

***FAÇADE RETROFIT STRATEGIES FOR ENERGY EFFICIENCY
IMPROVEMENT CONSIDERING THE HOT CLIMATIC CONDITIONS
OF SAUDI ARABIA***

BY
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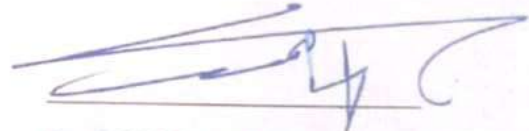
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Greetings to all the hope shining beacons in the midst of my darkness

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In the intricate tapestry of my academic journey, my deepest gratitude extends to Allah Almighty, the guiding light throughout my life.

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LIST OF ABBREVIATIONS

AC: Air Conditioner

APSC: Advance Passive Solar Collector

ASTFs: Active Solar Thermal Façades

BIPVT-DSF: Building-Integrated Photovoltaic Double-Skin Façade

DSFs: Double Skin Façades

DSS: Decision Support Systems

EC: Electrochromic

EMS: Energy Management System

ETFE: Ethylene Tetrafluoroethylene

ETICS: External Thermal Insulation Composite System

EUI: Energy Usage Intensity

FC: Fiber Cement Board

GC: Gas Chromic

ICB: Insulation Cork Boards

IEQ: Indoor Environment Quality

IR: Infrared Rays

IGU: Insulated Glass Units

MCDM: Multicriteria Decision-Making

MDF: Medium-Density Fiberboard

MEEFS: Multi-Functional Energy-Efficient Façade Systems

PCM: Phase Change Material

PET: Polyethylene Terephthalate

PUR: Polyurethane

PV-DSF: Photovoltaic Insulated Glazing Unit

PV-IGU: Double Envelope Combined with Photovoltaic Cells

REC: Renewable Sources

SHGC: Solar Heat Gain Coefficient

TPC: Transparency Photovoltaic Coating

VU TU: Ventilation Units Technical Unit

ABSTRACT

Full Name : [WESAM AHMAD HUSSEIN RABABA]
Thesis Title : [Facade Retrofit Strategies for Energy Efficiency Improvement
Considering the Hot Climatic Conditions of Saudi Arabia]
Major Field : [Architecture]
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Saudi Arabia faces significant challenges related to the increasing energy consumption due to the prevailing hot climatic conditions. In this regard, the residential sector is responsible for over 50% of Saudi Arabia's electricity demand. This makes facade retrofit strategies very important to reduce cooling electricity and improve thermal comfort in the residential sector. This study evaluates the effectiveness of facade retrofit strategies in reducing cooling electricity consumption at KFUPM dorms. The study uses Design Builder software to compare the effectiveness of external wall upgrades, window replacements, and shading devices. buildings. Individually, the study found that wall retrofitting resulted in a higher reduction of cooling electricity compared to window and shading device retrofitting for this typology of facade. However, wall retrofitting requires a longer time to recover the investment compared with window and shading device retrofitting where the shortest payback period of 15.4 years for Case A and 14.24 years for Case B using External Thermal Insulation Composite System (ETICS) scenario. While the shortest payback period for adopting windows retrofit strategies was 4.83 years for Case A and 3.77 years for Case B utilizing triple glazing scenario. Adding louvers resulted in the shortest payback period by 4.6 years for Case A and 3.44 years for Case B comparing with all shading devices scenarios and other individual facade retrofit strategies. In contrast the combination of ETICS, window louvers, and windows with low-emissivity coating and argon gas demonstrated the best performance in reducing cooling energy by around 16% for Case A and 17% for Case B and offering the shortest payback period of about 14.8 for Case A and 13.7 for Case B years as compared with individual external wall retrofit strategies. The study provides valuable insights and guidelines for improving the energy efficiency and sustainability of existing buildings in hot climates.

ملخص الرسالة

الاسم الكامل: وسام احمد حسين رابعه

عنوان الرسالة: استراتيجيات تحديث الواجهة لتحسين كفاءة الطاقة مع الأخذ في الاعتبار الظروف المناخية الحارة في المملكة العربية السعودية.

التخصص: العمارة

تاريخ الدرجة العلمية: 31 ديسمبر

تواجه المملكة العربية السعودية تحديات كبيرة تتعلق بزيادة استهلاك الطاقة بسبب الظروف المناخية الحارة السائدة. وفي هذا الصدد، يعتبر القطاع السكني مسؤولاً عن أكثر من 50% من الطلب على الكهرباء في المملكة العربية السعودية. وهذا يجعل استراتيجيات تحديث الواجهة مهمة جداً لتقليل كهرباء التبريد وتحسين الراحة الحرارية في القطاع السكني. تقوم هذه الدراسة بتقييم فعالية استراتيجيات تحديث الواجهة في تقليل استهلاك كهرباء التبريد في مساكن الطلبة بجامعة الملك فهد للبترول والمعادن. لمقارنة فعالية ترقيات الجدران الخارجية واستبدال النوافذ وأجهزة التظليل. تستخدم الدراسة برنامج Design Builder بشكل فردي، وجدت الدراسة أن التعديل التحديثي للجدار أدى إلى انخفاض أكبر في كهرباء التبريد مقارنة بتعديل النوافذ وأجهزة التظليل لهذا النوع من الواجهة. ومع ذلك، يتطلب التعديل التحديثي للجدار وقتاً أطول لاسترداد الاستثمار مقارنة بتعديل النوافذ وأجهزة التظليل حيث أقصر فترة استرداد تبلغ 15.4 عاماً للحالة "أ" و 14.24 عاماً للحالة "ب" باستخدام سيناريو نظام العزل الحراري المركب. في حين أن أقصر فترة استرداد لاعتماد استراتيجيات تحديث النوافذ كانت 4.83 سنة للحالة أ و 3.77 سنة للحالة ب باستخدام سيناريو الزجاج الثلاثي. أدت إضافة فتحات التهوية إلى أقصر فترة استرداد بمقدار 4.6 سنوات للحالة (أ) و 3.44 سنة للحالة (ب) مقارنة بجميع سيناريوهات أجهزة التظليل واستراتيجيات تحديث الواجهة الفردية الأخرى. وعلى النقيض اظهر المزيج الاداء الافضل في توفير الطاقة بنسبة 16% للحالة (أ) و 17% للحالة (ب) المكون من نظام العزل الحراري المركب ، وفتحات النوافذ، والنوافذ ذات الطلاء منخفض الانبعاثات وغاز الأرجون وتقديم أقصر فترة استرداد تبلغ حوالي 13.7 سنة للحالة (أ) و 14.8 سنة للحالة (ب) مقارنة باستراتيجيات التعديل التحديثي الفردي توفر الدراسة رؤى وإرشادات قيمة لتحسين كفاءة استخدام الطاقة واستدامة المباني القائمة في المناخات الحارة.

CHAPTER 1

INTRODUCTION

The world faces many challenges related to global warming and climate change, buildings are one of the most crucial sources of carbon dioxide emissions and energy consumption, and they have led to increased concerns about energy consumption and environmental sustainability. Retrofitting of existing buildings has become necessary to improve the building energy efficiency and comfort of occupants. In Saudi Arabia, where hot climatic conditions prevail, effective facade retrofit strategies have a crucial role in reducing cooling electricity and enhancing thermal comfort. Therefore, this study aims to investigate the impact of different facade retrofit strategies in this regard. This is expected to contribute to the knowledge aiming at improving buildings sustainability and enhancing decision-making processes in this regard. This part of the study presents a background of the topic, in addition to explaining the main research problem, objectives, significance, methodology, and limitations.

1.1 Background

There are several problems the world is currently facing including climate change. This demonstrated by the rising global temperatures due to global warming and the number of serious consequences worldwide. Over the past century, certain regions have seen a

temperature increase of 2.5 °C (A Freedman, 2013). Therefore, governments around the globe are taking actions to address this issue. Construction industry is a major contributor to climate change, accounting for over 40% of material consumption, 30% of the world's electricity use and more than 35% of worldwide emissions of greenhouse gases. In addition, the residential structure sector plays a significant role as housing is responsible of about 25% of global energy usage (IEA, 2014).

According to some estimates, the construction sector and buildings need to reduce its overall Carbon Dioxide (CO₂) emissions by 77% by 2050 to prevent the Earth's temperature from rising by more than 2°C (A Thompson, 2017). Developed nations have already implemented multiple measures to save energy, resulting in a decline in CO₂ emissions (Nejat et al., 2015). However, the situation is different for developing countries, where CO₂ emissions are still on the rise. The urgency of the climate crisis necessitates effective solutions for greenhouse gas emissions reduction, with the building sector playing a crucial role in achieving this goal.

Currently, Saudi Arabia is facing significant challenges related to energy consumption due to its hot climatic conditions, which resulted in high cooling demand in buildings. Many existing buildings suffer from green construction practices, which contributed to this challenge. As a result, Saudi Arabia has one of the highest rates of global energy consumption, with per capita consumption almost three times higher than the world average (IEA, 2014). This has led to the country ranking 13th in terms of electricity consumption globally and being the Gulf Cooperative Council (GCC) nation that consumes the highest amount of fossil fuels (Asif, 2016).

The residential sector is not an exception in terms of energy consumption. This is true for Saudi Arabia, where most of the residential buildings are 10-30 years old (Al-Homoud & Krarti, 2021). Despite the severe desert environment of Saudi Arabia, around 70% of its buildings lack thermal insulation (Figure 1), which confirms the need for thermal retrofit interventions.

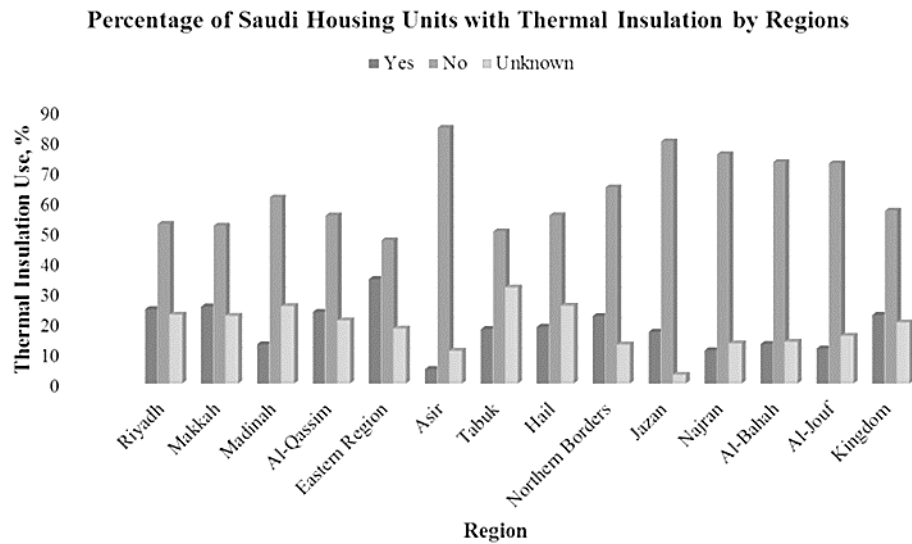


Figure 1 Percentage of Saudi housing units with thermal insulation by region (GASat, 2018)

To address these concerns, energy efficiency measures and retrofitting of existing structures are deemed necessary. Moreover, the Saudi Vision 2030 aims to increase environmental and economic sustainability of the country (Vision 2030, 2016; Ahmed & Asif, 2020). According to some estimates, the emissions from buildings sector globally could double by 2030 if no actions were implemented (Ahmed & Asif, 2020). Therefore, there is a crucial need to implement energy conservation and management strategies in the Saudi construction sector, where energy retrofitting of residential buildings is a viable solution in this regard (Hamida et al., 2020).

1.2 Problem statement

Saudi Arabia is currently facing great challenges associated with the increasing energy consumption in buildings. There is a need to implement a more sustainable building design strategies to address the current and future energy and environmental challenges (Brandão & Lanzinha, 2021). This is essentially important in the residential sector, which is responsible for over 50% of Saudi Arabia's electricity demand. This will be more challenging in the future due to the rapid population growth (Liang, 2019), where construction industry and buildings are the primary contributor to energy consumption in Saudi Arabia (Heidari Matin, 2022).

Energy consumption for air conditioning is a particular challenge in this regard (Chwieduk, 2017), where refrigeration and air conditioning consume about 80% of domestic electricity due to the lack of thermal insulation in most of these buildings (Thomsen et al., 2016). Even though Saudi Arabia has a severe desert climate, around 70% of its buildings lack thermal insulation (GASat, 2018), where about 90% of buildings are constructed using concrete (Al-Homoud & Krarti, 2021). In this context, a primary challenge revolves around the design and retrofit of building facades that resist heat gains and improve energy efficiency in buildings.

Thus, the aim of this study is to propose and examine multiple façades retrofit strategies that help reducing cooling demand in residential buildings located in Saudi Arabia. This is intended to provide design recommendations to the practitioners and decision-makers in the Saudi construction sector.

1.3 Objectives and goals

Based on the above-mentioned research problem statement, this study aims to propose and examine multiple façades retrofit strategies that help reducing cooling demand in residential buildings located in Saudi Arabia. This is essential to improve the energy efficiency and sustainability of these buildings, which is in alignment with the Sustainable Development Goals and the Saudi Vision 2030. The study objectives are:

1. To discuss the concept of energy-efficient facades and specify retrofit strategies that could be implemented, considering the climatic conditions of Saudi Arabia.
2. To investigate the impact of different facade retrofit strategies on building's cooling energy performance considering walls, windows, and shading devices.
3. To recommend design guidelines for facade retrofitting in Saudi Arabia that can improve energy efficiency in buildings.

1.4 Study significance

This study tackles an important topic of research that aims at improving energy efficiency of buildings. Although considerable amount of research has targeted design strategies of new building in this regard, more effort is needed to find out how to improve energy efficiency in the existing buildings. One effective approach in this context is building envelop retrofit including building facades. Rationalizing energy consumption of buildings is consistent with the global sustainability agenda and the Saudi Vision 2030 as well, which prioritizes enhancing energy savings in buildings through promoting sustainable and modern design strategies. Therefore, the implementation of façade retrofit strategies can

contribute significantly to achieving these goals. The importance of research could be summarized in the following points:

- Provide a review of façades retrofit strategies considering context-specific retrofit strategies that take into account the climate and local market of Saudi Arabia.
- Focus on retrofitting of facades including walls and windows, which represent most of the building envelop surface area, and evaluate its impact on the building energy performance.
- Provide valuable practical recommendation in this regard, which help designers, engineers, and decision-making to select the most effective building retrofit technique considering the conditions of Saudi Arabia. This includes analyzing economic efficiency of retrofit strategies and recommending guidelines about their implementations.

1.5 Limitation

Every research has a specific scope and some limitations. In evaluating building facade retrofit strategies and observing their impact on electricity consumption, this study has some limitations as follows:

- The study is limited to retrofitting of buildings located in hot climatic conditions of Saudi Arabia, namely the Eastern Province.
- The study is limited to the geometrical characteristics of the examined case study.

The study has encountered some difficulties including data availability. Retrofit strategies require large amounts of data but the electricity consumption data of the examined

buildings was unavailability (no electricity metering). Data related to the maintenance cost of the strategies proposed was unavailable too.

1.6 Thesis structure

This study includes five chapters as shown in **Figure 2**:

Chapter 1 Introduction: This part presents a general background about the excessive energy consumption in Saudi Arabia due to the desert environment and hot climate.

Chapter 2 Literature review: This part presents a review of the current studies on the various renovation strategies of building facades.

Chapter 3 Methodology: This chapter explains the research framework and methods and the tools used in data collection and analysis using numerical parametric simulation.

Chapter 4 Result and Discussion: This chapter displays quantitative and qualitative data analysis in tabular form and visual representations.

Chapter 5 Conclusion: the thesis concluded with design recommendations related to building facades retrofit.

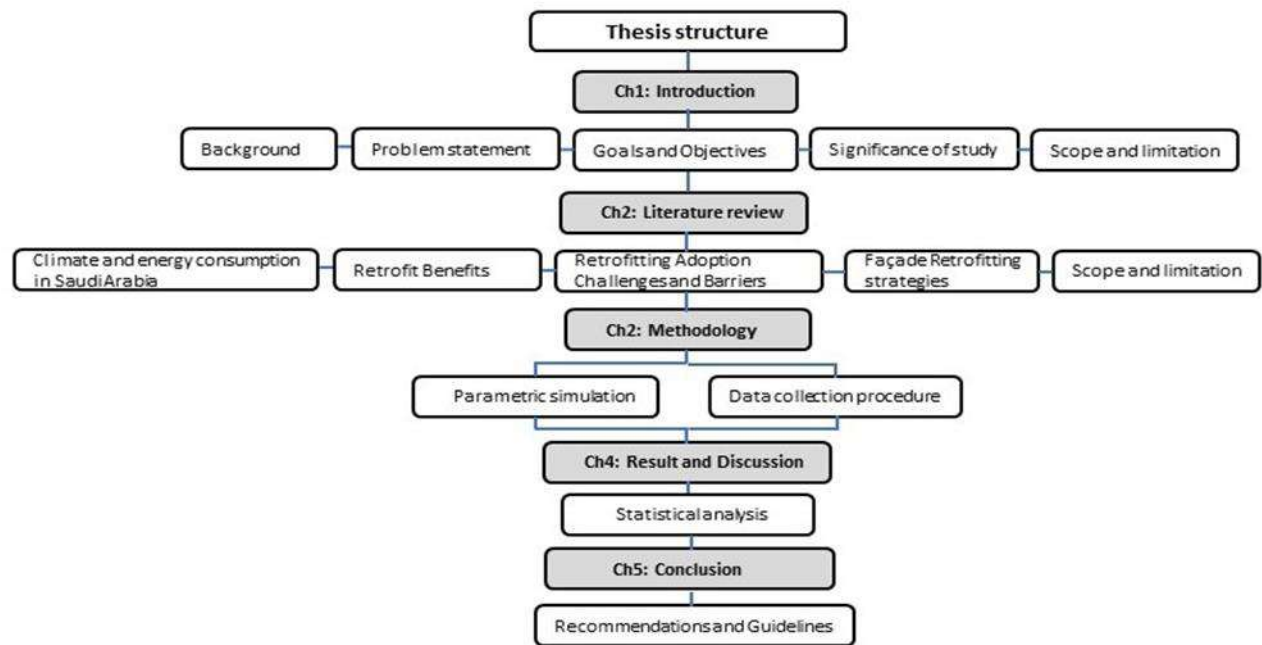


Figure 2 Thesis structure

CHAPTER 2

LITERATURE REVIEW

This chapter presents a detailed background including multiple related studies about building retrofit strategies. It focuses on facades because of their main role in heat transfer between the building and the outdoor environment. This chapter provides a review of the related studies in this regard and focuses on strategies that align with the local conditions of Saudi Arabia, aiming to generate meaningful recommendations contextualized for the region.

2.1 Energy consumption and the role of buildings

The increase in electricity consumption and CO₂ emissions has been a major challenge in recent times, as it is the primary factor causing global warming and climate change. It is currently one of the major challenges related to the construction sector, particularly in terms of energy consumption, heat transfer, and thermal comfort (Borràs et al., 2022). Energy consumption in the field of construction constitutes 36%-40% of the total amount of energy consumed globally (Sierra-Pérez et al., 2018). Building envelope plays an important role in the energy use of buildings, and facades are among the most important components in this regard (Brandão & Lanzinha, 2021).

Facades also include windows, which are one of the weakest elements in heat transfer resistance in buildings (Kalamees & Kuusk, n.d.). Therefore, the effectiveness of passive heating and cooling will significantly rely on façade design to consume less energy (Salvalai et al., 2017) .

One of the most important approaches is to remodel the existing building stock in order to improve its performance and reduce its environmental impact. Innovative solutions are more important than ever to reduce greenhouse gas emissions resulting from the construction industry. (Brandão & Lanzinha, 2021) . This includes adding additional wall insulation and replacing windows and doors to enhance insulation (Borràs et al., 2022)

2.2 Climate and energy consumption in Saudi Arabia

Saudi Arabia has a desert environment with high temperatures during the day and a drop in temperature at night. The summertime average temperature is 45 °C, although the surrounding air might be as hot as 50 °C (Alshahrani & Boait, 2018) This leads to huge consumption of energy

Climate of Saudi Arabia could be divided into five subzones, which are: hot-dry maritime subzone, cold-dry with a desert subzone, hot-dry with a desert subzone, hot-dry with a maritime desert subzone, subtropical with a Mediterranean subzone and mountains subtypes (**Figure 3**). The cities of Dhahran, Qurayyat, Riyadh, Jeddah, and Khamis Mushait could represent these five inhabited climate areas However, the prevailing conditions are the hot climatic conditions, with a clear increase in humidity in some areas, which requires significant amount of energy in buildings (Alrashed & Asif, 2015; Kharrufa & Adil, 2012).

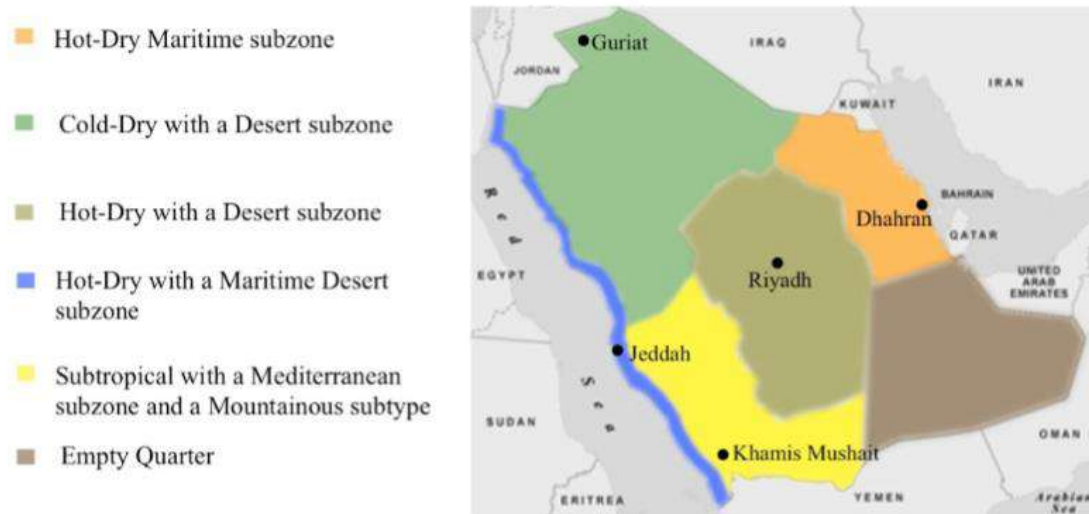


Figure 3 Saudi Arabia's climate zones (Alrashed & Asif, 2015)

As shown in **Figure 4**, residential buildings account for the highest share of Saudi Arabia's electrical energy use. Saudi Arabia's residential sector accounted for 44% of the nation's total power consumption in 2018, which is the highest percentage among all sectors (M. Krarti et al,2020).

The average annual energy usage intensity (EUI) for Saudi dwellings is 249.5 kWh/yr.m² for cooled spaces. This means an average annual energy cost indicator (ECI) of 70.3 SR/yr.m² (i.e. 18.75 USD/yr.m²). The annual expense of energy accounts for 2–20% of the entire Saudi family income (Al-Homoud & Krarti, 2021). Due to population and economic expansion, Saudi Arabia has witnessed an increase in electricity usage of roughly 7% every year. Moreover, half of all energy production is used by the residential sector. The residential sector is a primary driver of Saudi Arabia's nearly three-fold increase in energy consumption above the world average (Ahmed & Asif, 2020).

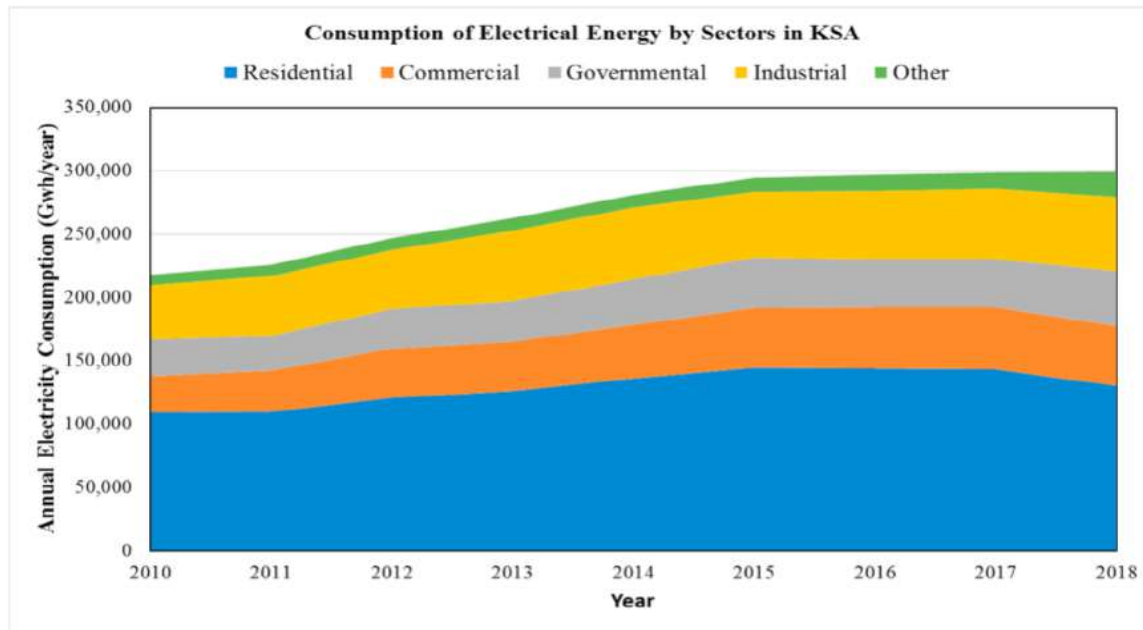


Figure 4 Annual Electricity consumption by sectors (SECO; 2018)

As shown in **Figure 5**, only 8.31% of the total stock is newly constructed houses with an age of 5 years or less, compared to 23.15 percent for houses aged 5 to 10, and 22.1 percent for houses aged 20 to 30. The highest percentages are 31.09% for houses aged 10 to 20 and 22.1 percent for houses aged 20 to 30 (Thomsen et al., 2016) . Concrete makes up 89.54% of all dwelling construction materials. Buildings made of stone made up 0.02% of the housing stock, while those made of block/clay made up 10.44%. The latter two are primarily found in vernacular houses (Al-Homoud & Krarti, 2021) .

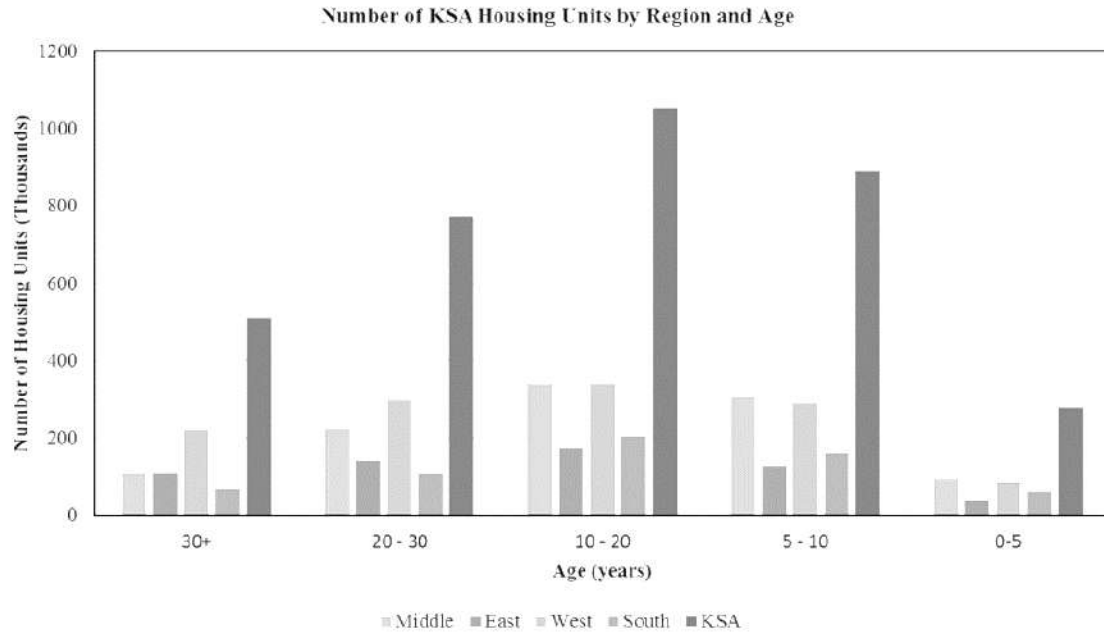


Figure 5 Number of Saudi Arabia Housing unit by Region & Age (GASat, 2018)

The rapidly increasing energy consumption in these buildings, especially the old inefficient ones, shows clearly that energy usage must be decreased for the residential sector to be sustainable in the future. It is possible to do this by either replacing the old buildings with new sustainable houses or, more practically, by retrofitting the existing houses to make them more energy-efficient (Ahmed & Asif, 2020) .

Building retrofit benefits

Energy retrofitting, sometimes referred to as energy refurbishing or energy renovation, is primarily the updating of a structure's components that have an effect on the building's energy usage, either directly or indirectly. Lighting, heating, cooling, and other energy-using equipment are examples of direct components. The regulation of environmental elements, such as controlling the influx of solar radiation and air infiltration, plays a pivotal role in determining a building's energy efficiency. Indirect components like wall insulation,

glass type, and other elements within the building envelope significantly influence the overall energy consumption of buildings. Retrofitting may be divided into: 1) major retrofitting, 2) minor retrofitting, and 3) deep retrofitting. (M. Holladay, 2010). The fundamental difference between the three types of retrofitting is the energy effect of the energy efficiency measures and their associated costs. The building's power usage should be reduced by about 50% through deep retrofit. Major retrofitting costs more than minor retrofitting but is more elaborated and has a greater impact (Moran et al., 2020).

- **Energy saving**

Most residential buildings still rely mostly on fossil fuels and are not energy efficient. It's crucial to make planning tools available for housing renovation interventions (Donato et al., 2022) so that they can be converted into energy-efficient buildings that are in compliance with the established regulatory standards (Ruiz-Varona et al., 2022). As has been presented above, the construction industry is in urgent need of a vigorous innovation process that aims at improving energy efficiency and lowering the associated cost.

Energy usage in 2050 would be 80% lower than it was in 2005 if the current building stock underwent considerable energy rehabilitation (Cucuzza et al., 2022). The retrofitting effort sought to increase interior comfort, lower energy consumption for heating and cooling, and achieve a high level of energy efficiency. A global reduction in energy demand of up to 36% would be possible if significant renovation techniques were widely used (Donato et al., 2022).

- **Indoor comfort**

It is challenging to achieve indoor comfort at lower levels of energy consumption. However, research showed that retrofitting can significantly improve indoor comfort attaining good Indoor Air Quality and successfully delivering thermal comfort for the inhabitants (Gomes et al., 2021 ; Donato et al., 2022) . Productivity is significantly influenced by the quality of the interior environment (IEQ), especially the thermal energy, acoustic, illumination, and air quality characteristics, as well as the inhabitants' control over these parameters (Wargocki & Wyon, 2017).

- **Cost-efficiency**

Retrofit interventions have a direct economic benefit which results from a significant decrease in energy usage (Cova et al., 2021) . When the duration of the investment time approaches the breakeven point, the payback time is the period it will take for the investment to recoup its initial cost (Andaloro et al., 2022).

- **Environmental impact**

Building renovations have a significant influence on buildings' operational energy consumption, which in turn has a significant impact on their environmental impact (Thomsen et al., 2015). That's why developing unique and innovative solutions is important to decrease emissions of greenhouse gases and foster the growth of the building sector (Van Gulck et al., 2020). To evaluate suitability of each renovation option, a post-renovation evaluation should be conducted including energy performance, thermal modeling, and life cycle assessments (Sierra-Pérez et al., 2018). There are several

suggestions and choices available to make building renovations more energy-efficient (Thomsen et al., 2015).

2.2 Building retrofit challenges

The potential for energy retrofits to reduce building energy usage and carbon emissions may face some challenges during implementation. A wide variety of concerns were addressed in this regard.

Socio-cultural obstacles for example can be connected to knowledge and information, which suggests that residents' lack of understanding is preventing them from taking action to save energy (Bertoldi et al., 2021). Uncertainty regarding the advantages of energy-efficiency techniques and technologies is the main source of these technical and informational hurdles (Medineckienė & Björk, 2011). This also includes fear from using unfamiliar technologies (Davies & Osmani, 2011), as well as uncertainties on the economic impacts of implementing them (Theodoridou et al., 2012).

Some economic barriers exist too. High initial costs and lengthy payback periods are usually referred to as economic challenges in the literature (Stieß & Dunkelberg, 2013; Weiss et al., 2012). Investment costs of home remodeling are excessive, particularly for low-income families (Baek & Park, 2012).

2.3 Façade retrofitting strategies

Reduced energy use while retaining thermal comfort, improved architectural quality, reduced carbon footprint, and assurance of cost-effectiveness of retrofitting interventions are the essential signs of a successful retrofit approach. However, a number of these signs may conflict with each other (Ayodele, 2020). The construction industry offers a promising avenue for developing efficient, feasible, and easily deployable retrofitting techniques to meet energy targets in the face of global warming (Serrano-Jiménez et al., 2023).

Buildings are a major focus of the power conservation industry since they are one of the biggest energy consumers. Retrofitting the structure's envelope, which has a significant influence on cooling and heating loads, is a fundamental goal of retrofit projects (Kamel & Memari, 2022). Building envelope is considered a crucial part in achieving energy savings, as it influences the amount of energy utilized by a building (Brandão and Lanzinha, 2021). The energy usage of a building is significantly impacted by the building envelope, and retrofitting interventions aimed at improving its performance have demonstrated reductions in energy consumption of 15% to 34% for each property. This reflects the need for retrofit strategies to be tailored to the specific climatic conditions of the building's location (Ayodele, 2020).

2.3.1 Material properties

When assessing the thermal performance of a building, emphasis is given to passive measures and overactive ones to prioritize thermal comfort. This approach promotes energy-efficient measures that aim to enhance the thermal efficiency of the envelope (Etxebarria-Mallea et al., 2021). Retrofitting interventions aimed to improving the building energy performance of the envelope are affected by the three primary mechanisms of heat transfer, i.e. convection, radiation, and conduction, where all of them contribute to heat gain and loss (Kamel & Memari, 2022).

In relation to the thermal efficiency of a building envelope, the R-Value serves as an indicator of insulation performance, whereby a higher R-Value implies better performance. Its impact is mainly directed at roof, wall, and floor components to enhance comfort and reduce energy consumption. Nevertheless, the appropriateness of the insulation level is contingent upon the climate type, location and construction characteristics (Ayodele, 2020; Loga et al., 2016).

The Retrofit goal is to increase the thermal efficiency of the building envelope through actions like replacing windows, installing new sealing to reduce air leakage, and reducing the U-value by adding more insulation to the roof, façade, and flooring (Etxebarria-Mallea et al., 2021).

2.3.2 Walls retrofitting strategies

Building envelope is a crucial element in the renovation process as it can result in significant energy savings of up to 60-80% (Sierra-Pérez et al., 2018). The addition of

insulation, both internal and external, is a common approach to improving thermal efficiency of walls (Thomsen et al., 2016) .

The primary objective of insulation is to enhance wall efficiency while minimizing thermal bridges and insulating connection areas between walls and ceilings, which are prone to heat transfer (Van Gulck et al., 2020). The strategies of wall retrofitting are summarized in

Figure 6.

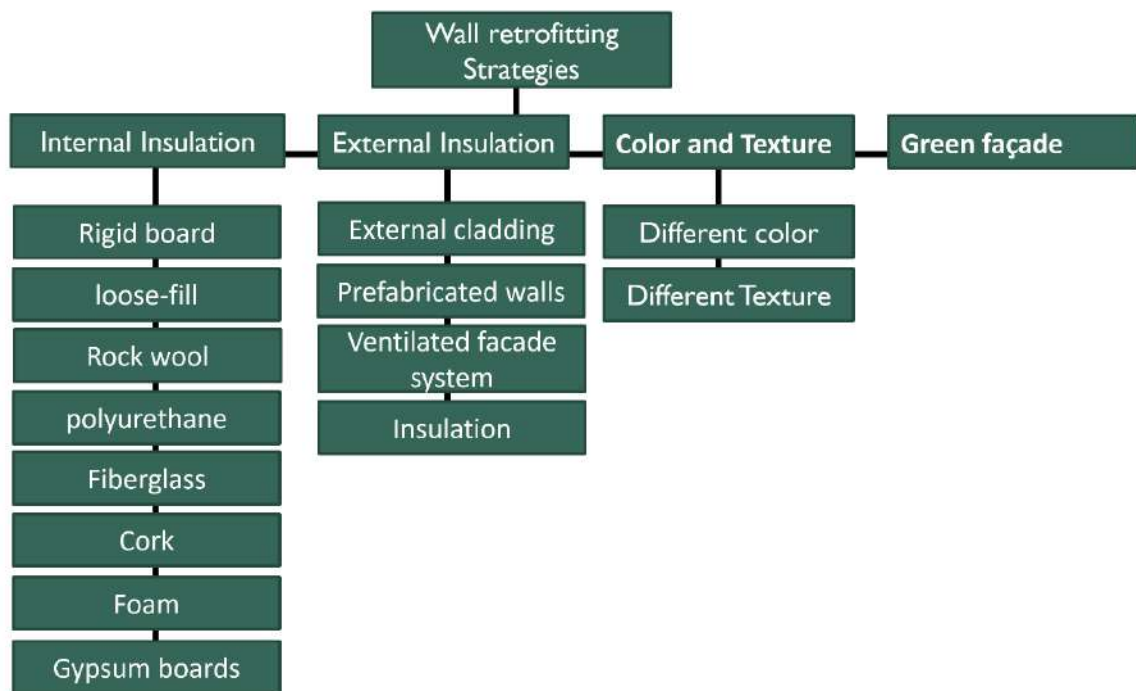


Figure 6 Summary of retrofitting strategies for the external walls

- **Internal insulation**

This involves adding new materials to the building interior without affecting its external appearance. One of such materials is cork, which has the potential to improve energy and insulation performance on a large scale. (Thomsen et al., 2016; Sierra-Pérez et al., 2018c)

Other standard materials for insulation, such as fiberglass, also known as polyurethane, wool from rocks, and cellulose, can also be utilized in a variety of forms, including bats, rolls around, loose-fill, and rigid board (Kamel & Memari, 2022). Another option is to use porcelain foam to add an inner layer that increases thermal comfort efficiency for building occupants (Mohelnikova et al., n.d.).

