.39	767.84
38	1	Optimal Strategics	Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	50mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	19413.26	762.43
39	1	Optimal Strategics	Wood Mashrabiya	4T+0.3V+4TL (S1.10) series	60mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18645.27	779.46
57	2	Optimal Strategics	Wood Mashrabiya	4T+0.3V+4TL (S1.10) series	50mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18841.25	773.99

Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Construction	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
58	2	Optimal Strategics	Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16956.30	845.28
64	3	Optimal Strategics	Wood Mashrabiya	4T+0.3V+4TL (S1.16) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	19083.11	766.47
87	4	Optimal Strategics	Wood Mashrabiya	4T+0.3V+4TL(D80) series	60mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17103.34	839.98
96	5	Optimal Strategics	Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16153.53	874.14
108	6	Optimal Strategics	Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Multi Aerogel Blanket	17327.54	838.41
124	8	Optimal Strategics	Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18131.01	800.30
131	9	Optimal Strategics	Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	60mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18284.00	795.07
139	10	Optimal Strategics	Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	50mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18457.24	783.93
145	10	Optimal Strategics	Wood Mashrabiya	4T+0.3V+4TL(D80) series	60mm Vacuum Insulation Panels	70mm Vacuum Insulation Panels	17446.17	832.47
6	0	Optimal Strategics	Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	70mm Vacuum Insulation Panels	17299.66	840.34
47	3	Optimal Strategics	Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	60mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18279.19	797.66
48	3	Optimal Strategics	Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16147.27	874.19
60	4	Optimal Strategics	Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	60mm Vacuum Insulation Panels	70mm Vacuum Insulation Panels	18610.96	787.12
61	4	Optimal Strategics	Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	60mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16293.22	872.89
81	5	Optimal Strategics	Aluminium Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	60mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	19209.66	769.98
88	6	Optimal Strategics	Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	60mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17109.15	842.62
91	6	Optimal Strategics	Aluminium Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	19074.37	770.02
129	11	Optimal Strategics	Aluminium Mashrabiya	4T+0.3V+4TL (S1.10) series	60mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18645.04	772.79
136	12	Optimal Strategics	Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	60mm Vacuum Insulation Panels	140mm Multi Aerogel Blanket	17470.62	839.96

Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Construction	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
140	13	Optimal Strategics	Aluminium Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	50mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	19397.07	760.56
151	14	Optimal Strategics	Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	50mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18468.71	791.95
152	14	Optimal Strategics	Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18136.00	803.40
160	15	Optimal Strategics	Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	200mm XPS Boards Insulation	140mm Vacuum Insulation Panels	18546.71	789.71
178	18	Optimal Strategics	Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	50mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16502.68	872.08
2	0	Optimal Strategics	GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	70mm Vacuum Insulation Panels	17347.41	833.89
3	0	Optimal Strategics	GRC Mashrabiya	4T+0.3V+4TL(D80) series	60mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17149.36	838.85
24	0	Optimal Strategics	GRC Mashrabiya	4T+0.3V+4TL (S1.10) series	50mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18909.79	776.75
25	0	Optimal Strategics	GRC Mashrabiya	4T+0.3V+4TL (S1.10) series	60mm Vacuum Insulation Panels	70mm Vacuum Insulation Panels	19047.82	773.62
26	0	Optimal Strategics	GRC Mashrabiya	4T+0.3V+4TL (S1.10) series	60mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18711.29	780.53
44	1	Optimal Strategics	GRC Mashrabiya	4T+0.3V+4TL (S1.10) series	70mm Vacuum Insulation Panels	70mm Vacuum Insulation Panels	18905.58	776.99
45	1	Optimal Strategics	GRC Mashrabiya	4T+0.3V+4TL (S1.10) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18572.06	783.09
50	2	Optimal Strategics	GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	60mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18333.62	785.53
89	5	Optimal Strategics	GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18199.96	805.23
95	5	Optimal Strategics	GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17003.48	843.62
152	12	Optimal Strategics	GRC Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	19148.07	761.51
155	12	Optimal Strategics	GRC Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16184.85	862.94
205	21	Optimal Strategics	GRC Mashrabiya	4T+0.3V+4TL (S1.16) series	50mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	19476.93	759.35
223	26	Optimal Strategics	GRC Mashrabiya	4T+0.3V+4TL(D80) series	200mm XPS Boards Insulation	140mm Vacuum Insulation Panels	17426.75	830.65

Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Construction	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
98	4	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14817.53	713.28
127	6	Optimal Strategics	Standard Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14903.96	703.43
151	8	Optimal Strategics	Standard Courtyard + GRC Mashrabiya	4T+0.3V+4TL (S1.16) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16249.04	629.32
165	10	Optimal Strategics	Standard Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15562.45	643.78
191	12	Optimal Strategics	Standard Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14847.57	711.82
221	14	Optimal Strategics	Standard Courtyard + GRC Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16237.84	631.86
228	16	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15520.69	646.07
275	20	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14324.65	768.53
276	20	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16137.63	633.32
37	1	Optimal Strategics	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14846.59	712.33
44	1	Optimal Strategics	Semi-open Courtyard + Aluminium Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16184.74	631.54
65	3	Optimal Strategics	Semi-open Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15560.68	649.36
126	6	Optimal Strategics	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14350.44	761.95
140	8	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15519.52	649.72
153	8	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16136.10	634.78
171	10	Optimal Strategics	Semi-open Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15605.02	642.08
207	13	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14818.34	717.89
243	16	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	4T+0.3V+4TL (S1.16) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16149.06	634.15
284	20	Optimal Strategics	Semi-open Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14904.28	705.25

Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Construction	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
37	2	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14817.36	716.53
41	2	Optimal Strategics	Sunshade Courtyard + Aluminium Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16180.66	633.93
63	3	Optimal Strategics	Sunshade Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14349.49	765.80
108	7	Optimal Strategics	Sunshade Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15556.54	643.31
119	7	Optimal Strategics	Sunshade Courtyard + GRC Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16241.04	629.81
128	8	Optimal Strategics	Sunshade Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14846.49	709.86
134	8	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14326.97	770.17
172	11	Optimal Strategics	Sunshade Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15605.64	640.86
190	12	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+4TL (S1.16) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16148.93	635.57
199	13	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15516.79	651.90
212	14	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16135.80	636.65
4	0	Optimal Strategics	Narrow Upper Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14960.91	833.03
80	4	Optimal Strategics	Narrow Upper Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15473.15	787.54
100	5	Optimal Strategics	Narrow Upper Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15519.40	783.43
127	7	Optimal Strategics	Narrow Upper Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	15445.21	790.06
129	7	Optimal Strategics	Narrow Upper Courtyard + Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14931.42	839.67
140	8	Optimal Strategics	Narrow Upper Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16274.61	738.65
156	9	Optimal Strategics	Narrow Upper Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16194.59	745.29
176	11	Optimal Strategics	Narrow Upper Courtyard + GRC Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16933.32	726.90

Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Construction	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
196	13	Optimal Strategics	Narrow Upper Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16825.54	728.41

Table A4- 2. Details of Parameters, Variables, and Performance for Optimal Final Strategic Solutions Across Different Saudi Climate Zones.

The location	Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Insulation Type	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
TABUK	77	3	Optimal Strategics	Standard Courtyard	4T+0.3V+4TL(D80) series (3)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14762.83	500.44
TABUK	4	0	Optimal Strategics	Standard Courtyard	4T+0.3V+5TL(XDTB0159) series (4)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13725.20	523.65
TABUK	73	4	Optimal Strategics	Semi-open Courtyard	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13430.08	508.97
TABUK	82	4	Optimal Strategics	Semi-open Courtyard	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14390.93	481.70
TABUK	54	2	Optimal Strategics	Sunshade Courtyard	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14470.03	485.01
TABUK	115	8	Optimal Strategics	Sunshade Courtyard	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13490.97	509.41
TABUK	91	5	Optimal Strategics	Upward Contracted Courtyard	4T+0.3V+5TL(XDTB0159) series (4)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	14225.69	594.07
TABUK	169	10	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series (3)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	11821.51	738.29
TABUK	285	23	Optimal Strategics	Standard Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series (3)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	11892.11	731.16
TABUK	209	14	Optimal Strategics	Standard Courtyard + GRC Mashrabiya	4T+0.3V+4TL (S1.16) series (1)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13164.32	559.61
TABUK	147	9	Optimal Strategics	Standard Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series6	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	12549.47	627.74
TABUK	122	7	Optimal Strategics	Standard Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series (3)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	11853.72	736.61
TABUK	98	5	Optimal Strategics	Standard Courtyard + GRC Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series (5)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13156.34	549.16
TABUK	163	10	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series6	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	12506.66	636.76
TABUK	145	8	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series (4)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	11365.04	813.53

