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Analysis of window parameters and shading strategies in buildings in hyper-arid desert coastal climates: a case study for Kuwait

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Abstract
The construction sector faces numerous environmental issues, such as natural resource depletion, greenhouse gas (GHG) emissions, air pollution, and human-caused global warming, to mention a few. The energy consumption in the building sector in Kuwait is increasing due to its hot climate, in which a large part of Kuwait's total electricity consumption comes from residential buildings due to its high energy usage per capita and its hot climate. The main reason for this consumption is the refrigeration loads and air conditioning. This study investigates the impacts of window parameters (window-to-wall ratio (WWR) and glazing type), shading devices, and building orientation on the energy and daylighting performance of residential buildings in Kuwait. The research addresses the challenge of achieving energy-efficient and sustainable designs in hot climates where cooling demands are significant. Using DesignBuilder software, this research analysed annual energy consumption, energy use intensity, and daylight factors (average and maximum) to evaluate these parameters. Results reveal that Dbl Clr 6mm/6mm Air as glazing type, a 1 m projection overhang as a shading device, and 20% of WWR reduced annual energy consumption by 16.55% while maintaining adequate daylight levels. Additionally, a comparative analysis of a modified design versus a base model demonstrated significant energy savings in both Kuwait City and Sabah Al Ahmad. These findings provide actionable insights for architects and policymakers aiming to enhance building sustainability in the Cooperation Council for the Arab States of the Gulf (GCC) region.

Keywords Green building · Window-to-wall ratio (WWR) · Kuwait · GCC · Design builder

1 Introduction

Buildings consume a substantial amount of energy in hot areas, primarily due to cooling demands. Improving energy efficiency is not only an economic need, but also a critical step towards sustainability, decreasing demand on energy supplies and maintaining thermal comfort under adverse weather situations [1]. Kuwait is regarded as one of the wealthiest countries Worldwide, but it also uses a lot of energy [2]. Kuwait's energy consumption per capita is estimated to be 17.815 MWh/person/year in 2022 (a 20% growth from 2000–2022), placing it fifth in the world, according to a report by the International Energy Agency (IEA) [3]. About 48.5% of Kuwait's total final electrical consumption in 2022 will come from residential buildings, making them the sector that uses the most electricity [3]. Furthermore, given Kuwait's

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historical population growth and an infusion of overseas workers, the building sector is under enormous pressure to develop quickly while meeting predicted energy consumption. As a result, there is a greater emphasis on implementing energy-saving methods, legislation, and research projects to improve the energy efficiency of residential and commercial buildings. This requirement has been accompanied by research activities encompassing different aspects of energy efficiency, including demand-side management measures, low-energy building systems, building regulations, urban-scale retrofits, and passive design methods [4].

Social development and the national economy are mainly based on the construction industry because it facilitates the required buildings and infrastructure for humankind [5]. However, the construction industry has numerous environmental problems: the depletion of natural resources, greenhouse gas (GHG) emissions, air pollution, and human-caused global warming, to mention a few [6, 7]. This industry consumes 40% of the total raw materials and emits 50% of the global GHG emissions [8]. Climate change and the energy crisis are increasing concerns about the implementation of sustainability globally. The internal environment and climate of the building sector are closely associated with the productivity and health of its occupants. So, the focus on the development of green buildings is an increasing research trend [9], which aims to minimise the negative environmental impacts of the operation and construction of any buildings [10]. The benefits of such a recently emerged innovative concept are to mitigate climate change, reduce negative environmental effects, and improve the sustainable design of buildings [11]. On the other hand, the main barriers to using sustainable building materials for sustainable construction in Kuwait are a lack of understanding, competent employees and the lack of green building materials (GBM) adoption regulations, the absence of government support/incentives, and the rigid mentality of the general public to any major change [12].

The problems of the construction sector are rapidly increasing in the Middle Eastern countries. Hence, there is an urgent need to improve this sector to reach the same level as in developed countries. Kuwait is one such country in the Middle East that is struggling to reduce construction challenges. The sector therein faces many challenges in terms of performance and productivity [13]. Note that Kuwait's climate is considered a hyper-arid desert coastal climate [14], where the energy consumption from the building sector is increasing due to its hot climate. A large part of the country's total electricity consumption comes from the residential building sector due to its high energy usage per capita. Note that the main reason for this high energy consumption is mainly the refrigeration loads and the large number of air conditioning systems used, which consists of 57% of the peak consumer demand [15]. According to Kuwait Energy Outlook 2019 [16], the electrical demand for air conditioning (AC) systems was over 70%, while the yearly electricity consumption in residential buildings in Kuwait was more than 45% [16]. In Europe, the same quantity of energy is used to heat buildings, and thus the European governments have implemented legislation to reduce building energy usage by 20% in 2020 and 50% in 2050. Windows contribute significantly towards a building's energy loss/gain. Active and passive strategies can be used to reduce energy loss. The Kuwait Green Building Council (KGBC) [17] has introduced the application of insulating material and enhanced air-conditioning ducts. Building efficiency has a direct connection with window size and aspect ratio when it comes to building design. Windows allow the entry of sunlight into buildings and offer escape and visual access to the outside during a fire. They also allow the entry of air and temperature control through the use of outside air. Contemporary cities employ windows as the foremost architecture of skyscrapers due to visual contact with the surroundings and the aesthetic look of buildings within the urban landscape. Windows and window frames are responsible for over 60% of building energy loss in hot-arid climates, whereas heat loss and solar radiation gain through windows are responsible for approximately 40% of cooling load [18].

Several studies have examined the elements that influence building energy performance, some of which may be modified. Examples include the building's façade, technological systems, shape, and orientation. One of the most important factors influencing building energy performance is the influence of shading, whether active or passive, on heat input via windows. Taking into account the positioning of the shading systems, exterior shading was observed to function better than interior systems. An appropriate window-to-wall ratio might potentially cut energy usage. However, the relevance of daylighting and the building's architecture may influence the factor of heat gain [19]. Recent advances in shading devices, orientation strategies, and window technology provide potential to enhance building efficiency [20, 21]; however, their effectiveness in arid climates remains underexplored. Furthermore, their usefulness in dry conditions is yet uncertain. Previous studies have generally examined individual design factors without considering their overall influence on energy usage and daylighting performance. Furthermore, there are few comparative assessments of changed compared to unmodified building designs in various areas around Kuwait. This study aims to address this gap by examining the impacts of window size, glazing type, shading devices, and orientation on yearly energy consumption, energy usage intensity, and daylight variables. This research, which makes use of current modeling tools and methodology, gives practical insights for constructing energy-efficient and sustainable buildings in Kuwait and the GCC. For this, particularly, the impacts of window designs on energy performance are analysed using the commercially available building design software, DesignBuilder.

The efficiency of green buildings is based on the location of the building, renovation of different new construction types, design of the green building concept, energy efficiency, construction materials, green building methods and appropriate quality standards, sources of alternative energies, and water conservation [22, 23]. The overall climate of the Gulf region is classified as a hyper-arid desert coastal climate. Notably, the performance of any green buildings is determined by the climate in which they are located. For instance, buildings in hot climates consume more energy, mainly for the cooling process. According to Alsulaili et al. [24], green buildings in Kuwait could reduce the energy consumption in the cooling process by 10,000 kWh as in July (one of the hottest months in Kuwait) compared to conventional buildings, as shown in Fig. 1. Green materials, essential components of the green building concept in the construction industry, are important to improve building performance.

According to Meena et al. [25], green buildings can save 20–30% and 40–50% in water and energy, respectively, compared to traditional buildings. Also, 8% of air quality can be improved thanks to green buildings with further protection of the ecosystem and biodiversity. According to Xiong et al. [26], outdoor air pollution, insufficient ventilation, and indoor sources all have an impact on indoor air quality. Some of the sources of contaminants that might occasionally cause indoor air quality to be noticeably worse than outdoor air includes particulate matter, mould, and chemicals emitted from synthetic textiles, furnishings, paints, and household goods [25]. On the other hand, green building design costs are 32% more than conventional building design, while fittings and finishing costs are 32% and 28% more, respectively [27]. Economically, the overall cost of green building construction is 280–410 dollars less than that of traditional structures. Note that the building design impacts the energy performance of any building. For example, Watfa et al. [28] investigated the influence of building design on energy consumption in Abu Dhabi. The research was performed for August as it is the hottest month in the UAE when the orientation angle of the building changes from 0° (north) to 180° (south). The total monthly energy consumption and the peak energy consumption decreased by 1.27% and 8.0%, respectively. Also, the energy consumption reduces by 0.5% when the window-to-wall ratio reduces by 15%. Window redistribution to cover various locations of elevations while retaining windows-to-wall areas constantly lowered the building's total energy usage.

Aldabesh et al. [29] found that reflectance of the glazing surface (Double-glazing system) is more successful than glazing thickness (Triple-glazing) in lowering cooling load and solar gains (SHGC > U-value). When the conduction gains or heat transfer owing to the temperature differential between exterior and internal glazing sides, were assessed, the findings showed that the overhangs reversed 86% of the decreased impact from the reflecting double-glazing system. This is because, for the identical glazing specifications, the double-glazing system lowered conduction gains by 20.1%, but the combination of double-glazing and overhang reduced them only by 2.8%. Triple glazing (Triple-glazing) was the most efficient in lowering conduction gains (43.7% reduction) because of its higher glazing thickness. In general, the double-glazing system was chosen as the most effective technique for reducing the yearly cooling demand. The conduction gains represent the elements' thermal performance (SHGC and U-values) in relation to climatic variables (relative humidity and outside temperature).