- **External insulation**

External insulation for retrofitting existing buildings offers a comprehensive range of benefits, including energy efficiency, cost savings, occupant comfort, and environmental sustainability. External insulation involves adding new layers and utilizing insulation materials between the outer walls, and the roof in order to minimize thermal bridges. Various retrofitting techniques were adopted in previous literature including: ventilated façade, and External Thermal Insulation Composite System (ETICS), prefabricated panel. Additionally, external cladding could increase insulation effectiveness in addition to enhancing the appearance of the building. (Thomsen et al., 2016) . This includes a range of masonry components, including prefabricated walls, clay bricks, concrete bricks, and sand lime bricks. Results showed that prefabricated walls used 25% less energy than unfinished walls, 23% less energy than sand lime stones, and 16% less energy than concrete bricks (Al-Sanea et al., 2012).

Ventilated façade: is a system consisting of an external facade attached to an internal facade using a frame structure by installing an insulating layer and an external cladding on top of the original facade, creating a gap for natural ventilation. This creates an air gap between them that is ventilated (Halawa et al., 2017) as shown in **Figure 7** . Such a system can reduce cooling demand in different climates, especially in orientations that receive

solar radiation (South, East, and West) and calm wind conditions (Fantucci et al.,2020). Different types of cladding can be used as a finishing layer, along with insulating materials such as polyurethane PUR and extruded polystyrene insulation XPS. It has been shown that a ventilated facade system comprising (PUR) insulation and fiber cement board (FC) with solid wood can provide higher thermal comfort levels in buildings (Thomsen et al., 2016).

External Thermal Insulation Composite System (ETICS) : is a solution for improving the thermal insulation and energy efficiency of existing buildings by applying an insulating layer on the exterior of the existing facade, which is then covered by a thin finishing layer (often made of cement or tar) or cladding (Moradpoor et al.,2022), as shown in **Figure 8** in this type of external insulation the existing layer covered with a final finish having different insulation materials. However, as comparison study between ETICS using Insulation Cork Boards ICB and Expanded polystyrene EPS found that expanded polystyrene (EPS) requires lower energy consumption to fulfil the heating and cooling needs of a flat, due to its lower U-Value (Silvestre, 2019). Findings revealed a high efficiency of ETICS retrofitting which indicated that the major retrofit strategy, incorporating ETICS with (EPS) insulation, results in a 24.12% reduction in total energy intensity compared to the base model (Sharma, 2022).

Prefabricated wall: this type of insulation offers a time-efficient, versatile solution, enhancing energy efficiency and structural integrity. Precision-engineered off-site, they streamline the process, providing a cost-effective, sustainable, and minimally disruptive upgrade for existing buildings. Previous literature used prefabricated modular panels for building envelope insulation as solution for the retrofitting of existing building, which

consist of a timber frame structure filled with mineral wool (Kalamees, 2017) as shown in **Figure 9**. Prefabricated panel mainly made of concrete and timber which typically smaller in size for concrete panel, while timber panels are larger and offer a fully integrated solution with windows and services (Cucuzza et al., 2022) prefabricated wooden panel installed on the main facade of the building, which has additional aesthetic values (Ibañez Iralde et al., 2021). In principle, other lightweight structures and insulation materials are also conceivable. In this type of insulation to get accurate information about the unevenness and roughness of the existing surfaces and inhomogeneity of windows location, 3D laser scanning of the envelope conduct before the design in this context. (Kalamees, 2017)

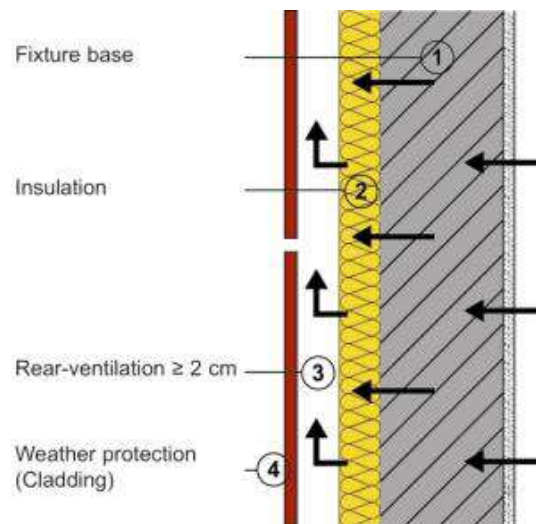


Figure 7 Ventiladed facade strategy

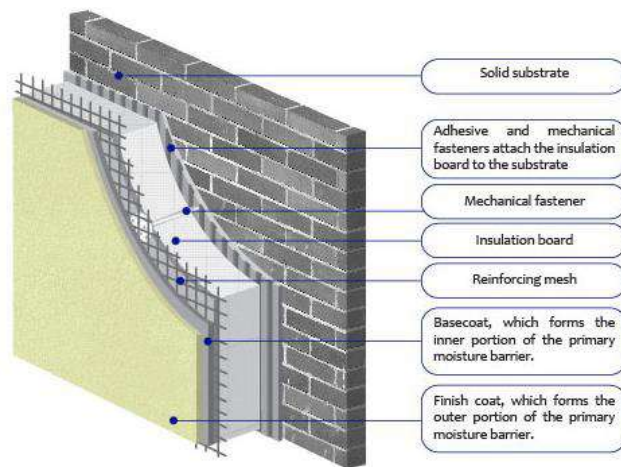


Figure 8 External Thermal Insulation Composite System

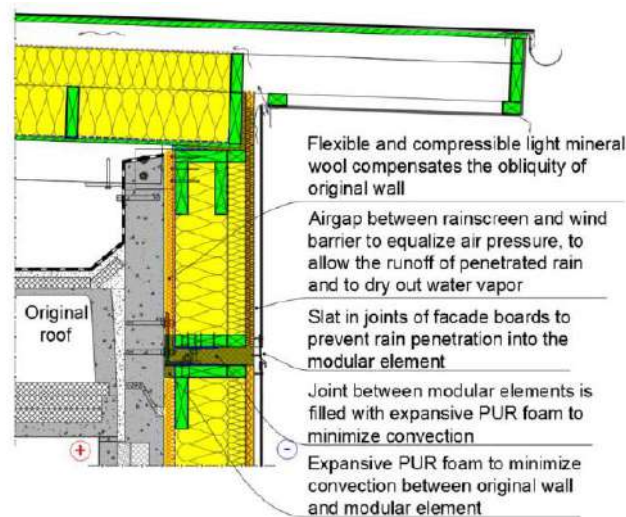


Figure 9 Prefabricated wood panel (Kalamees, 2017)

- **Color and texture**

Numerous additives are available to decrease materials' absorption of solar heat when exposed to it. Among these elements are colors, which have varying levels of reflectivity to incident solar radiation. The texture is also a significant factor using different finishing techniques, where different colors and textures can contribute to reducing heat absorption (Van Gulck et al., 2020).

- **Green façade**

In hot regions, green facades help maintain comfortable indoor temperatures during summer months by reducing thermal transmission. Studies have shown that green facades can reduce thermal transmission significantly in such areas. Green facades and roofs act as insulating surfaces that reduce thermal transmission, thus helping to conserve energy (Yu et al., 2021).

2.3.3 Windows retrofitting strategies

Openings in buildings are crucial to sustain its thermal comfort. To encourage energy saving, several solutions have been used in this regard such as the use of double or triple-glazed windows (Sequeira & Gouveia, 2022) . Prior research has also investigated the effect of window construction materials, with a particular emphasis on glazing type. Findings from a study conducted in Riyadh and Dhahran demonstrated that the use of suitable glazing material can result in significant energy savings in hot climates (Al-Sanea, 2002). The strategies are summarized as shown in **Figure 7**.

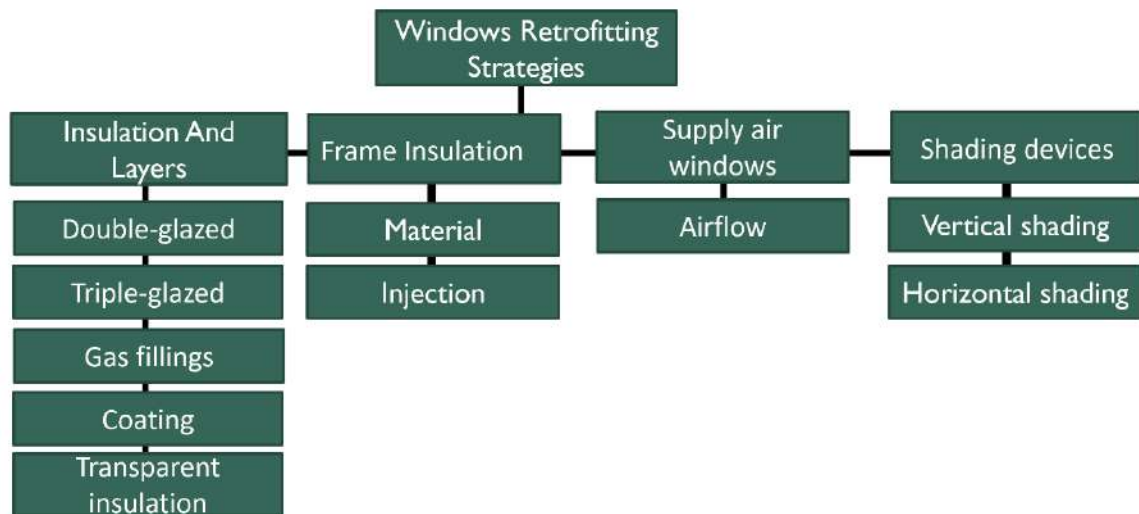


Figure 10 Summary of retrofitting strategies for the external windows

- **Glazing layers and glazing insulation**

Insulated glass windows are recommended for better sun protection to improve energy efficiency in buildings (Kunkel, 2015). Double-glazed and triple-glazed windows have been found to significantly contribute to energy conservation (Sequeira & Gouveia, 2022). However, thermal performance of these windows is influenced by the type of glass and the

use of a thermal breaker in the system. Further studies have explored enhancing the performance of double-glazed windows by incorporating gas fillings between the panes of glazing and utilizing low-emittance coating on the glass (Ayodele, 2020). Moreover, the use of aerogel as a translucent or transparent insulation material has been suggested to improve the thermal performance of the glazing system (Ascione et al., 2021).

- **Supply air windows:**

As shown in **Figure 11**, an innovative and affordable retrofit technique is to use supply air windows. This strategy could be effectively used to circulate hot air back to the room whenever needed as it flows through the window frame (Ala-Kotila et al., 2020).

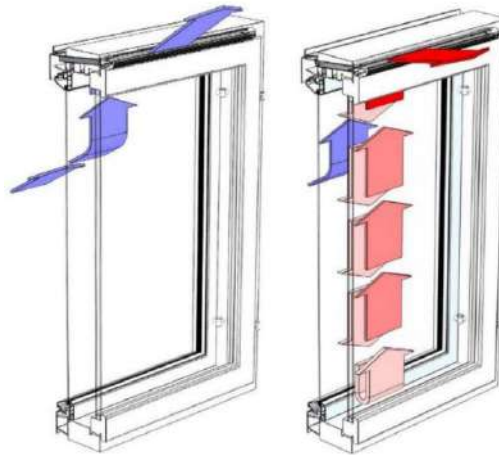


Figure 11 Supply air windows (Ala-Kotila et al., 2020)

- **Window frame insulation:**

To improve the thermal performance of windows, the frame material plays an important role in two ways, either by replacing the frame with better-performing materials such as wood or improve the aluminum frames by injecting polyurethane foam for thermal insulation (Serrano-Jiménez et al., 2023).

- **Shading device systems**

Shading devices offer flexibility to allow for modifications and improvements in both daylighting and cooling energy savings, which can be achieved by reducing heat gain (Bessoudo et al., 2010). Previous investigations on the effect of various shading methods, including vertical fins and overhangs, on indoor temperature and solar heat gain protection, demonstrated that opening windows was the most effective method for reducing solar gain and lowering indoor temperatures, followed by overhangs and vertical fins, respectively (Offiong & Ukpoho, 2004).

2.3.4 Smart retrofitting strategies

Smart strategies are divided into strategies based on their thermal properties and strategies based on smart control, which include a range of applications in the field of retrofitting. These are represented in the following points:

1) Smart glass

Smart glass is characterized by its ability to control the degree of shading, as it is divided into passive and active types, as shown in **Figure 12**:

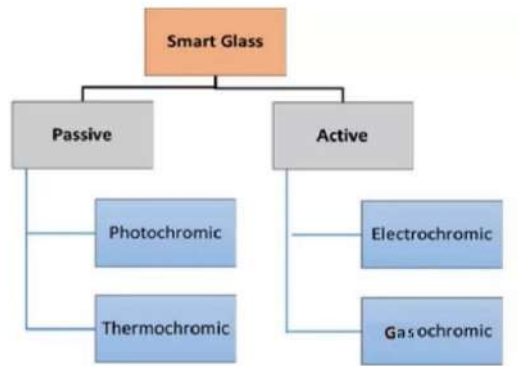


Figure 12 Smart Glass Types

- **Gas chromic glazing:** By using chemical chromic materials that are activated by oxygen or hydrogen gases, the gas chromic (GC) window responds to infrared (IR) rays (Nageib et al., 2020). GC windows are referred to as active smart windows because an additional mechanism is required to pump the gases and activate the gas chromic material (Feng et al., 2016). Porosity tungsten trioxide (WO_3) film is the chemo chromic film for GC windows that may be instantly deposited on the inside surface of the outer glazing pane. Other gas chromic materials, such as nickel dioxide (NiO) and alloys of magnesium, might be used as replacement materials for GC windows (Liang, 2019).
- **Electrochromic:** A dynamic phenomenon known as electrochromic is distinguished by the reversible transformation of glass from transparent to colored states. When a voltage of up to 10 Volts Dc is supplied, optical absorption causes the change. The control method for electrochromic devices is often dependent on the amount of solar radiation, interior operating temperature, indoor lighting

intensity, or the outside temperature. Electrochromic systems can be operated manually or automatically by building management systems.

The electrochromic layer (electrode), the electrolyte (ion-conducting layer), the ion storage layer (counter-electrode), and the two transparent conductors are the other three layers that make up a typical electrochromic device. This multi-layered structure can be formed on flexible polymeric films, such as Polyethylene terephthalate PET, or between laminated glass substrates, and then integrated into the surface 2 of a double-pane Insulated Glass Units IGU. (Hoon Lee et al., 2020) The electrochromic window system with no shading, which decreases heat gain by 53%–59% in both summer and winter, was shown to be the most efficient and effective intervention compared with other types of window glass like Gas chromic glazing, Photochromism and Thermochromic glazing (Ayodele, 2020).

- **Photochromism:** Glass naturally transforms from a clear to a colorful state due to increased absorbance in response to solar radiation wavelengths, primarily UV, in a dynamic process known as photochromic. The glass immediately returns to its transparent condition when the radiation source is withdrawn, either passively through thermal recovery or aggressively via heating in the darkness using electrothermal coatings (Cruz et al., 2017).
- **Thermochromic glazing** is a type of passive dynamics technology that covers glass surfaces with thin, flexible inorganic coatings or polymeric films. In reaction to the rising temperature of the coat, this enables the glass to passively change from clear to colored states while preserving transparency throughout. The progressive shift in the material's nanostructure between the clear and colored states is

explained in (Abdul Mujeebu et al., 2016). Figure 10 shows the details of aforementioned smart glass types.

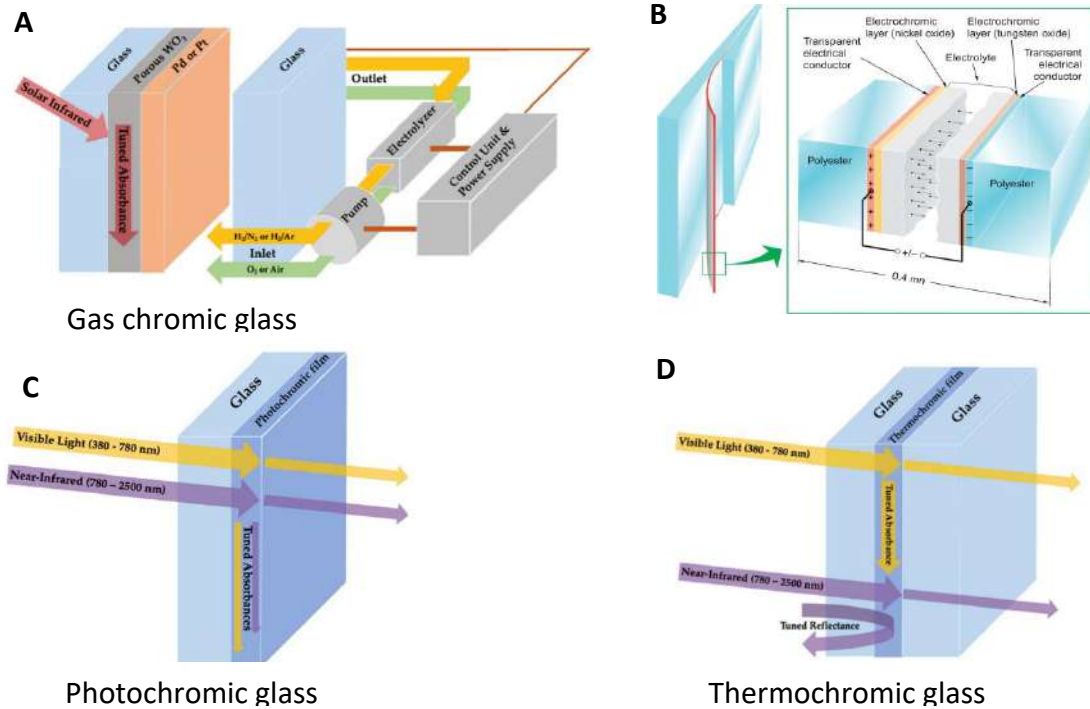


Figure 13 Smart glass types, A) Gas chromic (Liang, 2019), B) Electrochromic (Ayodele, 2020), C) photochromic (Cruz et al., 2017), D) Thermochromic (Abdul Mujeebu et al., 2016).

2) Innovative windows

- **Smart windows/ “SELFIE” (Smart and Efficient Layers for Innovative Envelope):** is a visible unit made up of three layers: The first layer is made of glasses with PVB and nanomaterials, a hollow space with an electric shading mechanism, and a low-E glass layer that has a U-value of $1.2 \text{ W/m}^2 \text{ K}$. The goal of this study was to assess how well these prototypes work across different locations (Gallo & Romano, 2017).

- **“Prototype ACTRESS (active, responsive, and solar)”**: This module is made of two main parts, one of which is transparent and the other opaque. The opaque module comprises an exterior composed of glass-laminated photovoltaic cells and an internal structure comprised of 5 layers, two of which are materials that phase-change materials with melting temperatures of 23°C and 27°C. An electric heating sheet that is positioned between the two-phase change material layers PCM activate them and enables thermal energy storage. A 120 mm vented air cavity separates the interior from the exterior components. The transparent module, which takes up 50% of the façade, features a Venetian curtain that is coated in highly reflective low-emissivity glasses in the exterior area and a bottom piece constructed of tripled low-emissivity glass with argon gas embedded in the hollow (Favoino et al., 2014).

3) Responsive shading devices

Current developments in material science and control technology have made it possible to create high-performance facades. A responsive facade is a kind of high-performance facade that adapts its features, functions, and behavior to the needs and preferences of its users to enhance thermal, visual, and acoustic performance and cut back on building energy use (Heidari Matin, 2022). These adjustments are done considering the various boundary conditions that could exist throughout the day and in various seasons, including day-night cycles. As a result, an adaptable building envelope may be thought of as one that can change its properties and control a variety of interior factors (Kamel & Memari, 2022).

Outer dynamic shading facade

- **Adaptable shading façade:** In a study conducted by Shahin in 2019, two methods of using adaptable shading facades were presented. The first method was implemented in the Media-ICT building in Barcelona. It utilized an ethylene tetrafluoroethylene (ETFE) polymer-coated system with lamellar fins. These fins were controlled by pneumatic mechanisms that responded to solar sensors. This method achieved approximately 20% energy savings. The second method, showcased in the Al Bahr Tower located in Abu Dhabi, involved the use of triangular polytetrafluoroethylene (PTFE) panels coated with a thin layer of micro-perforated fiberglass. These panels were installed at a height of 2 meters on the facade of the building. The panels were able to reduce solar heat gain by 50%. As a result, they were able to lower HVAC energy consumption (Shahin, 2019). As shown in **Figure 11**.
- **Kinetic mechanics:** Matheou et al. (2020) proposed two methods that utilize kinetic mechanics to regulate daylight and enhance residents' viewing conditions. The first method involved using eight triangular-shaped elements, each with six folds, inspired by origami design principles. These modules were designed to manage daylight and provide visual comfort using a wire-based system. The second method used a membrane with a thin textile layer that could be adjusted by cables to create various configurations. These facade systems were implemented in a four-story building in Cyprus. As shown in **Figure 11**.
- **Elastic kinetic systems:** Barozzi et al. (2016) introduced a design inspired by the reversible elastic deformation seen in plants. This system utilizes a hinge-free

flapping mechanism, with polymer louvers supported by glass filaments. The top and bottom actuator positions of the louvers enable elastic deformation, permitting sunlight to pass through and augmenting natural illumination. As shown in **Figure 14**.



Al Bahr towers, Abu Dhabi



(a)

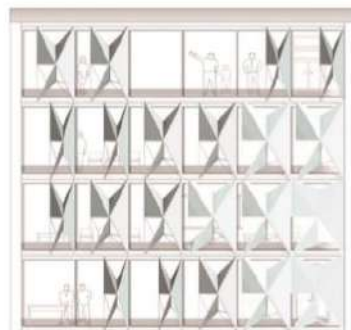


Media-ICT building,



(b)

Thematic Pavilion Yeosu



Responsive façade, Cyprus

Figure 14 Responsive shading Device, Al Bahr towers (Shahin, 2019), Responsive façade (Matheou et al., 2020), Thematic Pavilion (Barozzi et al., 2016).

- **Inner dynamic louver system:** The usage of an internal dynamic louver system in building design is the most affordable and controlled choice. They are appropriate for mass manufacturing and may be used in both newly constructed and restored buildings because these systems are frequently integrated into window systems. Blinds with two layers and a curtain wall with two layers that have a programmable opening and closing cavity are two examples of this design strategy. However, it should be emphasized that inner variable louver devices are mostly used in industrial buildings (Zhang et al., 2022).

Table 1 shows the smart strategies for windows and their impact on energy, as it appears that there is a lack of application of such strategies in hot climates, where most of the studies have focused on Europe.

Table 1 Examples on the use of Smart Retrofitting strategies

Retrofitting strategies /Applied System	Country	Climate	Seasons of Analysis	Method	Energy saving	Citation
Inner dynamic louver system	US	Cold	cooling	Simulation	-	(Zhang et al., 2022)
Shading system/ based on a folding technique of “origami”	Cyprus	Cold Climate		prototype	-	(Matheou et al., 2020)

Various adaptive building envelopes	Barcelona, Abu Dhabi, Spain. Canada, Toronto.	Cold & Hot Climate		Real case	A solar gain reduced of 50% in Abu Dhabi, increased air circulation and ventilation in Toronto, and buildings in Barcelona save roughly 20% of their energy.	(Shahin, 2019)
Smart windows/ "SELFIE"	Florence, Milan and Italy, Palermo.	Cold Climate	Cooling and heating	Prototype		Gallo et al. (Gallo and Romano, 2017)
Electrochromic smart glass	U. K	Cold Climate	Cooling	Simulation	80% less energy is used for cooling compared to typical glazing, and 76% less is used if internal shading is used. Additionally, a higher standard of indoor air is attained.	Favoino et al. (Favoino and Overend, 2015)
Prototype ACTRESS	Italy	Cold Climate	Cooling and heating	Prototype		Favoino et al. (Favoino et al., 2014)

2.4 Integrated retrofitting strategies

Retrofit projects use a range of materials, systems, techniques, and simulation tools. It is essential to comprehend the effects of these methods in various settings, how frequently they are used, and how well new products on the market perform. This section investigates many integrated retrofit strategies, including upgrading walls and roofs, installing cool roofs, increasing windows' U-value, and adding external insulation. Air leaks, floors, façades, windows, and roofs are just a few of the building envelope components to which these retrofit methods may be applied. Also, they are appropriate for use in the residential buildings sector (Hong et al., 2019; Kamel & Memari, 2022).

2.4.1 Smart materials

- **Phase change material (PCM)**

PCMs have high thermal inertia and undergo a phase shift by absorbing heat when a specific temperature range is reached, usually between 23 - 26 °C. A liquid-to-gas, solid-to-solid, or gas-to-liquid phase shift can occur. In contrast, the PCM releases heat at night when the surrounding temperature exceeds the predetermined level. These materials have an operating temperature range of 20 - 35 °C and can be used in walls, floors, and ceilings (Kamel & Memari, 2022).

- **Temperature-responsive elements**

Thermo-bimetals are metallic components made of two distinct metal alloy sheets that have the capacity to bend on their own in seconds (Casini, 2014). The lamination of these metals,

which expand at various speeds, results in the bimetallic reaction. (Adriaenssens et al., 2014). The bimetal reverts to its normal shape when the heat source goes away. Some architectural ideas that employ these multifunction metals for usage in facade systems include outer kinetic skins built of thermos-bimetals to provide sun control (Casini, 2014). Solutions for designing dynamic facades do not require sophisticated electronics, sensors, or actuators (Adriaenssens et al., 2014). As shown in **Figure 15**.

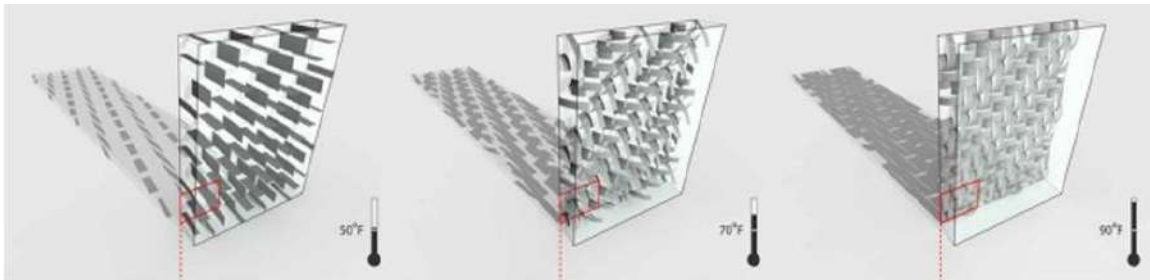


Figure 15 Thermobimetals Workflow

2.4.2 Integrated systems

A promising strategy for retrofitting systems is the fusion of conventional and cutting-edge materials. The development of a modular retrofit system using cutting-edge materials makes installation easier and assures efficiency.

- **Multi-functional energy-efficient façade systems (MEEFS):** In addition to their thermal advantages, Meefs system can also improve a building's visual appearance.

Meef's system consists of 3 main parts:

Structure of MEEF: The Meefs system will use thin structural panels that may be attached to an existing façade using an anchor mechanism to create the system's structural framework.

Operating control system: A complex smart energy system that allows for control of all moveable parts is integrated into the building face. The structure's energy infrastructure will be completely integrated with this technology.

Technological modules: The Meefs system is made up of structure modules and technological units, each of which has a particular technology or set of technologies that may be used to lower the building's basic energy demands or provide energy from renewable sources (Paiho et al., 2015). As shown in **Figure 16**.

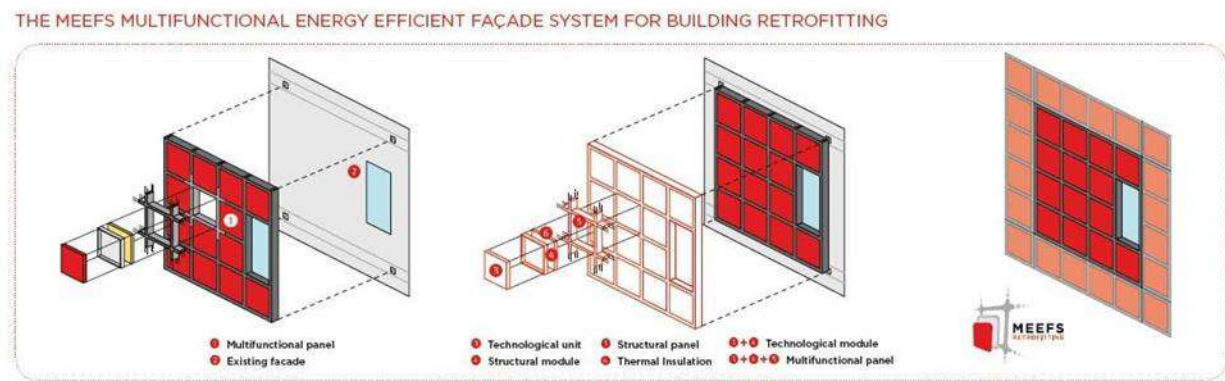


Figure 16 Movable Constructions Process (Paiho et al., 2015)

- **Active solar thermal façades (ASTFs):** By absorbing solar energy and gaining heat from the thermal absorber, alternative facade systems like Active Solar Thermal Façades (ASTFs) may function as both external walls and solar collector elements. Conduction, convection, and radiation are the methods by which these systems can transport heat (Zhang et al., 2015). As shown in **Figure 17**.

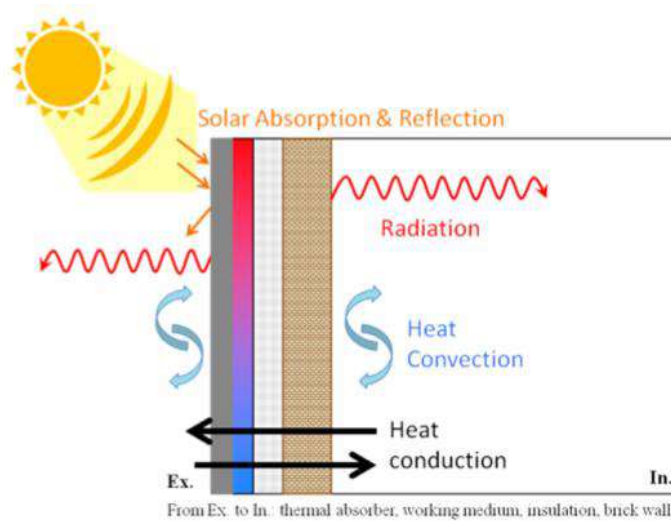


Figure 17 Active Solar Thermal Façades Workflow (Zhang et al., 2015)

- **Double-skin façade**

The double-skin façade is a cutting-edge method of upgrading a façade to increase energy efficiency. It entails covering the current transparent façade with an outer glazed surface. A layer of insulation that is warmed by solar radiation that may be evacuated if it gets too hot is created in the cavity between the two layers. Shading equipment can be fitted inside the system space to maximize solar heat protection (Kim et al., 2015). As shown in **Figure 18**.

Double skin façades (DSFs) have been recognized as a potential retrofit method for providing thermally protected areas and energy savings. For instance, a basic DSF may save cooling and heating loads by up to 90% and 30%, respectively (Pomponi et al., 2016), with additional saving energy possible through shading devices. Alternative materials have been suggested in other investigations, including plastic instead of the glass, while some researchers have concentrated on analyzing the link between cavity thickness and

power saving (Alberto et al., 2017). Building-Integrated Photovoltaics (BIPV) may be used with DSF to produce power.

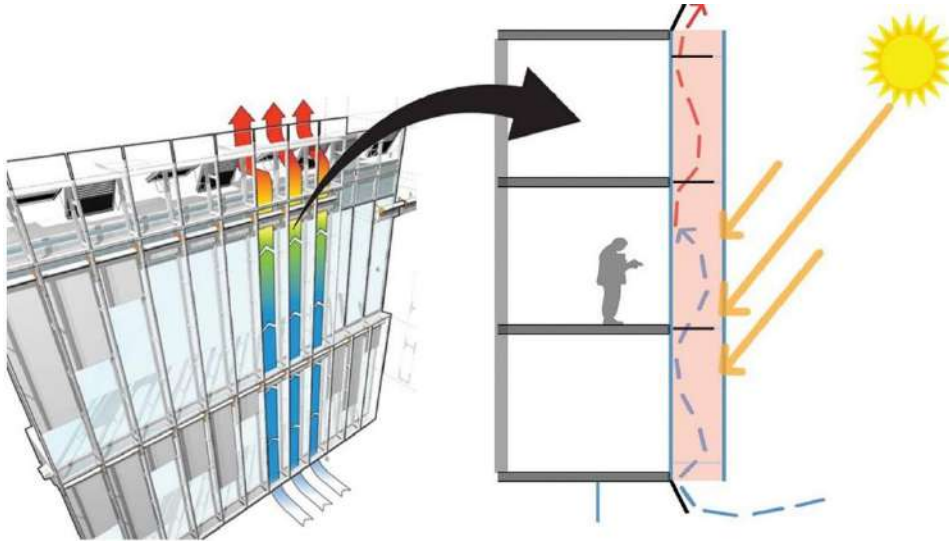


Figure 18 Double-skin façade (Pomponi et al., 2016)

Table 2 shows integrated strategies that include the entire facade (windows and walls) and their impact on energy consumption.

Table 2 Integrated Retrofitting Strategies

Retrofitting strategies /Applied System	City/Type of building	Climate	Seasons of Analysis	Method	Saving energy	Citation
walls /DSF paired with movable shading elements	Italy	Cold Climate	Cooling and Heating season	Real case	In cold season, reduces preheats the ventilation air and thermal losses. In hot	(Baldinelli, 2009)

					season, the heating is reduced.	
Walls/DSF using plastic	Italy	Cold Climate	Cooling and Heating season	Simulation (Energyplus)	Reducing the cooling electricity demand (34.9% and 45.1%).	(Scorpio et al., 2019)
Walls/DSF- BIPVT	Tehran, Iran	Hot Climate	Heating and cooling season	Simulation (Energyplus)	The heat load reduction by about 3.2%. It can enhance the building performance of 34.3% Globally	Shakouri et al. (Shakouri et al., 2020)
Walls/DSF- PV vs IGU-PV	China	Different Climates	Cooling and Heating season	Simulation (Energyplus)	Best results are found in mild climates, where PV-DSF achieves energy savings of 46.9% and 44.8%,	(Wang et al., 2017)

					respectively	
Multi-functional Energy-Efficient Façade Systems (MEEFS)	Finland	Cold Climate	Heating and cooling season	Real case		(StatisticsFinland,2013)
Active Solar Thermal Façades	France	Cold Climate	Heating season	Real case		(Zhang et al., 2015)

CHAPTER 3

MATERIALS AND METHODS

This chapter provides a detailed explanation of the research methodology used to investigate facade retrofit strategies including individual and combined strategies. The goal is to analyze strategies that could reduce cooling energy demand and achieve energy savings in the residential sector. This was conducted with reference to a real-time case study, which is a student dorm at King Fahd University of Petroleum and Minerals (KFUPM) in Dhahran, Saudi Arabia. This is also conducted considering the hot and humid climatic conditions of the Eastern Province of Saudi Arabia. The methodology framework as shown in **Figure 19** includes: 1. Case study selection, 2. Data collection, 3. Retrofit strategies selection, 4. Data analysis, 5. Result and discussion, 6. Conclusion, and 7. Recommendations.

The study was conducted by reviewing relevant literature on façade retrofit strategies, and involved analyzing both quantitative and qualitative data. The collected data was evaluated using Design-Builder software, on-site visits, thermography, and optimization analysis.