The location	Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Insulation Type	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
TABUK	45	1	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series (5)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13054.38	568.13
TABUK	21	0	Optimal Strategics	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	11850.70	729.87
TABUK	291	23	Optimal Strategics	Semi-open Courtyard + Aluminium Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13095.49	568.42
TABUK	149	9	Optimal Strategics	Semi-open Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	12545.78	628.93
TABUK	169	10	Optimal Strategics	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	11389.60	807.90
TABUK	240	17	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	12509.07	640.22
TABUK	187	11	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13052.52	575.12
TABUK	192	12	Optimal Strategics	Semi-open Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	12599.45	624.16
TABUK	73	3	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	11822.62	737.30
TABUK	242	17	Not Optimal	Semi-open Courtyard + Wood Mashrabiya	4T+0.3V+4TL (S1.16) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13058.70	578.69
TABUK	181	11	Not Optimal	Semi-open Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	11894.70	731.95
TABUK	165	10	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	11822.41	737.05
TABUK	62	2	Optimal Strategics	Sunshade Courtyard + Aluminium Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13094.78	567.09
TABUK	60	2	Optimal Strategics	Sunshade Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	11391.00	810.32
TABUK	80	4	Optimal Strategics	Sunshade Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	12548.59	628.37
TABUK	103	5	Optimal Strategics	Sunshade Courtyard + GRC Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13155.91	557.18
TABUK	41	1	Not Optimal	Sunshade Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	11849.70	738.85
TABUK	148	9	Not Optimal	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	12725.05	624.64

The location	Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Insulation Type	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
TABUK	144	9	Optimal Strategics	Sunshade Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	12598.60	623.90
TABUK	138	8	Not Optimal	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+4TL (S1.16) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13057.48	574.30
TABUK	243	18	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	12508.59	637.16
TABUK	221	15	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13053.25	570.31
TABUK	95	5	Optimal Strategics	Narrow Upper Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	12403.01	777.78
TABUK	195	14	Optimal Strategics	Narrow Upper Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	12444.24	771.44
TABUK	113	6	Optimal Strategics	Narrow Upper Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	12370.19	783.57
TABUK	183	12	Optimal Strategics	Narrow Upper Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13176.25	641.65
TABUK	120	6	Optimal Strategics	Narrow Upper Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13076.43	663.93
TABUK	85	4	Optimal Strategics	Narrow Upper Courtyard + GRC Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13759.96	609.01
TABUK	57	2	Optimal Strategics	Narrow Upper Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	13645.02	615.49
ABHA	73	3	Optimal Strategics	Standard Courtyard	4T+0.3V+4TL(D80) series (3)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	8450.97	2425.46
ABHA	95	5	Optimal Strategics	Standard Courtyard	4T+0.3V+5TL(XDTB0159) series (4)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7742.53	2549.58
ABHA	35	1	Optimal Strategics	Semi-open Courtyard	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7565.72	2622.14
ABHA	143	8	Optimal Strategics	Semi-open Courtyard	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	8174.43	2490.71
ABHA	153	8	Optimal Strategics	Sunshade Courtyard	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	8256.18	2455.11
ABHA	206	14	Optimal Strategics	Sunshade Courtyard	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7591.35	2612.46
ABHA	51	2	Not Optimal	Upward Contracted Courtyard	4T+0.3V+5TL(XDTB0159) series (4)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	8559.45	2751.07