Elnabawi et al. [30] investigated whether low-emissivity (low-e) glazing with clear glass may reduce solar gain while preserving daylight. Managing the inside temperature increases is critical for decreasing cooling demand. A large share

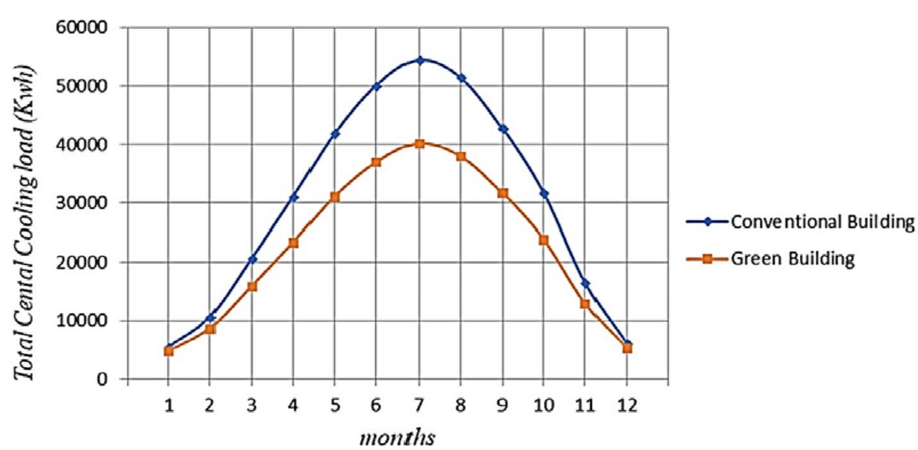


Fig. 1 Comparison between conventional and green buildings in terms of monthly central cooling load in Kuwait from January to December [24]

of heat increases were caused by equipment and lighting. Ventilative cooling may be excellent in transferring heat in arid climates. Almufarrej and Erfani [31] evaluated three early design factors and analysed their effect on annual energy consumption and peak values, simulated under Kuwaiti climatic conditions. In this simulation, the buildings' Window to wall ratio (WWR), orientation, and compactness are modified, and it was discovered that buildings with longer spans facing North are the most energy efficient. Designers' judgments on building WWR have the ability to save up to 40% on net energy use. Furthermore, using the peak load estimate, the HVAC system capacity may be lowered by 30%. The highest variances related to changes in compactness or orientation are less than 5% for the various WWRs examined. Access to such facts is critical for directing designers and making early design decisions relevant to those variables for buildings in Kuwait. Climate features are an important component in understanding the thermal behaviour of buildings.

Kulaib et al. [32] clarified that the technique of energy management in buildings with AC in Kuwait has become complex due to excessive energy consumption in the building sector. The influence of various operational factors, both theoretically and empirically, on the decrease in AC energy consumption was investigated. The use of exterior shading screens, external curtains, and the planting of shade-giving plants or bushes near windows would be a highly efficient technique of minimising heat input in buildings under humid and hot climatic conditions while also conserving electricity. Furthermore, employing fewer glass surfaces in exterior walls would reduce the energy consumption of the building, as would the use of small windows with correct shading. Using double-glazed windows, light-coloured walls and roofs, and insulation in walls and roofs might reduce building electricity usage by up to 45%. Alaidroos and Krarti [33] confirmed that shade is one of the most common and significant ideas in literature for reducing solar gains in hot regions, which may be implemented inside or externally. Evola et al. [34] also emphasised the necessity of using appropriate shading systems in highly glazed office buildings, as it greatly decreases the energy required for space cooling and increases thermal comfort while minimising interior overheating. Furthermore, interior daylight illuminance remains at appropriate levels to support visual tasks; illuminance distribution is enhanced, and glare danger is significantly decreased. Nevertheless, the efficiency of each shading technique varies. First, inside blinds should be avoided since they provide far less comfort than exterior blinds. The results show that exterior solar control films operate well in all orientations; however, external (roller) blinds are highly successful on south-facing glazed façades but perform worse than solar control films in west-facing glazed façades. Despite these findings, significant restrictions remain. Many studies concentrate on a single parameter rather than investigating the whole influence of window size, glazing type, shading, and orientation. Furthermore, previous research frequently ignores the unique characteristics of hyper-arid desert countries like Kuwait, where strong solar radiation and high temperatures impair building performance. To fill these gaps, this study examines the impact of window dimensions and shading tactics on both energy efficiency and daylighting performance in residential structures. By comparing results from two metropolitan areas (Kuwait City and Sabah Al Ahmad), this study gives specific insights on optimizing window design for sustainable building in Kuwait's climate.

2 Methodology

This research is a quantitative method. Buildings in Kuwait have a large heat gain resulting from the natural Kuwaiti climate, which poses the question, "How can modifying window design impact building energy performance in the standard Kuwait building design?". The first step in this research is to identify the research question, which is the improvement of the building energy performance by enhancing their designs. Studying the design of vernacular architecture in Kuwait allows for identifying the key issues related to buildings. Then, a case study is selected for the model based on commercially available software, DesignBuilder [35]. The parameters studied were glazing types, window size, and shading devices. Figure 2 illustrates the main framework of this research.

The building selected is located in Kuwait with geographic coordinates are 29.3759° N of Latitude, 47.9774° E of Longitude, and 55 m Elevation. The second location for the building was in Sabah Al Ahmad with the geographic coordinates of 28.928676° N of Latitude, 47.548753° E of Longitude, and 173 m elevation. The maximum and minimum air temperature in Kuwait was 45.37 °C in August and 7.75 °C in January, as shown in Fig. 3. Fig. 4 illustrates the solar resource map that provides the estimated solar energy summary available for power generation and other applications of energy. Also, it presents the average daily/yearly sum of the global horizontal irradiation (GHI) covering from 1990 to 2018.

A typical residential building in Kuwait was selected for this study, representing common construction practices and energy consumption patterns. The building consists of one floor with a total floor area of 221.5 m^2, featuring a reinforced concrete structure with insulated walls and a flat roof, as illustrated in Table 1. The HVAC system used in the building includes air-colled chiller. The building under consideration contains three master bedrooms, a living room, a kitchen, a