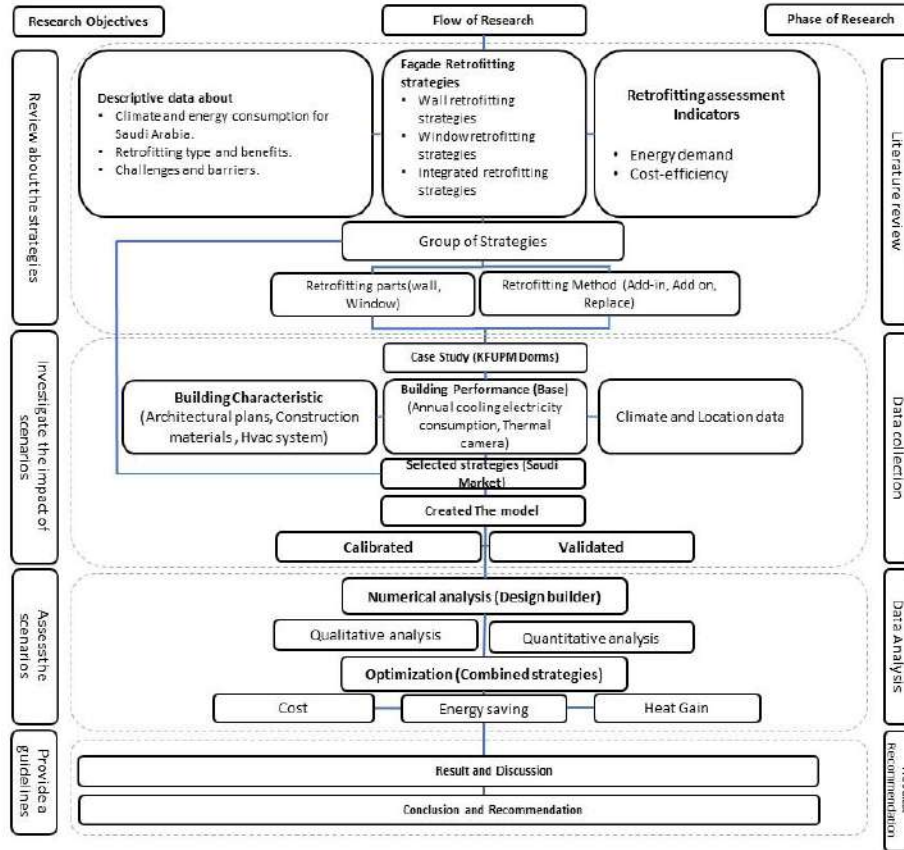


Figure 19 Methodology framework

3.1 Data collection

The research involved a comparative analysis that required both qualitative and quantitative data. The data collected from the buildings required assessment using appropriate software, on-site visits, and thermography surveys (Brandão, 2021). The case study involved gathering detailed information of KFUPM dorms from the project department at KFUPM University. This information included the architectural plans, building materials, and their specifications. Building characteristics, performance, and climate and location data were among the qualitative and quantitative data collected.

3.2 Case study selection

The selected case study is located in Dhahran city in the Eastern Province of Saudi Arabia. This city represents a major climatic zone in Saudi Arabia, which is hot dry climatic conditions, with high humidity levels in some months (Alrashed & Asif, 2015). The selected building is a typical student dormitory at King Fahd University of Petroleum and Minerals (KFUPM), which has 48 student-dorms, resulting in substantial electricity consumption.

3.2.1 Building characteristics

Data on the characteristics of the building was collected through on-site visits to the project department at KFUPM. Archives related to 2D drawings, construction details and material specifications were also obtained. The building has three floors with a total area of 4318 m². Façades are made of large concrete panels with rectangular windows. The building has an L-shaped configuration, has 3 stairs, and is oriented 17 degrees away from north towards west from. Each floor has 29 bedrooms, where each room is shared by two students. There are 3-bathroom zones, a lobby, a study room, and a mechanical room on each floor, **Figures 20 and 21.**



Figure 20 View of the male student's dorm at KFUPM

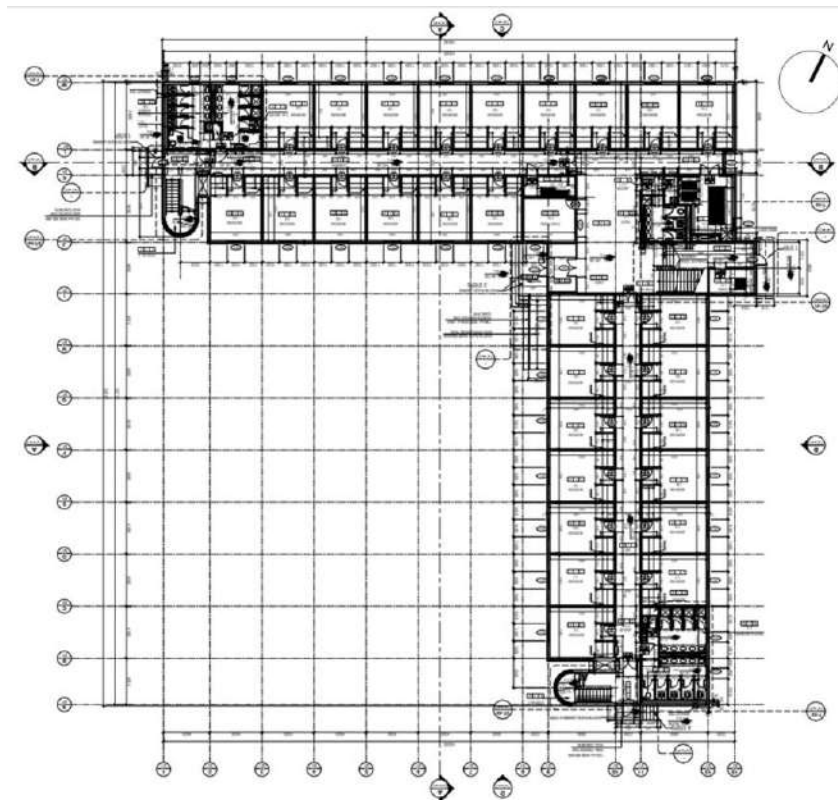


Figure 21 Male student's dorms plan

The study collected external wall drawings and other 2D drawings of the case study to create an accurate building model. The building is made of precast concrete, which is the main building material as shown in **Figure 22**. The external walls are mainly composed of a 27 cm precast wall panel with 4 cm of EPS insulation materials. The quantitative data of the physical, thermal, geometric, and size parameters of the vertical envelope components are summarized in **Table 3**.

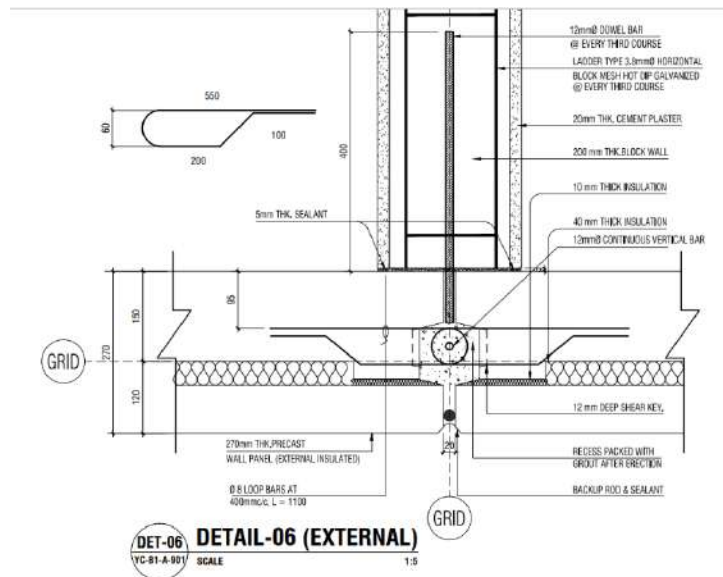


Figure 22 External wall details.

Table 3 Structural characteristics of the building envelope

Case study	Envelope Material details		R-value W/m ² K
External walls	Pre-cast concrete wall	15 cm	0.071
	Rigid polystyrene insulation	4 cm	0.25
	Pre-cast concrete wall	8 cm	0.029
Total		27cm	0.35
Internal walls	Masonry concrete unit	20 cm	0.37
Roof	Concrete tile	4 cm	0.029
	Rigid insulation	6 cm	0.25
	Waterproof	0.7 cm	-
	Concrete screed	5 cm	0.17
	Hollow core concrete slab	20 cm	0.314
	Total	44 cm	
Floor	Ceramic Tile	3.5 cm	0.027
	Concrete screed	7 cm	0.17
	Hollow core concrete slab	20 cm	0.314
	Total	30.5 cm	

Figures 23 and 24 present the window details for the student dorms. They are sliding windows with dimensions of 1.5m by 1.2m. The windows have an aluminum frame without a thermal break and double 6mm bronze tint glass with a 12mm air gap. The thermal transmittance of the glazing is 2.66 W/(m².K) and the Solar Heat Gain Coefficient is 0.861. Table 4 presents the characteristics of these windows.

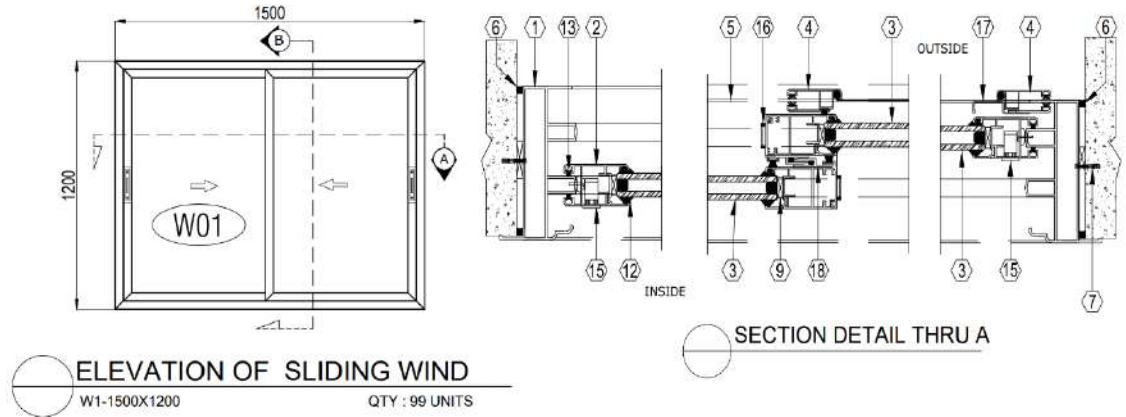


Figure 23 Elevation of windows

Figure 24 Window section details

Table 4 Characteristics of the Windows

Case study	Material details		U-value W/m ² K
External Windows	Bronze Tint Glaze	6 mm	
	Air Gap	12 mm	
	Clear Glaze	6 mm	
Total		24mm	2.66
Dimension of windows			1.5*1.2 m
Number of windows			99

The architectural drawings show that the openings within the structure follow a uniform distribution. This ensures that every student room has one window that is directly exposed to the sun. However, no solar protection was provided. As could be noticed in the building elevations, the total area of all elevations is 2031.66 square meters, with a cumulative opening area of 201.78 square meters. This results in a window-to-wall ratio of 9.93%, as shown in **Table 5**.

Table 5 Building's Elevations Details

Elevation	Facade Area (m²)	Openings Area (m²)	Window-to-Wall Ratio%
North	477.46	53.46	11.2%
West	533	50	9.4%
South	507.02	43.4	8.6%
East	514.1	54.92	10.7%
Total area for elevations	2031.66 m²	201.78 m²	9.93%

3.2.2 HVAC System details

During summer, buildings require intense cooling due to the extremely high outdoor temperatures. At the university's housing facilities, a water-cooled chiller station provides cooling to 21 residential buildings that house students. The occupancy density is 0.045 person/m². On-site visits were conducted to gather the necessary data in this regard to create an accurate model.

The chiller used is an electrically-driven centrifugal YORK YK with a nominal capacity of 2100KW and a Coefficient of Performance (COP) of 5.5, as shown in **Figure 26**. The chiller unit is linked intricately to four cooling towers linked to the chiller, which are connected to a pipeline carrying chilled water and distributed to cooling vents within the residential rooms. The system configuration is illustrated in **Figure 25**.

The water-cooled chiller's operational load is determined by the temperature difference between the inlet and outlet of the housing space. Thus, as the internal space temperature approaches the desired level of thermal comfort, the cooling load decreases. However, the chiller system operates continuously throughout the year due to the high external temperature in the region.

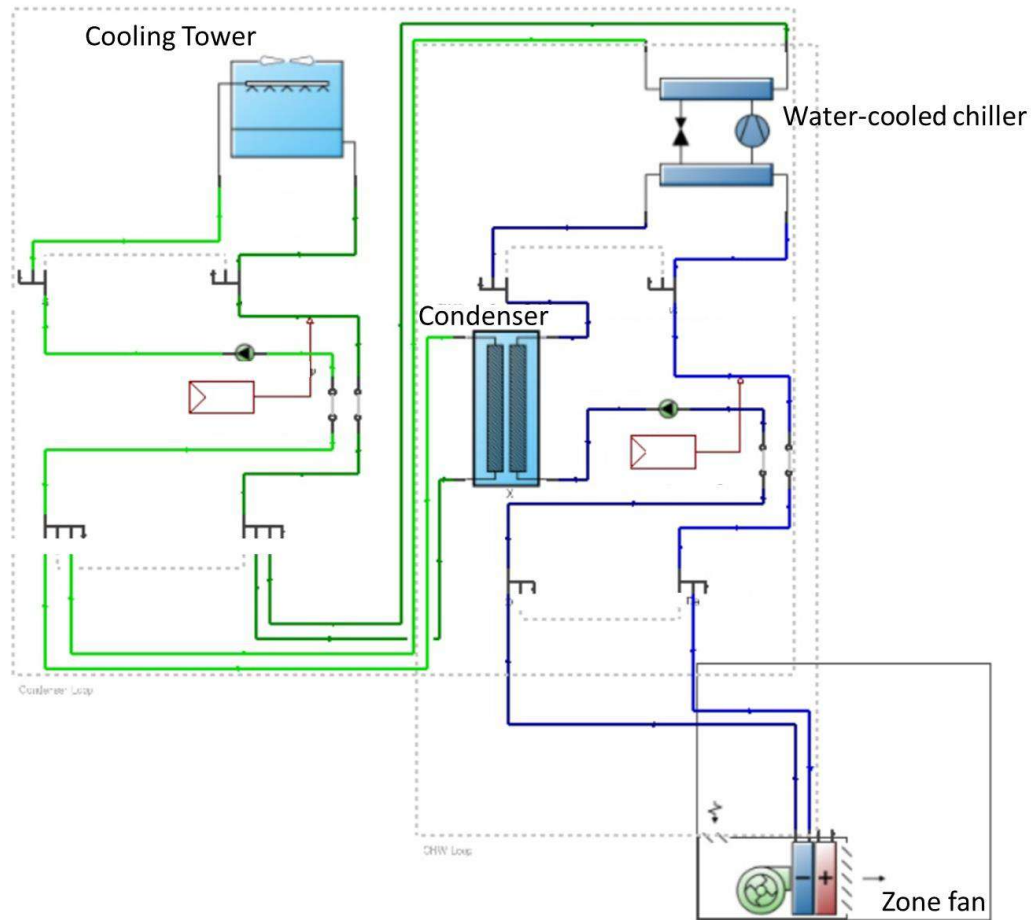


Figure 25 Water-cooled chiller system

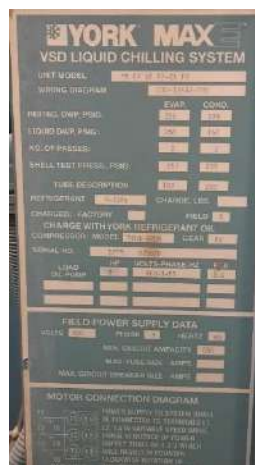


Figure 26 Water specifications

3.2.3 Façade Area-weighted average surface temperature

In this stage of study, on-site measurements were conducted to evaluate the current status of the façade and calculate the area-weighted average surface temperature, including heat leakage using a thermal camera as follows:

Summer time in Saudi Arabia is very hot, with an average temperatures exceeding 40°C (104°F) in most regions. The summer months (June to September) have the longest days, with sunrise around 5 am and sunset around 7 pm and the peak of temperature hours usually occur in the early afternoon, between 12 pm and 3 pm (climatestotravel, 2020).

Accordingly, the measurements were conducted on 5 September 2023, between 2.30 pm and 3.00 pm.

Figure 27 and 28 present the obtained thermal images. Thermal scales were adjusted according to the wall orientation to allow a better understanding of the identified anomalies.

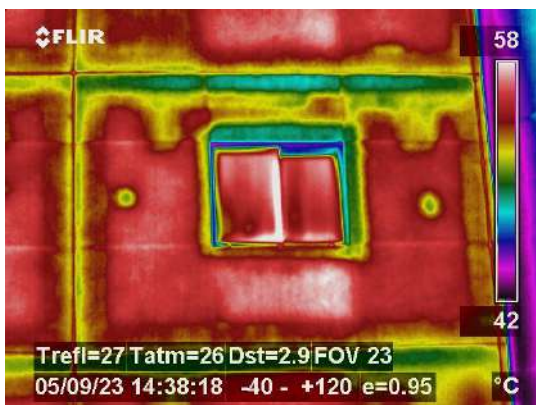


Figure 28 Thermography photo 1

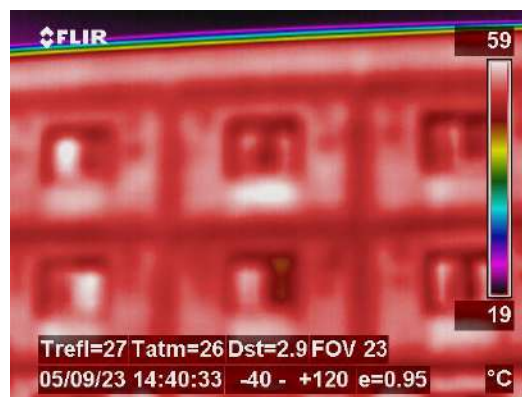


Figure 27 Thermography photo 2

The thermal images show anomalies in the surface temperatures of the facade, The anomalies of facade temperatures were divided according to temperature zones in **Figure 29** into v1, v2, v3, v4, and v5, and the average surface temperature for both the external walls and the windows was calculated based on the area of each these zones.

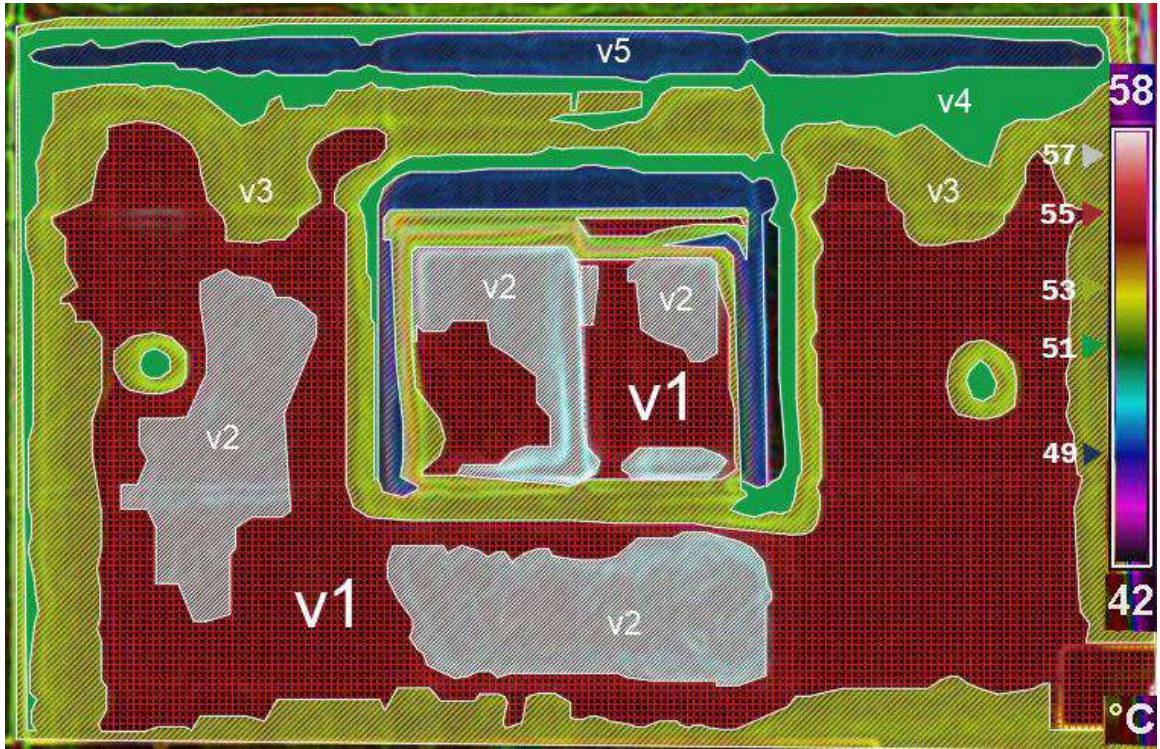


Figure 29 Temperature zones

The following equation was used to calculate the area-weighted average surface temperature:

$$V = \sum v_n \cdot A_n / A_t$$

Where v_n is zonal temperature ($^{\circ}\text{C}$), A_n is area of that zone (m^2), and A_t is total surface area (m^2)

Table 6 displays the average surface temperature of the external walls and windows on the southwest facade of the student housing. By analyzing the thermography results and using the aforementioned equation, the surface temperature was calculated. As a result, the external walls have an average surface temperature of 53.96°C, while the windows have an average surface temperature of 53.82°C. The high surface temperature of the facade is due to the materials used in construction, as the external walls are mainly composed of concrete and the windows have absorptive glass.

Table 6 Average of temperature surface for facade

Temperature Zone	Area (m ²)	Surface Temperature (°C)
V1	6.244	55
V2	1.451	57
V3	4.035	53
V4	1.269	51
V5	0.653	49
Façade Average Temperature (°C)		53.96
V1	0.5664	55
V2	0.6714	57
V3	0.5584	53
V5	0.4887	49
Window Average Temperature (°C)		53.82

The main findings obtained from the thermographic measurements were as follows:

- In the facades with a southwestern orientation, which have greater exposure to sunlight, an anomalous condition was observed in the temperature surface for the external walls in the part below the windows, with a significantly increased temperature compared to the rest of the wall.
- It was noted in the same facade that there was an anomaly in the connection area between walls and floors with low surface temperature compared to the surrounding areas, which may indicate heat leakage.
- In the windows, a high surface temperature of the glass was observed compared to the surrounding area, which causes a significant heat gain and raises the indoor temperature.

3.3 Selection of retrofit strategies

Different facade retrofitting strategies were selected to improve the building's performance and reducing the cooling electricity demand, in addition to that, the selection was contingent upon several factors including materials' availability in the Saudi market and practical viability of implementation in construction. Thus, different retrofit strategies were selected as follows:

- **Strategy A:** The application of external insulation, with repercussions in cooling seasons for opaque envelope elements.
- **Strategy B:** The substitution or add-in insulation for the existing windows, considering the effect harsh weather on the glazed elements.
- **Strategy C:** The application of solar films and smart glazing for the existing glazed elements.
- **Strategy D:** The application of different types of shading devices (external and internal) on the facade.

3.3.1 Façade retrofitting scenarios

Facade retrofit strategies were selected based on the important parts of the facade, where the strategies were divided into: A. external wall insulation strategies, B&C. windows retrofitting strategies, and D. shading device strategies. This study examined different scenarios for each strategy to investigate its impact on cooling electricity reduction by employing different materials that are available in the Saudi market. The cost for each scenario was collected by reaching out to several companies to acquire pricing information for these strategies, enabling a cost-effectiveness analysis of energy demand reduction. These retrofitting strategies are categorized into three distinct groups as following:

- **External Insulation Scenarios (Strategy A)**

The study initially investigated three primary retrofit strategies based on a comprehensive review of existing literature: prefabricated wood, External Thermal Insulation Composite System (ETICS), and ventilated facade. The specific configurations for these strategies are detailed as follows: Prefabricated modular panels are composed of a timber frame structure filled by a layer of mineral wool with a total thickness of 14 cm. The ETICS strategy involves applying an 8 cm layer of expanded polystyrene (EPS) insulation material to the external walls, reinforced with a mesh and a 2 cm plaster finish. The ventilated facade, characterized as a dynamic construction strategy, primarily incorporates 5 cm of extruded polystyrene (XPS) insulation material, a 2.5 cm air gap, and a 2.5-3 cm finishing layer. Various cladding materials from the Saudi market are utilized as part of the ventilated facade system, as shown in **Table 7**.

Table 7 External walls strategies proposed

No	Strategy	Cost (SAR/ m²)
S-WA-1	Ventilated façade with ACP sheet cladding	430
S-WA-2	Ventilated façade with Fiber cement board (FC)	200
S-WA-3	External Thermal Insulation Composite Systems (ETICS)	150
S-WA-4	Prefabricated wood element	450
S-WA-5	Ventilated façade with Limestone cladding	380
S-WA-6	Ventilated façade with sandstone cladding	430
S-WA-7	Ventilated façade with AAC Brick cladding	240
S-WA-8	Ventilated façade with WPC cladding	340

- **Windows scenarios (Strategy B+C)**

In addressing window properties, thermal behavior is defined by three elements: the glass panes, the space between panes (multi-glazed windows), and the number of panes (single, double, or triple). The permutation of these elements influences thermal resistance and offers retrofitting options for windows with low transmission coefficients, such as multi-pane systems with coatings or gases. That includes sets of scenarios: smart glass by replacing the base windows with electrochromic glass which is a double smart glass with 6mm thickness for glass panes and 13 mm air gap, this kind of glass can change color to prevent heat from the sun from entering spaces when the outside temperature reaches 24 C. Moreover, second strategy is applying a low-emissivity coating for the base window where Low-e coatings are thin, transparent layers that are typically applied to the surface of window glass. These coatings are designed to reflect and emit radiant heat, reducing the

amount of heat that passes through the window. A third strategy is to replace the double glass with triple glass with the same properties for the base window by 6 mm thick bronze glass with 13 mm air gaps. The fourth strategy is to fill the base windows and previous strategies with argon gas and investigate it's impact of argon gas on each strategy. as shown in **Table 8**:

Table 8 Windows strategies proposed

No	Strategy	Glass and Insulation Type	Cost (SAR/m ²)
S-W-1	Smart glass	Electrochromic	1200
S-W-2	Coating	Low-E	250
S-W-3	Increases Layers	Triple -glazed	320
S-W-4	Insulation	Double-Argon	20
S-W-5	Smart glass + Insulation	Electrochromic+ Argon	1220
S-W-6	Coating + Insulation	Low-E + Argon	270
S-W-7	Increases Layers + Insulation	Triple + Argon	340

- **Shading Devices (Strategy D)**

External shading devices are vital for curbing heat gains in daytime-occupied buildings, and require careful design. This study investigates the effectiveness of certain shading devices including louvers, smart blinds, and overhangs with different materials in reducing annual energy consumption for KFUPM student dorms. That includes set of scenarios as shown in **Table 9**:

Table 9 Shading devices strategies

No	Strategy	Cost (SAR/ m ²)
S1S-S-1	Electric Blinds	800
S-S-2	Window louver	300
S-S-3	Wood-Overhang	400
S-S-3	Metal-Overhang	750

3.4 Data analysis

The study analyzed the impact of the above-mentioned strategies on energy consumption in the examined building using a numerical simulation. Data analysis is summarized as the following points:

3.4.1 Model calibration

In this study, Design Builder (DB) was selected for simulation. The building has been simulated as shown in **Figure 30** to match the geometrical characteristics of the examined case study.

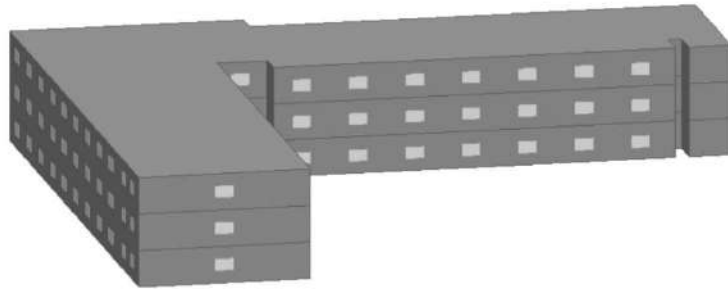


Figure 30 Model view

This also requires a detailed definition of weather and area data zoning, building materials, openings, space activity and occupancy rates, natural ventilation rates, and heating, ventilation, and air conditioning (HVAC) systems.

The building is occupied during both summer and winter seasons. The occupancy schedule is set based on logical judgment and common practice. The sensible and latent loads produced by the actual number of people occupying each space and the computer equipment have been considered. The building is used 24 hours per day, seven days per week, from Jan 1 to December 31, with different load levels of use. The basic information for the model is shown in **Table 10**.

Table 10 Student dorms Building Base Case Main Characteristics

Location	Dhahran 26.27° latitude / 50.17° Longitude
Number of floors	3
Floor Area (m ²)	1210.76 m ²
Floor Height (m)	2.9 m
Façade surface area (m ²)	2031.66 m ²
Glazing area (m ²)	201.78 m ²
Glazing ratio (%)	9.93%
Occupancy schedule	24/7 on
Density of occupancy	0.045 person/m ²
HVAC system	Detailed Water-cooled chiller
Nominal capacity	2100 KW
Cop	6
Cooling setpoint	23
Number of cooling tower	4

3.4.2 Model validation

Accurate validation of the simulation model is critical to ensure that reliable results are provided. Thus, model validation was performed at the beginning of this research. The building has been simulated to function exactly as it is. The energy model was calibrated based on the comparison between simulated HVAC energy consumption data and actual consumption data obtained for the chiller plant for one year.

According to **Table 11** the annual cooling electricity consumption of the modeled building was **477073.9** kWh. The actual **cooling electricity consumption for one building was about 493714.29** kWh, which was obtained from the field. This shows a discrepancy of 3.37% in energy consumption. However, this is an acceptable error margin considering the complexity of software equations and their underlying numerical mechanisms that makes it a hard task to model annual human behavior. Hence, the results of the building energy model are considered to correspond to surveyed data with high accuracy. This is also in agreement with the estimated annual cooling electricity consumption based on Energy Use Intensity (EUI), which were determined to be 182 kWh/m²/year for the eastern region of Saudi Arabia (Krarti, 2020). And considering that the energy usage of air conditioner systems has increased to 70% of overall power consuming in the apartment buildings in the eastern of Saudi Arabia (Alshahrani & Boait, 2018), the calculated annual energy consumption for cooling was 462,462 kWh. This shows a discrepancy of 3.78% when compared to the field measurements.

Table 11 Comparison of annual electricity consumption between the actual and simulated case

Simulated annual cooling electricity consumption (kWh)	Actual annual cooling electricity consumption (kWh)	Estimated annual cooling electricity consumption based on floor area (A) and Energy Use Intensity (EUI), (kWh)
477073.9	493714.3	462,462.0

3.5Retrofitting assessment

The study conducted a comparative analysis utilizing Design Builder for the aforementioned facade retrofitting strategies. Subsequently, the proposed strategies were individually assessed with a primary focus on reducing energy consumption and costs. The evaluation primarily involved comparing the strategies based on their financial efficiency, employing the payback period equation as a key metric.

- **Payback Calculation**

Calculating payback means knowing when the initial expenditure of a retrofit alternative will be covered by the reduced utility cost and power use. The following equation is used to calculate the payback period:

$$N_i = R / (E_b - E_c) * x$$

Where N_i is payback period (years), R is total retrofit cost (SAR), E_b is energy consumption prior to investment (kWh.year), E_c is energy consumption after investment (kWh.year), and x is electricity cost (SAR per kWh).

As could be seen in the equation, a simple payback period (SPP) is determined by dividing the cost of implementing the Energy conservation opportunities by the annual energy savings. **Table 12** shows the electricity tariffs set by the Saudi Electricity Company for different building sectors in Saudi Arabia. In the specific case study discussed, the cooling energy consumption exceeds 10,000 kWh, resulting in an associated energy price of 0.32 SAR/kWh.

Table 12 Electricity tariff in the Kingdom of Saudi Arabia

Monthly electricity consumption in kWh	Residential and Commercial tariff in Halala/kWh	Industrial tariff in Halala/kWh
1-1000	5	12
1001-2000	5	12
2001-3000	10	12
3001-4000	10	12
4001-5000	12	12
5001-6000	12	12
6001-7000	15	12
7001-8000	20	12
8001-9000	24	12
9001-10000	28	12
Over 10000	32	12

- **Optimization Method for Combined Strategies**

A group of strategies has been proposed for each of these components. The main objective of this study is to enhance the cooling energy performance of the building and investigate the impact of the individual and combined strategies on cooling energy consumption.

To facilitate the evaluation and comparison of the combined strategies for external walls, windows, and shading devices, a set of four key performance indicators has been selected. These indicators include heat gains, cooling energy consumption, , and financial efficiency. Hence, based on these indicators, an optimization framework was implemented. Employing the computational capabilities of Design Builder, a systematic comparative analysis of the various strategies has been undertaken to discern the most effective approach to improve building's energy efficiency and reduce its environmental impact.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the findings of the comparative study conducted using numerical analysis. The primary objective is to evaluate the impact of various façade strategies, including external insulation for walls, windows, and shading devices, on reducing cooling electricity consumption in the examined building at King Fahd University of Petroleum and Minerals (KFUPM) in the eastern province of Saudi Arabia. Furthermore, the financial efficiency of each strategy was analyzed using simple payback period. The chapter is split into two parts: the first part investigates the effects of individual façade retrofit strategies, while the second part details the outcomes of the combined façade retrofit strategies.

4.1 Base case performance

As mentioned above, this study has selected a student housing building at KFUPM as a case study. It is worth noting that the student dorms comprise approximately 20% of the university's overall area, with 48 residential buildings, which increases the potential of retrofitting these buildings to save a great deal of energy at the university level. Students tend to spend most of their time in these buildings, resulting in significant cooling energy consumption, which can reach 493714.29 kWh for each building due to the hot weather. **Figure 31** provides a visual representation of the university's student housing zone at KFUPM campus.



Figure 31 Top view of the student dormitory complex

The university student housing zone is planned using a typical L-shaped building in a variety of orientations as shown in **Table 13**. It could be observed that student dorm buildings with orientations 1 and 2 account for 79% of all residential buildings, indicating a higher percentage than the rest. In contrast, each of the remaining orientations constitutes less than 10% for each one, as shown in **Table 13**. As a result, the study has focused on these two orientations, referred to as cases A and Case B.

Table 13 Types of building's orientation

	Orientation 1	Orientation 2	Orientation 3	Orientation 4	Orientation 5	Orientation 6	Orientation 7	Orientation 8

Degree	197	17	124	214	242	62	90	0
Number of Buildings	25	13	4	1	1	2	1	1
Percentage	52%	27%	8.3%	2.08%	2.08%	4.16%	2.08%	2.08%

Following the validation process presented in Chapter 3, a comprehensive assessment of the building's performance was conducted, with a particular emphasis on energy consumption for cooling and heat gains through the building fabric. This was achieved through an intensive numerical analysis using Design Builder program.

As presented in **Tables 14 and 15**, a modeled of Case A consumes electricity energy of 477,073.9 kWh per year for cooling, while Case B recorded a higher cooling electricity consumption of 483,005.2 kWh. This is attributed to its orientation which resulted in a higher window exposure at the southern façade. As a result, Case B receives more heat gains through the facade openings compared to Case A, whereas Case A had a higher heat gain amount from the external walls, as shown in Table 14 and 15.

Table 14 Building's performance Case (A)

	U-value (wall) (W/m2-K)	U-value (windows) (W/m2-K)	Annual Cooling Electricity Consumption (kWh)	Wall Heat Gains (kWh)	Glazing Heat Gains (kWh)
Base Case (A)	0.563	2.665	477073.9	56649.46	30117

Table 15 Building's performance Case (B)

	U-value (wall) (W/m ² -K)	U-value (windows) (W/m ² -K)	Annual Cooling Electricity Consumption (kWh)	Wall Heat Gain (kWh)	Glazing Heat Gain (kWh)
Base Case (B)	0.563	2.665	483005.2	56363.76	30766.19

Figure 32 shows the monthly cooling energy consumption end-use distribution based on occupancy. The maximum cooling electricity demand reaches a peak between June and October. Cooling accounts for around 70% of the annual electricity consumption. The building exhibit a high cooling electricity demand in October, where Case A consumes 57365.32kWh and Case B consumes 57158.48 kWh.

Accordingly, enhancing the thermal performance of these buildings through façade retrofiting is expected to save a great deal of electricity cost. In this regard, the study explored several strategies that are implemented on the exterior walls, windows and solar shading devices.

Figure 33 shows a significant increase in fabric heat gain for both Case A and B, mainly between the months of May and October. In Case A, the peak heat gains for walls and glazing were 10,366.79 kWh and 4,997.642 kWh, respectively. On the other hand, Case B presented similar values of heat gains, which were 10,363.39 kWh and 5,016.553 kWh for walls and glazing, respectively.