The location	Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Insulation Type	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
ABHA	142	7	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series (3)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	6531.51	3232.17
ABHA	564	56	Not Optimal	Standard Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series (3)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	6539.67	3244.77
ABHA	292	18	Optimal Strategics	Standard Courtyard + GRC Mashrabiya	4T+0.3V+4TL (S1.16) series (1)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7381.43	2731.83
ABHA	580	60	Optimal Strategics	Standard Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series6	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7005.22	2878.67
ABHA	279	17	Optimal Strategics	Standard Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series (3)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	6544.54	3208.25
ABHA	183	9	Not Optimal	Standard Courtyard + GRC Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series (5)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7388.44	2731.95
ABHA	529	48	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series6	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	6981.22	2890.25
ABHA	315	20	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series (4)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	6212.67	3433.67
ABHA	44	1	Not Optimal	Standard Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series (5)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7307.06	2762.21
ABHA	267	17	Not Optimal	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	6553.18	3228.67
ABHA	403	31	Optimal Strategics	Semi-open Courtyard + Aluminium Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7338.75	2738.71
ABHA	67	3	Optimal Strategics	Semi-open Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7007.39	2878.37
ABHA	51	2	Optimal Strategics	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7336.64	2751.94
ABHA	86	4	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	6981.89	2899.21
ABHA	295	19	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	6207.53	3430.93
ABHA	124	6	Optimal Strategics	Semi-open Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7049.86	2858.24
ABHA	237	14	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	6525.88	3226.38
ABHA	316	21	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	4T+0.3V+4TL (S1.16) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7296.23	2760.87

The location	Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Insulation Type	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
ABHA	132	6	Optimal Strategics	Semi-open Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	6576.22	3199.86
ABHA	258	16	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	6520.74	3215.30
ABHA	81	3	Optimal Strategics	Sunshade Courtyard + Aluminium Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7338.06	2734.43
ABHA	236	14	Optimal Strategics	Sunshade Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	6229.55	3420.96
ABHA	239	15	Optimal Strategics	Sunshade Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7010.78	2878.22
ABHA	61	2	Not Optimal	Sunshade Courtyard + GRC Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7339.79	2766.27
ABHA	157	8	Not Optimal	Sunshade Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	6544.49	3218.93
ABHA	190	11	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	6209.40	3427.34
ABHA	196	12	Optimal Strategics	Sunshade Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7042.94	2852.34
ABHA	260	16	Not Optimal	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+4TL (S1.16) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7259.72	2806.06
ABHA	211	13	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	6983.11	2884.69
ABHA	144	7	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7304.63	2764.90
ABHA	351	23	Not Optimal	Narrow Upper Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7376.27	3291.58
ABHA	145	7	Not Optimal	Narrow Upper Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7368.52	3349.57
ABHA	488	37	Not Optimal	Narrow Upper Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7311.16	3264.24
ABHA	418	28	Not Optimal	Narrow Upper Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7884.95	2992.01
ABHA	522	42	Not Optimal	Narrow Upper Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	7757.72	2954.35
ABHA	584	50	Not Optimal	Narrow Upper Courtyard + GRC Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	8164.85	2811.14