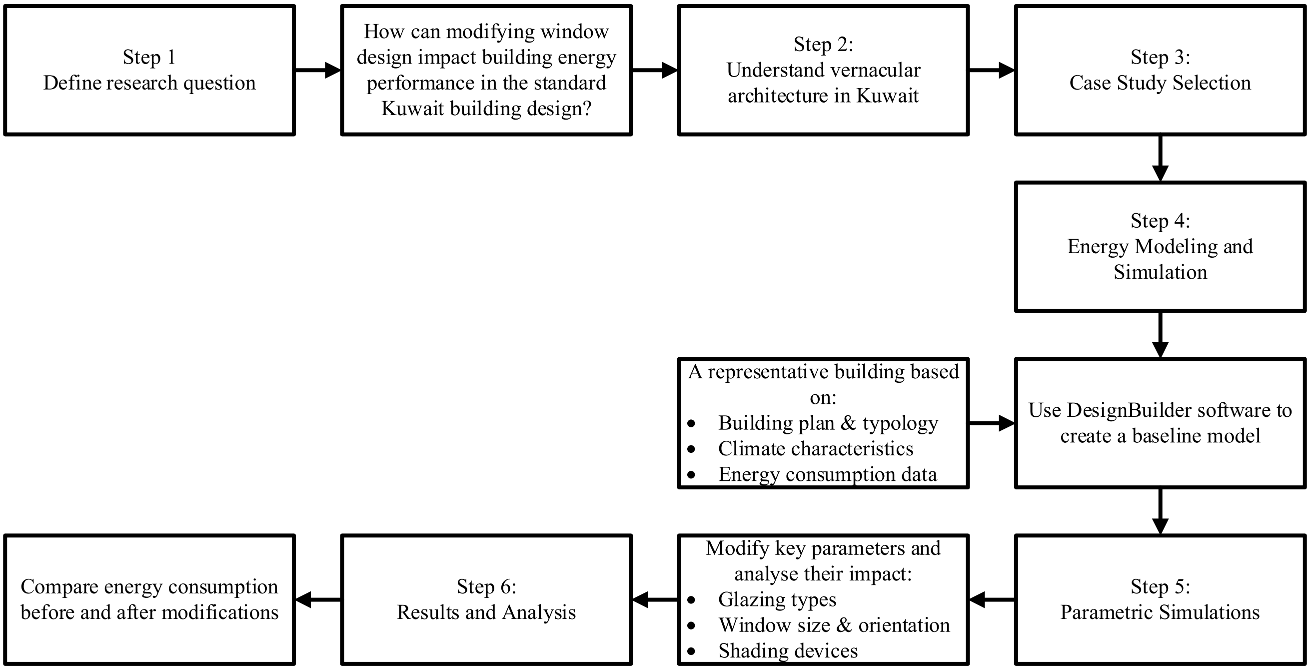


Fig. 2 Framework of research

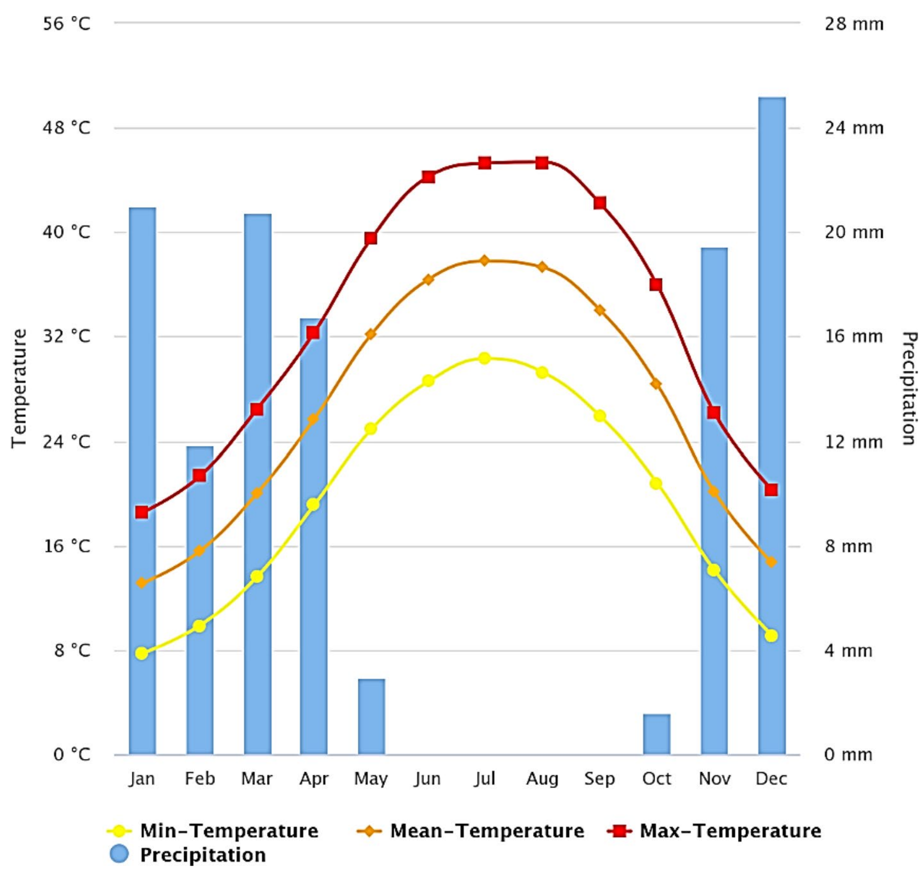
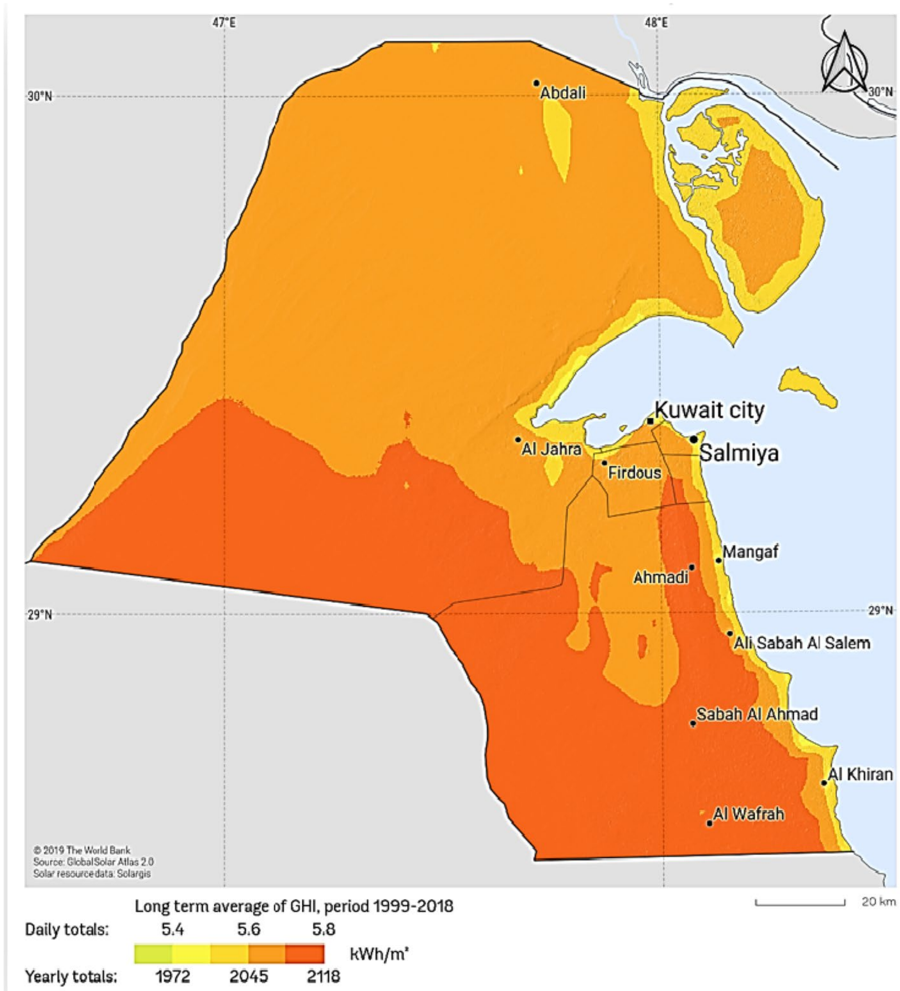


Fig. 3 Min, Max, and mean temperature and participants in Kuwait (1990–2020) [36]

guest room, and a lavatory. Figure 5 shows the building plan simulated by AutoCAD and then by DesignBuilder. DesignBuilder is a software tool used for simulating the energy performance of buildings that provides a range of features and tools to help users optimise building energy efficiency and sustainability, including energy modelling, building physics

Fig. 4 Global horizontal irradiation of Kuwait [37]



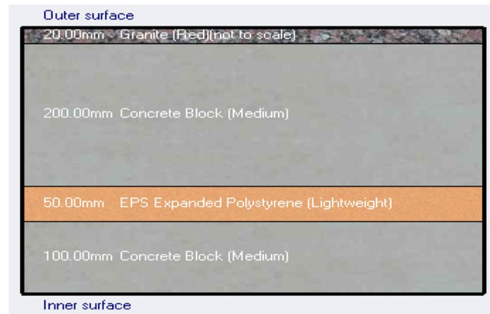
simulations, and renewable energy analysis. It is a popular choice for architects, engineers, and building designers, and that has a variety of applications, including LEED certification, energy audits, and building performance optimisation [38]. The Sun path diagram aids in visualising the courses travelled by the Sun as it passes through the sky during the year, as shown in Fig. 6. After that, energy efficiency measures were applied to this building and optimised the design of the windows. The building model was created using DesignBuilder, where the geometry, construction materials, and thermal characteristics were accurately established. The weather data for Kuwait City was uploaded using an EnergyPlus Weather (EPW) file, ensuring that the simulation scenarios accurately represent actual climatic patterns such as solar radiation, harsh temperatures, and little rainfall. Windows were modelled with various glazing types, sizes, and shading arrangements to determine their impact on energy consumption and daylighting performance.

The selection of simulation parameters was based on previous studies, building codes, and Kuwait's climatic conditions. The key parameters analysed include window size, glazing type, shading devices, and orientation. The WWR was varied at 40%, 35%, 20%, 15%, and 10% to analyse the trade-off between daylighting and cooling loads. Eight glazing scenarios were tested, which are single clear glass (baseline), Double clear glazing (Dbl Clr) 6mm/6mm Air, Dbl Clr 3mm/6mm Air, Dbl Clr 3mm/6mm Arg, Dbl Blue 6mm/6mm Air, Triple clear glazing (Trp Clr) 3mm/6mm Air, Trp Clr 3mm/6mm Arg, and Thermochromic Glazing. These were chosen based on their ability to reduce solar heat gain while maintaining adequate daylight levels.

Regarding shading devices, external horizontal overhangs, vertical fins, and louvre were simulated with different lengths of projection to determine their effectiveness in reducing cooling demand. The building was rotated to different angles, assessing how orientation impacts solar heat gain and daylight distribution throughout the year.