Figure 32 Cooling electricity consumption for case A&B

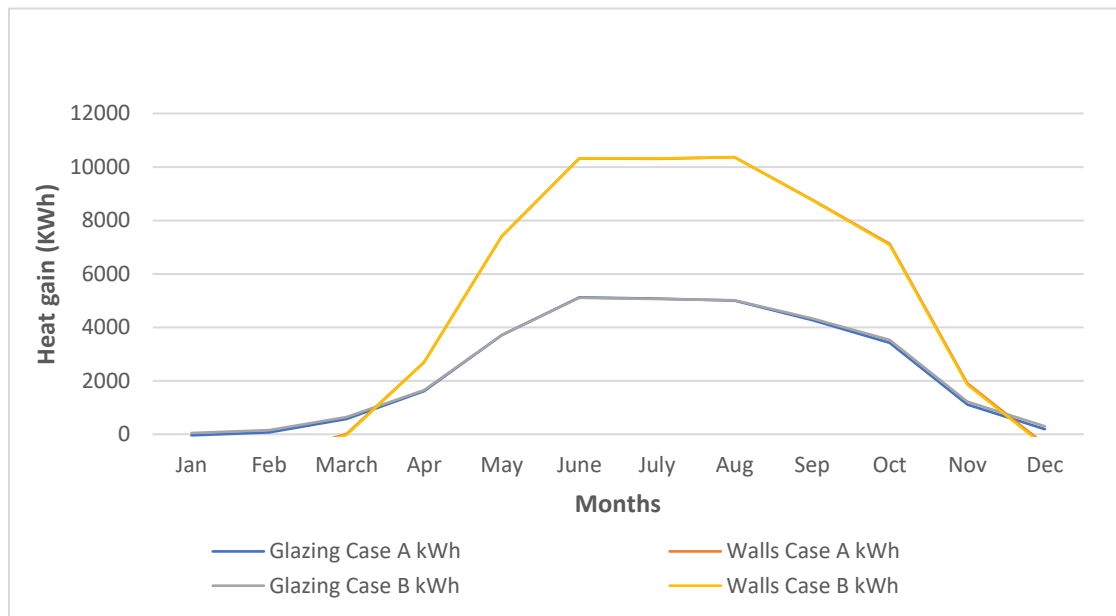


Figure 33 Facade Heat Gains for case A&B

4.2 External wall retrofitting strategies

Various external insulation strategies for the external wall of the façade have been selected and examined individually using Design Builder software. In this regard, the study compared eight retrofitting scenarios that could be potentially implemented in Saudi Arabia.

The selected strategies ranged from slandered construction for prefabricated wood and ETICS strategies to dynamic construction for the ventilated facade strategy. The latter offers greater flexibility than standard construction strategies, allowing for easy changes and replacements for the finishing layers. An effort was made to choose several insulation materials that are readily available in the Saudi market with a variety of finishing layers, as shown in **Table 16**.

Table 16 highlights that the choice of retrofitting strategy significantly impacts the building's thermal performance. One crucial criterion in selecting a cladding strategy is its thermal performance, assessed through the U-value, which indicates the rate of heat transfer through a building element. Strategies like "External Insulation/Prefabricated Wood Panel" and "External Insulation/ACP Sheet" offer remarkably low U-values of 0.153 W/m²K and 0.14 W/m²K, respectively, making them more-efficient for energy-efficient designs. Another commendable option is the ventilated facade with WPC cladding, recognized for its high heat retention capacity. However, the strategy of a ventilated facade utilizing limestone, sandstone, or brick cladding as a finishing layer has a higher U-value, reaching 0.24 W/m²K. Despite the aesthetic appeal and traditional style that may influence choices, the selection of a

cladding strategy should consider project-specific requirements, including budget constraints.

Table 16 Thermal properties of the materials used in the external wall retrofitting scenarios

NO	Strategy	Dynamic Construction	Material combination	Thicknes s (m)	Wall U-Value (Before) (W/m²K)	Wall U-Value (After) (W/m²K)
S-WA-1	VF with ACP cladding	Ventilated facade - XPS	ACP sheet + XPS	0.1	0.563	0.153
S-WA-2	VF with FC cladding	Ventilated facade -XPS	XPS + FC	0.1		0.124
S-WA-3	External Thermal Insulation Composite Systems (ETICS)	Standard (ETICS)	EPS + Plaster	0.1		0.16
S-WA-4	External Insulation	Standard (Prefabricated wood panel)	Wood with wool fibers Insulation	0.3		0.14
S-WA-5	VF with Limestone cladding	Ventilated facade - XPS	XPS + Limestone	0.1		0.194
S-WA-6	VF with Sandstone cladding	Ventilated facade - XPS	XPS + Sandstone	0.1		0.195
S-WA-7	VF with AAC Brick cladding	Ventilated facade - XPS	XPS + Brick	0.12		0.192
S-WA-8	VF with WPC cladding	Ventilated facade - XPS	XPS + WPC	0.1		0.223
VF= Ventilated Façade, ACP = Aluminum Composite Panel, FC= Fiber Cement Board, AAC= Autoclaved Aerated Concrete, WPC= Wood Plastic Composite, XPS = Extruded Polystyrene Board, EPS= Expanded Polystyrene						

4.2.1 Heat gain reduction of external walls

This section aims to assess the impact of the different external insulation strategies of external walls on heat gains. The study considered EPS and XPS as insulating materials in this regard due to their availability in the Saudi market where the required data about their use could be obtained from the concerned experts. The strategies aimed to reduce the U-value of the base external wall of the building's facade and mitigate heat gains, which improves thermal comfort conditions indoors. The strategies varied in composition, encompassing three primary strategies with various cladding options to enhance the building's insulation performance.

Figure 34 and 35 illustrates the performance of the building's external wall strategies in reducing heat gain during summer months from April to November. Heat gain increases steadily from April and reaches its peak until the end of September, then drops slowly until January. Case 1 and Case 2 exhibited similar heat gain patterns throughout the year.

The study found commendable performance for all scenarios in mitigating wall heat gain for both Case A and Case B. The prefabricated wood scenario emerged as the most efficacious during summer months from April to November, demonstrating a significant reduction of heat gain due to the low U value. Following closely were the Ventilated Facade -ACP and Ventilated Facade -WPC scenarios. Heat gains increases in the following options respectively: Ventilated Facade -AAC, ETCIS, Ventilated Facade -Sandstone, and Limestone), respectively, and the least effective in reducing heat gain is the Ventilated Facade -Fiber Cement scenario. The previous results show a superiority of heat gain reduction for ventilated façade-ACP in the rest of months as

compared with prefabricated wood strategy due of its dynamic construction strategy. A buffer zone is created by the air gap in the ventilated facade, which permits air circulation to aid in heat dissipation and maintain a lower temperature near the building envelope. This can be particularly advantageous during months with lower external temperatures. Meanwhile, the prefabricated strategy may exhibit greater heat reduction during the remaining months due to its insulation properties.

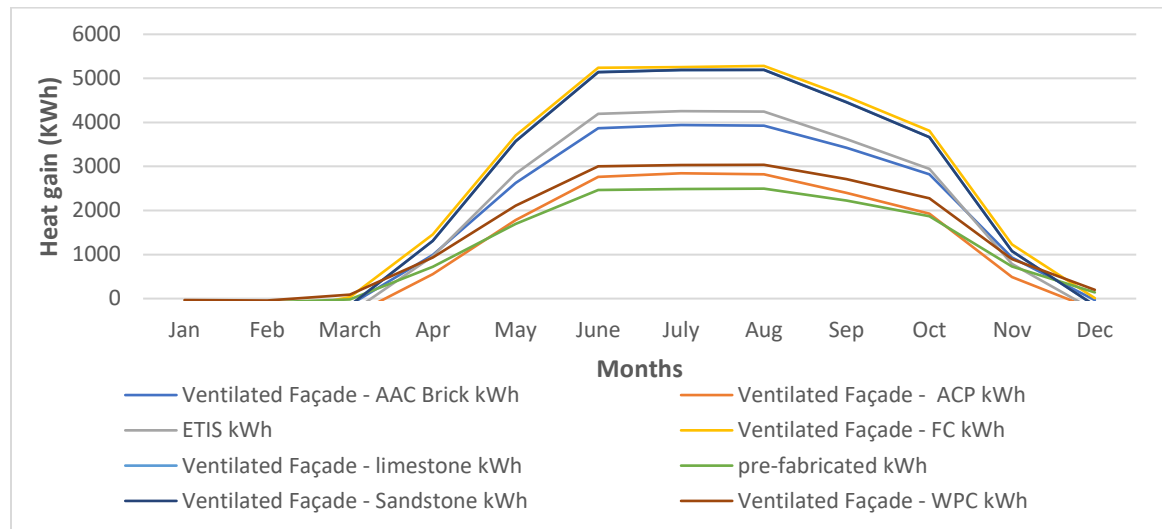


Figure 34 Monthly Wall Heat Gains for Case A

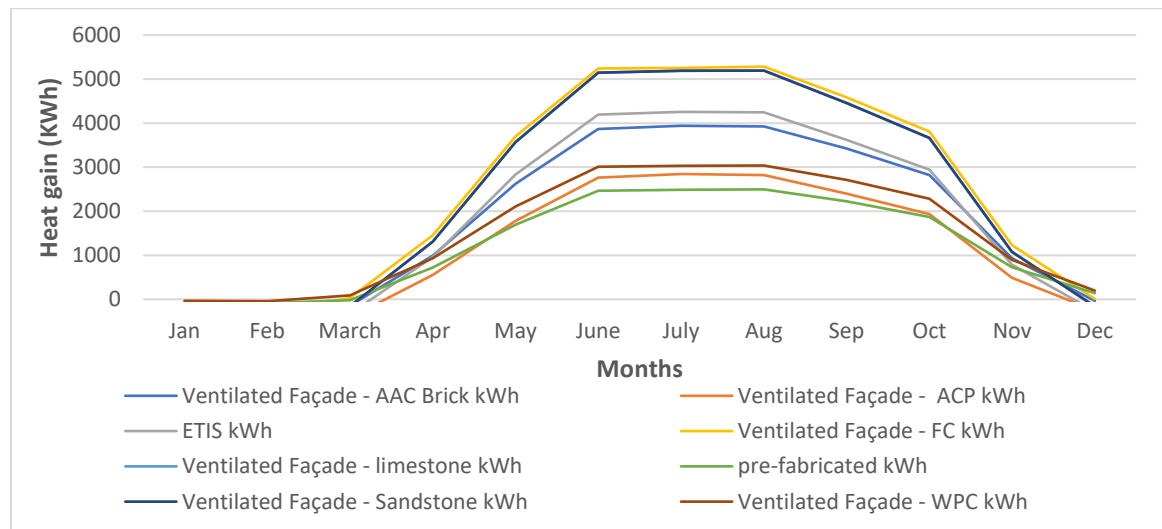


Figure 35 Monthly Wall Heat Gains for Case B

Figure 36 illustrates the annual reduction of heat gain for the proposed scenarios of Case A and Case B. The study found that all proposed scenarios significantly reduced the heat gain of the building's facade, with the percentage of decrease ranging from 50% to 75% in both cases. The ventilated facade - ACP scenario presented the most substantial reduction, reaching 75.38% for Case A and 75.40% for Case B, with slight variations in reduction observed for both cases. This could be observed in the amount of heat gains for each scenario as shown in **Figure 37**. Prefabricated wood panel scenario closely followed, achieving a reduction of 74.14% for Case 1 and 74.15% for Case B.

Other scenarios also contributed significantly to heat gain reduction including WPC cladding and AAC brick cladding (ETICS), respectively. The ventilated facade -FC was considered the least effective among the scenarios at 47.16% for Case A and 47.17% for Case B.

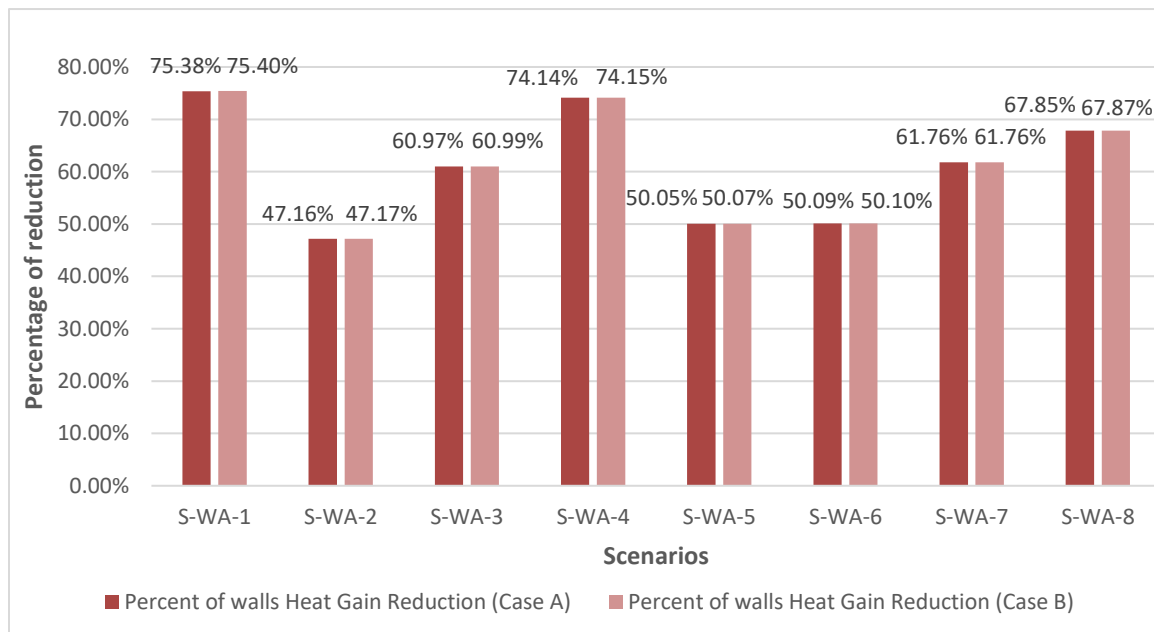


Figure 36 Percentage of annual heat gain reduction for case A & case B with external wall strategies

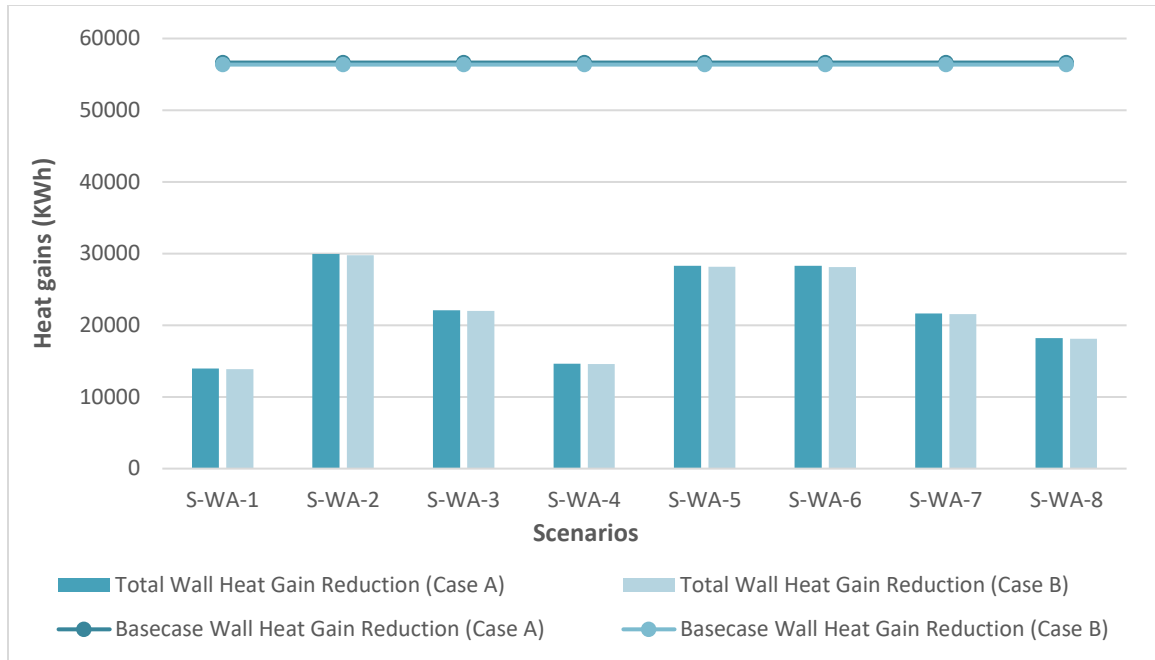


Figure 37 Annual heat gains for case A & case B before and after walls retrofitting.

Furthermore, Table 17 illustrates the amount of reduction in heat gain for each proposed scenario for both Case A and Case B before and after facade retrofitting strategies application. The study found that the reduction in heat gain corresponds proportionally to the decrease in the U-value of the main wall of the facade following the implementation of the proposed scenarios. Notably, the decrease in the u-value for the base wall from 0.56 W/m²K to 0.15 W/m²K by Ventilated Facade - ACP scenario demonstrated a significant reduction, amounting to 42,701.29 kWh for Case A and 42,500.16 kWh for Case B.

The prefabricated wood panel scenario showed a reduction of 41,997.65 kWh for Case A and 41,791.28 kWh for Case B. Conversely, the Ventilated Facade - FC scenario exhibited the least reduction in annual heat gain by 26,716.91 kWh for Case A and 26,587.3 kWh for Case B. The study found that the building's orientation at an angle of 197 degrees contributed a heat gain reduction by a mount of 200 KWH for Case A, which was higher than for Case B with a 17-degree.

Table 17 The annual heat gain reduction for case A & case B with wall retrofit strategies

No	Strategy	Case A				Case B			
		Heat Gains (KWH) (Before)	Heat Gains (KWH) (after)	Total Reduction	Percent of Reduction	Heat Gains (KWH) (Before)	Heat Gains (KWH) (after)	Total Reduction	Percent of Reduction
S-WA-1	VF with ACP cladding	56649.46	13948.17	42701.29	75.38%	56363.76	13863.6	42500.16	75.40%
S-WA-2	VF with FC cladding		29932.55	26716.91	47.16%		29776.46	26587.3	47.17%
S-WA-3	External Thermal Insulation Composite Systems (ETICS)		22108.97	34540.49	60.97%		21986.22	34377.54	60.99%
S-WA-4	External Insulation		14651.81	41997.65	74.14%		14572.48	41791.28	74.15%
S-WA-5	VF with Limestone cladding		28294.44	28355.02	50.05%		28144.13	28219.63	50.07%
S-WA-6	VF with Sandstone cladding		28274.18	28375.28	50.09%		28123.94	28239.82	50.10%
S-WA-7	VF with AAC Brick cladding		21665.49	34983.97	61.76%		21551.02	34812.74	61.76%
S-WA-8	VF with WPC cladding		18212.8	38436.66	67.85%		18111.96	38251.8	67.87%
VF= Ventilated Façade, ACP = Aluminum Composite Panel, FC= Fiber Cement Board, AAC= Autoclaved Aerated Concrete, WPC= Wood Plastic Composite, XPS = Extruded Polystyrene Board, EPS= Expanded Polystyrene									

4.2.2 Cooling electricity reduction

Evaluating and comparing the impact of the different retrofitting strategies on cooling energy savings and reduction is essential for achieving sustainable building design. Simulation results of retrofitting strategies provide valuable insights into their

performance compared to the baseline consumption of 477073.9 kWh for Case A and 483005.2 kWh for Case B.

Figure 38 and 39 demonstrate the monthly cooling consumption for Case A and Case B. The prefabricated wood wall strategy resulted in a significant cooling electricity reduction, particularly noticeable during May to October. Although all strategies have different impacts on energy consumption, the ventilated facade strategy employing WPC, ACP, and AAC brick claddings is superior to the ETCIS strategy. However, the ventilated facade strategy utilizing sandstone, limestone, and fiber cement exhibits the highest energy consumption as compared with other scenarios. This highlights the direct relationship between cooling energy demand and the thermal characteristics of each strategy due to the significant reduction in facade heat gain and U-value for each scenario.

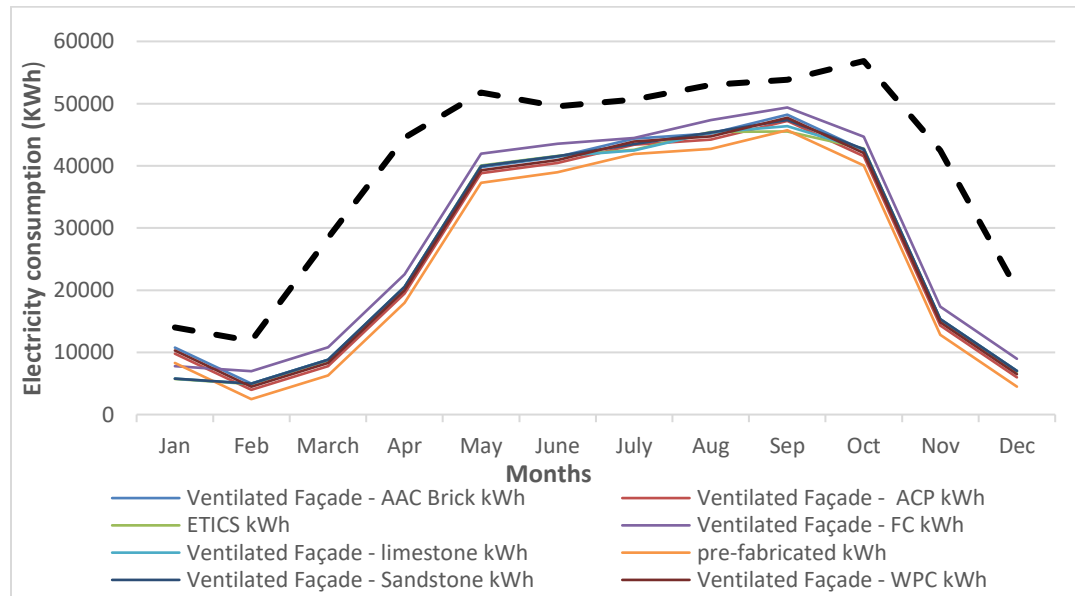


Figure 38 Monthly cooling electricity for each scenario of external wall retrofitting (Case A)

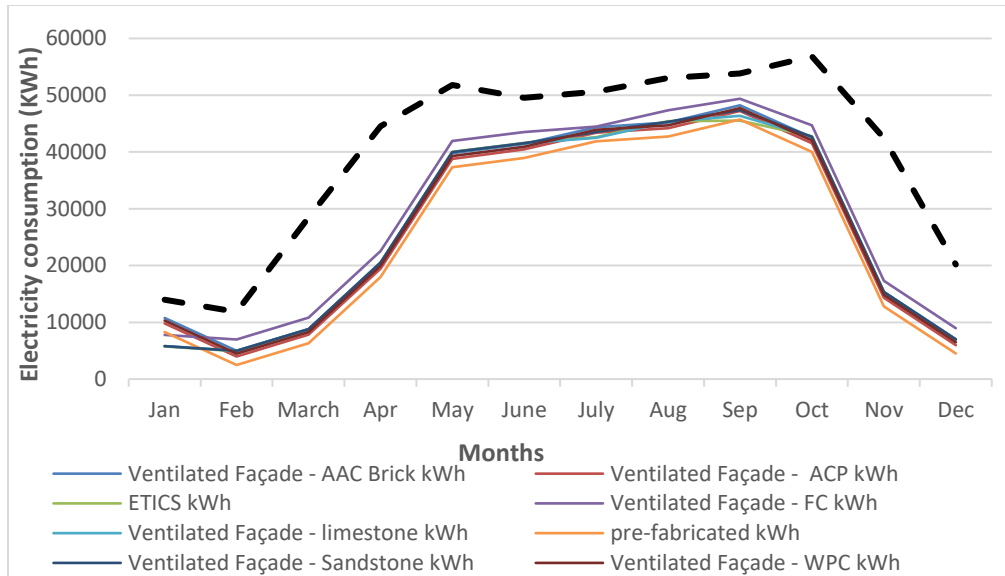


Figure 39 Monthly cooling electricity for each scenario of external wall retrofitting (Case B)

Figure 40,41 illustrates the effects of different retrofitting strategies on the annual energy r of the examined building. Notably, prefabricated wood elements strategy demonstrated the highest energy reduction, with percentage of annual reduction 18.04% for case A and 18.66% for case B. Followed closely by ACP sheet or Aluminum Composite Panel (PE) strategy, despite differences in thickness relative to prefabricated wood, proved to be highly effective, achieving a noteworthy annual reduction rate of 15.81% for case A and 16.23 for case B. Followed by WPC cladding and brick cladding strategies reduced the annual cooling electricity by 15.37% for case A and 15.91% for case B, respectively.

Conversely, the External Thermal Insulation Composite Systems (ETICS) strategy displayed a relatively low reduction compared to the other retrofitting strategies, indicating its comparatively less impact of energy reduction. The fiber cement retrofit approach had the lowest reduction among all presented scenarios, with a percentage of 11.8% for Case B and 11.06% for Case A.

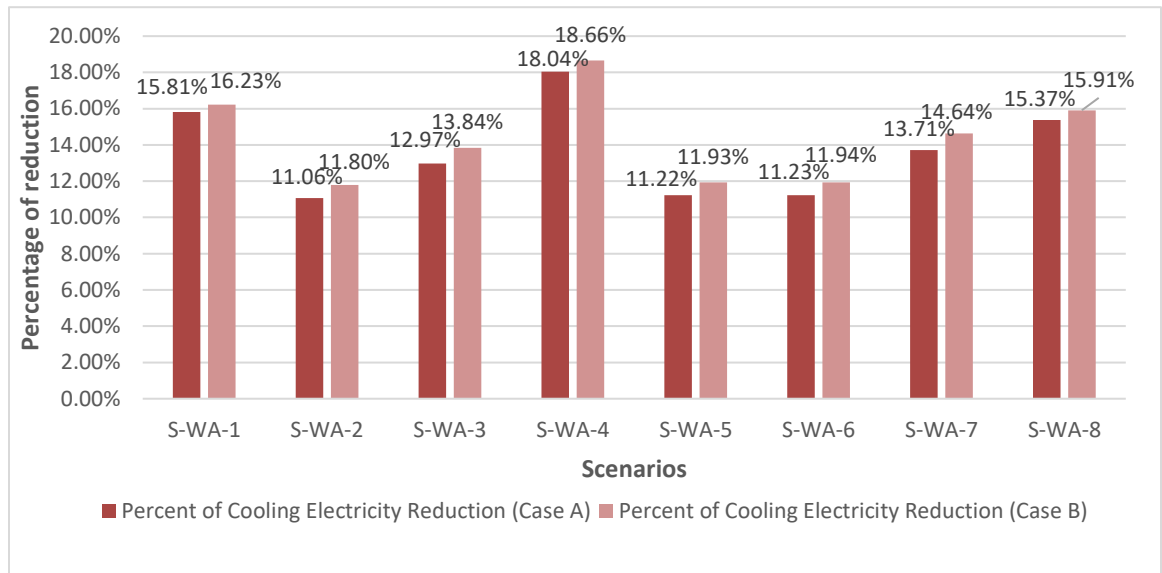


Figure 40 Percentage of annual cooling electricity reduction for case A & case B before and after external wall retrofitting

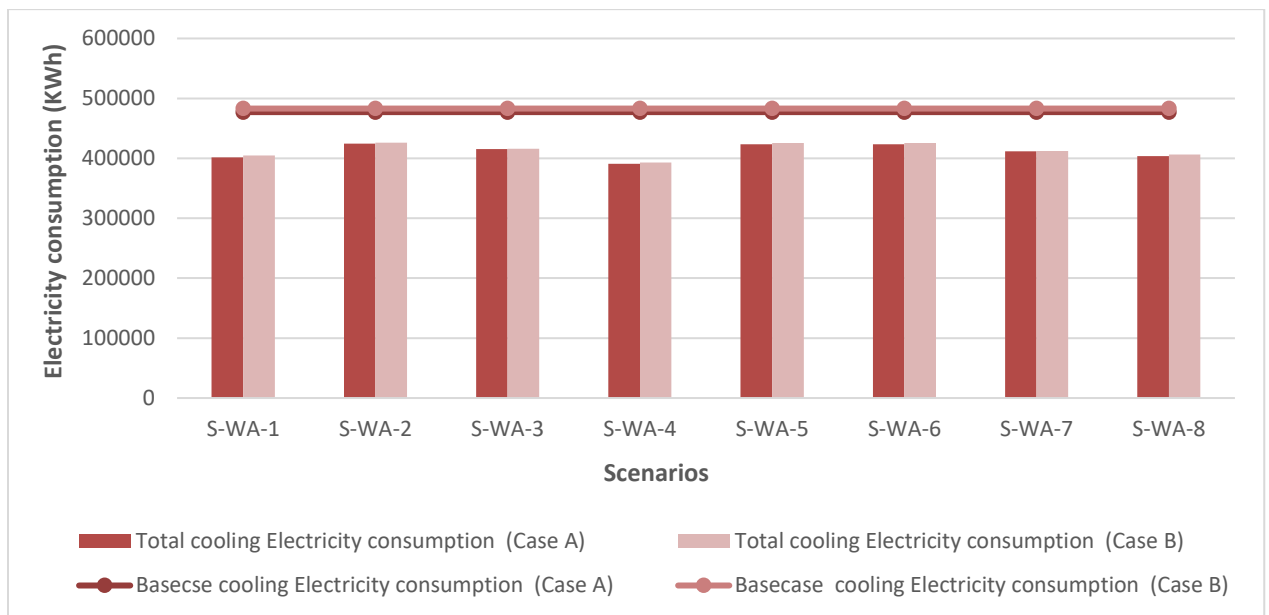


Figure 41 Amount of annual cooling electricity consumption before and after wall retrofitting for case A & case B

As presented in Table 18 a summary of the annual reduction in cooling energy consumption for both Case A and Case B. The retrofitting strategy that incorporated prefabricated wooden elements showed the most significant reduction, with an annual amount of 86,050.1 kWh for Case A and 90,125.8 kWh for Case B. Similarly, the use of ACP sheets or aluminum composite panels (PE) achieved substantial annual energy reduction amounts of 75,401.3 kWh for Case A and 78,401.3 kWh for Case B. Additionally, the WPC cladding and brick cladding retrofitting strategies resulted in annual energy reduction amounts of 73,345.2 kWh for Case A and 76,819.3 kWh for Case B, respectively.

However, the ventilated facade - FC retrofitting strategy showed a relatively modest reduction amount compared to other retrofit strategies, indicating its comparatively weaker impact on energy consumption reduction. Lastly, fiber cement had the lowest reduction rate among all retrofitting scenarios, with amount of reduction by 56,980.6 kWh for Case B and 52,759.3 kWh for Case A.

Table 18 A comparison of the annual cooling electricity reduction in case A & case B with wall retrofitting strategies

No	Strategy	Case A				Case B			
		Cooling Electricity (KWH) (Before)	Cooling Electricity (KWH) (after)	Total Reduction	Percent of Reduction %	Cooling Electricity (KWH) (Before)	Cooling Electricity (KWH) (after)	Total Reduction	Percent of Reduction %
S-WA-1	VF with ACP cladding	477073.9	401672.6	75401.3	15.81%	483005.2	404603.9	78401.3	16.23%
S-WA-2	VF with FC cladding		424314.6	52759.3	11.06%		426024.6	56980.6	11.8%
S-WA-3	External Thermal Insulation Composite Systems (ETICS)		415182.4	61891.5	12.97%		416156.3	66848.9	13.84%
S-WA-4	External Insulation		391023.8	86050.1	18.04%		392879.4	90125.8	18.66%
S-WA-5	VF with Limestone cladding		423533.5	53540.4	11.22%		425367.2	57638	11.93%
S-WA-6	VF with Sandstone cladding		423489.6	53584.3	11.23%		425322.6	57682.6	11.94%
S-WA-7	VF with AAC Brick cladding		411651.1	65422.8	13.71%		412293	70712.2	14.64%
S-WA-8	VF with WPC cladding		403728.7	73345.2	15.37%		406185.9	76819.3	15.91%
VF= Ventilated Façade, ACP = Aluminum Composite Panel, FC= Fiber Cement Board, AAC= Autoclaved Aerated Concrete, WPC= Wood Plastic Composite, XPS = Extruded Polystyrene Board, EPS= Expanded Polystyrene									

4.2.3 Cost-efficiency

The assessment of facade retrofit strategies for Case A and Case B requires considering the relationship between the investment cost, and the payback period.

Figure 42 presents the payback period for each scenario, specifically related to the cost in the Saudi market. It also shows the financial recovery periods for each of them, based on the amount of savings in cooling energy consumption.

It is worth noting that external insulation strategies have a longer financial recovery period due to the high initial price of materials. However, at the end of the period, the scenarios will intersect with the basic scenario, and the building will begin to benefit from the savings. The External Thermal Insulation Composite Systems (ETICS) scenario had the shortest period of financial recovery by 15.39 years for Case A and 14.24 years for Case B. This shorter payback period compared with other scenarios is due to the availability and the low cost in the Saudi market. The ACC Brick cladding scenario followed with a period of 23.3 years for Case A and 21.55 years for Case B. The Fiber Cement Board (FC) scenario had a duration of 24.1 for Case A and 22.29 for Case B, with a slight difference. Meanwhile, other scenarios need a longer time, more than thirty years to recover the cost.

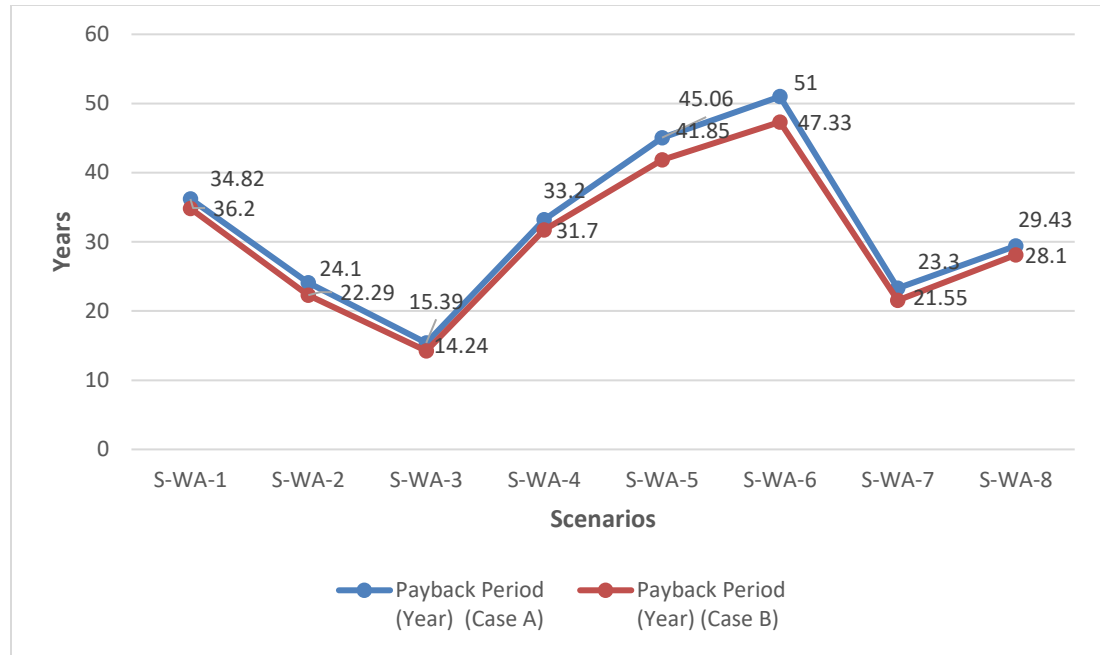


Figure 42 Payback period of wall retrofitting investment

As shown in Table 19 the annual recovered cost and the payback period for each scenario. Among the scenarios, the ETICS scenario has the lowest initial cost of 304,749 SAR and a relatively shorter recovery period.

The prefabricated wood scenario offered the highest cooling energy cost reduction of 27536.03 SAR for Case A and 28840.26 SAR for Case B. However, its high initial cost of 914247 SAR resulted in a long payback period of 31 years.

Table 19 Investment cost & payback period for case A & B with a different wall retrofit strategies

No	Strategy	Unit cost (SAR)	Unit	Case A			Case B		
				Total Cost (SAR)	Annual Cooling Cost Reduction (SAR)	Payback Period (Year)	Total Cost (SAR)	Annual Cooling Cost Reduction (SAR)	Payback Period (Year)
S-WA-1	VF with ACP cladding	430	m ²	873613.8	24128.42	36.2	873613.8	25,088.42	34.82
S-WA-2	VF with FC cladding	200	m ²	406332	16882.98	24.1	406332	18233.8	22.29
S-WA-3	External Thermal Insulation Composite Systems (ETICS)	150	m ²	304749	19805.28	15.39	304749	21391.65	14.24
S-WA-4	External Insulation	450	m ²	914247	27536.03	33.2	914247	28840.26	31.7
S-WA-5	VF with Limestone cladding	380	m ²	772030.8	17132.93	45.06	772030.8	18,444.16	41.85
S-WA-6	VF with Sandstone cladding	430	m ²	873613.8	17146.98	51	873613.8	18,458.43	47.33
S-WA-7	VF with AAC Brick cladding	240	m ²	487598.4	20935.3	23.3	487598.4	22,627.9	21.55
S-WA-8	VF with WPC cladding	340	m ²	690764.4	23470.46	29.43	690764.4	24,582.18	28.1
VF= Ventilated Façade, ACP = Aluminum Composite Panel, FC= Fiber Cement Board, AAC= Autoclaved Aerated Concrete, WPC= Wood Plastic Composite, XPS = Extruded Polystyrene Board, EPS= Expanded Polystyrene									

4.3 Windows retrofitting strategies

Achieving an effective facade retrofit in the hot climates necessitates minimizing solar gains through windows. The decision-making process for retrofitting requires careful consideration of both energy savings and economic feasibility to recommend practical solutions. Direct solar radiation on the site of the selected case study during summer extends from 9:00 am to 7:00 pm, peaking at 0.86 kW/ m^2 at midday, while diffuse horizontal solar radiation maintains a stable value of 0.11 kW/ m^2 .

To mitigate the summer heat gains, replacing existing window glass panes is an efficient method to reduce cooling demand in conditioned spaces, and extend thermal comfort hours. In this study, the base window of the building consists of double 6mm bronze glass with a 13mm air cavity, featuring a thermal transmittance of $2.66 \text{ W/(m}^2\text{-K)}$, and Solar Heat Gain Coefficient of 0.497.