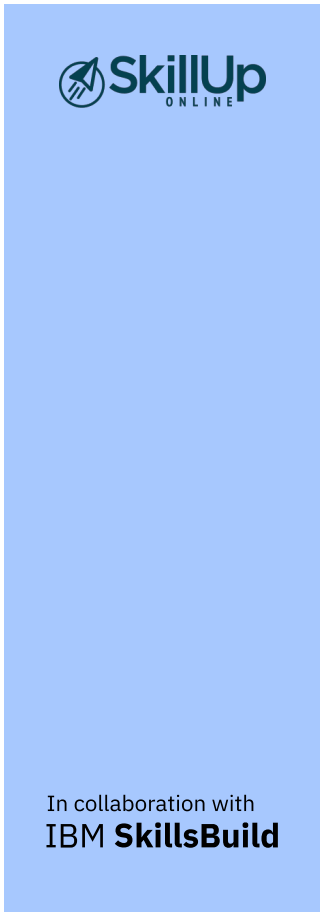
The location	Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Insulation Type	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
ABHA	324	21	Not Optimal	11Narrow Upper Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	8141.09	2860.91
Dammam	44	1	Optimal Strategics	Standard Courtyard	4T+0.3V+4TL(D80) series (3)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	19983.50	723.26
Dammam	0	0	Optimal Strategics	Standard Courtyard	4T+0.3V+5TL(XDTB0159) series (4)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18828.23	731.34
Dammam	83	4	Optimal Strategics	Semi-open Courtyard	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18514.64	722.25
Dammam	55	2	Optimal Strategics	Semi-open Courtyard	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	19578.52	708.50
Dammam	57	2	Optimal Strategics	Sunshade Courtyard	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	19668.26	710.65
Dammam	48	2	Optimal Strategics	Sunshade Courtyard	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18580.95	723.26
Dammam	29	1	Optimal Strategics	Upward Contracted Courtyard	4T+0.3V+5TL(XDTB0159) series (4)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	19512.18	757.70
Dammam	134	7	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series (3)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16745.93	756.31
Dammam	176	10	Not Optimal	Standard Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series (3)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16831.06	753.93
Dammam	210	13	Not Optimal	Standard Courtyard + GRC Mashrabiya	4T+0.3V+4TL (S1.16) series (1)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18282.93	751.07
Dammam	17	0	Optimal Strategics	Standard Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series6	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17522.82	740.90
Dammam	207	13	Optimal Strategics	Standard Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series (3)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16777.01	752.96
Dammam	231	15	Not Optimal	Standard Courtyard + GRC Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series (5)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18494.74	772.59
Dammam	87	4	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series6	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17480.73	746.73
Dammam	191	11	Optimal Strategics	Standard Courtyard + Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series (4)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16205.53	782.58
Dammam	122	6	Not Optimal	Standard Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series (5)	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18147.21	751.63
Dammam	108	5	Optimal Strategics	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16776.74	753.02

The location	Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Insulation Type	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
Dammam	237	15	Not Optimal	Semi-open Courtyard + Aluminium Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18192.90	750.42
Dammam	166	10	Not Optimal	Semi-open Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17521.54	744.03
Dammam	160	9	Not Optimal	Semi-open Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16466.52	803.59
Dammam	194	12	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17482.29	743.23
Dammam	279	19	Not Optimal	Semi-open Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18144.04	750.47
Dammam	144	8	Not Optimal	Semi-open Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17577.54	746.38
Dammam	196	12	Optimal Strategics	Semi-open Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16742.50	755.63
Dammam	249	16	Not Optimal	Semi-open Courtyard + Wood Mashrabiya	4T+0.3V+4TL (S1.16) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18156.79	751.49
Dammam	276	19	Not Optimal	Semi-open Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17060.34	778.26
Dammam	176	11	Not Optimal	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16976.97	775.84
Dammam	103	5	Not Optimal	Sunshade Courtyard + Aluminium Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18419.01	774.59
Dammam	160	9	Optimal Strategics	Sunshade Courtyard + Aluminium Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16226.26	774.12
Dammam	201	13	Not Optimal	Sunshade Courtyard + Aluminium Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17520.14	744.31
Dammam	214	13	Not Optimal	Sunshade Courtyard + GRC Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18266.21	751.25
Dammam	102	5	Optimal Strategics	Sunshade Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16779.96	751.81
Dammam	162	9	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+5TL(XDTB0159) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	16204.87	779.25
Dammam	216	14	Not Optimal	Sunshade Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17582.17	745.55
Dammam	219	14	Not Optimal	Sunshade Courtyard + Wood Mashrabiya	4T+0.3V+4TL (S1.16) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18157.92	751.43