Energy efficiency measures encompass a range of actions and technologies aimed at decreasing the amount of energy required for specific tasks or desired outcomes. These measures include the installation of high-efficiency

Table 1 Characteristics of the existing building design plan

<table>
<tr><th>Characteristics</th><th>Description</th></tr>
<tr><td>Number of stories</td><td>One floor</td></tr>
<tr><td>Total height</td><td>3.5 m</td></tr>
<tr><td>Total area</td><td>221.5 m^2</td></tr>
<tr><td>WWR</td><td>40%</td></tr>
<tr><td>Window height</td><td>1.5 m</td></tr>
<tr><td>Window shading</td><td>No shading</td></tr>
<tr><td>Glazing type</td><td>Clear glazing</td></tr>
<tr><td>Type of glass</td><td>Single clear 6 mm (Sgl Clr 6mm) (SG)</td></tr>
<tr><td>External wall construction</td><td>
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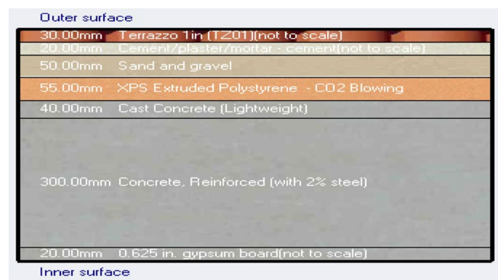
<tr><td>Roof construction</td><td>
</td></tr>
<tr><td>HVAC system</td><td>Air-cooled chiller</td></tr>
</table>

lighting, heating, ventilation, and air conditioning (HVAC) systems, as well as energy-efficient appliances. Improving building insulation and implementing air sealing techniques are also effective measures. Additionally, energy-efficient building design strategies like passive solar heating and cooling can be employed. Utilising energy management systems enables the optimisation of energy usage and the reduction of waste. Regular maintenance and tune-ups of equipment ensure optimal efficiency. Promoting energy-saving behaviours among occupants, such as turning off lights and electronics when not in use, are another important measure. Furthermore, installing renewable energy systems like solar panels or wind turbines offers the opportunity to offset energy consumption with clean and sustainable alternatives. These energy efficiency measures collectively contribute to reducing energy consumption and promoting sustainable practices [39]. Implementing energy efficiency measures can result in significant cost savings, improved comfort and productivity, and reduced environmental impact.

Simulations were conducted in DesignBuilder to evaluate the performance metrics, such as Annual Energy Consumption (kWh), Energy Use Intensity (kWh/m^2), Average Daylight Factor (%), Maximum Daylight Factor (%), and Maximum Daylight Factor (%). Annual Energy Consumption (kWh) measures the total electricity used for cooling, lighting, and HVAC systems. On the other hand, energy Use Intensity (kWh/m^2) assesses the energy consumption per unit area, allowing for comparisons between different configurations. Regarding to average Daylight Factor (%), it represents the overall daylight availability inside the building. Additionally, the maximum Daylight Factor (%) identifies areas with excessive daylight exposure, which can lead to glare and thermal discomfort. Each simulation was run for a full year, using an hourly timestep to capture seasonal variations. The results were then compared across different window configurations to identify the optimal combination for minimising energy consumption while maximising daylight efficiency.

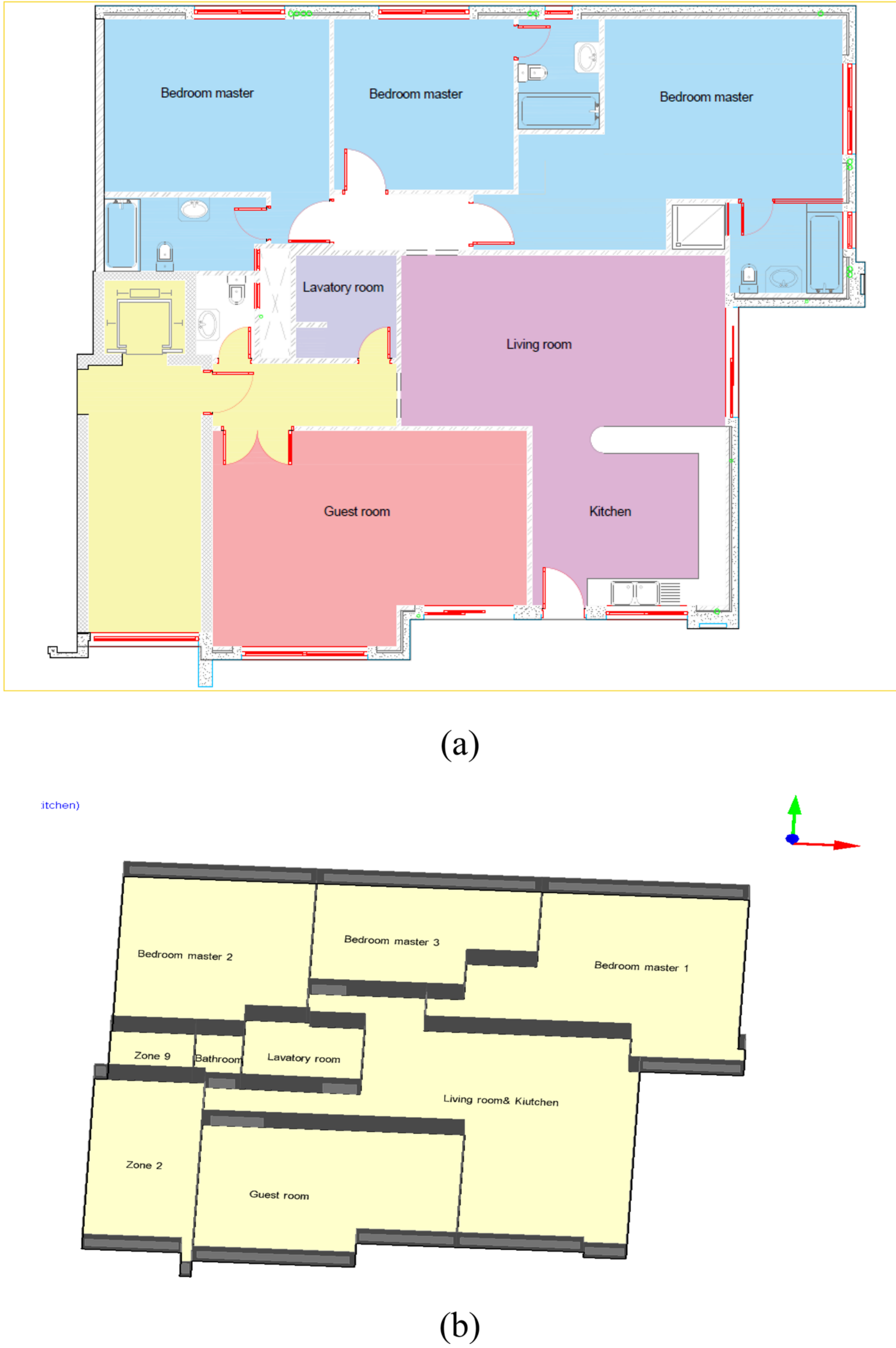
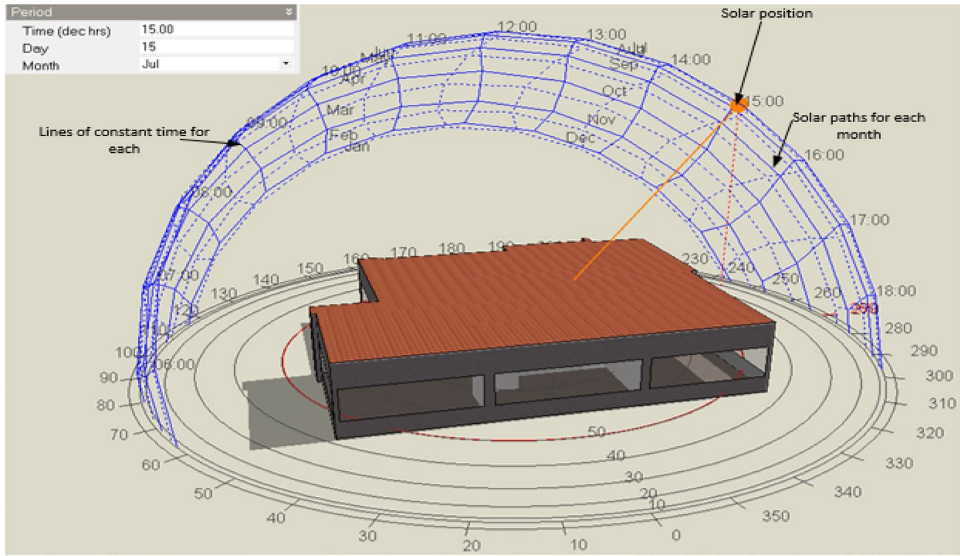


Fig. 5 Existing building design plan: **a** by AutoCAD; **b** by DesignBuilder

To validate the simulation results, the DesignBuilder model's yearly consumption of energy was compared to real-world data from the selected building. The overall electrical consumption reflected on the building's utility bills served as a reference. To clarify, energy consumption in Kuwait is billed and collected annually rather than monthly, making monthly comparisons inaccurate. In a given year, the total energy consumption for the validation case is 49,589,8 kWh. In the modelling scenario, the total energy consumption is approximately 50,489.77 kWh. However, a significant problem in the validation process was a lack of specific occupant schedule data, which influences internal heat gains, illumination, and HVAC consumption. To reduce this uncertainty, conventional occupancy profiles from ASHRAE and local energy standards were used. The results of the simulation were then compared to previous studies on residence energy consumption in Kuwait to confirm that they reflected normal consumption patterns in similar climates. Although some variances occur due to changes in occupant behaviour and HVAC system efficiency, the validation procedure indicates that the model accurately represents yearly energy performance under regular

Fig. 6 The Sun path diagram



operational conditions. Future studies might enhance validation by combining real-time monitoring with field data to optimise occupant behaviour inputs.