The study evaluates the impact of different glazing retrofit strategies and their relationship to the cooling load. The investigated glazing strategies include increasing the number of glazing panes using triple glazing, applying a Low-E glass coating, and using smart glazing, specifically electrochromic glazing. Additionally, an insulation strategy is considered by incorporating argon gas between the glass panes for both the base case A and B.

Table 20 shows the change in the U-value and solar heat coefficient (SHGC) of the glass after replacing the glass panels. Smart glass by electrochromic reduces the U-value to $1.7 \text{ W/(m}^2\text{-K)}$, significantly improving the building's cooling energy consumption, and Solar Heat Gain Coefficient of 0.155. Triple glazing reduces the U-value to $1.726 \text{ W/(m}^2\text{-K)}$, and Solar Heat Gain Coefficient of 0.422. Low-E double

glazing achieves the lowest u-value reduction up to 1.76 W/(m²-K), with Solar Heat Gain Coefficient of 0.38.

Moreover, insulation with argon gas is considered a good solution for reducing heat gained directly from solar radiation in hot climates. Filling argon gas inside the double glazing for the base case has a minor impact on u-value which was reduced from 2.665 to 2.51 W/(m²-K). However, combining argon insulation with other strategies achieved a significant impact on the u-value for the window. The u-value for the smart glazing with argon insulation is 1.493 W/(m²-K), which is similar to the case of low-e double glazing with argon insulation. The lowest reduction when combining the strategies with insulation is triple glazing with insulation with a u-value of 1.593 W/ (m² -K).

Table 20 Windows strategy properties

No	Strategy		U-value W/ (m ² - K)	SHGC
	Base Case	-	2.665	0.497
S-W-1	Smart glass	Electrochromic	1.7	0.155
S-W-2	Coating	Low-E	1.761	0.38
S-W-3	Increases Layers	Triple -glazed	1.726	0.422
S-W-4	Insulation	Double-Argon	2.51	0.495
S-W-5	Smart glass + Insulation	Electrochromic+ Argon	1.493	0.144
S-W-6	Coating + Insulation	Low-E + Argon	1.493	0.373
S-W-7	Increases Layers + Insulation	Triple + Argon	1.593	0.42

4.3.1 Heat gain reduction of windows

The window-to-wall ratio (WWR) on the north, south, east, and west facades of two buildings, Case A and Case B, were observed to be slightly different. The north facade of Case A had a higher WWR of glass, while the south facade of Case B had the highest WWR of glass, accounting for 11.2% of the total facade. This variation results in increased heat gain and solar exposure from the windows on the south facade. Since the south-facing facade receives direct sunlight throughout the day, it serves as the primary source of natural illumination for the building's interior spaces.

Consequently, elevated indoor temperatures are observed, which in turn cause increased energy consumption to maintain indoor thermal comfort. The use of base window glass with higher thermal conductivity coefficient and solar heat gain coefficient (SHGC) further exacerbates the problem.

The study involved monthly heat gain comparisons for both Case A and Case B before and after examining the proposed scenarios.

As shown in **Figure 43 and 44** The results showed that electrochromic glass was the most effective strategy in reducing heat gains, followed by low-e layered glass and triple glass, respectively, during the summer period from May to October. Furthermore, the filling of argon gas between the layers of glass resulted in a significant reduction in heat gain, particularly in low-e glass insulated with argon, compared to its non-insulated counterpart.

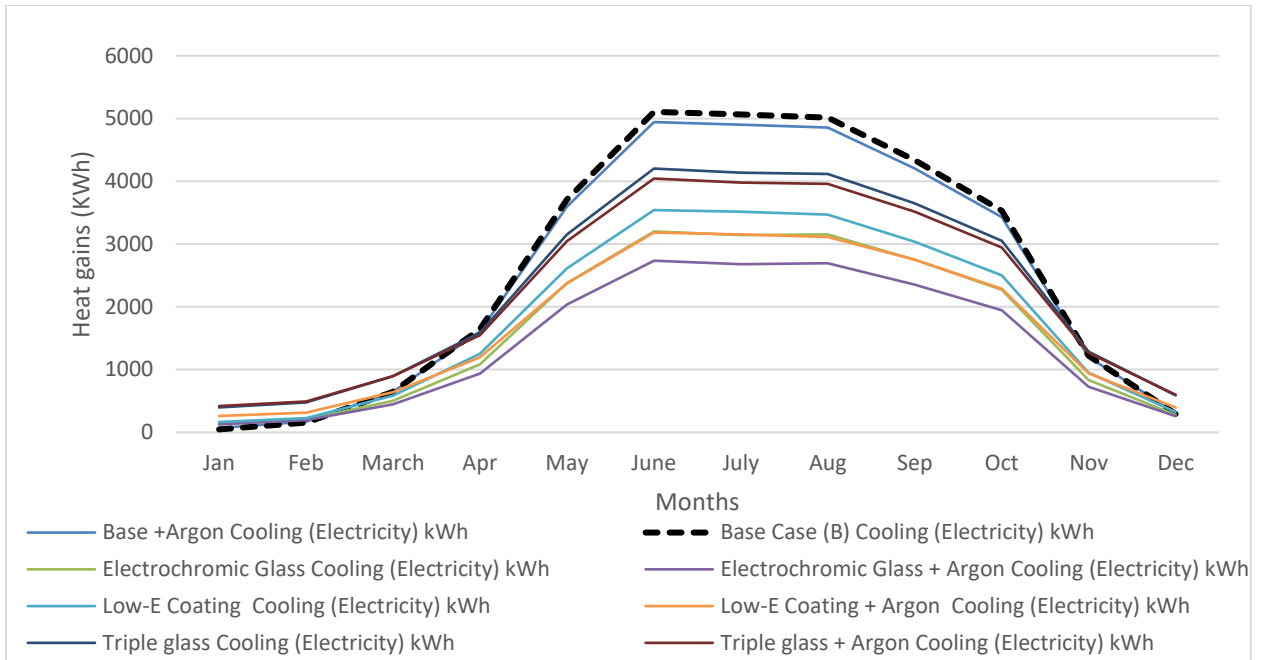


Figure 43 Monthly glazing Heat Gain for each scenario of windows retrofitting (Case A)

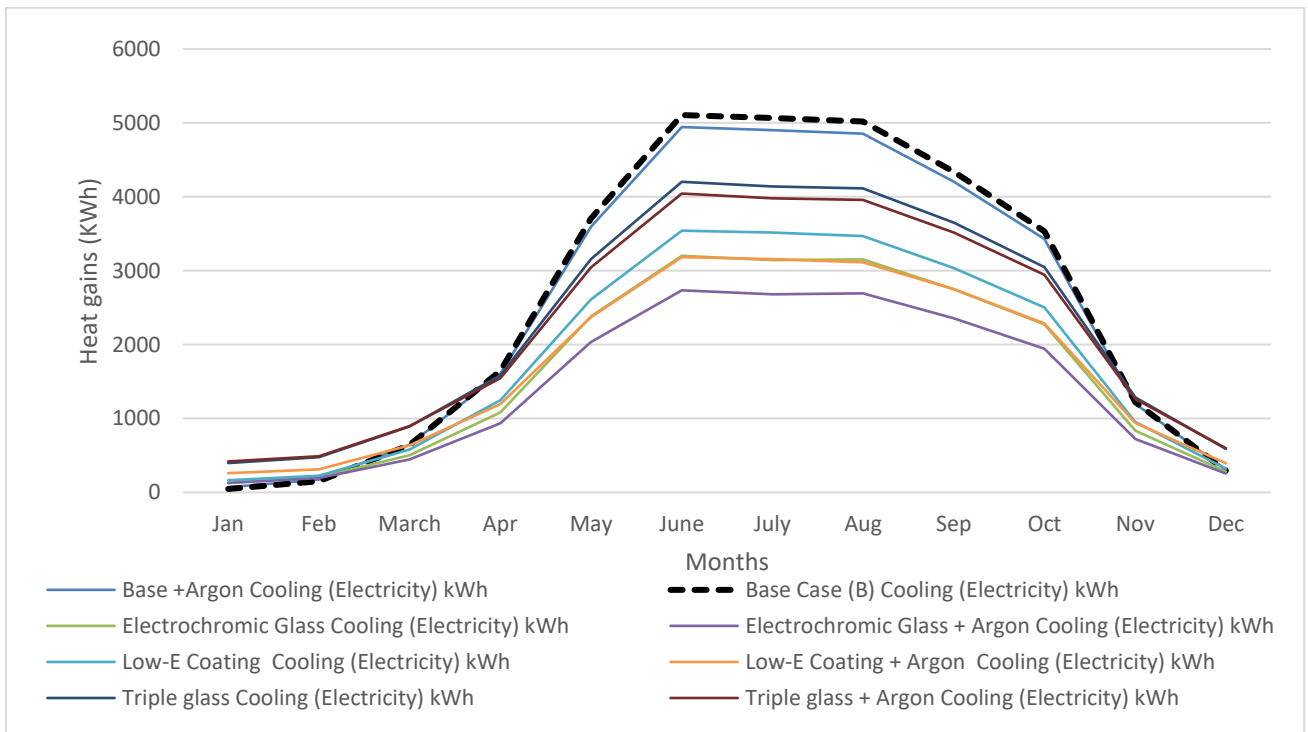


Figure 44 Monthly glazing Heat Gain for each scenario of windows retrofitting (Case B)

Figure 45,46 presents the annual heat gains percentage reduction and the number of gains for the proposed scenarios of Case A and Case B. The results show that smart glass insulated by argon gas had the most superior performance in reducing heat gain compared to the other scenarios, with a reduction of up to 35.66% for Case A and 35.2% for Case B, due to its distinct feature of having the lowest U-value. The other scenarios, low-E coating and triple glazing, followed with a heat gain reduction of approximately 28% and 10.72%, respectively, compared to the base window.

Furthermore, filling the argon gas significantly increases insulation and reduces heat gain. However, insulating the window of the base case with argon gas has only a minor effect, reducing the heat gain by 2.72% for Case A and 2.74% for Case B. It was also observed that the efficiency of argon gas in insulation varied according to the glass type and thermal properties. The smart glass insulated by argon gas improved the heat gain reduction by 9%, reaching a total of approximately 45%. Conversely, insulating triple glazing and Low-E coating reduced the heat gain by 13% and 33%, respectively. This implies that insulating triple glazing with argon increased the reduction by 3%, and

insulating low-e coating with argon increased the reduction by 5%.

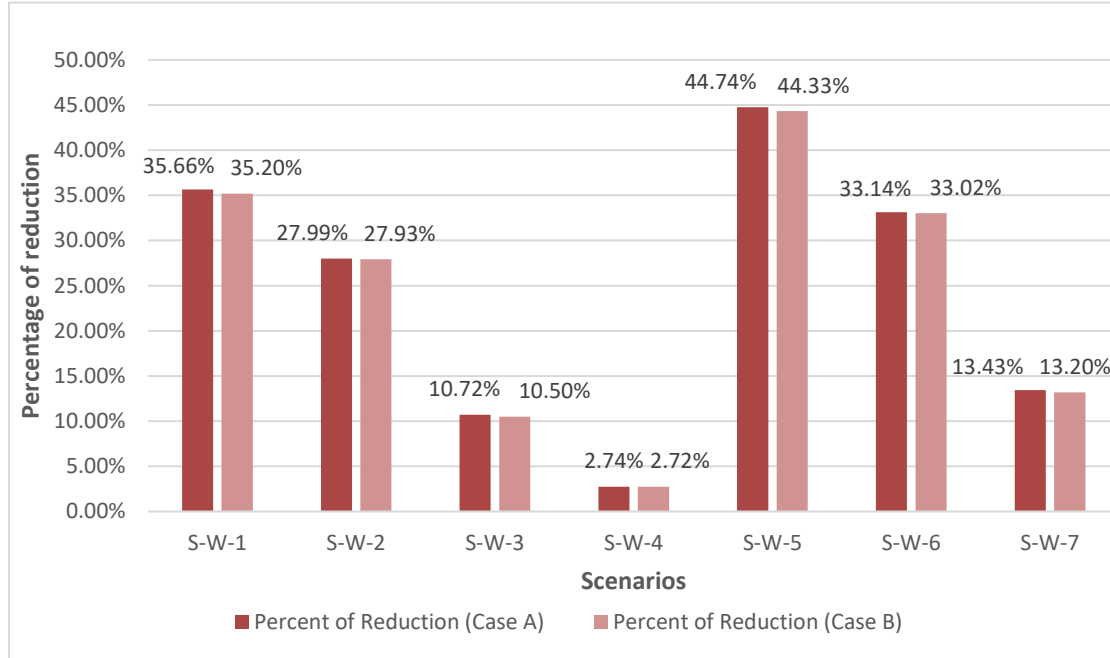


Figure 45 Percentage of annual heat gains reduction for each windows retrofitting scenario of case A & B

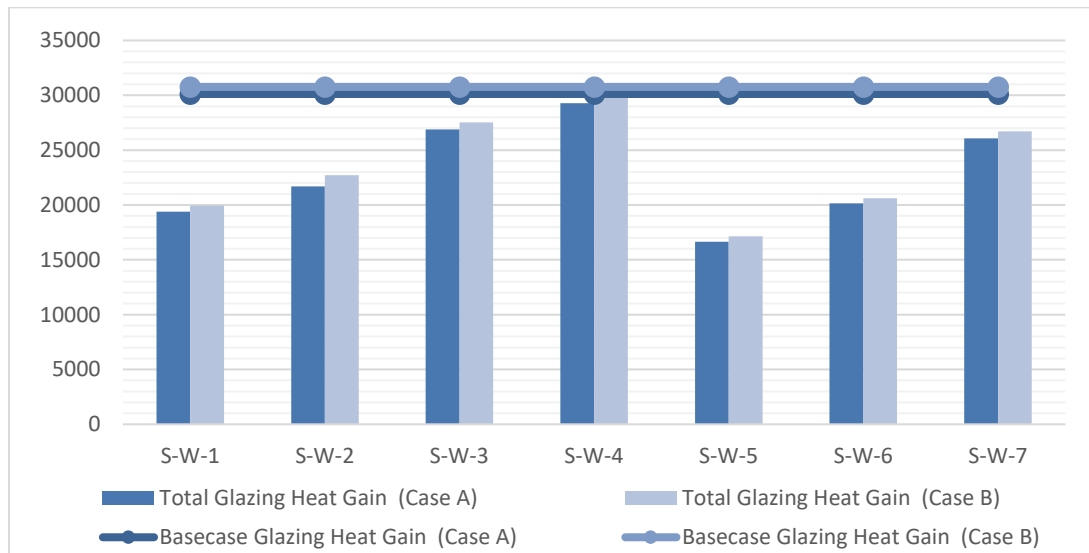


Figure 46 Amount of annual heat gain reduction for case A & case B before and after windows retrofitting

Heat gain reduction amounts for each proposed window strategy, highlighting the superiority of the smart window strategy employing electrochromic glass, as shown in **Table 21**. The results showed that adding insulation with argon leads to improving the

performance of strategies by reducing heat gain, as previously mentioned. Whereas, the smart glass strategy insulated by argon achieves the highest reduction in heat gain, about 13,475.71 for case (A) and 13,639.26 for case (B). This is followed by strategy is low-e coating insulated by argon, which reduces the heat gain by 9,979.41 for Case A and 10,160.17 for Case B. The least effective strategy is triple glazing with argon insulation, which reduces the heat gain by 4,043.96 for Case A and 4,059.54 for Case B.

Table 21 The annual heat gain reduction for case A & case B with windows retrofit scenarios

No	Strategy		Case A				Case B			
			Heat Gain (KWH) (Before)	Heat Gain (KWH) (after)	Total Reduction	Percent of Reduction %	Heat Gain (KWH) (Before)	Heat Gain (KWH) (after)	Total Reduction	Percent of Reduction %
S-W-1	Smart glass	Electrochromic	30117.48	19376.4	10741.08	35.66%	30766.2	19821.54	10831.74	35.2%
S-W-2	Coating	Low-E		21687.41	8430.07	27.99%		22173.39	8064.84	27.93%
S-W-3	Increases Layers	Triple - glazed		26889.29	3228.19	10.72%		27536.64	3229.56	10.5%
S-W-4	Insulation	Double-Argon		29292.13	825.35	2.74 %		29929.52	836.68	2.72%
S-W-5	Smart glass + Insulation	Electrochromic+ Argon		16641.77	13475.71	44.74%		17026.95	13639.26	44.33%
S-W-6	Coating + Insulation	Low-E + Argon		20138.07	9979.41	33.14%		20606.03	10160.17	33.02%
S-W-7	Increases Layers + Insulation	Triple + Argon		26073.52	4043.96	13.43%		26706.66	4059.54	13.2%

4.3.2 Cooling electricity reduction

The study analyzed the monthly cooling electricity consumption for Case A and Case B as illustrated in **Figures 47 and 48**. The results indicate that the demand for cooling electricity was highest from May to the end of October, with a sudden increase observed from April to May. The peak demand continued until October, followed by a steady decline from the end of October to January. The study found that window retrofitting was a crucial strategy for reducing building cooling energy. Both Case A and Case B showed a substantial reduction in cooling energy consumption after examining various window glass and insulation types.

Among the various scenarios examined, the electrochromic glass demonstrated remarkable efficiency in significantly reducing cooling consumption, whether being with or without argon insulation. It outperformed other scenarios, followed by triple glass and Low-E coating, respectively.

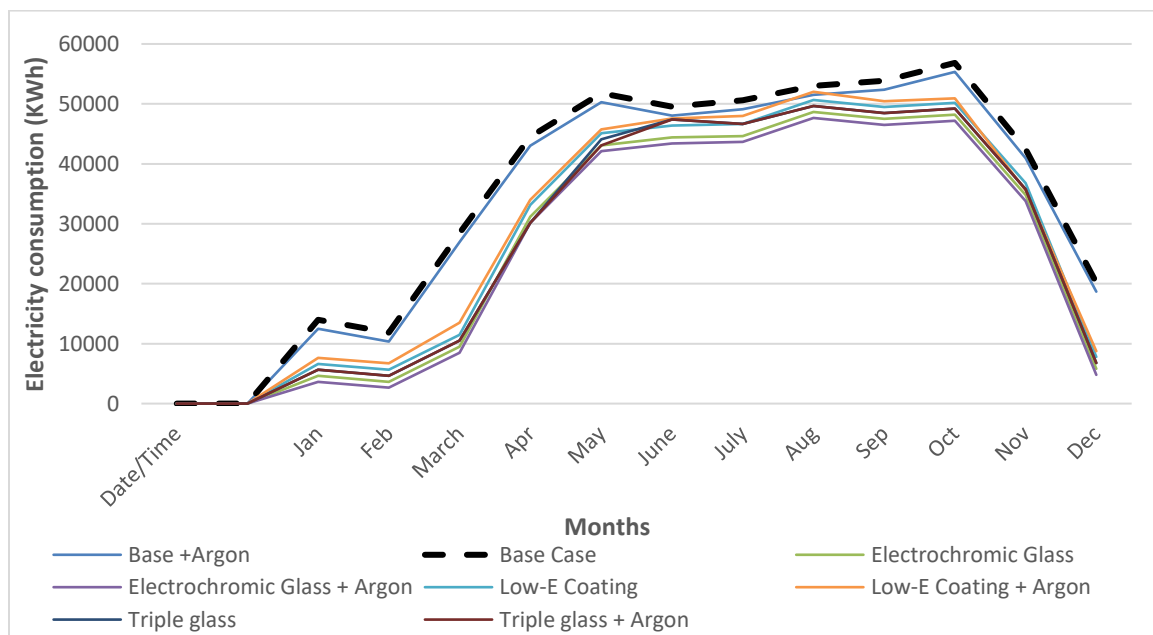


Figure 47 Monthly cooling electricity consumption for each scenario of windows retrofitting (Case A)

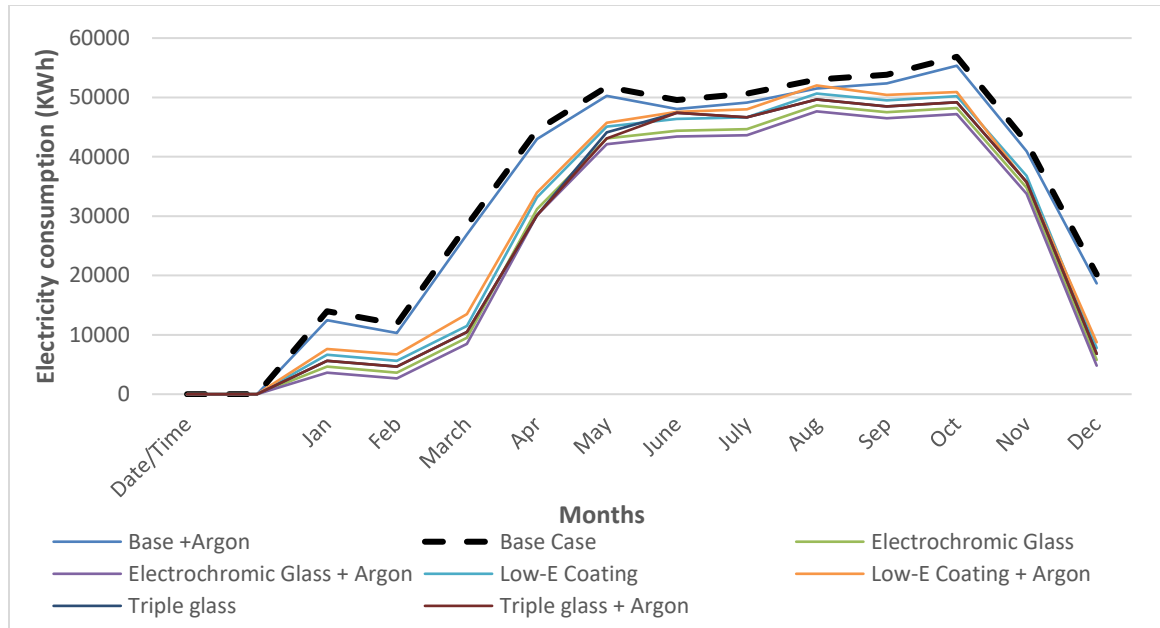


Figure 48 Monthly cooling electricity consumption for each scenario of windows retrofitting (Case B)

Figure 49,50 shows the percentage of cooling electricity reduction for Case A and Case B. It was observed that the windows retrofitting strategies have a more pronounced impact on reducing cooling electricity consumption for in Case B as compared to Case A. This difference is attributed to the orientation of Case B, which is angled at 17 degrees, while Case A is oriented at 197 degrees. This orientation difference results in a 3.2% higher window-to-wall ratio in Case B as compared to Case A.

Consequently, the increased exposure of Case B to sunlight, especially during summers, leads to elevated interior temperatures, thus increasing the demand for cooling to maintain thermal comfort. In general, the results indicate that the most effective window retrofitting strategy for reducing cooling energy consumption is the smart window strategy, whether insulated or non-insulated. The triple glass and Low-E coating strategies follow closely in effectiveness, while filling the basic window with argon gas has proven to be the least effective strategy.

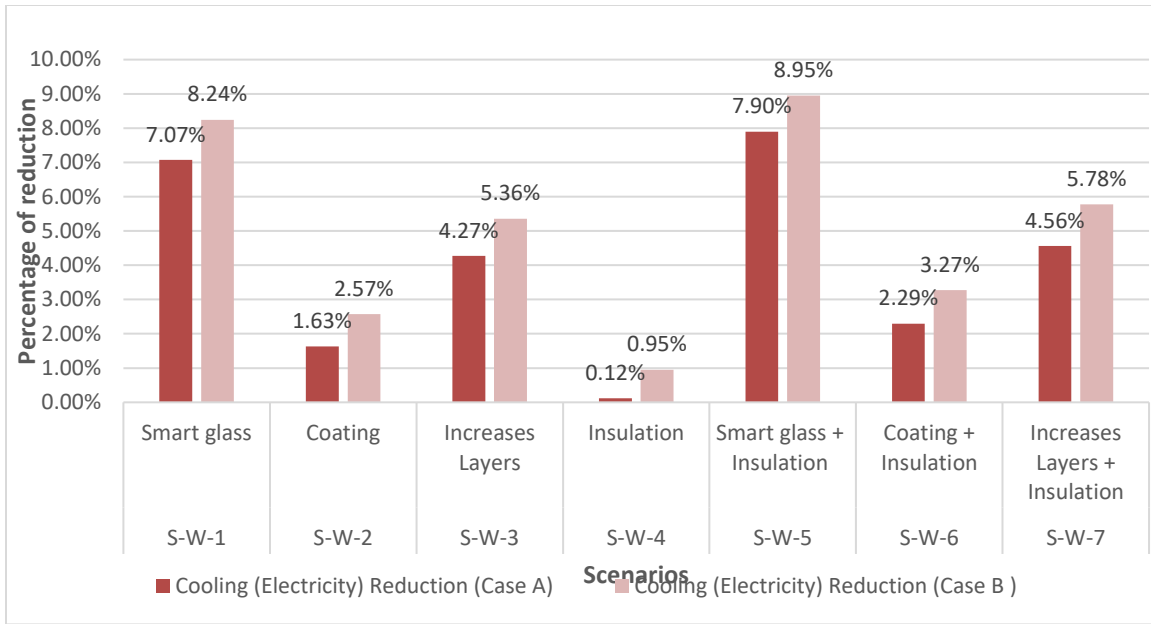


Figure 49 Percentage of annual cooling electricity reduction for case A & case B with windows retrofitting strategies

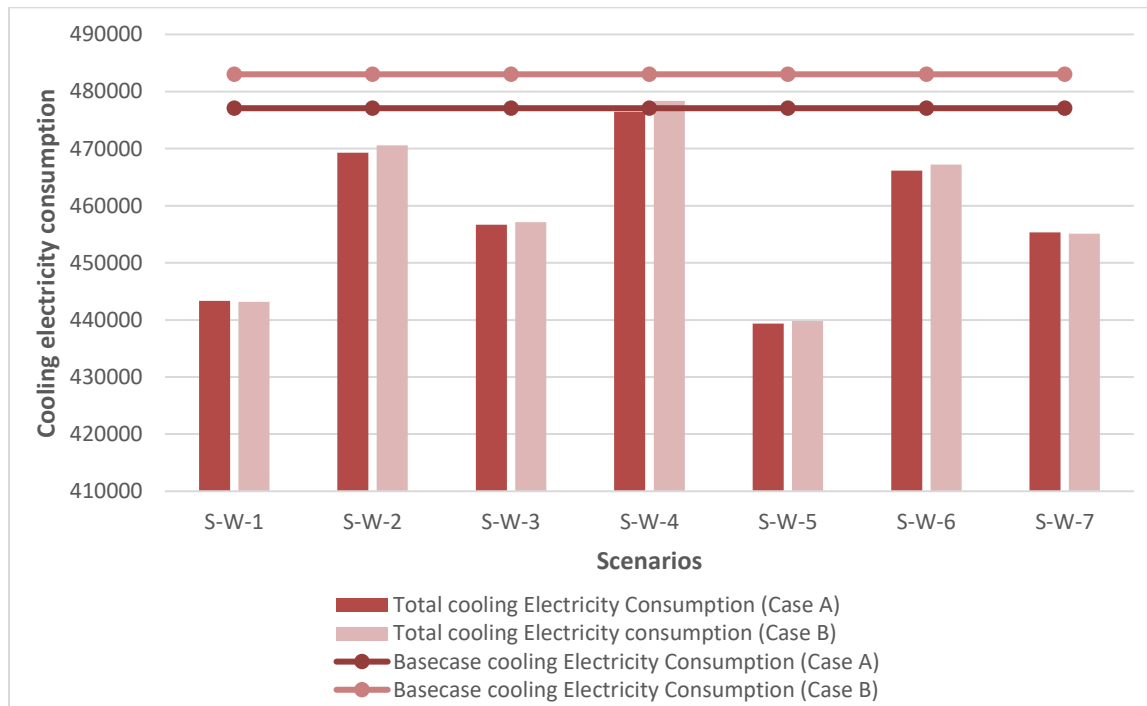


Figure 50 Amount of annual cooling electricity consumption before and after windows retrofitting for case A & case B

The annual cooling energy consumption of the building after windows upgrades presented in **Table 23**. The results indicate that the reduction in air conditioning energy consumption is limited due to the building's low window-to-façade area ratio.

As previously mentioned, the findings demonstrate the effectiveness of smart glass in reducing cooling energy consumption for both Case A and B by 7.07% and 8.24%, respectively. This resulted in a reduction of 33749.8 KWh for Case A and 39846.3 KWh for Case B.

Triple glazing was considered the second-best option with a 4.27% reduction in cooling electricity for Case A and 5.36% for Case B, resulting in a reduction of 20380.9 KWh for Case A and 25870.1 KWh for Case B. In comparison, Low-E coatings had a minor effect on energy savings, reducing it by 1.4%. For Case A, the cooling energy decreased by 7777.8 KWH of annual cooling electricity consumption, whereas decreased by 12422.3 KWH for Case B, as shown in **Table 22**.

Moreover, it was observed that the cooling energy reduction for all strategies increased when insulated with argon gas. The cooling reduced for Case A by 7.90%, 4.56%, and 2.29% for smart glass, triple glazing, and low-E coatings, respectively. While it reached 8.95%, 5.78%, and 3.27%, respectively, for Case B. Additionally, it was observed that filling argon gas for the base windows of Case B was ten times more effective in reducing cooling energy consumption than Case A.

It was observed that the triple glazing insulated by argon gas Scenario has a greater effect in reducing cooling energy than the low-e coatings insulated by argon gas scenario as shown in **Figure 49**. Although the u-value of the coatings is lower than triple glazing which accounts 1.49, 1.59 W/ (m² -K), respectively, the marginal

difference in u-value (0.1 W/ (m² -K)) favoring low-e coating glass insulated by argon gas was evident. On other hand, it's worth noting that SHGC for triple glazing was higher than low-e coating scenario which were 0.42, 0.37, respectively, the marginal differences in SHGC (0.05) favored the triple glazing insulated by argon gas strategy. Therefore, although the difference in u-value is twice as high as the difference in SHGC between the two mentioned scenarios, the superiority in SHGC value showed a greater effect of triple glass on reducing cooling energy. as shown in **Table 20**. The previous findings demonstrate that the solar heat gain coefficient (SHGC) has a greater impact on window strategies than the u-value in a hot climate, in addition to the significance of Solar Heat Gain Coefficient as a critical factor influencing the performance of window strategies. Which plays a pivotal role to minimize the penetration of sunlight into the building's interior space.

Table 22 Comparison of the annual cooling electricity reduction in case A & case B with windows retrofitting strategies

No	Strategy		Case A				Case B			
			Cooling Electricity (KWH) (Before)	Cooling Electricity (KWH) (after)	Total Reduction	Percent of Reduction %	Cooling Electricity (KWH) (Before)	Cooling Electricity (KWH) (after)	Total Reduction	Percent of Reduction %
S-W-1	Smart glass	Electrochromic	477073.9	443324.1	33749.8	7.07%	483005.2	443140.29	39846.3	8.24%
S-W-2	Coating	Low-E		469296.1	7777.8	1.63%		470582.9	12422.3	2.57%
S-W-3	Increases Layers	Triple -glazed		456693	20380.9	4.27%		457135.1	25870.1	5.36%
S-W-4	Insulation	Double-Argon		476470.5	603.4	0.12%		478379.4	4625.8	0.95%
S-W-5	Smart glass + Insulation	Electrochromic+ Argon		439365.5	37708.4	7.90%		439778.6	43208.8	8.95%
S-W-6	Coating + Insulation	Low-E + Argon		466127.6	10946.3	2.29%		467211.5	15793.7	3.27%
S-W-7	Increases Layers + Insulation	Triple + Argon		455315.3	21758.6	4.56%		455092	27913.2	5.78%

4.3.3 Cost-efficiency

In this section of the study, the payback period was calculated for each proposed scenario for Case A and Case B. The findings have shown that the smart windows have contributed to substantial savings. However, the high initial cost has caused a longer payback period comparing with other scenarios. Conversely, the lower initial cost for triple glazing made it the option that has the shortest payback period. These results have been depicted in **Figure 51**.

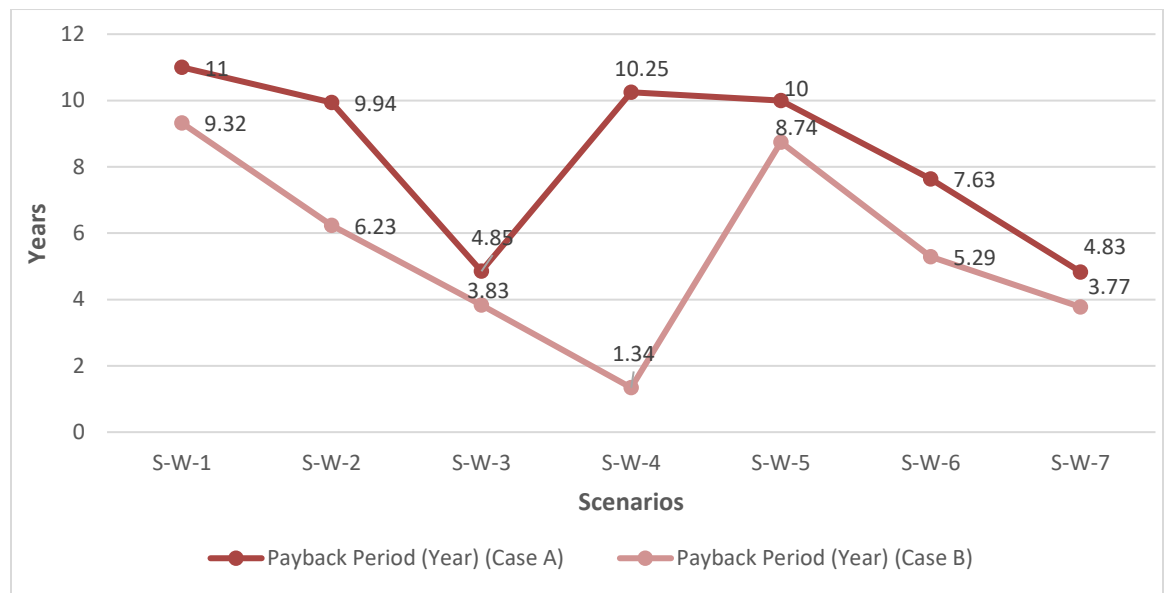


Figure 51 Payback period for window retrofit strategies investment

Initial cost for each scenario, where the calculation of financial efficiency for each scenario depends on the amount of cooling electricity reduction and the cost for Case A and Case B as presented in **Table 23**. It was observed that the investment cost of electrochromic glass is significantly high, 118,800 SAR, while the investment cost for triple glazing and Low-E glass is lower. However, electrochromic glass has contributed

to significant energy reduction that has led to considerable savings in the cost of cooling energy by 10799.94 SAR for Case A and 12750.82 SAR for Case B. It has been observed that adding argon gas has increased the value of the savings and decreased the payback period to 10 years for Case A and 8.74 years for Case B.

Furthermore, Triple glass has demonstrated a saving in cooling energy consumption of 6,521.89 SAR for Case A and 8,278.43 SAR for Case B, while the investment cost was 33660 SAR, making the payback period short compared to the rest of the scenarios. Moreover, adding argon gas has increased the cost saving to 6,962.75 SAR for Case A and 8,932.22 SAR for Case B. Accordingly, with argon gas insulation, the recovery period has decreased to 4.83 years for Case A and 3.77 years for Case B. The scenario with the lowest cost saving among the mentioned scenarios is 2,488.9 SAR for Case A and 3,975.14 SAR for Case B. However, the recovery period is less than the payback period for electrochromic glass, and the scenario intersects with the basic case after 9.94 years for Case A and 6.23 years for Case B. Additionally, insulation with argon reduces the payback period to 7.63 years for Case A and 5.29 years for Case B.

Table 23 Investment cost & payback period for case A&B with windows retrofit strategies

No	Strategy		Unit cost (SAR)	Unit	Case A			Case B		
					Total Cost (SAR)	Annual Cooling Cost Reduction (SAR)	Payback Period (Year)	Total Cost (SAR)	Annual Cooling Cost Reduction (SAR)	Payback Period (Year)
S-W-1	Smart glass	Electrochromic	1200	Number	118800	10799.94	11	118800	12750.82	9.32
S-W-2	Coating	Low-E	250	Number	24750	2488.9	9.94	24750	3975.14	6.23
S-W-3	Increases Layers	Triple -glazed	320	Number	31680	6521.89	4.85	31680	8278.43	3.83
S-W-4	Insulation	Double-Argon	20	Number	1980	193.09	10.25	1980	1480.26	1.34
S-W-5	Smart glass + Insulation	Electrochromic + Argon	1220	Number	120780	12066.67	10	120780	13826.82	8.74
S-W-6	Coating + Insulation	Low-E + Argon	270	Number	26730	3502.82	7.63	26730	5053.98	5.29
S-W-7	Increases Layers + Insulation	Triple + Argon	340	Number	33660	6962.75	4.83	33660	8932.22	3.77

4.4 Shading devices strategies

This section investigates a number of shading devices options that could be implemented in the retrofit process. Shading devices help regulate sunlight and heat entering a building, reducing the need for excessive air conditioning. This leads to lower energy consumption and improved energy efficiency. The study aims to evaluate their effect on the cooling energy consumption of the investigated case study.