The location	Iteration	Generation	Category	Parameter	Glazing type	External Wall Insulation Type with (EIFS)	Flat Roof Insulation Type	Cooling energy (kWh)	Discomfort (All Clothing) (hr)
Dammam	167	10	Optimal Strategics	Sunshade Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17481.60	743.49
Dammam	220	14	Not Optimal	Sunshade Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18145.33	754.53
Dammam	265	19	Optimal Strategics	Narrow Upper Courtyard + Aluminium Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17463.65	786.68
Dammam	211	15	Optimal Strategics	Narrow Upper Courtyard + GRC Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17517.10	786.42
Dammam	43	2	Optimal Strategics	Narrow Upper Courtyard + Wood Mashrabiya	4T+0.3V+4TL(D80) series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	17428.20	787.71
Dammam	144	8	Not Optimal	Narrow Upper Courtyard + GRC Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18319.42	777.45
Dammam	237	17	Optimal Strategics	Narrow Upper Courtyard + Wood Mashrabiya	3T+0.76P+3T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18205.71	773.14
Dammam	267	19	Not Optimal	Narrow Upper Courtyard + GRC Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	19037.45	779.89
Dammam	251	18	Not Optimal	Narrow Upper Courtyard + Wood Mashrabiya	4T+12Ar+4TL (S1.10) +0.3V+4T series	70mm Vacuum Insulation Panels	140mm Vacuum Insulation Panels	18904.80	778.01

Appendix 3: Course Certificates





October 7th, 2024 - December 20th, 2024
Completion certificate presented to

Abdullah Alshabanat

For successful completion of Guided Learning Experience in Data Analytics and submission of the final capstone project in 2024

Ana Gaspar
Learning Delivery Portfolio Manager

IBM **SkillsBuild** Completion Certificate

This certificate is presented to

Abdullah Alshabanat

for the completion of

Project Based Learning Programme in Data Analysis| October 2024

(PLAN-339642202411)

According to the Your Learning Builder - Plans system of record

Completion date: 23 Oct 2024 (GMT)

IBM **SkillsBuild**

Data Fundamentals

ISSUED TO

Abdullah Alshabanat



Issued on: 23 OCT 2024 | Issued by: IBM SkillsBuild
Verify: https://www.credly.com/go/Hvy2mUbd

Certificate produced on: 22 June 2023

University of Nottingham
UK | CHINA | MALAYSIA

Certificate of Attendance

Mr Abdullah Alshabanat

has completed the following training course(s)

Course Name	Course Date(s)	Sessions in course	Sessions Attended
Qualitative Methods in Practice: Elite Interviewing	03-05-2023	0.5	1

Professor Lucy Donaldson
Associate Pro-Vice Chancellor for the Researcher Academy and Research Career Development

Mr Richard Cowley
Co-Director of Professional Development

This Certificate of Attendance is issued by the University of Nottingham, for attendance at short courses. One training point is equivalent to half a day of tutor contact time or independent study.

Certificate produced on: 1 July 2022

University of Nottingham
UK | CHINA | MALAYSIA

Certificate of Attendance

Mr Abdullah Alshabanat

has completed the following training course(s)

Course Name	Course Date(s)	Training Units obtained	Sessions in course	Sessions Attended
Research integrity: concise (standalone online learning course)	01-10-2021	0.00	0	1

Professor Lucy Donaldson
Associate Pro-Vice Chancellor for the Researcher Academy and Research Career Development

Mr Richard Cowley
Co-Director of Professional Development

This Certificate of Attendance is issued by the University of Nottingham, for attendance at short courses. One training point is equivalent to half a day of tutor contact time or independent study.

Certificate produced on: 28 July 2022

University of Nottingham
UK | CHINA | MALAYSIA

Certificate of Attendance

Mr Abdullah Alshabanat
has completed the following training course
Research integrity: comprehensive (standalone online learning course) on the 01-10-2021
and receives 0.00 training unit(s)

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr Richard Cowley
Co-Director of Professional Development

This Certificate of Attendance is issued by the University of Nottingham, for attendance at short courses. One training point is equivalent to half a day of tutor contact time or independent study.

Certificate produced on: 9 June 2023

University of Nottingham
UK | CHINA | MALAYSIA

Certificate of Attendance

Mr Abdullah Alshabanat
has completed the following training course
Getting Started with Mixed Methods Research (webinar) on the 01-06-2023

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr Richard Cowley
Co-Director of Professional Development

This Certificate of Attendance is issued by the University of Nottingham, for attendance at short courses.