3 Results and discussion

The existing building was developed in terms of window size, glazing type, and adding shading devices. The Annual Energy Consumption and Energy Use Intensity (Electricity) are the main factors that were taken into account to select the modified design for each term. The basic design was fixed and changes were made each time for the size of the windows, the type of glass, and the shading devices. After that, the modified design for each term is selected for developing the basic design.

3.1 Window size

According to Pathirana et al. [40], the WWR is an important factor to consider when designing energy-efficient buildings. It refers to the ratio of window area to wall area in a building's envelope. In general, a higher WWR means more natural light and views but also more heat gain in the summer and heat loss in the winter. In this study, the WWR of the base design is 40%, with 50,489.77 kWh of Annual Energy Consumption. When the WWR is 20%, the Annual Energy Consumption decreases by around 11.4% compared to when the WWR is 40%. Similarly, when the WWR is 10%, the Annual Energy Consumption drops by approximately 17.1% compared to the same reference value of 40% WWR, as shown in Fig. 7.

Also, the Energy Use intensities of S.4 and S.6 were 402.96 kWh/m^2 and 377.27 kWh/m^2, respectively. These results indicate that the WWR should be less than 40% in warm climates, in which 10% of WWR can reduce the daylight entering the building, so 20% is the modified design. Table 2 illustrates the differences in window sizes in the basic design. Also, Foroughi et al. [41] mentioned that to optimise energy efficiency in buildings, it is recommended to maintain a WWR of less than 40% in hot climates and less than 25% in cold climates by using a parametric design. This helps to minimise unwanted solar heat gain or heat loss through the windows, which can put strains on HVAC systems. Alwetaishi and Benjeddou [42] confirmed that the WWR should be at least 20% to give adequate daylight for the indoor environment, particularly in buildings that demand daily activity. If the WWR exceeds 20% in a hot climate, it will just increase the cooling demand and have no meaningful effect on the daylight factor. As a result, it is not suggested to elevate the WWR by more than 20%, especially in the case of the north orientation to have a better view of the outdoors.

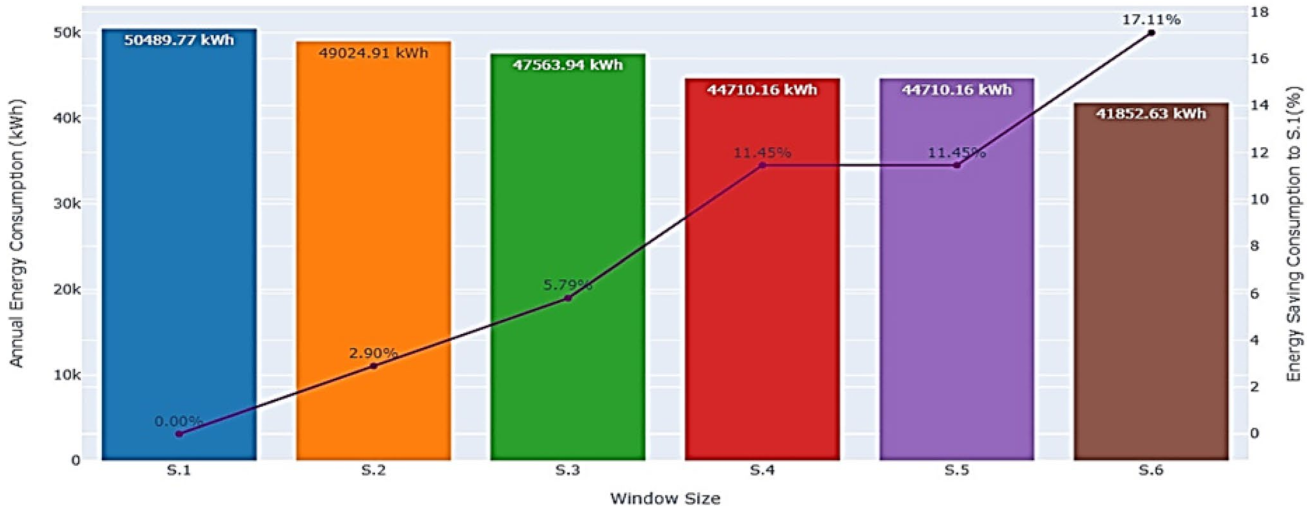


Fig. 7 Comparison of window sizes (S.1: 40%; S.2: 35%; S.3: 30%; S.4: 20%; S.5: 15%; S.6: 10%); Y-axis (right side): energy consumption savings based on S.1; Y-axis (left side): annual energy consumption of each scenarios

Table 2 The differences in window sizes in the basic design

	S.1	S.2	S.3	S.4	S.5	S.6
WWR	40%	35%	30%	20%	15%	10%
Glazing type	Clear glazing	Clear glazing	Clear glazing	Clear glazing	Clear glazing	Clear glazing
Type of glass	SGL CLR 6MM	SGL CLR 6MM	SGL CLR 6MM	SGL CLR 6MM	SGL CLR 6MM	SGL CLR 6MM
Shading device	No-shading	No-shading	No-shading	No-shading	No-shading	No-shading
U-value (W/m^2 K)	6.121	6.121	6.121	6.121	6.121	6.121
Solar heat gain coefficient (SHGC)	0.810	0.810	0.810	0.810	0.810	0.810
Light transmission	0.881	0.881	0.881	0.881	0.881	0.881
Annual energy consumption (kWh)	50,489.77	49,024.91	47,563.94	44,710.16	43,244.54	41,852.63
Energy use intensity (electricity) (kWh/m^2)	454.92	441.74	428.61	402.96	389.78	377.27

3.2 Glazing type

The standard U-values on windows measure the rate and heat loss at which it occurs. It is a measure of the rate of heat transfer through a structure (such as a wall or roof) divided by the difference in temperature across that structure. The overall performance in preventing heat and keeping it from leaking to the outside is indicated by the U-values, which are expressed in W/m^2 K. The lower the U-value, the better the window's thermal performance. According to Akrama et al. [43], the U-value of single glazing is very high compared with other types of glazing, as shown in Fig. 8. For instance, double glazing has a low U-value which means the low solar heat entering during the widow. The double and triple glazing studied impacts on the basic design in terms of Annual Energy Consumption. According to Jaffar et al. [44], the single glazing system is the most commonly used in residential buildings in Kuwait.

There are eight types of window glazing studied in this research, as shown in Table 3. When comparing G.2, G.6, and G.8 with S.1, 4.13%, 5.45%, and 9.06% of Annual Energy Consumption decreased in the cases of G.2, G.6, and G.8, respectively, as shown in Fig. 9. In these cases, the U-values are 3.094 W/m^2 K, 2.178 W/m^2 K, and 2.130 W/m^2 K of Dbl Clr 6mm/6mm Air, Trp Clr 3mm/6mm Air, and Thermochromic Glazing, respectively. These values are lower than the U-value of Sgl Clr 6mm, about 46.5%, 62.3%, and 63.1%, respectively. In terms of solar heat gain coefficient (SHGC), the SHGC of Dbl Clr, Trp Clr, and Thermochromic Glazing are lower than Sgl Clr by approximately 14.5%, 16.7%, and 30.5%, respectively. However, the main drawback of high glazing, such as triple glazing, is the decrease in natural daylight. In terms of Thermochromic Glazing, its drawback is very high cost. The modified type of glazing window is Dbl Clr 6mm/6mm Air. Mahmoud [45] studied the effect of several glazing types with varying window orientations

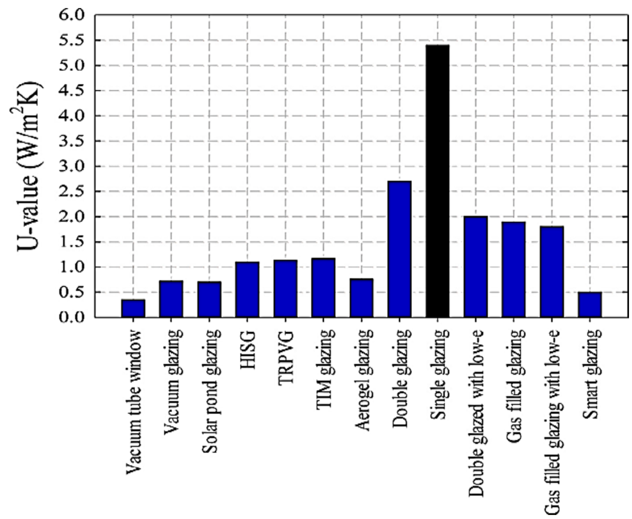


Fig. 8 Windows with several functions and great thermal resistance [43]

and WWR (10% and 20%) on energy consumption in a typical room in an office building located in the hot climate of Aswan, Egypt. Single clear glasses with thicknesses of 3 and 6 mm, as well as 6 mm double glass, were tested with filling choices of air, argon, and nano aerogel. Compared to 3mm single clear glass, double glazing filled with nanogel and argon with WWR = 10% had the greatest results, saving 12.71%, 3.66%, 4.18%, and 6.51% for West, North, East, and South orientations, respectively. According to Walid Yehia AbdelHAdy El-Eshmawy et al. [46], when comparing single clear, double clear, and triple clear glazing, single clear is the poorest, followed by double clear and finally triple clear, but the difference between the two is not significant. These results confirmed that the Double Clear 6mm/6mm Air glazing type achieved the best overall energy efficiency, daylighting performance, and cost-effectiveness. It reduces cooling loads, improves indoor thermal comfort, and ensures enough daylight penetration without inappropriate glare. It provides much higher insulation than single glazing. However, triple glazing and advanced coatings are still more economical and practical for Kuwait's environment.