The investigation includes three commonly used types of shading devices in Saudi Arabia, illustrated in **Figure 52**, this includes:

1. smart blinds composed of aluminum, with dimensions of 1.5 by 1.2 meters, which were used for internal shading
2. louvers with window dimensions of 1.5 by 1.2 meters,

3. overhangs made of wood and steel, each with a depth of 1 meter As shown in **Table**

24.

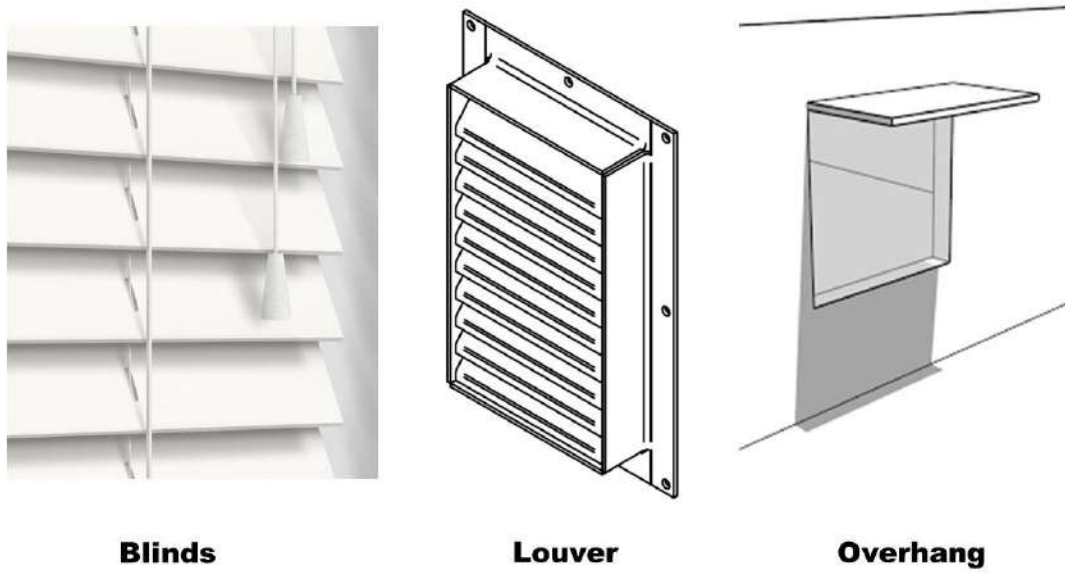


Figure 52 Types of shading devices

Table 24 Shading devices strategies properties

No	Strategy	Dimension
S-S-1	Electric Blinds	1.5*1.2
S-S-2	Window louver	1.5*1.2
S-S-3	Wood-Overhang	1.5*1.0
S-S-4	Metal-Overhang	1.5*1.0

4.4.1 Heat gain reduction of windows

Four different shading device scenarios were suggested in the baseline research to mitigate heat gains from windows. Notably, these scenarios divided into two categories: inside shading devices, such as smart shading devices, and exterior shading devices, such as overhangs and louvers. As shown in **Figure 53** and **54**. The monthly impact of the proposed scenarios on reducing heat gains from windows revealed a significant decrease during the peak temperatures of summer, particularly from April to October.

However, the effectiveness of the scenarios varied. Smart blinds exhibited a notable reduction in heat gain, especially from June to August. However, it showed lower efficiency than the other scenarios in the rest of the month, due to the set point of closing the slats which set to close when the outside temperature reached 24 °C. Furthermore, the louvers were the most effective in reducing heat gain for the windows, especially in September and October. In the other months, the reduction was comparable to the overhang scenario, which had a consistent performance during the summer period. Additionally, the material composition (wood or steel) of the overhang did not affect the heat gain reduction significantly, with both scenarios showing equal reductions in cooling energy.

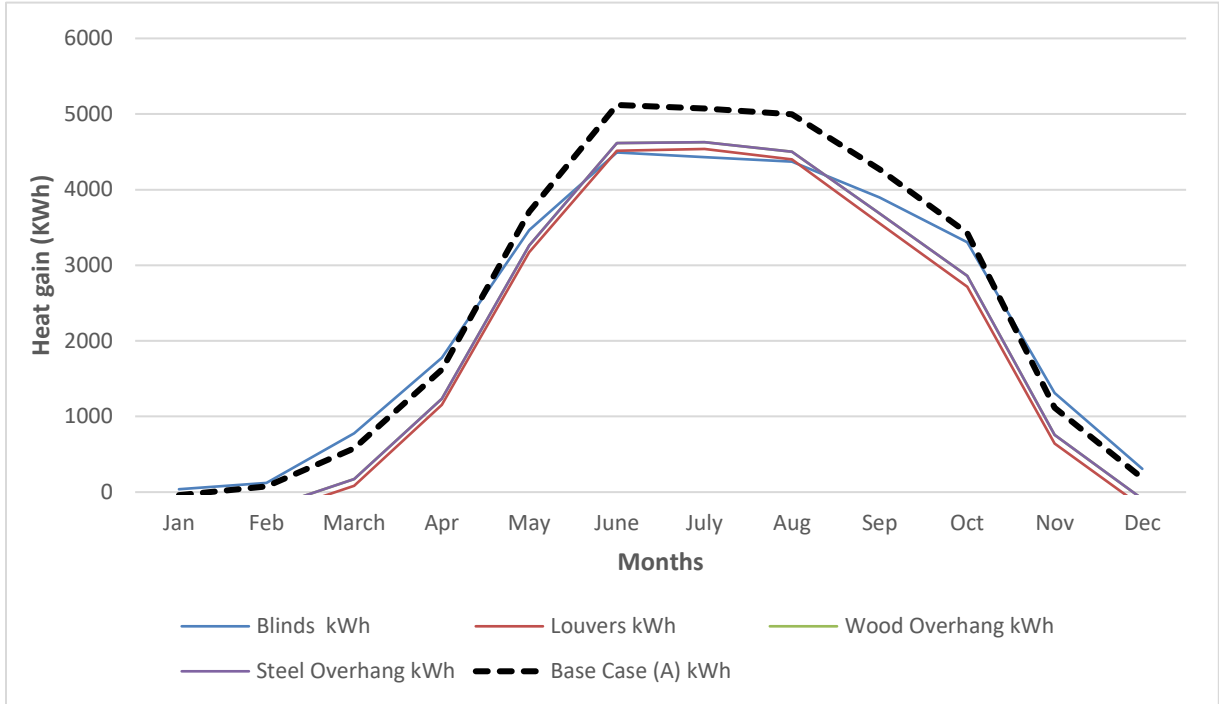


Figure 53 Monthly glazing heat gains for each scenario compared with base case (Case A)

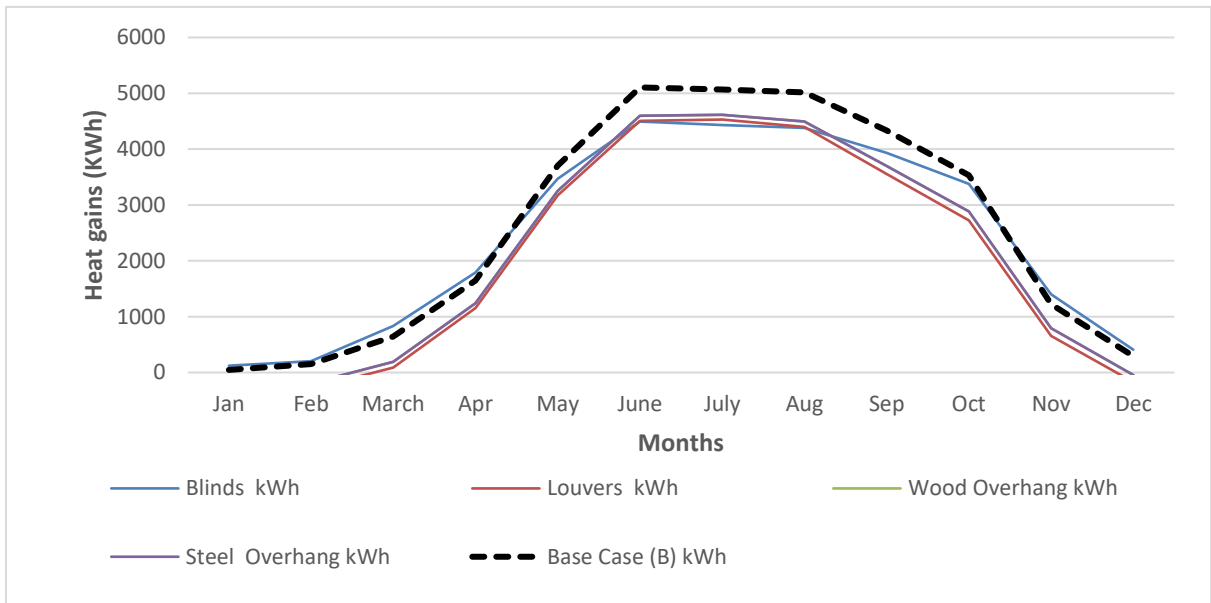


Figure 54 Monthly gain for each scenario compared with base case (Case B)

Figure 55 shows the percentage of annual heat gain reduction for the proposed scenarios. The results showed that the external shading strategies were more effective than the internal shading devices in reducing the heat gains of windows as shown in **Figure 56**. Therefore, the optimal scenario was using external louvers, which resulted in a higher percentage of annual heat gains reduction. Wood and steel overhangs followed closely, both showing a similar reduction effect. However, blinds were the least effective in reducing heat gain.

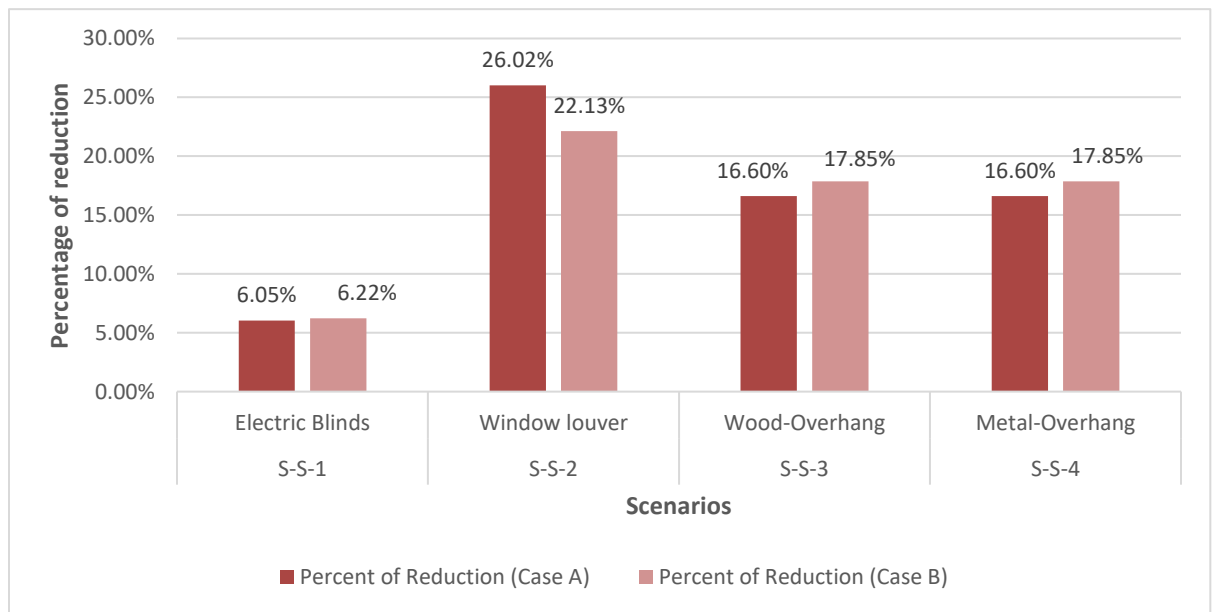


Figure 55 Percentage of annual heat gain reduction for case A & case B when different shading devices was added

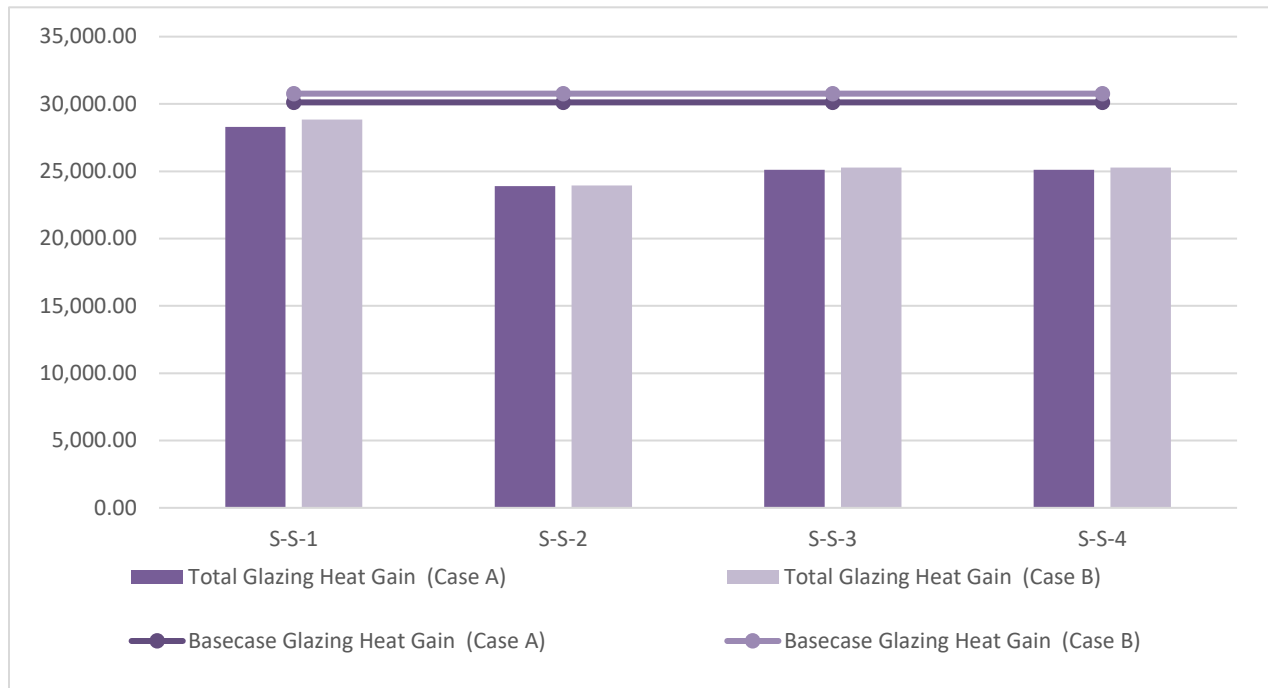


Figure 56 Amount of annual heat gains for case A & case B before and after adding shading devices

The amount of heat gains reduction for the different examined shading device strategies. As mentioned previously, the results showed the superiority of the louvers strategy in reducing heat gains as presented in **Table 25**. Louvres a tilt angle of 15 degrees led to a reduction in heat gains by 26.02% and 22.13% for Case A and Case B, respectively. It was observed that employing louvers in Case B is less efficient compared to Case A since Case A is more exposed to the sun, particularly to low sunlight, due to the orientation of the building. This was followed by the use of overhangs, led to a reduction in heat gains by 16.6% and 17.85% for Case A and Case B, respectively. In addition, the use of smart curtains showed a lower reduction in heat gain by 6.05% and 6.22% for Case A and Case B, respectively. The reason for this is

the advantage of external shading devices in preventing heat from reaching the windows directly.

Table 25 The annual heat gain reduction for case A & case B with shading devices retrofit strategies

No	Strategy	Glazing heat gain (Before) (kWh)	Case A			Case B			
			Glazing heat gain (After)(kWh)	Total of Reduction	Percent of reduction	Glazing heat gain (Before) (kWh)	Glazing heat gain (After)(kWh)	Total of Reduction	Percent of reduction
S-S-1	Electric Blinds	30117.48	28295.08	1,822.4	6.05%	30766.2	28852.67	1,913.53	6.22%
S-S-2	Window louver		23899.89	6,217.59	26.02%		23956.73	6,809.47	22.13%
S-S-3	Wood-Overhang		25116.27	5,001.21	16.6%		25275.85	5,490.35	17.85%
S-S-4	Metal-Overhang		25116.27	5,001.21	16.6%		25275.85	5,490.35	17.85%

4.4.2 Cooling electricity reduction

Windows with higher heat gain coefficients transmit more thermal radiation to the interior spaces of the building, resulting in higher cooling loads. Moreover, solar gain increases the thermal load of the building's interior spaces when it directly penetrates the building, which has a larger impact than the heat gain from the glass. This section investigates the effect of using shading strategies considering three categories: louvers, overhangs, and smart blinds.

Figure 57 and 58 show the monthly cooling electricity consumption for each scenario of shading devices compared with base case. The study found a sharp increase the electricity consumption during the summer time from the beginning of April and

continue until the end of October. Hence, it was observed that the influence of all scenarios becomes evident starting from the month of April. The louver strategy was more effective than the other scenarios from May to June. Subsequently, after August, the effect of louver strategy becomes very similar to the effect the overhang strategy.

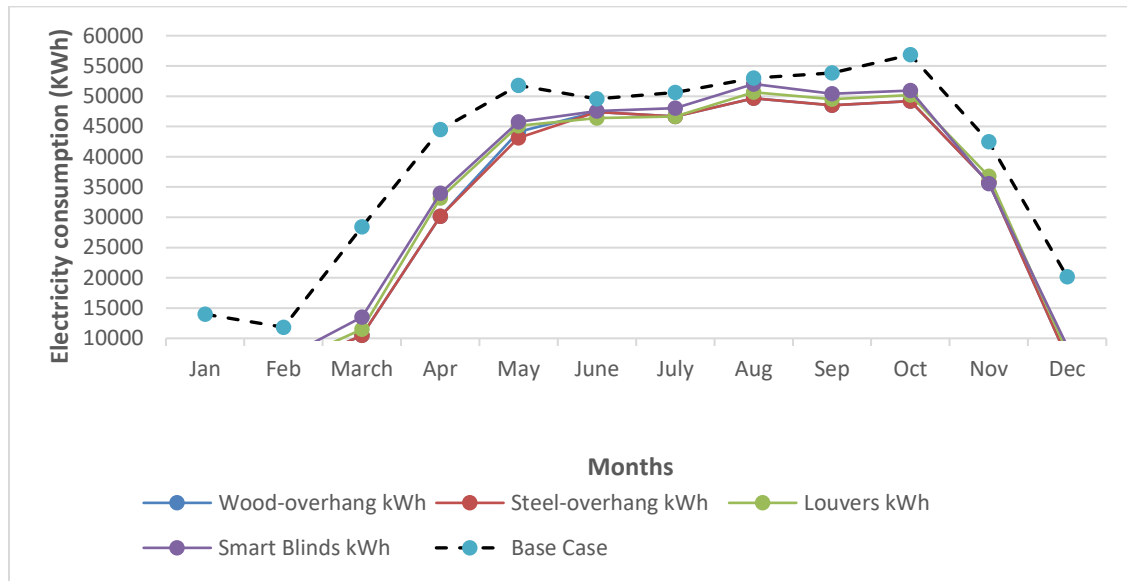


Figure 57 Monthly cooling electricity for each scenario of shading devices (Case A)

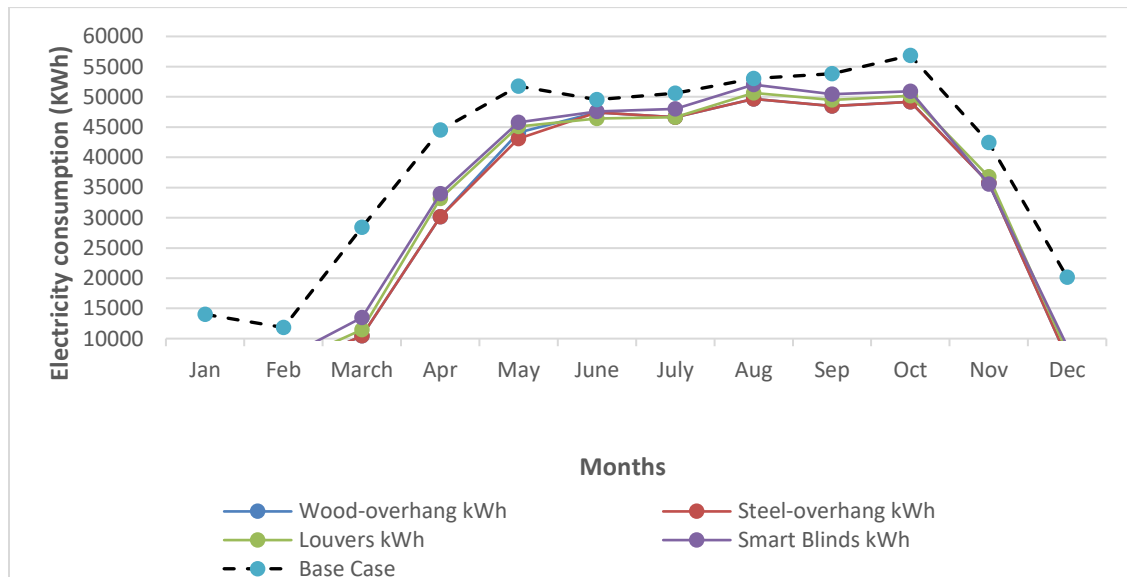


Figure 58 Monthly cooling electricity for each scenario of shading devices (Case B)

Figure 59,60 illustrates the percentage of annual cooling energy reduction for both Case A and Case B. The results showed that the blinds scenario has the highest energy reduction in both Case A and Case B, closely followed by louvers and overhang respectively.

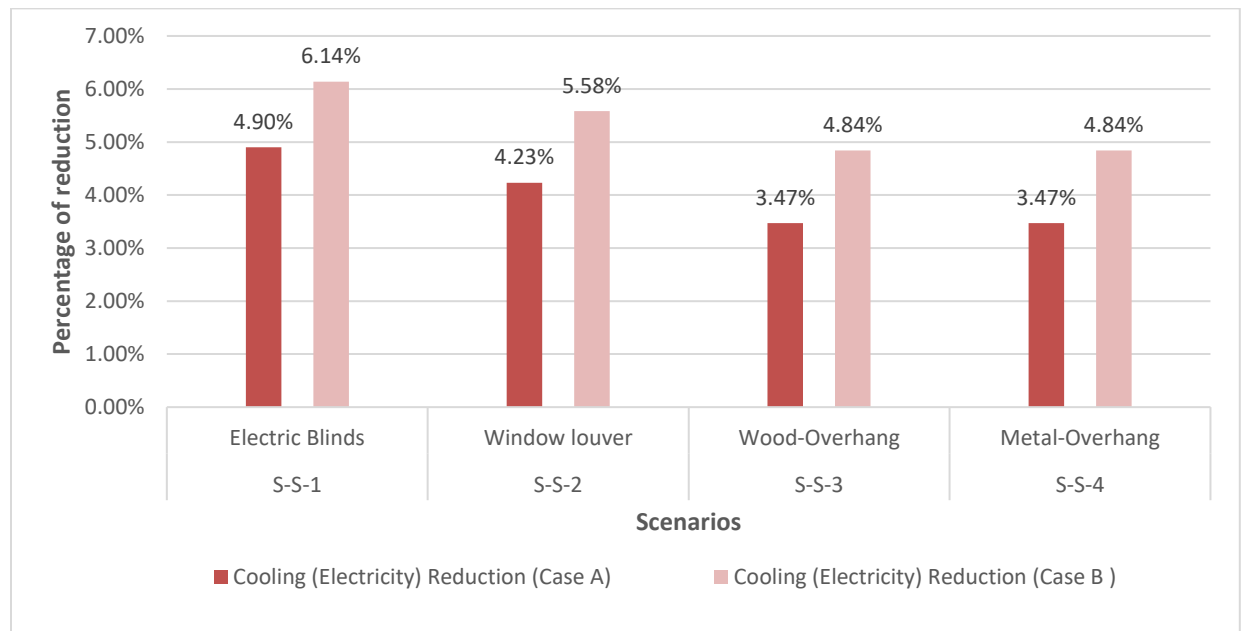


Figure 59 Percentage of annual cooling electricity reduction for case A & case B after shading retrofit strategies

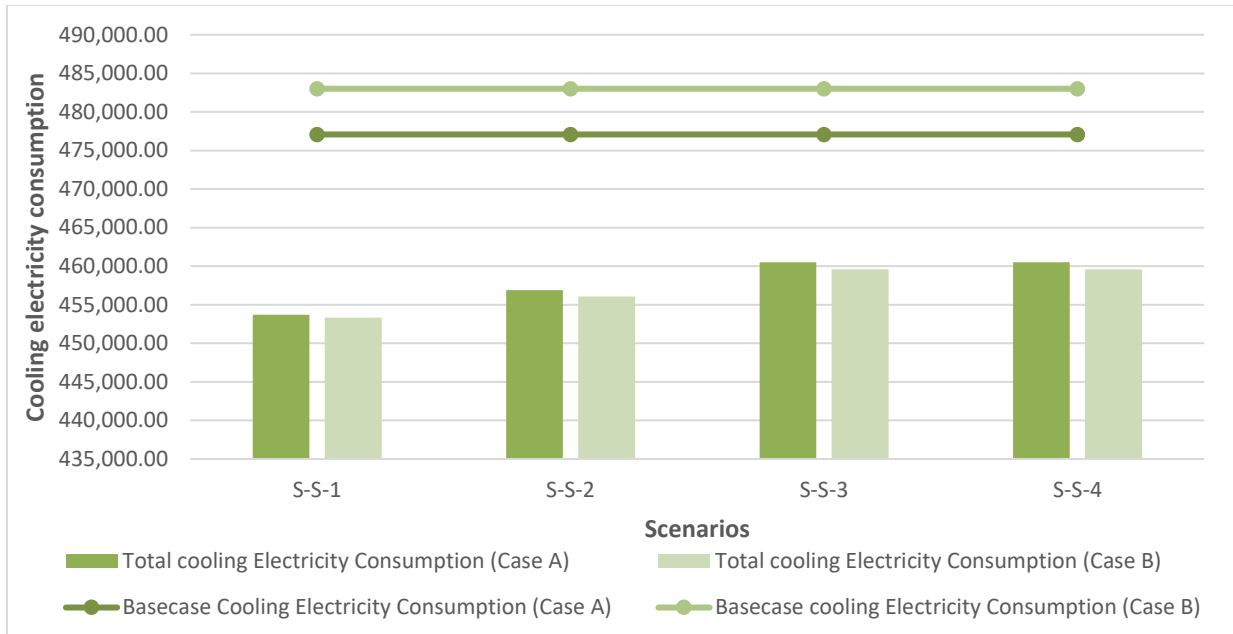


Figure 60 Annual cooling electricity consumption for case A & case B before and after shading devices retrofitting

The amount of annual cooling electricity reduction for the different shading device scenarios for case a and case B presented in **Table 26**. Notably, the smart blinds system demonstrates some cooling electricity reduction of 23,387.6 kWh representing a percentage of 4.90% for case A, and a reduction of 29,659.1 KWH, representing a percentage of 6.14% in Case B. This is followed closely by the louver scenario, which resulted in a reduction of 4.23% for Case A and 5.58% for Case B. Overhang scenario exhibits the least reduction in cooling electricity with percentage of 3.47% for Case A and 4.84% for Case B.

Table 26 A comparison of the annual cooling electricity reduction in case A & case B with shading device strategies

No	Strategy	Cooling Electricity (Before)(kWh)	Case A			Case B			
			Cooling Electricity (After)(kWh)	Total of Reduction	Percent of Reduction	Cooling Electricity (Before) (kWh)	Cooling Electricity (After)(kWh)	Total of Reduction	Percent of reduction
S-S-1	Electric Blinds	477073.9	453686.3	23,387.6	4.90%	483005.2	453346.1	29,659.1	6.14%
S-S-2	Window louver		456891.9	20,182	4.23%		456049.9	26,955.3	5.58%
S-S-3	Wood-Overhang		460506.8	16,567.1	3.47%		459608.5	23,396.7	4.84%
S-S-4	Metal-Overhang		460506.8	16,567.1	3.47%		459608.5	23,396.7	4.84%

4.4.3 Cost-efficiency

The optimum strategy for shading devices in terms of cost efficiency was determined based on the amount of electricity reduction cost and the total initial cost. **Figure 61** presents the payback period and the total cost for each scenario, the result found that the louver scenario is the most cost efficient compared with other scenarios with the shortest payback period for case A and case B. This is followed closely by wood overhang with longer payback period. Smart blinds and then steel overhangs.

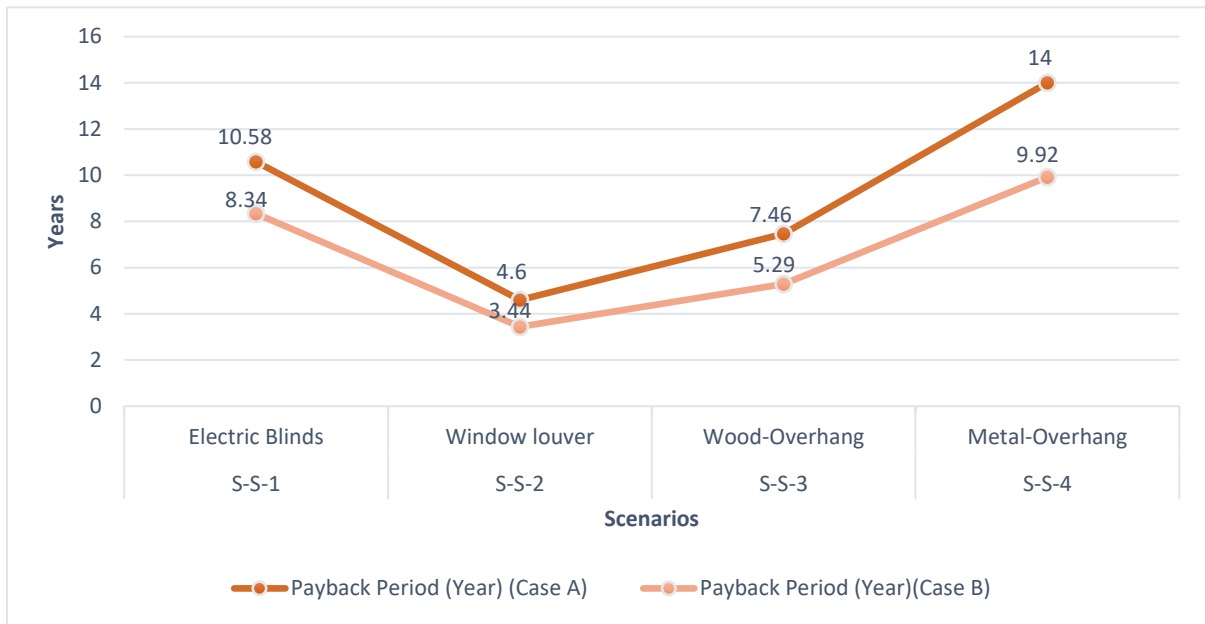


Figure 61 Payback period for shading devices strategies investment

Total cost, cooling energy saving, and the payback period for each proposed shading device scenario presented in **Table 27**, where the cost for each scenario has been obtained from the Saudi market in the study area. It was observed that some scenarios have a high initial cost compared with the cooling energy saving such as smart blinds and steel overhangs, which have a total cost of 79,200 SAR and 74,250 SAR, respectively.

The results showed that the louver scenario is the most cost-efficient strategy that can recover the total cost within the shortest period by 4.6 years for Case A and 3.44 years for Case B. This was followed by wood overhang, smart blinds, and steel overhang respectively. Despite that the smart blinds have a higher cooling electricity reduction and cost saving compared to the other scenarios by 7484.03 SAR for case A and 9490.91 SAR for case B, this shading device type has a high cost which resulted in a relatively long payback periods of 10.58 years in Case A and 8.34 years in Case B. The

steel overhang has the longest payback period by 14 years in Case A and 9.92 years in Case B.

Table 27 Initial cost & payback period for case A&B with shading devices strategies

No	Strategy	Unit cost	Unit	Case A			Case B		
				Total Initial Cost (SAR)	Annual Cooling Cost Reduction (SAR)	Payback Period (Year)	Total Initial Cost (SAR)	Annual Cooling Cost Reduction (SAR)	Payback Period (Year)
S-S-1	Electric Blinds	800	Number	79,200	7484.03	10.58	69300	9490.91	8.34
S-S-2	Window louver	300	Number	29,700	6458.24	4.6	24750	8625.7	3.44
S-S-3	Wood-Overhang	400	Number	39,600	5301.47	7.46	34650	7486.94	5.29
S-S-4	Metal-Overhang	750	Number	74,250	5301.47	14	74250	7486.94	9.92

4.5 Combined façade retrofit strategies

In this part of the study, various window and wall retrofit configurations were assessed. This aims to investigate the impact of these configurations on cooling energy reduction and the simple payback period (SPP) of the façade. Seven window scenarios are compared with the Baseline windows, integrated with nine wall compositions and four shading device scenarios. The optimization process results in 224 different façade composition scenarios that form the Pareto front. Which is a feature that allows users to optimize the design of a building by focusing on various aspects, it integrates advanced algorithms and modeling techniques to streamline the design process and improve the overall performance of the building and identify the most efficient and sustainable solutions. Figure 58 and 59 show the impact of these scenarios on cooling energy reduction and SPP.

The identified optimal solutions prioritize reduced cooling energy and cost, highlighting the payback period as the main driver for optimization decisions in this section. **Figures 62,63** show optimal solutions associated with reduced cooling energy and cost. The optimization study identified three optimal solutions in this regard as follows: external insulation scenario of ETCIS with double-glazed window insulated by Argon, ETCIS with Low-e coating windows, and ETCIS with Low-e coating windows and Argon gas insulation. Louvers are used as shading devices in the three combined scenarios. It is noteworthy that external insulation of walls has a more significant impact on cooling energy compared to windows. This is due to the ratio of openings to walls.

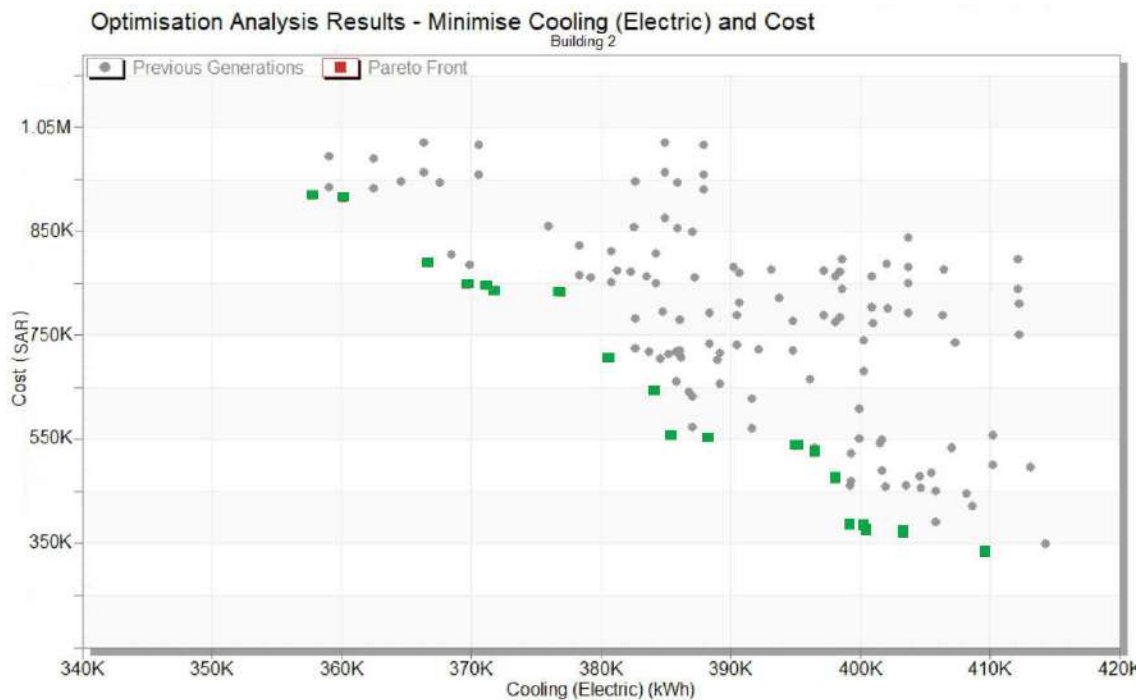


Figure 62 Optimization analysis results (case A)

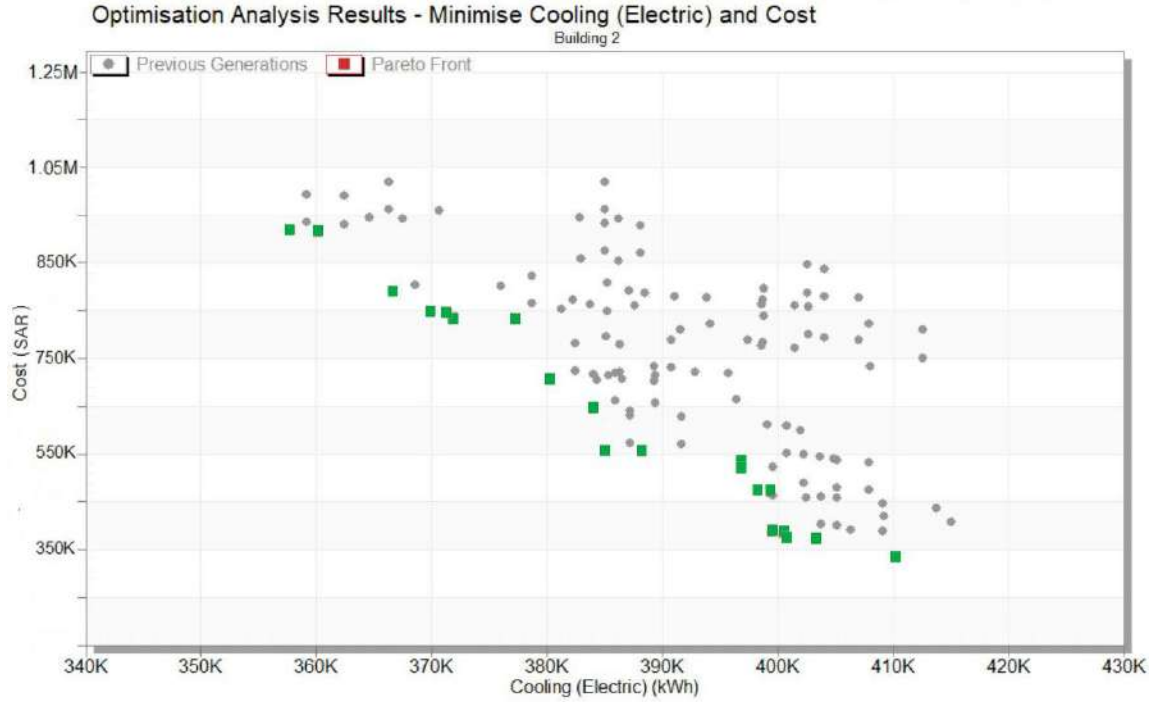


Figure 63 Optimization analysis results (case B)

4.5.1 Heat gain reduction

Figure 64 ,65 demonstrates the effect of the different combined facade strategies to reduce the heat gains of walls and windows in Case A and Case B. It presents the variations of the annual glazing heat gain reduction for the three combined strategies, while wall heat gain reduction remains constant due to the identical external insulation used in the three combined strategies, which is ETCIS. Among these strategies, scenario 3 exhibits the best glazing heat gain reduction, followed by scenario 2 and scenario 1. Therefore, the integration of these facade strategies offers a comprehensive and effective solution, significantly contributing to the overall energy efficiency of the building.