Certificate produced on: 2 May 2023

University of Nottingham
UK | CHINA | MALAYSIA

Certificate of Attendance

Mr Abdullah Alshabanat
has completed the following training course
Preparing for your Viva (Webinar) on the 26-04-2023

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr Richard Cowley
Co-Director of Professional Development

This Certificate of Attendance is issued by the University of Nottingham, for attendance at short courses.

Certificate produced on: 10 July 2023

University of Nottingham
UK | CHINA | MALAYSIA

Certificate of Attendance

Mr Abdullah Alshabanat
has completed the following training course
Research Data Management (standalone online learning course)
and receives 1.00 training unit(s)

Professor Lucy Donaldson
Associate Pro-Vice Chancellor for the Researcher Academy and Research Career Development

Mr Richard Cowley
Co-Director of Professional Development

This Certificate of Attendance is issued by the University of Nottingham, for attendance at short courses. One training point is equivalent to half a day of tutor contact time or independent study.

Certificate produced on: 15 June 2022

University of Nottingham
UK | CHINA | MALAYSIA

Certificate of Attendance

Mr Abdullah Alshabanat
has completed the following training course
Structuring Your Thesis (face to face) on the 12-05-2022
and receives 0.00 training unit(s)

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr Richard Cowley
Co-Director of Professional Development

This Certificate of Attendance is issued by the University of Nottingham, for attendance at short courses. One training point is equivalent to half a day of tutor contact time or independent study.

Certificate produced on: 15 June 2022

University of Nottingham
UK | CHINA | MALAYSIA

Certificate of Attendance

Mr Abdullah Alshabanat
has completed the following training course
Where to publish: Tools to help you choose (online) on the 19-05-2022
and receives 0.00 training unit(s)

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr Richard Cowley
Co-Director of Professional Development

This Certificate of Attendance is issued by the University of Nottingham, for attendance at short courses. One training point is equivalent to half a day of tutor contact time or independent study.

Certificate produced on: 15 June 2022

University of Nottingham
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Certificate of Attendance

Mr Abdullah Alshabanat
has completed the following training course
Qualitative Methods in Practice: Interdisciplinary Research (online) on the 08-06-2022
and receives 0.00 training unit(s)

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr Richard Cowley
Co-Director of Professional Development

This Certificate of Attendance is issued by the University of Nottingham, for attendance at short courses. One training point is equivalent to half a day of tutor contact time or independent study.

Certificate produced on: 15 June 2022

University of Nottingham
UK | CHINA | MALAYSIA

Certificate of Course Completion

Mr Abdullah Alshabanat
has completed the following training course
Project Management: Support & Benefits Realisation (Online Course)
with the following result:

Passed

on

17/05/2022 11:17:09

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr. Richard Cowley
Co-Director of Professional Development

This Certificate of Course Completion is issued by the University of Nottingham, for completing an online course.

Certificate produced on: 15 June 2022

University of Nottingham
UK | CHINA | MALAYSIA

Certificate of Course Completion

Mr Abdullah Alshabanat
has completed the following training course
Project Management: Training & Business Readiness (Online Course)
with the following result:

Passed

on

17/05/2022 11:18:45

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr. Richard Cowley
Co-Director of Professional Development

This Certificate of Course Completion is issued by the University of Nottingham, for completing an online course.

Certificate produced on: 15 June 2022

University of Nottingham
UK | CHINA | MALAYSIA

Certificate of Course Completion

Mr Abdullah Alshabanat
has completed the following training course
Win-Win Negotiations for Conflict Resolution (Online Course)
with the following result:

Passed

on

16/05/2022 18:53:25

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr. Richard Cowley
Co-Director of Professional Development

This Certificate of Course Completion is issued by the University of Nottingham, for completing an online course.

Certificate produced on: 15 June 2022

University of Nottingham
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Certificate of Course Completion

Mr Abdullah Alshabanat

has completed the following training course
Thomas-Kilmann Conflict Model (Online Course)
with the following result:

Passed

on

16/05/2022 20:56:58

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr. Richard Cowley
Co-Director of Professional Development

This Certificate of Course Completion is issued by the University of Nottingham, for completing an online course.