3.3 Shading device and orientation

The tilted façade' self-shading effect should be credited with improving thermal performance and lowering cooling loads. The tilted facade system functions as an integrated solar shading system, since the outward inclined façade conceals the sun, reducing heat gain from the sun and, as a result, cooling load, similar to overhang shading. The cooling demand lowers as the angle of tilt increases because of less solar energy transfer into the building during the summer months. The heating load has the reverse effect, with higher heating loads with the tilt angle increases. Although the additional heating load is undesirable, the general cooling and heating demand reduces as the tilt angle increases. This occurs due to the predominant cooling tendency of architecture in hot climates. There are more chilly days than heated days; therefore, increasing the angle of tilt is useful throughout the year. Actually, "cooling" would cost more than "heating". In places with hot summers and warm winters, the building's heating load is significantly lower than its cooling load [47]. In addition, shading devices are one of the most effective passive methods, as well as being simple and affordable to use. They regulate the amount of sunshine that reaches the area while preventing direct sunlight, which generates uncomfortable glare, and so decreasing the heat intake, giving the residents thermal comfort and energy savings [48, 49]. According to Koç and Kalfa [50], the shading devices could be of different types, such as Overhang, Horizontal Louvre, Vertical Louvre, and Side fans (Egg-crate), as shown in Fig. 10. The horizontal louvre has the lowest lighting and heating energy consumption. In this research, four scenarios of shading devices, namely SH.1–SH.9, have been employed in the basic design, as shown in Table 4. When comparing the SH.1, SH.2, SH.5, and SH.9 with S.1, 10.62%, 6.52%, 10.43%, and 8.29% of Annual Energy Consumption decreased in the cases of SH.1, SH.2, SH.5, and SH.9, respectively. Also, the Energy Use Intensity of SH.1, SH.2, SH.5, and SH.9 were 406.71 kWh/m^2, 425.34 kWh/m^2, 407.59 kWh/m^2, and 417.28 kWh/m^2, respectively. Louvre, with 0.5m projection + 0.5 Overhangs, has the lowest value of the Annual Energy Consumption. Chandrasekaran et al. [49] confirmed that in a humid and hot region, horizontal fins or overhangs of one meter can minimise heat input by 10–12% in all orientations.

Table 3 The differences in glazing type in the basic design

Code	G.1	G.2	G.3	G.4	G.5	G.6	G.7	G.8
WWR	40%	40%	40%	40%	40%	40%	40%	40%
Glazing type	Single glazing	Double glazing	Double glazing	Double glazing	Double glazing	Triple glazing	Triple glazing	Thermochromic glazing
Type of glass	Sgl clr 3mm	Dbl Clr 6mm/6mm Air	Dbl Clr 3mm/6mm Air	Dbl Clr 3mm/6mm Arg	Dbl Blue 6mm/6mm Air	Trp Clr 3mm/6mm Air	Trp Clr 3mm/6mm Arg	Thermochromic glazing
U-value (W/m^2 K)	6.257	3.094	2.761	2.596	3.157	2.178	1.635	2.130
SHGC	0.858	0.7	0.761	0.761	0.486	0.682	0.679	0.569
Light transmission	0.898	0.781	0.812	0.812	0.505	0.738	0.738	0.578
Annual energy consumption (kWh)	50,968.46	48,403.19	49,110.48	49,122.65	46,059.22	47,736.58	47,773.82	45,915.55
Energy use intensity (electricity) (kWh/m^2)	459.22	436.16	442.52	442.62	415.09	430.17	430.48	413.79
Average daylight factor %	10.0	9.778	8.876	8.876	5.147	7.941	7.491	5.494
Maximum daylight factor %	47.968	45.231	42.012	42.012	23.238	38.379	38.379	25.390

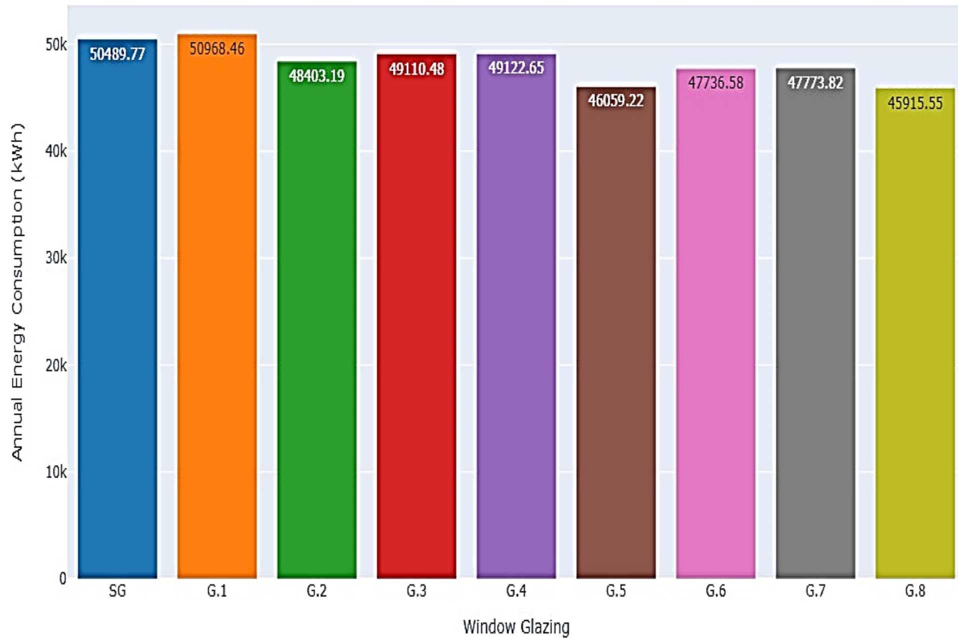


Fig. 9 Annual energy consumption (kWh) of the differences in glazing type; G1:Sgl clr 3mm; G2:Dbl Clr 6mm/6mm Air; G3:Dbl Clr 3mm/6mm Air; G4:Dbl Clr 3mm/6mm Arg; G5:Dbl Blue 6mm/6mm Air; G6:Trp Clr 3mm/6mm Air; G7:Trp Clr 3mm/6mm Arg; G8: thermochromic glazing

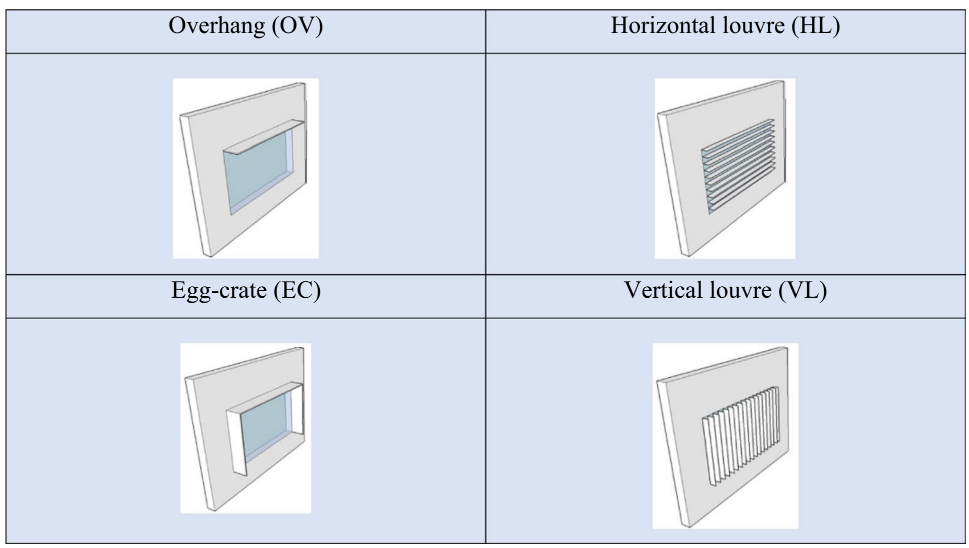


Fig. 10 The four shading devices adopted in this study; overhang, horizontal louvre, vertical louvre and egg-crate [50]

Alaidroos and Krarti [33] verified that WWR may be used to determine cost-effectiveness. The design of overhang is more effective for bigger windows, as demonstrated by a 1 m projection resulting in a maximum yearly decrease of 6.3% for a residence with 13% WWR.