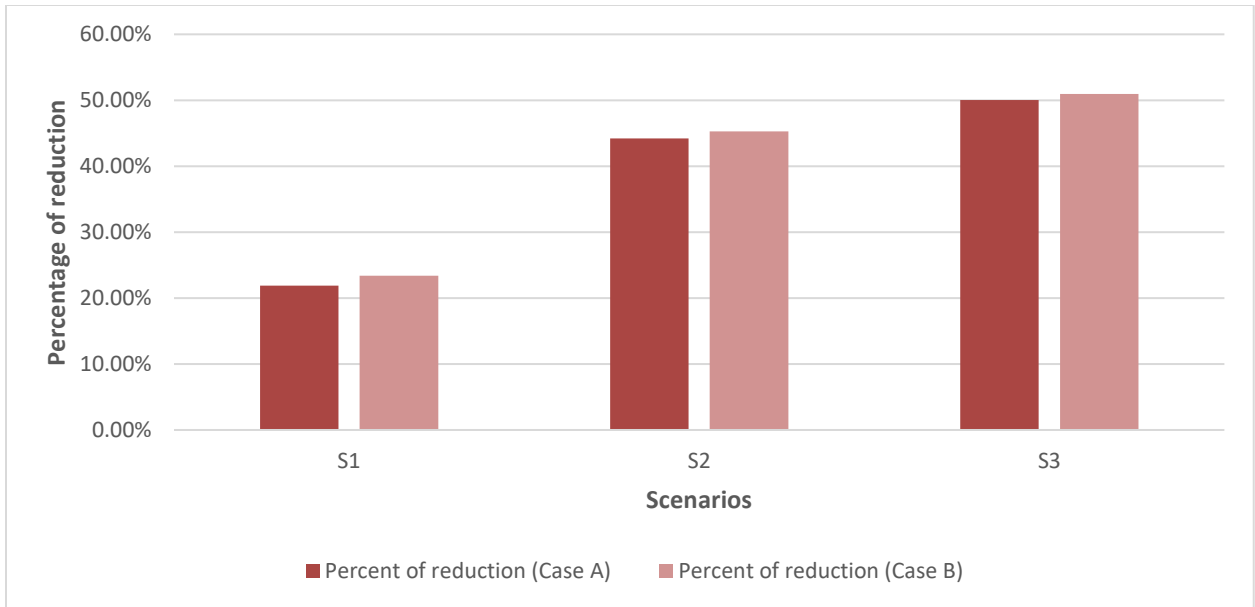


Figure 64 Percentage of annual heat gain reduction for case A & case B with combined retrofitting strategies

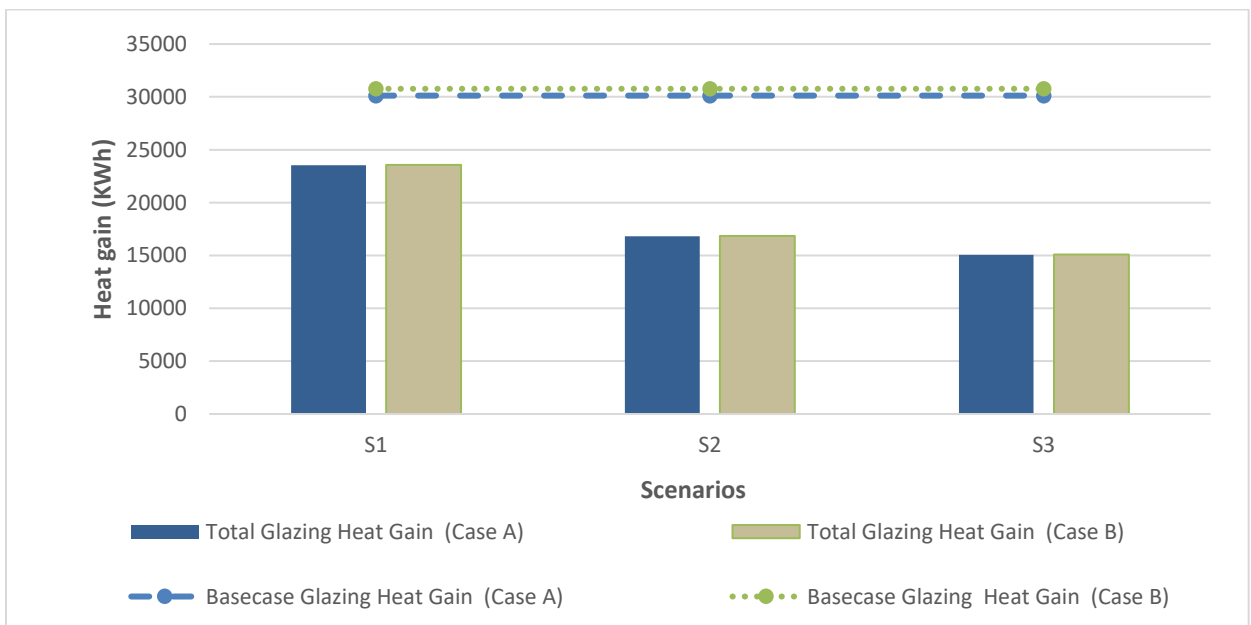


Figure 65 Annual heat gains for case A & B with combined strategies

The study evaluated 224 different scenarios involving external wall insulation, window retrofit, and shading retrofit strategies, selecting the top three most effective options for reducing glazing heat gain. The three optimal solutions all utilized the same external insulation method (ETICS) and shading device type (louvers), resulting in a heat gain reduction of approximately 60% by external insulation for the walls. However, the window retrofit methods were crucial in determining the most effective facade retrofitting scenario among the combined strategies.

Table 28 presents the results of glazing heat gain reduction for the three optimal scenarios. It was observed that scenario 3 has demonstrated the highest impact on heat gain reduction when using a Low-e coating insulated by argon gas for windows, resulting in a percentage reduction of 50.04% for Case A and 50.97% for Case B. In contrast, scenario 1 had the least heat gain reduction, with a reduction percentage of 21.9% for Case A and 23.38% for Case B, compared to the other two scenarios.

Table 28 The annual the heat gain reduction for case A & case B with combined retrofit strategies

No	Strategy	Glazing heat gain (Before) (kWh)	Case A			Case B			
			Glazing heat gain (After)(kWh)	Total of Reduction	Percent of reduction	Solar heat gain (Before) (kWh)	Glazing heat gain (After)(kWh)	Total of Reduction	Percent of reduction
S1	ETCIS+Louvers +Argon Insulation	30117.48	23524.7	6,592.78	21.9%	30766.2	23574.19	7,192.01	23.38%
S2	ETCIS+Louvers +Low-e coating		16801.27	13,316.21	44.2%		16838.62	13,927.58	45.27%
S3	ETCIS+Louvers +Low-e coating +Argon		15047.15	15,070.33	50.04%		15083.93	15,682.27	50.97%

4.5.2 Cooling electricity reduction

The observed heat gains reduction was reflected on the reduced annual cooling electricity reduction in the combined retrofitting strategies compared to the base case as shown in **Figure 66,67** and **Table 29**.

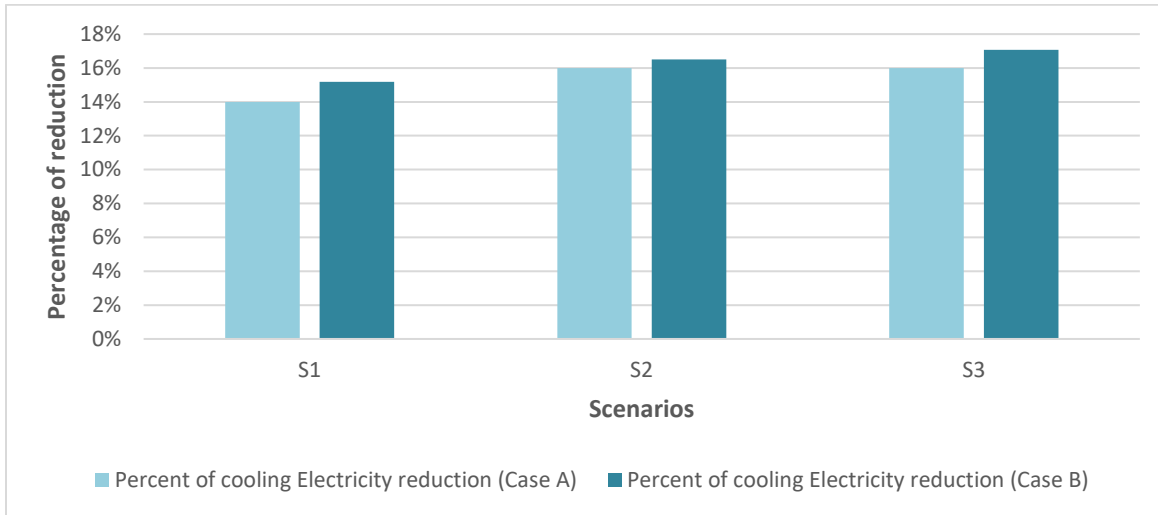


Figure 66 percentage of annual cooling energy reduction for case A & case B with combined retrofit strategies

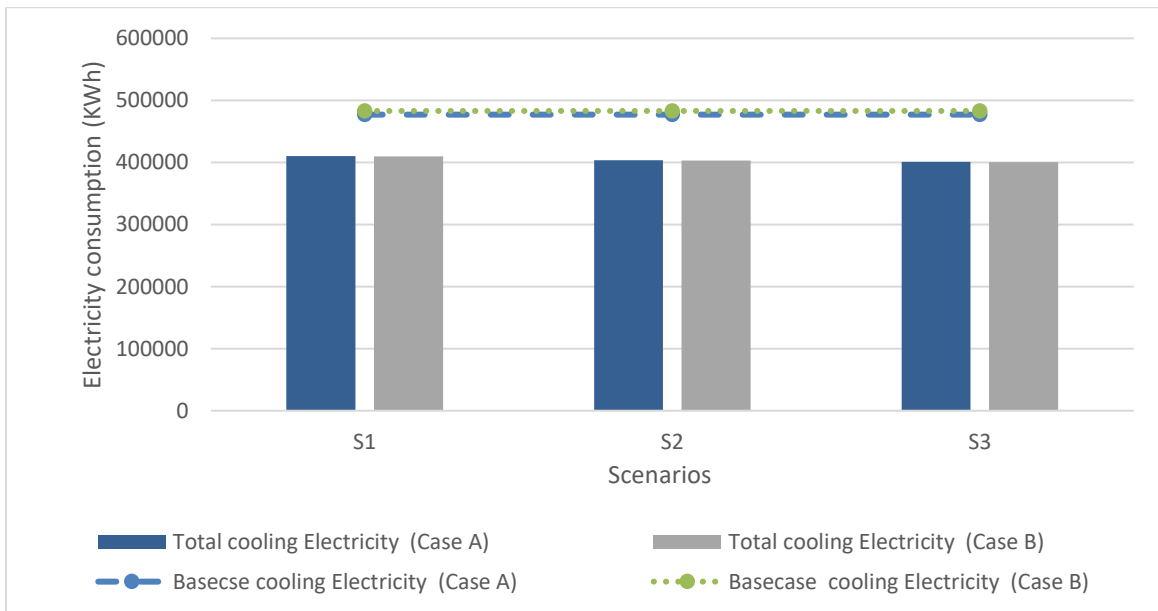


Figure 67 Annual cooling electricity consumption for combined strategies

Table 29, shows that scenario 3 demonstrated the highest reduction of cooling energy consumption, achieving a reduction of 16% for Case A and 17.08% for Case B compared to the base case. Scenario 2 closely followed by a reduction of 15.4% for Case A and 16.5% for Case B, while Scenario 1 exhibited the least reduction in cooling electricity consumption, with 14% for Case A and 15.18% for Case B.

It is necessary to point out the unified external insulation strategy for the external walls for the three scenarios, which is ETICS, has achieved a reduction in heat gain of about 60% which resulted in about 13% reduction in cooling load. This represents most of the improvement observed in the combined retrofit strategy. This indicates that the direct effect of external wall retrofit strategies has a higher impact than the effect of window retrofit strategies in reducing cooling electricity consumption.

Table 29 Comparison of the annual cooling electricity reduction in case A & case B with combined retrofitting strategies

No	Strategy	Case A				Case B			
		Cooling Electricity (KWH) (Before)	Cooling Electricity (KWH) (after)	Total Reduction	Percent of Reduction%	Cooling Electricity (KWH) (Before)	Cooling Electricity (KWH) (after)	Total Reduction	Percent of Reduction %
S1	ETCIS+Louver s+Argon Insulation	477073.9	410294.12	66,779.78	14%	483005.2	409685.12	73,320.08	15.18%
S2	ETCIS+Louver s+Low-e coating		403422.13	73,651.77	15.4%		403307.38	79,697.82	16.5%
S3	ETCIS+Louver s+Low-e coating +Argon		400832.03	76,241.87	16 %		400508.05	82,497.15	17.08%

4.5.3 Cost-efficiency

This section aims to find out the optimal retrofit solution that balance cooling energy reduction and financial feasibility. Based on the aforementioned findings, there was a

slight impact of combining the different retrofit strategies on cooling energy reduction. Most of the observed reduction comes from wall retrofitting. However, this slight effect should not be neglected, especially in mass housing cases such as our case, where the examined case study represents 48 buildings on campus.

Table 30 illustrates the payback period associated with each proposed scenario. The results indicate the third scenario is the most economically viable option, as it has the shortest payback period among the examined scenarios (14.8 years in Case A, and 13.68 years in Case B). However, the results found that window retrofitting in general is a more affordable investment with a shorter payback period and a comparable reduction in cooling energy demand. Therefore, window retrofitting has a higher cost-benefit weight than wall retrofitting, which emphasizes the importance of window replacement in improving energy efficiency.

Table 30 Initial cost & payback period for combined retrofit strategies investment.

No	Strategy	Case A			Case B		
		Total Initial Cost (SAR)	Cost of Reduction (SAR)	Payback Period (Year)	Total Initial Cost (SAR)	Cost of Reduction (SAR)	Payback Period (Year)
S1	ETCIS+Louvers+Argon Insulation	334469	21,369.5	15.65	334469	23,462.4	14.25
S2	ETCIS+Louvers+Low-e coating	359199	23,568.57	15.24	359199	25,503.3	14.08
S3	ETCIS+Louvers+Low-e coating +Argon	361179	24,397.4	14.8	361179	26,399	13.68

4.6 The correlation between the heat gain and cooling electricity

The previous results showed how different facade retrofit strategies affected the heat gains and consequently the cooling electricity consumption reduction. The correlation between the heat gains reduction obtained by each facade retrofit strategy and its subsequent effect on the reduction of cooling electricity consumption was investigated. The above analysis was conducted individually for each retrofit strategy, providing valuable insights into the complex relationships that govern energy efficiency.

After generating 448 scenarios of combined facade strategies for two orientations using the DesignBuilder optimization method, the study observed and analyzed the correlation between the individual impacts of walls' heat gain, glazing heat gain, and solar heat gain on cooling energy consumption. This analysis provides insights into the distinct contributions of each factor to the overall cooling load, allowing for a comprehensive understanding of their respective influences on energy efficiency.

Figures 68-70 illustrate the outcomes of the optimization analysis focused on minimizing cooling electricity consumption, aligning with the primary influencers on a building's cooling demand which include walls gain, glazing heat gains, and solar heat gains within combined scenarios. The depicted results portray a consistent trend wherein an increase in any of these three factors corresponds to a subsequent rise in the cooling electricity demand for the building. This general relationship underscores the interconnected nature of these influential factors, emphasizing their collective impact on the overall cooling load and highlighting the importance of targeted strategies to address each aspect for effective energy efficiency in buildings.

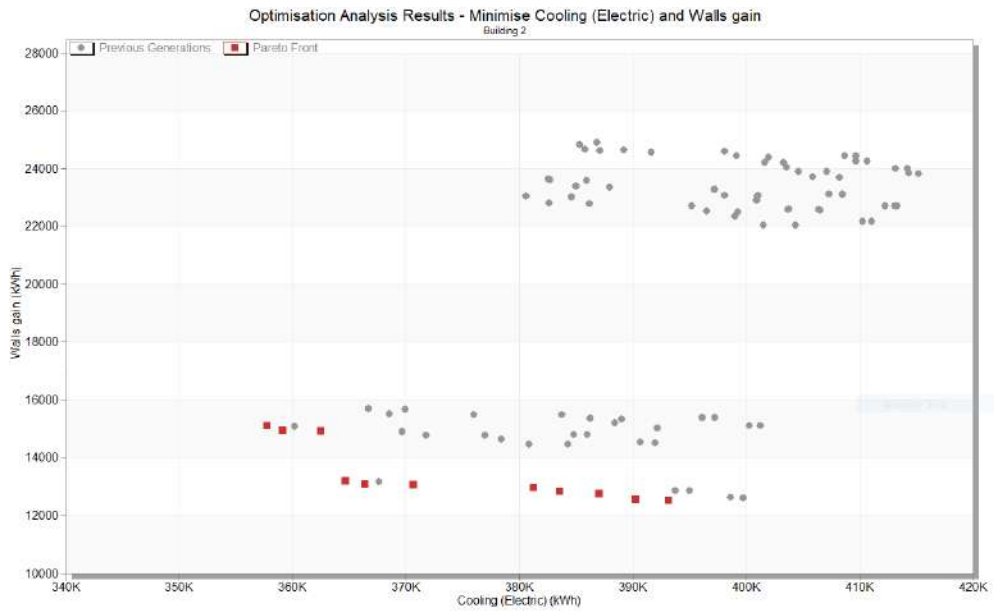


Figure 68 Optimization analysis results between wall heat gains with cooling electricity

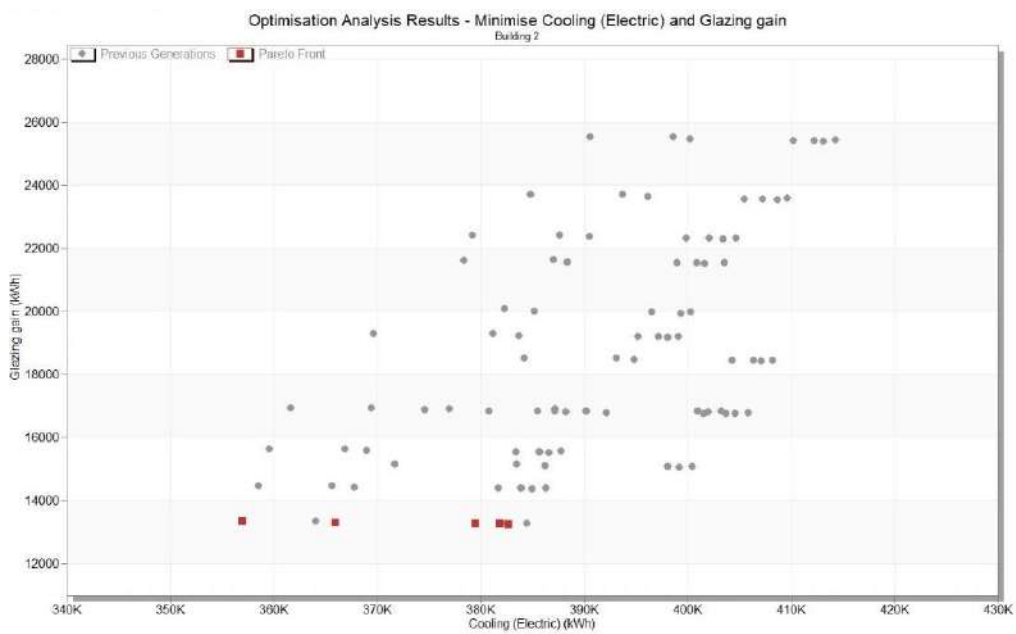


Figure 69 Optimization analysis results between glazing heat gains with cooling electricity

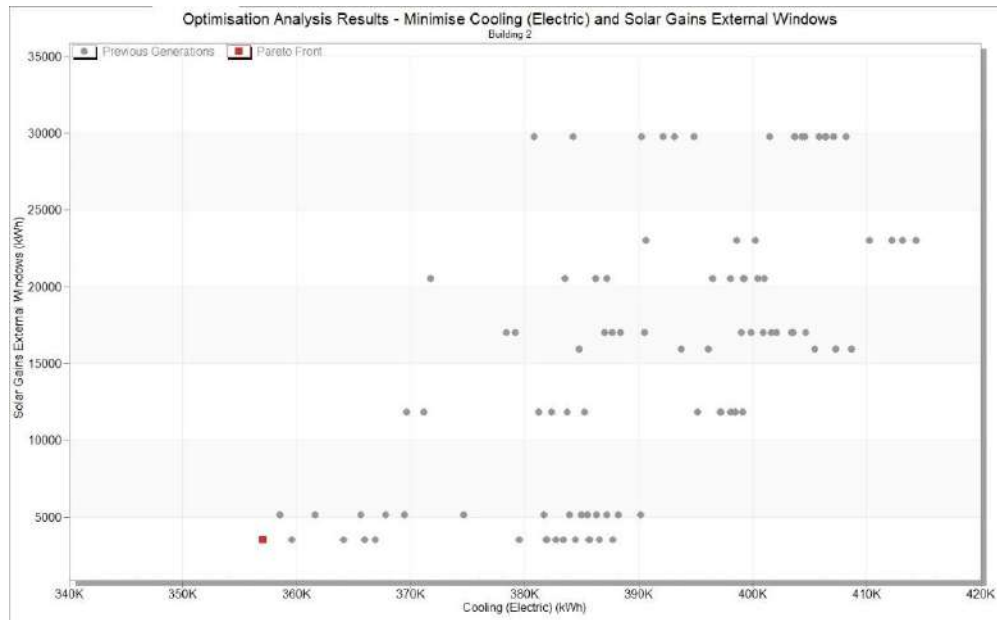


Figure 70 Optimization analysis results between solar heat gain with cooling electricity

In order to provide an accurate correlation between three input factors (wall's heat gain, window's heat gain, and solar heat gain) collectively and one output (cooling energy), cooling electricity, based on the values obtained from design builder optimization, a regression model was used for the results shown in figures 64-66 using the Minitab program. This statistical approach enabled the study to quantify the effect of each factor, allowing a precise understanding of how changes in wall heat gains, window heat gains and solar heat gains collectively contribute to the overall reduction in cooling load. Thus, the regression model serves as a powerful tool for policy makers, providing a predictive framework for estimating the outcomes of adopting specific retrofitting strategies in existing buildings.

The derived equation presents a linear regression model with high accuracy of 93% to show the relationship between the percentage of cooling electricity reduction and the percentage of walls heat gain reduction, windows heat gain reduction, and solar heat gain reduction from different parts of the building façade as shown in **Figure 67**.

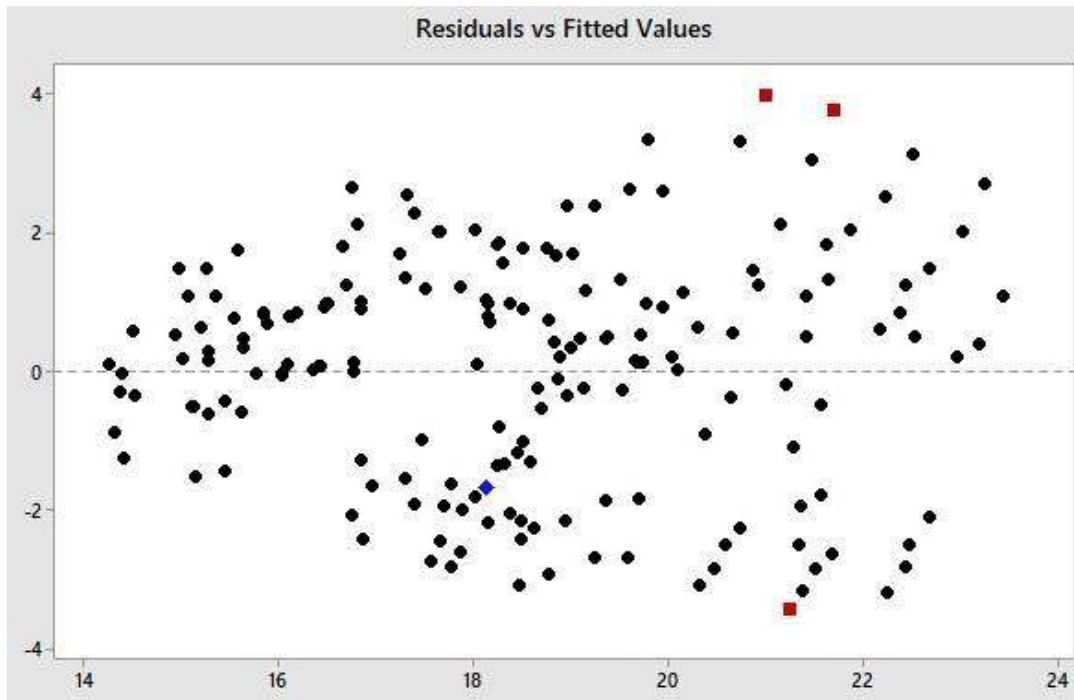


Figure 67 Multiple regression for cooling electricity reduction

It is important to mention that the study's findings were limited to the low window-to-wall ratio façade type. The equation is as follows:

$$\text{Cooling electricity} = 385187 - 4.11X - 1.44Y + 2.02Z$$

Where cooling electricity is the predicted cooling load, which represents the energy required for cooling the building(kWh), X is the wall heat gains (kWh), Y is the conductive windows heat gains (kWh), and Z is the solar heat gains through windows (kWh). The coefficient of X is 4.109, which means that for every 1 kWh increase in the annual wall heat gain, the cooling electricity consumption decreases by 4.109 kWh/year. This implies that improving the thermal performance of the external wall can reduce the cooling energy demand significantly. Similarly, the coefficients of Y

and Z show the effects of the windows and the shading devices on the cooling electricity consumption. The constant term is 385187, which is the estimated cooling electricity consumption when the heat gain from all parts is zero. This term can be interpreted as the base cooling energy demand of the building.

The hierarchy of significant parameters that have been shown to have an influence on reducing cooling electricity consumption provides important insights into the complex dynamics of building façade retrofitting techniques.

First of all, the importance of improving the thermal performance of exterior walls (X) highlights the critical function that insulation and heat resistance play in reducing heat transmission, particularly in areas with diverse climates. This result is consistent with the more general focus on energy-efficient building envelope upgrades.

Moreover, the second impactful factor represents by decreasing solar heat gains (Z) by means of shading devices and optimizing solar heat gain coefficient for windows highlights the importance of solar radiation control in the reduction of cooling load. Followed by reducing conductive heat gains from windows (Y), This finding highlights the need for comprehensive window solutions, including advanced glazing technologies and shading mechanisms, to optimize energy efficiency.

CHAPTER 5

CONCLUSION

The primary focus of this study was to assess the efficiency of various building facade strategies to reduce cooling energy consumption in Saudi Arabia hot climatic conditions, where temperatures reach about 50°C during the summer. The investigation was conducted for a student housing building located at King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia. The study considered two cases (Case A and Case B) where two main orientations and multiple façades retrofit strategies were considered. The research involved a comparative analysis of different façade strategies individually in the first part including: external insulation strategies for walls, windows retrofitting strategies, and shading devices strategies, considering diverse materials that available in Saudi market, with cost-efficiency assessment of each scenario. In the second part, the study focused on combining facade strategies together. This has been conducted employing the parametric modeling method using Design Builder program.

First of all, a significant annual cooling electricity consumption of 477073.9 kWh was calculated in the student dormitory building, resulting in a considerable cost of approximately 152,663 SAR per year for each university dormitory due to cooling energy expenses. In this regard, a total of eight scenarios for external insulation of walls, seven scenarios for the windows, and four scenarios of shading devices were identified as the potential ones to be effectively and practically applied in the Eastern Province of Saudi

Arabia, the study examined the individual effectiveness of facade strategies on external walls and windows. The external walls retrofitting scenarios demonstrated a substantial impact on reducing heat gains, which ranged between 50% to 75%. Consequently, lowering cooling energy consumption with a range of 11.8% to 16.34% for both Case A and Case B. It was observed that the orientations for the Case A and Case B with low window to wall ratio have a minor effect on the cooling electricity reduction.

It was observed that retrofitting materials of the different façade components (walls and windows) can significantly reduce the cooling electricity. Among these scenarios, the utilizing of prefabricated wood strategy was the most effective in terms of cooling reduction, which reached 18%, as compared to the other strategies of ventilated facade scenario with ACP, WPC cladding, ETICS, respectively. The ventilated facade with fiber cement cladding yields comparatively lower reduction in both Case A and Case B. The results showed that ventilated facades have different performance depending on the cladding layer, which makes them performed better than the external insulation strategy as compared with ETICS when using both types of cladding ACP and WPC.

Nevertheless, considering the prevailing prices in the Saudi market and accounting for the payback period, the outcomes demonstrate that the External Thermal Insulation Composite Systems (ETICS) and the scenarios involving External Ventilated Facade with Fiber Cement Board (FC) and Ventilated Facade with AAC Brick were the shortest payback period by 14, 21 years, respectively. Even though they have a relatively low effectiveness in decreasing the cooling energy and heat gain, their short payback periods make them the most suitable investment alternatives within the minimum time span.

Secondly, the proposed window retrofit strategies have been examined, which resulted in minimizing heat gains and consequently cooling energy consumption. Heat gain reduction between 13.5% and 45% was observed in this regard, resulting in a reduction of cooling electricity ranging between 3% and 9%, respectively.

Replacing the base window with a Smart window insulated by argon gas was the most effective strategy, which resulted in a cooling energy reduction of 9%. This was followed closely by triple glaze, low emissivity coating. The least effective scenario was adding argon gas to the base case window (the double-glazed window), which resulted in a cooling electricity reduction of 2%. However, when considering the cost, the results revealed that the triple glazing scenario can cover the cost of investment over the shortest recovery period of around four years, while the smart glazing had the longest period of 11 years. The results found that increasing layers of glass is more suitable for the facades with low window to wall ratio than utilizing a smart glazing.

Third, the study examined the effect of adding various shading devices due to their importance in blocking solar rays from entering the interior space and causing undesired solar heat gains. The results showed the effectiveness of the shading strategies with a reduction in cooling energy ranging from 4.84% to 6.14%. Cost of the suggested shading systems could be covered over a relatively short period as compared with wall retrofitting strategies. The result found that the adding a smart blind resulted in the highest reduction in cooling energy consumption by 6.14%, while the overhang strategy had the least reduction of 4.84%. On the other hand, taking into account the investment cost, the use of louvers can cover the cost over a shortest payback period of around 4 years, while the overhang strategy using steel and smart curtains has the longest period of 14.11 years.

The second part of the study focused on the importance of combined facade retrofit strategies in achieving more cooling energy savings within short payback periods compared to the examined individual retrofit strategies of external walls. Various retrofitting strategies of windows, walls, and shading devices were combined, which resulted in 224 different facade compositions. These were examined as combined retrofit scenarios by genetic algorithm optimization method, and has been found to offer a significant reduction in heat gains for walls by 60% and for windows by 50%. The study found the combination of ETCIS + louvers + low-emissivity coating with argon has demonstrated a superiority in reducing cooling energy by around 18% and a shorter recovery period of 15 years.

Based on the previous results, the study provided more insights into the complex relationships between the various factors that directly affect energy efficiency in terms of cooling electricity. A linear equation derived from the previous results was proposed to quantify the relationship between external walls heat gain, windows heat gain, solar gains reduction from different facade components and their impact on the cooling electricity reduction in residential buildings with window-to-wall ratio of 20%. This equation is as follows:

$$\text{Cooling} = 385187 - 4.11X - 1.44Y + 2.02Z$$

Where X is heating gain through external walls, Y is heating gain through windows and Z is solar heat gains. This is expected to provide a predictive framework for policymakers, allowing them to assess the impact of facade retrofitting strategies on cooling energy demand for existing buildings in the eastern province of Saudi Arabia. The most impactful

factor in reducing cooling electricity consumption is by improving thermal performance of external walls through reducing heat gains (X), followed by reducing solar heat gains by using shading devices and improving SHGC for windows (Z), followed by reducing conductive heat gains of windows (Y).

The study concluded with a set of guidelines and recommendations to help stakeholders involved in retrofitting of existing buildings in the Eastern Province of Saudi Arabia achieve substantial cooling energy savings within a short payback period.: These recommendations are as follows:

- Select strategies with the greatest financial benefit and shortest payback period by considering the economic feasibility and market availability of retrofit strategies, ensuring that the chosen interventions are consistent with energy efficiency goals and financial constraints.
- Facades play a crucial role in increasing the thermal gain of the building, which lead to raise the demand for cooling energy, thus priority should be given to improving the thermal performance of the external walls by choosing strategies that involve low u-value materials. The results showed the superiority of the ETICS strategy in reducing cooling energy within a short recovery period.
- Minimize the solar heat transfer into the interior space by incorporating effective shading devices for the facades, especially the southern facade, and enhancing the solar heat gain coefficient (SHGC) for the windows when choosing glazing type. The study showed that using louvers and wood overhang has the best performance and the shortest recovery period to reduce the effect of solar radiation on cooling demands.

- Reduce heat gains through windows by reducing the u-value of window components through implementing solutions like low-emissivity coatings, double glazing, or smart window technologies, which contribute significantly to reducing the u-value. The results showed that the best strategies are increasing the number of glazing layers and the use of argon as an insulating gas for the facades.
- Combining retrofitting strategies contributes a greater energy reduction within a shorter payback period as compared to individual walls retrofitting strategies. The results showed that the best combined strategies available in the Saudi market are (ETCIS + louvers + low-emissivity coating with argon), which resulted in a 16% reduction in cooling load and a cost recovery period of 15 years.

For future research, it is important to expand the findings of the current study through examining the climatic conditions of different regions in Saudi Arabia. It is also recommended to examine other factors that can contribute the efficiency of façade retrofitting such as orientation and window-to-wall ratio. to the study also recommends studying the impact of heat island effect in this regard.

Appendix

In this section, the supplementary materials that complement and support the findings presented in the main body of the research was provided. The supplementary data included in this appendix consist of the values obtained from the optimization in Design Builder for all previous combined strategy scenarios. These values were used to create a multiple regression model aimed at discerning the individual effects of factors such as walls' heat gain, windows' heat gain, and solar heat gain on cooling electricity consumption. This comprehensive dataset facilitates a detailed examination of how each factor contributes to the overall energy consumption of residential buildings, providing valuable insights for future research and practical applications in building design and energy management.