Certificate produced on: 15 June 2022

University of Nottingham
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Certificate of Course Completion

Mr Abdullah Alshabanat

has completed the following training course
The Public Speaking Guru Confidence Builder (Online Course)
with the following result:

Passed

on

16/05/2022 20:57:29

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr. Richard Cowley
Co-Director of Professional Development

This Certificate of Course Completion is issued by the University of Nottingham, for completing an online course.

Certificate produced on: 15 June 2022

University of Nottingham
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Certificate of Course Completion

Mr Abdullah Alshabanat

has completed the following training course
Negotiation and Influencing People (Online Course with Assessment)
with the following result:

Passed

on

16/05/2022 20:57:20

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr. Richard Cowley
Co-Director of Professional Development

This Certificate of Course Completion is issued by the University of Nottingham, for completing an online course.

Certificate produced on: 15 June 2022

University of Nottingham
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Certificate of Course Completion

Mr Abdullah Alshabanat

has completed the following training course
Conflict Management (Online Course)
with the following result:

Passed

on

16/05/2022 18:55:09

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr. Richard Cowley
Co-Director of Professional Development

This Certificate of Course Completion is issued by the University of Nottingham, for completing an online course.

Certificate produced on: 15 June 2022

University of Nottingham
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Certificate of Course Completion

Mr Abdullah Alshabanat

has completed the following training course
Decision-Making Excellence (Online Course)
with the following result:

Passed

on

16/05/2022 18:53:03

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr. Richard Cowley
Co-Director of Professional Development

This Certificate of Course Completion is issued by the University of Nottingham, for completing an online course.

Certificate produced on: 15 June 2022

University of Nottingham
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Certificate of Course Completion

Mr Abdullah Alshabanat

has completed the following training course
Understanding Successful Negotiation (Online Course)
with the following result:

Passed

on

16/05/2022 18:53:13

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr. Richard Cowley
Co-Director of Professional Development

This Certificate of Course Completion is issued by the University of Nottingham, for completing an online course.

Certificate produced on: 15 June 2022

University of Nottingham
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Certificate of Course Completion

Mr Abdullah Alshabanat

has completed the following training course
Top 10 Mistakes of Managers (Online Course)
with the following result:

Passed

on

16/05/2022 18:54:45

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr. Richard Cowley
Co-Director of Professional Development

This Certificate of Course Completion is issued by the University of Nottingham, for completing an online course.

Certificate produced on: 15 June 2022

University of Nottingham
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Certificate of Course Completion

Mr Abdullah Alshabanat

has completed the following training course
Project Management: Project Strategy & Business Case (Online Course)
with the following result:

Passed

on

17/05/2022 11:19:06

Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

Mr. Richard Cowley
Co-Director of Professional Development

This Certificate of Course Completion is issued by the University of Nottingham, for completing an online course.

Certificate produced on: 15 June 2022

University of Nottingham
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Certificate of Course Completion

Mr Abdullah Alshabanat

has completed the following training course
Project Management: Project Design (Online Course)
with the following result:

Passed

on

18/05/2022 11:57:32

L Donaldson
Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

R Cowley
Mr. Richard Cowley
Co-Director of Professional Development

This Certificate of Course Completion is issued by the University of Nottingham, for completing an online course.

Certificate produced on: 15 June 2022

University of Nottingham
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Certificate of Attendance

Mr Abdullah Alshabanat
has completed the following training course
Literature Searching and the Literature Review - online standalone course
(2021/22) on the 01-10-2021
and receives 0.00 training unit(s)

L Donaldson
Professor Lucy Donaldson
Associate Pro-Vice-Chancellor for the Researcher Academy and Researcher Career Development

R Cowley
Mr Richard Cowley
Co-Director of Professional Development

This Certificate of Attendance is issued by the University of Nottingham, for attendance at short courses. One training point is equivalent to half a day of tutor contact time or independent study.