In addition, Shaik et al. [51] examined the relevance of different window glass fenestration and overhang shading device diameters. The study's findings suggest that increasing the size of the window overhang reduces heat absorption in buildings. Masoud et al. [52] demonstrated that in hot climates, louvers, vertical and horizontal shades and daylight scattering screens are more suited to reducing glare while introducing less heat into the environment. Furthermore, it is preferable to select shades with varied depths that, while giving shade in the summer, do not prevent sunlight from entering during the cold seasons. However, this design can increase the glare interning the building, which leads to uncomfort for the occupants. In this case, 1 m Projection Overhang is the modified design in terms of reduced glare. In terms of the impact of the orientation of the building on the orientation of the glazing, it is low impact in terms the energy consumption. On the other hand, daylight is very impacted based on the orientation of the building, as shown in Table 5 (Fig. 11)

Table 4 The differences in the shading device in the basic design

Code	SH.1	SH.2	SH.3	SH.4	SH.5	SH.6	SH.7	SH.8	SH.9	SH.10
WWR	40%	40%	40%	40%	40%	40%	40%	40%	40%	40%
Glazing type	Clear glazing	Clear glazing	Clear glazing	Clear glazing	Clear glazing	Clear glazing	Clear glazing	Clear glazing	Clear glazing	Clear glazing
Type of glass	Sgl Clr 6mm	Sgl Clr 6mm	Sgl Clr 6mm	Sgl Clr 6mm	Sgl Clr 6mm	Sgl Clr 6mm	Sgl Clr 6mm	Sgl Clr 6mm	Sgl Clr 6mm	Sgl Clr 6mm
Shading device	Louvre + overhangs (0.5 m projection)	Overhang + side-fins (0.5 m projection)	Overhang + side-fins (1.0 m projection)	Louvre + overhangs (1 m projection)	1 m projection louver	0.5 m projection louver	1.5 m projection louver	0.5 m overhang	1 m overhang	1.5 m overhang
Annual energy consumption (kWh)	45,125.89	47,199.52	45,587.21	43,897.24	45,225.53	46,990.75	44,970.23	47,771.22	46,302.60	45,497.1
Energy use intensity (electricity) (kWh/m^2)	406.71	425.34	410.84	395.64	407.59	423.46	405.29	430.47	417.28	410.03
Average daylight factor %	3.983	3.247	3.71	1.38	3.014	5.611	2.424	7.006	5.172	4.013
Maximum daylight factor %	23.641	12.868	16.951	12.141	18.824	28.867	2.424	33.875	30.213	24.795

Table 5 The differences in the orientation in the modified design

Code	OR1	OR2	OR3	OR4
Orientation	45°	60°	180°	270°
WWR	20%	20%	20%	20%
Window type	Dbl Clr 6mm/6mm Air	Dbl Clr 6mm/6mm Air	Dbl Clr 6mm/6mm Air	Dbl Clr 6mm/6mm Air
Shading device	1 m overhang	1 m overhang	1 m overhang	1 m overhang
Annual energy consumption (kWh)	42,358.30	42,369.69	42,290.33	42,428.95
Energy use intensity (electricity) (kWh/m^2)	381.82	381.92	381.2	382.45
Average daylight factor %	2.585	2.642	2.621	2.631
Maximum daylight factor %	15.808	16.314	18.424	20.555

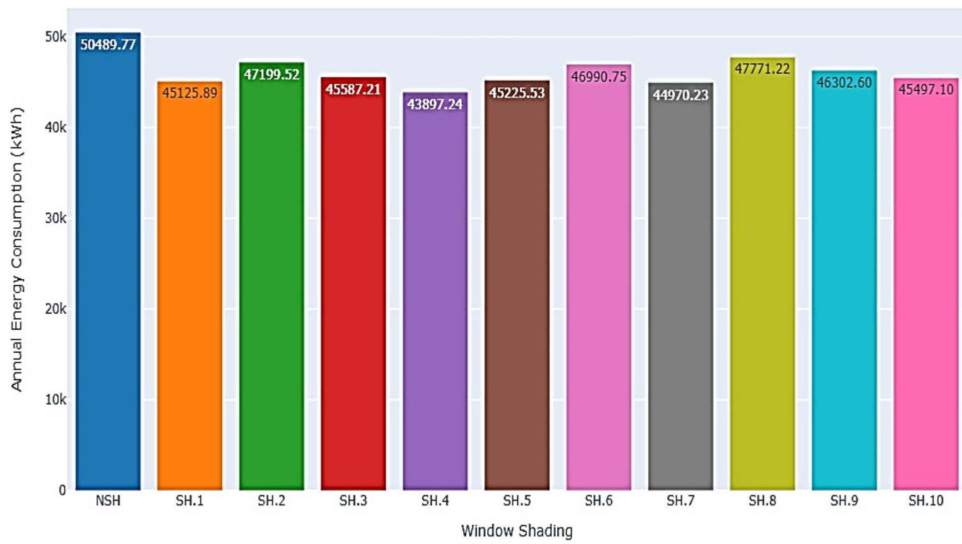


Fig. 11 Annual energy consumption (kWh) of the differences of shading device

4 Modified design

WWR and glazing type of the basic design were 40% and Sgl Clr 6mm, respectively. In terms of shading devices, there are not in the basic design. The basic design was developed by selecting the optimal parameters for WWR, glazing types, and shading devices in terms of reducing the Annual Energy Consumption. That means WWR became 20%, and the glazing type became Dbl Clr 6mm/6mm Air. In terms of the shading device, it became 1 m projection Overhang. The implementation of this design led to a notable reduction in Annual Energy Consumption, which decreased to 42,132.43 kWh, as shown in Table 6. Comparing this value to the Annual Energy Consumption of the basic design, the decrease amounted to a significant 16.55%.

The solar gains of the exterior window of the basic design were about 4970.27 kWh in August. Also, the total latent load of the basic design was 202.32 kWh in August, as shown in Figs. 12 and 13. These values are very high that increase the energy demand of the cooling process during the summer months in Kuwait. On the other hand, the solar gains of the exterior window of the modified design are 1178.49 kWh in August, as illustrated in Figs. 14 and 15. This value is decreased by about 76.3% compared with the solar gains of the exterior window of the basic design. When it comes to cooling requirements, the modified design necessitates roughly 35% less energy for cooling compared to the basic design. In February, the heating requirement was reduced by approximately 31.6% when comparing the modified design to the basic design.

In terms of the solar gains of the exterior window of the basic design during the year, it was about 54,847.56 kWh. Also, the zone sensible heating of the basic design was 1789.4 kWh, as shown in Figs. 16 and 17. On the other hand, the solar gain of the exterior window of the modified design is 13,266.39 kWh, as illustrated in Figs. 18 and 19. This value decreased by about 75.8% compared with the solar gains of the exterior window of the basic design. Also, in

Table 6 Building characteristics for the modified design

Code	Basic design		Modified design (Kuwait City)	
WWR	40%		20%	
Type of glass	Sgl Clr 6mm		Dbl Clr 6mm/6mm Air	
Shading device	No-shading device		1 m projection overhang	
U-value (W/m^2 K) of window	5.778		3.094	
	Kuwait City	Sabah Al Ahmad	Kuwait City	Sabah Al Ahmad
Latitude, longitude	29.3759°, 47.9774°	28.928676°, 47.548753°	29.3759°, 47.9774°	28.928676, 47.548753
SHGC	0.819	0.819	0.7	0.7
Light transmission	0.881	0.881	0.781	0.781
Annual energy consumption (kWh)	50,489.77	51,008.91	42,132.43	42,163.65
Annual energy consumption of cooling (kWh)	16,807.99	17,179.67	9448.46	9376.93
Annual Energy Consumption of heating (kWh)	7.35	5.53	0.23	0.02
Annual energy consumption of lighting (kWh)	25,297.75	5539.39	5539.39	5539.39
Energy use intensity (electricity) (kWh/m^2)	454.92	459.57	379.78	380.07
Cost (USD)	771,883.91	771,883.91	784,341.18	784,341.18

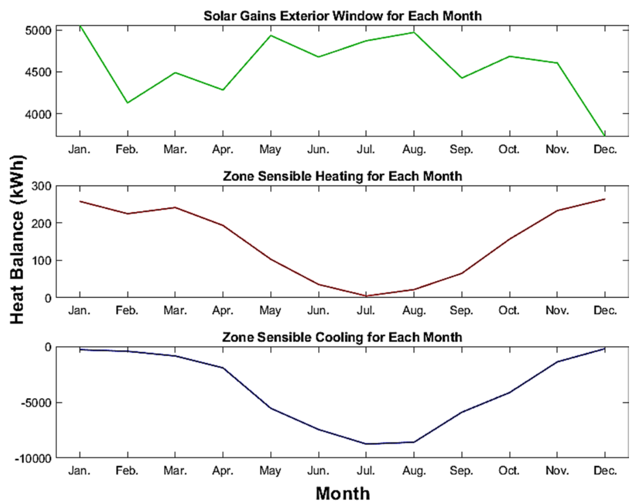


Fig. 12 Internal gains and solar for each month of the basic design in Kuwait City