Status ▾							
Iteration	Generation	Status ▾	Cooling (Electric) (kWh)	Walls gain (kWh)	Glazing template	External wall construction	Local shading type
7	0		399129.20	24428.43	Triple -Argon	ETICS	Copy of Louvers
63	3		399297.77	22493.90	Low-e Air	Brick ACC	Copy of Louvers
17	0		399763.39	12602.36		ACP	Steel of 1.0m Overhang
64	3		399763.39	12602.36		ACP	Wood of 1.0m Overhang
136	18		400279.55	15085.75	Double-Argon project	WPC	Wood of 1.0m Overhang
101	7		400943.22	22890.66	Triple -Argon	Copy of Limestone-Sand	Steel of 1.0m Overhang
99	7		400943.22	22890.66	Triple -Argon	Copy of Limestone-Sand	Wood of 1.0m Overhang
133	15		400961.24	22903.82	Triple -Argon	Limestone	Steel of 1.0m Overhang
124	12		400961.24	22903.82	Triple -Argon	Limestone	Wood of 1.0m Overhang
142	20		401023.58	23043.27	Low-e Air	Copy of Limestone-Sand	Copy of Louvers
111	8		401037.78	23056.50	Low-e Air	Limestone	Copy of Louvers
132	15		401261.48	15080.74		WPC	Steel of 1.0m Overhang
21	1		401261.48	15080.74		WPC	Wood of 1.0m Overhang
73	4		401557.96	22042.57	Low-e Argon	Brick ACC	Wood of 1.0m Overhang
75	4		401557.96	22042.57	Low-e Argon	Brick ACC	Steel of 1.0m Overhang
8	0		401694.59	24192.18	Triple -Argon	Fc	Steel of 1.0m Overhang
41	2		401694.59	24192.18	Triple -Argon	Fc	Wood of 1.0m Overhang
24	1		402011.79	24375.59	Low-e Air	Fc	Copy of Louvers
4	0		403307.38	24184.92	Low-e Air	ETICS	Copy of Louvers
42	2		403592.47	24049.38	Triple -Argon	ETICS	Wood of 1.0m Overhang
5	0		403592.47	24049.38	Triple -Argon	ETICS	Steel of 1.0m Overhang
32	1		403729.02	22578.41	Low-e Argon	Copy of Limestone-Sand	Wood of 1.0m Overhang
94	6		403729.02	22578.41	Low-e Argon	Copy of Limestone-Sand	Steel of 1.0m Overhang
48	2		403775.39	22591.39	Low-e Argon	Limestone	Steel of 1.0m Overhang
115	9		404369.89	22032.93	Low-e Air	Brick ACC	Steel of 1.0m Overhang
146	22		404369.89	22032.93	Low-e Air	Brick ACC	Wood of 1.0m Overhang
45	2		404529.07	22994.51	Low-e Argon	Fc	Steel of 1.0m Overhang

Status ▾							
Iteration	Generation	Status ▾	Cooling (Electric) (kWh)	Walls gain (kWh)	Glazing template	External wall construction	Local shading type
57	3		390241.66	12528.46	Low-e Argon	ACP	Wood of 1.0m Overhang
84	5		390660.81	14513.34	Double-Argon project	prefabricated wood	Steel of 1.0m Overhang
14	0		390660.81	14513.34	Double-Argon project	prefabricated wood	Wood of 1.0m Overhang
35	1		391680.15	24561.45	Electro-Air	ETICS	Wood of 1.0m Overhang
88	5		391680.15	24561.45	Electro-Air	ETICS	Steel of 1.0m Overhang
0	0		391967.59	14508.78		prefabricated wood	Wood of 1.0m Overhang
52	3		391967.59	14508.78		prefabricated wood	Steel of 1.0m Overhang
81	5		392209.78	15011.79	Low-e Argon	WPC	Wood of 1.0m Overhang
137	19		392209.78	15011.79	Low-e Argon	WPC	Steel of 1.0m Overhang
98	7		393140.13	12520.68	Low-e Air	ACP	Wood of 1.0m Overhang
82	5		393753.06	12845.11	Double-Argon project	ACP	Copy of Louvers
36	2		395013.19	12840.12		ACP	Copy of Louvers
100	7		395192.63	22699.66	Triple -Argon	Brick ACC	Copy of Louvers
26	1		396148.20	15372.69	Double-Argon project	WPC	Copy of Louvers
31	1		396509.50	22507.37	Low-e Argon	Brick ACC	Copy of Louvers
96	7		397208.62	23258.19	Triple -Argon	Copy of Limestone-Sand	Copy of Louvers
138	19		397231.03	23271.50	Triple -Argon	Limestone	Copy of Louvers
53	3		397261.48	15368.06		WPC	Copy of Louvers
105	7		398112.94	23057.36	Low-e Argon	Copy of Limestone-Sand	Copy of Louvers
40	2		398132.18	24587.16	Triple -Argon	Fc	Copy of Louvers
12	0		398628.00	12608.13	Double-Argon project	ACP	Steel of 1.0m Overhang
56	3		398628.00	12608.13	Double-Argon project	ACP	Wood of 1.0m Overhang
15	0		399023.23	22340.98	Triple -Argon	Brick ACC	Steel of 1.0m Overhang
148	22		399023.23	22340.98	Triple -Argon	Brick ACC	Wood of 1.0m Overhang
7	0		399129.20	24428.43	Triple -Argon	ETICS	Copy of Louvers
63	3		399297.77	22493.90	Low-e Air	Brick ACC	Copy of Louvers

Status ▾							
Iteration	Generation	Status ▾	Cooling (Electric) (kWh)	Walls gain (kWh)	Glazing template	External wall construction	Local shading type
61	3		384833.27	14792.26	Double-Argon project	prefabricated wood	Copy of Louvers
86	5		384972.22	23380.32	Electro-Argon	Copy of Limestone-Sand	Steel of 1.0m Overhang
147	22		384972.22	23380.32	Electro-Argon	Copy of Limestone-Sand	Wood of 1.0m Overhang
58	3		384995.52	23393.72	Electro-Argon	Limestone	Wood of 1.0m Overhang
28	1		384995.52	23393.72	Electro-Argon	Limestone	Steel of 1.0m Overhang
114	9		385357.22	24815.52	Electro-Argon	ETICS	Copy of Louvers
95	6		385816.65	24672.17	Electro-Argon	Fc	Steel of 1.0m Overhang
9	0		385816.65	24672.17	Electro-Argon	Fc	Wood of 1.0m Overhang
69	4		385931.15	23584.85	Electro-Air	Limestone	Copy of Louvers
1	0		385992.11	14787.08		prefabricated wood	Copy of Louvers
38	2		386162.80	22775.09	Electro-Air	Brick ACC	Wood of 1.0m Overhang
85	5		386162.80	22775.09	Electro-Air	Brick ACC	Steel of 1.0m Overhang
117	9		386238.10	15342.11	Low-e Argon	WPC	Copy of Louvers
79	4		386829.69	24894.61	Electro-Air	Fc	Copy of Louvers
92	6		387065.57	12741.94	Triple -Argon	ACP	Steel of 1.0m Overhang
55	3		387096.46	24602.68	Electro-Argon	ETICS	Wood of 1.0m Overhang
30	1		387096.46	24602.68	Electro-Argon	ETICS	Steel of 1.0m Overhang
143	21		387980.11	23344.74	Electro-Air	Copy of Limestone-Sand	Steel of 1.0m Overhang
141	20		387980.11	23344.74	Electro-Air	Copy of Limestone-Sand	Wood of 1.0m Overhang
67	4		387993.99	23358.16	Electro-Air	Limestone	Steel of 1.0m Overhang
131	15		387993.99	23358.16	Electro-Air	Limestone	Wood of 1.0m Overhang
144	21		388426.21	15207.00	Triple -Argon	WPC	Wood of 1.0m Overhang
13	0		388426.21	15207.00	Triple -Argon	WPC	Steel of 1.0m Overhang
126	12		388989.87	15333.03	Low-e Air	WPC	Copy of Louvers
78	4		389243.39	24637.69	Electro-Air	Fc	Steel of 1.0m Overhang
34	1		389243.39	24637.69	Electro-Air	Fc	Wood of 1.0m Overhang

Status ▾							
Iteration	Generation	Status ▾	Cooling (Electric) (kWh)	Walls gain (kWh)	Glazing template	External wall construction	Local shading type
150	25		375957.64	15488.01	Electro-Air	WPC	Wood of 1.0m Overhang
118	10		376976.66	14754.96	Low-e Air	prefabricated wood	Copy of Louvers
25	1		378395.28	14632.54	Triple -Argon	prefabricated wood	Steel of 1.0m Overhang
112	8		380560.45	23028.58	Electro-Argon	Brick ACC	Copy of Louvers
104	7		380864.04	14443.19	Low-e Argon	prefabricated wood	Steel of 1.0m Overhang
106	8		380864.04	14443.19	Low-e Argon	prefabricated wood	Wood of 1.0m Overhang
80	5		382595.47	23616.07	Electro-Argon	Limestone	Copy of Louvers
121	12		382657.92	22809.77	Electro-Argon	Brick ACC	Steel of 1.0m Overhang
72	4		382657.92	22809.77	Electro-Argon	Brick ACC	Wood of 1.0m Overhang
149	23		382680.77	23602.48	Electro-Argon	Copy of Limestone-Sand	Copy of Louvers
135	18		383738.26	15467.82	Triple -Argon	WPC	Copy of Louvers
22	1		384258.72	14436.46	Low-e Air	prefabricated wood	Wood of 1.0m Overhang
3	0		384258.72	14436.46	Low-e Air	prefabricated wood	Steel of 1.0m Overhang
134	15		384610.19	22998.06	Electro-Air	Brick ACC	Copy of Louvers
61	3		384833.27	14792.26	Double-Argon project	prefabricated wood	Copy of Louvers
86	5		384972.22	23380.32	Electro-Argon	Copy of Limestone-Sand	Steel of 1.0m Overhang
147	22		384972.22	23380.32	Electro-Argon	Copy of Limestone-Sand	Wood of 1.0m Overhang
58	3		384995.52	23393.72	Electro-Argon	Limestone	Wood of 1.0m Overhang
28	1		384995.52	23393.72	Electro-Argon	Limestone	Steel of 1.0m Overhang
114	9		385357.22	24815.52	Electro-Argon	ETICS	Copy of Louvers
95	6		385816.65	24672.17	Electro-Argon	Fc	Steel of 1.0m Overhang
9	0		385816.65	24672.17	Electro-Argon	Fc	Wood of 1.0m Overhang
69	4		385931.15	23584.85	Electro-Air	Limestone	Copy of Louvers
1	0		385992.11	14787.08		prefabricated wood	Copy of Louvers
38	2		386162.80	22775.09	Electro-Air	Brick ACC	Wood of 1.0m Overhang
85	5		386162.80	22775.09	Electro-Air	Brick ACC	Steel of 1.0m Overhang

Status ▾							
Iteration	Generation	Status ▾	Cooling (Electric) (kWh)	Walls gain (kWh)	Glazing template	External wall construction	Local shading type
34	1		389243.39	24637.69	Electro-Air	Fc	Wood of 1.0m Overhang
57	3		390241.66	12528.46	Low-e Argon	ACP	Wood of 1.0m Overhang
84	5		390660.81	14513.34	Double-Argon project	prefabricated wood	Steel of 1.0m Overhang
14	0		390660.81	14513.34	Double-Argon project	prefabricated wood	Wood of 1.0m Overhang
35	1		391680.15	24561.45	Electro-Air	ETICS	Wood of 1.0m Overhang
88	5		391680.15	24561.45	Electro-Air	ETICS	Steel of 1.0m Overhang
0	0		391967.59	14508.78		prefabricated wood	Wood of 1.0m Overhang
52	3		391967.59	14508.78		prefabricated wood	Steel of 1.0m Overhang
81	5		392209.78	15011.79	Low-e Argon	WPC	Wood of 1.0m Overhang
137	19		392209.78	15011.79	Low-e Argon	WPC	Steel of 1.0m Overhang
98	7		393140.13	12520.68	Low-e Air	ACP	Wood of 1.0m Overhang
82	5		393753.06	12845.11	Double-Argon project	ACP	Copy of Louvers
36	2		395013.19	12840.12		ACP	Copy of Louvers
100	7		395192.63	22699.66	Triple -Argon	Brick ACC	Copy of Louvers
26	1		396148.20	15372.69	Double-Argon project	WPC	Copy of Louvers
31	1		396509.50	22507.37	Low-e Argon	Brick ACC	Copy of Louvers
96	7		397208.62	23258.19	Triple -Argon	Copy of Limestone-Sand	Copy of Louvers
138	19		397231.03	23271.50	Triple -Argon	Limestone	Copy of Louvers
53	3		397261.48	15368.06		WPC	Copy of Louvers
105	7		398112.94	23057.36	Low-e Argon	Copy of Limestone-Sand	Copy of Louvers
40	2		398132.18	24587.16	Triple -Argon	Fc	Copy of Louvers
12	0		398628.00	12608.13	Double-Argon project	ACP	Steel of 1.0m Overhang
56	3		398628.00	12608.13	Double-Argon project	ACP	Wood of 1.0m Overhang
15	0		399023.23	22340.98	Triple -Argon	Brick ACC	Steel of 1.0m Overhang
148	22		399023.23	22340.98	Triple -Argon	Brick ACC	Wood of 1.0m Overhang
7	0		399129.20	24428.43	Triple -Argon	ETICS	Copy of Louvers

Status ▾							
Iteration	Generation	Status ▾	Cooling (Electric) (kBtu)	Walls gain (kBtu)	Glazing template	External wall construction	Local shading type
- (none)							
74	4		1225317.51	50935.87	Electro-Argon	prefabricated wood	Wood of 1.0m Overhang
68	4		1228961.00	51428.31	Electro-Air	prefabricated wood	Copy of Louvers
87	5		1236819.28	50863.52	Electro-Air	prefabricated wood	Wood of 1.0m Overhang
93	6		1250044.90	44623.06	Electro-Argon	ACP	Steel of 1.0m Overhang
116	9		1251126.35	53502.77	Electro-Argon	WPC	Copy of Louvers
62	3		1254282.58	44907.91	Electro-Air	ACP	Copy of Louvers
108	8		1257498.59	52925.69	Electro-Argon	WPC	Wood of 1.0m Overhang
140	20		1257498.59	52925.69	Electro-Argon	WPC	Steel of 1.0m Overhang
91	6		1261303.08	50789.78	Triple -Argon	prefabricated wood	Copy of Louvers
107	8		1262179.30	53438.52	Electro-Air	WPC	Copy of Louvers
77	4		1264666.10	44539.68	Electro-Air	ACP	Steel of 1.0m Overhang
102	7		1268438.26	50373.82	Low-e Argon	prefabricated wood	Copy of Louvers
150	25		1282820.70	52847.28	Electro-Air	WPC	Wood of 1.0m Overhang
118	10		1286297.76	50346.01	Low-e Air	prefabricated wood	Copy of Louvers
25	1		1291138.28	49928.31	Triple -Argon	prefabricated wood	Steel of 1.0m Overhang
112	8		1298526.16	78576.76	Electro-Argon	Brick ACC	Copy of Louvers
104	7		1299562.05	49282.21	Low-e Argon	prefabricated wood	Steel of 1.0m Overhang
106	8		1299562.05	49282.21	Low-e Argon	prefabricated wood	Wood of 1.0m Overhang
80	5		1305469.94	80581.36	Electro-Argon	Limestone	Copy of Louvers
121	12		1305683.03	77830.17	Electro-Argon	Brick ACC	Steel of 1.0m Overhang
72	4		1305683.03	77830.17	Electro-Argon	Brick ACC	Wood of 1.0m Overhang
149	23		1305760.98	80534.99	Electro-Argon	Copy of Limestone-Sand	Copy of Louvers
135	18		1309369.28	52778.41	Triple -Argon	WPC	Copy of Louvers
22	1		1311145.17	49259.26	Low-e Air	prefabricated wood	Wood of 1.0m Overhang
3	0		1311145.17	49259.26	Low-e Air	prefabricated wood	Steel of 1.0m Overhang

Status ▾							
Iteration	Generation	Status ▾	Cooling (Electric) (kWh)	Walls gain (kWh)	Glazing template	External wall construction	Local shading type
46	2		404638.07	23884.61	Low-e Argon	Fc	Steel of 1.0m Overhang
10	0		405878.60	23696.34	Low-e Argon	ETICS	Steel of 1.0m Overhang
122	12		406420.48	22581.14	Low-e Air	Limestone	Wood of 1.0m Overhang
127	13		406420.48	22581.14	Low-e Air	Limestone	Steel of 1.0m Overhang
16	0		406437.49	22568.12	Low-e Air	Copy of Limestone-Sand	Wood of 1.0m Overhang
113	8		406437.49	22568.12	Low-e Air	Copy of Limestone-Sand	Steel of 1.0m Overhang
39	2		406546.83	22548.89		Brick ACC	Copy of Louvers
139	20		407119.23	23875.63	Low-e Air	Fc	Wood of 1.0m Overhang
50	3		407119.23	23875.63	Low-e Air	Fc	Steel of 1.0m Overhang
43	2		407311.87	23108.01	Double-Argon project	Copy of Limestone-Sand	Copy of Louvers
123	12		407326.29	23121.28	Double-Argon project	Limestone	Copy of Louvers
23	1		408251.78	23685.41	Low-e Air	ETICS	Steel of 1.0m Overhang
109	8		408251.78	23685.41	Low-e Air	ETICS	Wood of 1.0m Overhang
54	3		408503.91	23100.27		Copy of Limestone-Sand	Copy of Louvers
20	1		408516.24	23113.53		Limestone	Copy of Louvers
76	4		408711.52	24439.99	Double-Argon project	Fc	Copy of Louvers
37	2		409678.00	24432.60		Fc	Copy of Louvers
33	1		409685.12	24257.06	Double-Argon project	ETICS	Copy of Louvers
130	14		410277.37	22154.14	Double-Argon project	Brick ACC	Wood of 1.0m Overhang
6	0		410277.37	22154.14	Double-Argon project	Brick ACC	Steel of 1.0m Overhang
51	3		410694.13	24247.88		ETICS	Copy of Louvers
120	11		411107.21	22147.57		Brick ACC	Steel of 1.0m Overhang
19	1		411107.21	22147.57		Brick ACC	Wood of 1.0m Overhang
70	4		412235.80	22695.22	Double-Argon project	Copy of Limestone-Sand	Wood of 1.0m Overhang
125	12		412235.80	22695.22	Double-Argon project	Copy of Limestone-Sand	Steel of 1.0m Overhang
60	3		412263.78	22708.25	Double-Argon project	Limestone	Wood of 1.0m Overhang

Untitled, Building 2

Analysis Summary Parametric Optimisation + UA/SA Data Visualisation

Status ▾

Iteration	Generation	Status ▾	Cooling (Electric) (kWh)	Glazing gain (kWh)	Glazing template	External wall construction	Local shading type
147	20		399763.39	26338.06		ACP	Steel of 1.0m Overhang
65	3		399763.39	26338.06		ACP	Wood of 1.0m Overhang
43	2		400279.55	25462.30	Double-Argon project	WPC	Steel of 1.0m Overhang
102	6		400508.05	15083.93	Low-e Argon	ETICS	Copy of Louvers
86	5		400943.22	21528.27	Triple -Argon	Copy of Limestone-Sand	Steel of 1.0m Overhang
121	10		400943.22	21528.27	Triple -Argon	Copy of Limestone-Sand	Wood of 1.0m Overhang
133	14		400961.24	21528.18	Triple -Argon	Limestone	Steel of 1.0m Overhang
58	3		400961.24	21528.18	Triple -Argon	Limestone	Wood of 1.0m Overhang
80	4		401023.58	16827.70	Low-e Air	Copy of Limestone-Sand	Copy of Louvers
21	1		401037.78	16827.61	Low-e Air	Limestone	Copy of Louvers
139	17		401261.48	26258.15		WPC	Wood of 1.0m Overhang
56	3		401261.48	26258.15		WPC	Steel of 1.0m Overhang
14	0		401557.96	16770.63	Low-e Argon	Brick ACC	Steel of 1.0m Overhang
45	2		401694.59	21502.93	Triple -Argon	Fc	Steel of 1.0m Overhang
41	2		402011.79	16802.79	Low-e Air	Fc	Copy of Louvers
113	8		403592.47	21539.33	Triple -Argon	ETICS	Wood of 1.0m Overhang
61	3		403729.02	16768.61	Low-e Argon	Copy of Limestone-Sand	Wood of 1.0m Overhang
9	0		403729.02	16768.61	Low-e Argon	Copy of Limestone-Sand	Steel of 1.0m Overhang
142	18		403775.39	16768.54	Low-e Argon	Limestone	Wood of 1.0m Overhang
129	13		403775.39	16768.54	Low-e Argon	Limestone	Steel of 1.0m Overhang
55	3		404369.89	18433.06	Low-e Air	Brick ACC	Wood of 1.0m Overhang
116	9		404369.89	18433.06	Low-e Air	Brick ACC	Steel of 1.0m Overhang
13	0		404638.07	16748.22	Low-e Argon	Fc	Steel of 1.0m Overhang
141	18		404638.07	16748.22	Low-e Argon	Fc	Wood of 1.0m Overhang
138	16		405514.21	23566.80	Double-Argon project	Brick ACC	Copy of Louvers
143	19		405878.60	16779.41	Low-e Argon	ETICS	Steel of 1.0m Overhang
70	1		406070.69	16770.41	Low-e Argon	ETICS	Wood of 1.0m Overhang

Edit Visualise Heating design Cooling design Simulation CFD Daylighting Cost and Carbon

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Analysis Summary Parametric Optimisation + UA/SA Data Visualisation

Status ▾

Iteration	Generation	Status ▾	Cooling (Electric) (kWh)	Glazing gain (kWh)	Glazing template	External wall construction	Local shading type
135	15		391680.15	17632.65	Electro-Air	ETICS	Wood of 1.0m Overhang
36	1		391680.15	17632.65	Electro-Air	ETICS	Steel of 1.0m Overhang
3	0		391967.59	26332.44		prefabricated wood	Steel of 1.0m Overhang
66	4		391967.59	26332.44		prefabricated wood	Wood of 1.0m Overhang
128	13		392209.78	16792.47	Low-e Argon	WPC	Wood of 1.0m Overhang
30	1		392209.78	16792.47	Low-e Argon	WPC	Steel of 1.0m Overhang
123	11		393140.13	18513.81	Low-e Air	ACP	Steel of 1.0m Overhang
54	3		393140.13	18513.81	Low-e Air	ACP	Wood of 1.0m Overhang
84	5		393753.06	23696.38	Double-Argon project	ACP	Copy of Louvers
115	9		394865.05	18460.57	Low-e Air	WPC	Wood of 1.0m Overhang
52	3		395013.19	24487.59		ACP	Copy of Louvers
110	8		395192.63	19193.74	Triple -Argon	Brick ACC	Copy of Louvers
103	6		396148.20	23617.62	Double-Argon project	WPC	Copy of Louvers
155	26		396509.50	15077.23	Low-e Argon	Brick ACC	Copy of Louvers
108	8		397208.62	19189.05	Triple -Argon	Copy of Limestone-Sand	Copy of Louvers
48	2		397231.03	19188.93	Triple -Argon	Limestone	Copy of Louvers
57	3		397261.48	24405.92		WPC	Copy of Louvers
10	0		398112.94	15074.41	Low-e Argon	Copy of Limestone-Sand	Copy of Louvers
134	15		398127.07	15074.35	Low-e Argon	Limestone	Copy of Louvers
146	20		398132.18	19163.39	Triple -Argon	Fc	Copy of Louvers
153	25		398628.00	25539.39	Double-Argon project	ACP	Wood of 1.0m Overhang
109	8		398628.00	25539.39	Double-Argon project	ACP	Steel of 1.0m Overhang
31	1		399023.23	21532.09	Triple -Argon	Brick ACC	Steel of 1.0m Overhang
130	13		399129.20	19199.73	Triple -Argon	ETICS	Copy of Louvers
73	4		399212.86	15053.44	Low-e Argon	Fc	Copy of Louvers
131	13		399297.77	16831.31	Low-e Air	Brick ACC	Copy of Louvers
147	20		399763.39	26338.06		ACP	Steel of 1.0m Overhang

Edit Visualise Heating design Cooling design Simulation CFD Daylighting Cost and Carbon

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Analysis Summary Parametric Optimisation + UA/SA Data Visualisation

Status ▾

Iteration	Generation	Status ▾	Cooling (Electric) (kWh)	Glazing gain (kWh)	Glazing template	External wall construction	Local shading type
104	7		385913.87	16284.78	Electro-Air	Copy of Limestone-Sand	Copy of Louvers
5	0		385931.15	16284.68	Electro-Air	Limestone	Copy of Louvers
53	3		385992.11	24485.13		prefabricated wood	Copy of Louvers
117	9		386162.80	17629.37	Electro-Air	Brick ACC	Wood of 1.0m Overhang
88	5		386162.80	17629.37	Electro-Air	Brick ACC	Steel of 1.0m Overhang
46	2		386238.10	15103.49	Low-e Argon	WPC	Copy of Louvers
34	1		386829.69	16260.05	Electro-Air	Fc	Copy of Louvers
69	4		387065.57	21621.15	Triple -Argon	ACP	Steel of 1.0m Overhang
11	0		387065.57	21621.15	Triple -Argon	ACP	Wood of 1.0m Overhang
98	6		387096.46	15156.13	Electro-Argon	ETICS	Steel of 1.0m Overhang
25	1		387096.46	15156.13	Electro-Argon	ETICS	Wood of 1.0m Overhang
83	5		387239.55	16918.10	Low-e Air	ACP	Copy of Louvers
112	8		387980.11	17624.54	Electro-Air	Copy of Limestone-Sand	Wood of 1.0m Overhang
148	21		387980.11	17624.54	Electro-Air	Copy of Limestone-Sand	Steel of 1.0m Overhang
20	1		387993.99	17624.47	Electro-Air	Limestone	Steel of 1.0m Overhang
4	0		387993.99	17624.47	Electro-Air	Limestone	Wood of 1.0m Overhang
127	12		388245.34	16292.97	Electro-Air	ETICS	Copy of Louvers
140	17		388426.21	21565.67	Triple -Argon	WPC	Steel of 1.0m Overhang
35	1		388989.87	16863.80	Low-e Air	WPC	Copy of Louvers
81	4		389243.39	17599.81	Electro-Air	Fc	Wood of 1.0m Overhang
64	3		389243.39	17599.81	Electro-Air	Fc	Steel of 1.0m Overhang
75	4		390241.66	16837.65	Low-e Argon	ACP	Steel of 1.0m Overhang
124	11		390241.66	16837.65	Low-e Argon	ACP	Wood of 1.0m Overhang
154	25		390660.81	25533.40	Double-Argon project	prefabricated wood	Steel of 1.0m Overhang
151	24		390660.81	25533.40	Double-Argon project	prefabricated wood	Wood of 1.0m Overhang
135	15		391680.15	17632.65	Electro-Air	ETICS	Wood of 1.0m Overhang
26	1		391680.15	17632.65	Electro-Air	ETICS	Steel of 1.0m Overhang

Edit Visualise Heating design Cooling design Simulation CFD Daylighting Cost and Carbon

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Analysis Summary Parametric Optimisation + UA/SA Data Visualisation

Status ▾

Iteration	Generation	Status ▾	Cooling (Electric) (kWh)	Glazing gain (kWh)	Glazing template	External wall construction	Local shading type
105	7		376976.66	16913.48	Low-e Air	prefabricated wood	Copy of Louvers
68	4		378395.28	21615.86	Triple -Argon	prefabricated wood	Wood of 1.0m Overhang
44	2		378395.28	21615.86	Triple -Argon	prefabricated wood	Steel of 1.0m Overhang
152	24		380864.04	16829.07	Low-e Argon	prefabricated wood	Steel of 1.0m Overhang
82	5		380864.04	16829.07	Low-e Argon	prefabricated wood	Wood of 1.0m Overhang
150	23		381243.05	19288.35	Triple -Argon	ACP	Copy of Louvers
27	1		382657.92	15152.78	Electro-Argon	Brick ACC	Steel of 1.0m Overhang
71	4		382657.92	15152.78	Electro-Argon	Brick ACC	Wood of 1.0m Overhang
16	0		382680.77	13970.28	Electro-Argon	Copy of Limestone-Sand	Copy of Louvers
74	4		383539.11	15150.37	Low-e Argon	ACP	Copy of Louvers
101	6		384258.72	18505.23	Low-e Air	prefabricated wood	Wood of 1.0m Overhang
137	16		384258.72	18505.23	Low-e Air	prefabricated wood	Steel of 1.0m Overhang
91	5		384610.19	16289.35	Electro-Air	Brick ACC	Copy of Louvers
90	5		384833.27	23693.75	Double-Argon project	prefabricated wood	Copy of Louvers
107	7		384972.22	15148.53	Electro-Argon	Copy of Limestone-Sand	Wood of 1.0m Overhang
136	16		384972.22	15148.53	Electro-Argon	Copy of Limestone-Sand	Steel of 1.0m Overhang
26	1		384995.52	15148.45	Electro-Argon	Limestone	Steel of 1.0m Overhang
76	4		384995.52	15148.45	Electro-Argon	Limestone	Wood of 1.0m Overhang
78	4		385357.22	13976.96	Electro-Argon	ETICS	Copy of Louvers
12	0		385816.65	15127.49	Electro-Argon	Fc	Steel of 1.0m Overhang
8	0		385816.65	15127.49	Electro-Argon	Fc	Wood of 1.0m Overhang
104	7		385913.87	16284.78	Electro-Air	Copy of Limestone-Sand	Copy of Louvers
5	0		385931.15	16284.68	Electro-Air	Limestone	Copy of Louvers
53	3		385992.11	24485.13		prefabricated wood	Copy of Louvers
117	9		386162.80	17629.37	Electro-Air	Brick ACC	Wood of 1.0m Overhang
88	5		386162.80	17629.37	Electro-Air	Brick ACC	Steel of 1.0m Overhang
46	2		386238.10	15103.49	Low-e Argon	WPC	Copy of Louvers

Edit Visualise Heating design Cooling design Simulation CFD Daylighting Cost and Carbon

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Analysis Summary Parametric Optimisation + UA/SA Data Visualisation

Status ▾

Iteration	Generation	Status ▾	Cooling (Electric) (kWh)	Glazing gain (kWh)	Glazing template	External wall construction	Local shading type
Optimal Designs							
72	4	Optimal ...	357741.15	14051.43	Electro-Argon	prefabricated wood	Copy of Louvers
32	1	Optimal ...	366668.94	14008.50	Electro-Argon	WPC	Copy of Louvers
18	0	Optimal ...	380560.45	13974.44	Electro-Argon	Brick ACC	Copy of Louvers
96	6	Optimal ...	382595.47	13970.25	Electro-Argon	Limestone	Copy of Louvers
29	1	Optimal ...	384073.54	13948.63	Electro-Argon	Fc	Copy of Louvers
(none)							
60	3		359105.11	15228.04	Electro-Argon	prefabricated wood	Steel of 1.0m Overhang
15	0		359105.11	15228.04	Electro-Argon	prefabricated wood	Wood of 1.0m Overhang
99	6		360172.92	16383.89	Electro-Air	prefabricated wood	Copy of Louvers
50	2		362475.95	17721.43	Electro-Air	prefabricated wood	Wood of 1.0m Overhang
39	2		362475.95	17721.43	Electro-Air	prefabricated wood	Steel of 1.0m Overhang
47	2		364626.29	14054.79	Electro-Argon	ACP	Copy of Louvers
70	4		366352.00	15231.32	Electro-Argon	ACP	Wood of 1.0m Overhang
93	5		366352.00	15231.32	Electro-Argon	ACP	Steel of 1.0m Overhang
119	9		367593.94	16386.38	Electro-Air	ACP	Copy of Louvers
59	3		368536.46	15185.55	Electro-Argon	WPC	Wood of 1.0m Overhang
106	7		368536.46	15185.55	Electro-Argon	WPC	Steel of 1.0m Overhang
118	9		369651.44	19285.67	Triple -Argon	prefabricated wood	Copy of Louvers
94	6		369908.24	16331.41	Electro-Air	WPC	Copy of Louvers
33	1		370637.05	17723.43	Electro-Air	ACP	Wood of 1.0m Overhang
92	5		370637.05	17723.43	Electro-Air	ACP	Steel of 1.0m Overhang
145	19		371742.56	15144.39	Low-e Argon	prefabricated wood	Copy of Louvers
67	4		375957.64	17667.83	Electro-Air	WPC	Steel of 1.0m Overhang
125	11		375957.64	17667.83	Electro-Air	WPC	Wood of 1.0m Overhang
105	7		376976.66	16913.48	Low-e Air	prefabricated wood	Copy of Louvers
60	4		377046.70	21615.86	Triple -Argon	prefabricated wood	Wood of 1.0m Overhang

Edit Visualise Heating design Cooling design Simulation CFD Daylighting Cost and Carbon

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Analysis Summary Parametric Optimisation + UA/SA Data Visualisation

Status ▾

Iteration	Generation	Status ▾	Cooling (Electric) (kWh)	Glazing gain (kWh)	Glazing template	External wall construction	Local shading type
1	0		408251.78	18442.43	Low-e Air	ETICS	Wood of 1.0m Overhang
89	5		408503.91	24346.06		Copy of Limestone-Sand	Copy of Louvers
38	2		408516.24	24345.92		Limestone	Copy of Louvers
100	6		408711.52	23524.34	Double-Argon project	Fc	Copy of Louvers
19	1		409678.00	24308.64		Fc	Copy of Louvers
144	19		409685.12	23574.19	Double-Argon project	ETICS	Copy of Louvers
42	2		410277.37	25416.66	Double-Argon project	Brick ACC	Steel of 1.0m Overhang
79	4		410277.37	25416.66	Double-Argon project	Brick ACC	Wood of 1.0m Overhang
97	6		410694.13	24360.06		ETICS	Copy of Louvers
132	14		411107.21	26211.03		Brick ACC	Steel of 1.0m Overhang
24	1		412235.80	25411.33	Double-Argon project	Copy of Limestone-Sand	Steel of 1.0m Overhang
7	0		412235.80	25411.33	Double-Argon project	Copy of Limestone-Sand	Wood of 1.0m Overhang
17	0		412263.78	25411.19	Double-Argon project	Limestone	Wood of 1.0m Overhang
63	3		412263.78	25411.19	Double-Argon project	Limestone	Steel of 1.0m Overhang
120	10		413098.67	26205.36		Limestone	Steel of 1.0m Overhang
2	0		413098.67	26205.36		Limestone	Wood of 1.0m Overhang
149	21		413182.11	25376.24	Double-Argon project	Fc	Steel of 1.0m Overhang
77	4		413182.11	25376.24	Double-Argon project	Fc	Wood of 1.0m Overhang
22	1		413284.55	26205.17		Copy of Limestone-Sand	Wood of 1.0m Overhang
87	5		413284.55	26205.17		Copy of Limestone-Sand	Steel of 1.0m Overhang
0	0		414271.41	26168.54		Fc	Steel of 1.0m Overhang
51	2		414271.41	26168.54		Fc	Wood of 1.0m Overhang
85	5		414344.42	25426.64	Double-Argon project	ETICS	Wood of 1.0m Overhang
62	3		414344.42	25426.64	Double-Argon project	ETICS	Steel of 1.0m Overhang
95	6		415239.23	26221.01		ETICS	Steel of 1.0m Overhang
37	2		415239.23	26221.01		ETICS	Wood of 1.0m Overhang

Edit Visualise Heating design Cooling design Simulation CFD Daylighting Cost and Carbon

Untitled, Building 2

Analysis Summary Parametric Optimisation + UA/SA Data Visualisation

Status ▾

Iteration	Generation	Status ▾	Cooling (Electric) (kWh)	Glazing gain (kWh)	Glazing template	External wall construction	Local shading type
28	1		405978.60	16779.41	Low-e Argon	ETICS	Wood of 1.0m Overhang
40	2		406420.48	18430.08	Low-e Air	Limestone	Steel of 1.0m Overhang
6	0		406420.48	18430.08	Low-e Air	Limestone	Wood of 1.0m Overhang
49	2		406437.49	18430.13	Low-e Air	Copy of Limestone-Sand	Wood of 1.0m Overhang
111	8		406546.83	24353.33		Brick ACC	Copy of Louvers
114	9		407119.23	18406.11	Low-e Air	Fc	Wood of 1.0m Overhang
122	10		407311.87	23560.43	Double-Argon project	Copy of Limestone-Sand	Copy of Louvers
126	11		407326.29	23560.29	Double-Argon project	Limestone	Copy of Louvers
23	1		408251.78	18442.43	Low-e Air	ETICS	Steel of 1.0m Overhang
1	0		408251.78	18442.43	Low-e Air	ETICS	Wood of 1.0m Overhang
89	5		408503.91	24346.06		Copy of Limestone-Sand	Copy of Louvers
38	2		408516.24	24345.92		Limestone	Copy of Louvers
100	6		408711.52	23524.34	Double-Argon project	Fc	Copy of Louvers
19	1		409678.00	24308.64		Fc	Copy of Louvers
144	19		409685.12	23574.19	Double-Argon project	ETICS	Copy of Louvers
42	2		410277.37	25416.66	Double-Argon project	Brick ACC	Steel of 1.0m Overhang
79	4		410277.37	25416.66	Double-Argon project	Brick ACC	Wood of 1.0m Overhang
97	6		410694.13	24360.06		ETICS	Copy of Louvers
132	14		411107.21	26211.03		Brick ACC	Steel of 1.0m Overhang
24	1		412235.80	25411.33	Double-Argon project	Copy of Limestone-Sand	Steel of 1.0m Overhang
7	0		412235.80	25411.33	Double-Argon project	Copy of Limestone-Sand	Wood of 1.0m Overhang
17	0		412263.78	25411.19	Double-Argon project	Limestone	Wood of 1.0m Overhang
63	3		412263.78	25411.19	Double-Argon project	Limestone	Steel of 1.0m Overhang
120	10		413098.67	26205.36		Limestone	Steel of 1.0m Overhang
2	0		413098.67	26205.36		Limestone	Wood of 1.0m Overhang
149	21		413182.11	25376.24	Double-Argon project	Fc	Steel of 1.0m Overhang
77	4		413182.11	25376.24	Double-Argon project	Fc	Wood of 1.0m Overhang

Edit Visualise Heating design Cooling design Simulation CFD Daylighting Cost and Carbon

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