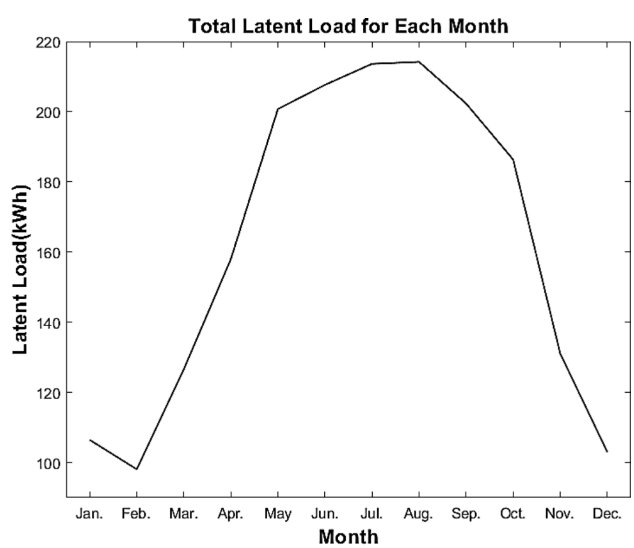


Fig. 13 Total latent load for each month of the basic design in Kuwait City

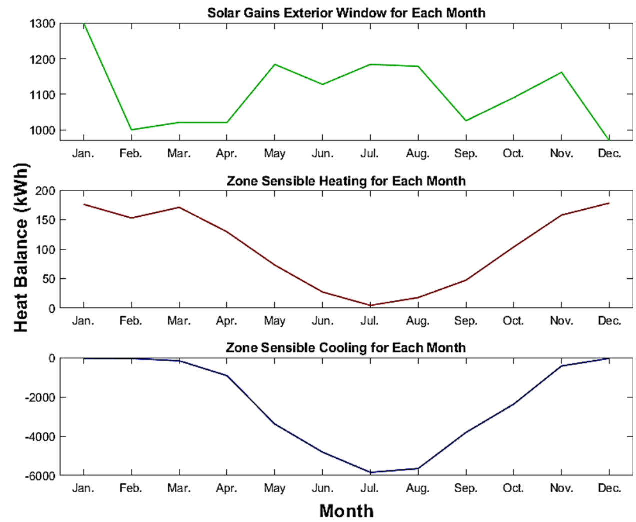


Fig. 14 Internal gains and solar for each month of the modified design in Kuwait City

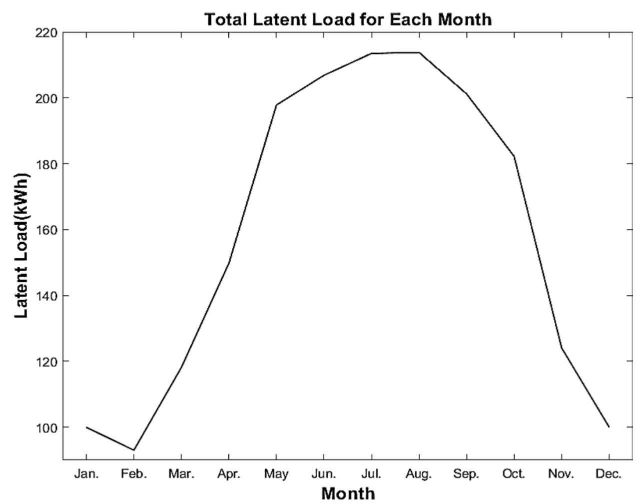


Fig. 15 Total latent load for each month of the modified design in Kuwait City

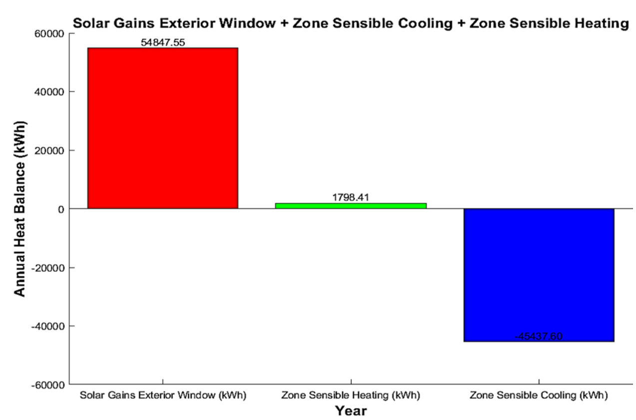


Fig. 16 Internal gains and solar during the year of the basic design in Kuwait City

terms of the cooling requirements, approximately 39.5% less energy is required to cool in the modified design when compared with the basic design. During warm months, the heating requirement was reduced by about 30.6% while comparing the modified design with the basic design.

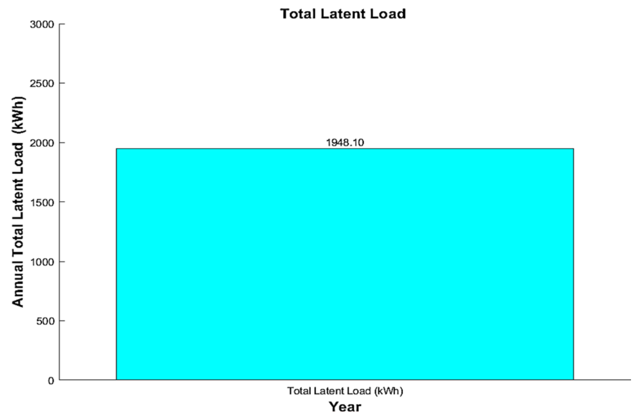


Fig. 17 Total latent load during the year of the basic design in Kuwait City

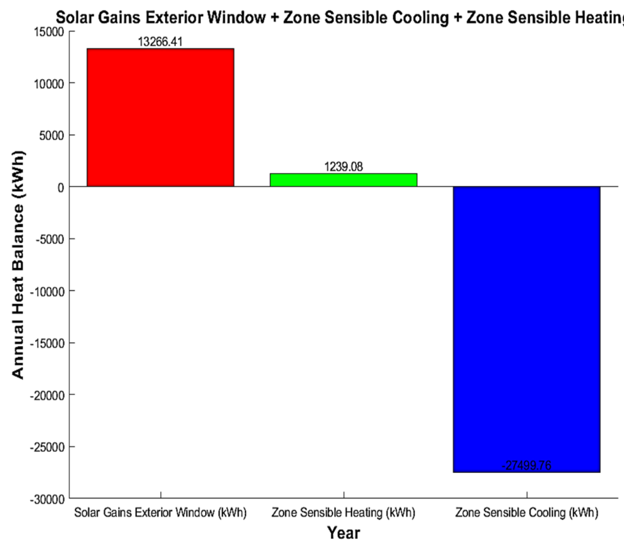


Fig. 18 Internal gains and solar during the year of the modified design in Kuwait City

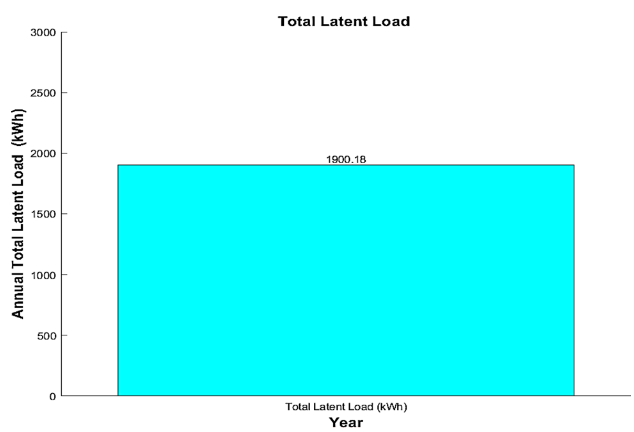


Fig. 19 Total latent load during the year of the modified design in Kuwait City

5 Conclusion

In hyper-arid desert coastal climates, the energy efficiency in buildings can bring a multitude of benefits. With scorching temperatures and limited water resources, these regions can benefit greatly from buildings that are designed to conserve energy and water. Energy-efficient buildings can help reduce the demand for energy-intensive cooling systems, lowering electricity bills and reducing greenhouse gas emissions. Additionally, energy-efficient buildings can provide better indoor air quality and thermal comfort, especially in the desert climates where temperatures can be extreme. The results of this research showed that Annual Energy Consumption is decreased to approximately 11.4% and 17.1% when the WWR is decreased to 20% and 10%, respectively. When comparing Dbl Clr 6mm/6mm Air, Trp Clr 3mm/6mm Air, and Thermochromic Glazing with Sgl Clr 6mm, 4.13%, 5.45%, and 9.06% of the Annual Energy Consumption of these buildings, which have these types of glazing decreased, respectively. When comparing the building which has Louvre, 0.5 m projection + 0.5 Overhangs, Overhang + Sidefins (0.5 m projection), 1 m projection Louvre, and 1 m projection Overhang with the building has no shading, 10.62%, 6.52%, 10.43%, and 8.29% of annual energy consumption decreased, respectively. The basic design was developed in terms of WWR, glazing types, and shading devices by choosing the modified choice in each parameter. The solar gains exterior window of the modified design is decreased by about 75.8% compared with the basic design.

In order to optimise the energy efficiency of buildings, future work can focus on the optimisation of exterior walls and floors. Further investigations can be conducted to explore innovative materials and construction techniques that enhance insulation properties, minimise thermal bridging, and improve overall energy performance. Additionally, advanced modelling and simulation tools can be employed to analyse the thermal behaviour of different wall and floor configurations, allowing for the identification of optimal designs. The integration of renewable energy systems, such as solar panels or geothermal heat pumps, into the building envelope can also be investigated to further enhance energy efficiency. Furthermore, considering the potential of incorporating smart technologies and automation systems to regulate and optimise energy usage within the building can be explored. By undertaking these future research efforts, significant advancements can be made in optimising the energy efficiency of buildings, leading to reduced energy consumption and a more sustainable built environment.

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Declarations

Competing interests The authors declare no competing interests.

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