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Influence of the Advancement in the LED Lighting Technologies on the Optimum Windows-to-Wall Ratio of Jordanians Residential Buildings

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Abstract: Based on recent developments and the predicted future advancement of lighting technologies, researchers are now questioning the extent to which daylight is effective in lowering the overall energy consumption of buildings. As light-emitting diode (LED) luminaires are highly energy efficient, the amount of power consumed for lighting purposes can be reduced, even in situations where the lighting system is at its full power. It has already been demonstrated that LED-lighting technologies can facilitate significant energy savings through minimizing window size (the main source of heat loss in buildings), and there is considerable potential for developing the LEDs' source efficacy and lighting-product efficiency to ultimately achieve levels of efficacy of approximately 350 lumens per Watt (lm/W). For building designs to be sustainable in the future, it is critical that the windows-to-wall ratio (WWR) is optimized to minimize both heating and cooling loads, as well as the total energy consumed by the building for lighting, according to the efficiency of the LED, while still maintaining a suitable lighting level for occupants. This research examines the influence of the WWR on the total amount of energy consumed by standard buildings in Jordan using various LED luminaires (existing and projected efficiencies). DesignBuilder software was utilized to analyze the effect of LED-technology development on optimizing the WWR for a typical residential structure in Jordan. The research presents beneficial recommendations with respect to optimizing the WWR for primary decision-makers in the design of residential buildings with enhanced energy efficiency, considering the losses and gains associated with solar heat and light to capitalize on solar energy with no adverse impacts by windows size. The outcomes suggest a WWR of 17% could be achieved by typical residential buildings in Jordan that have extremely efficient LED lighting systems (350 lm/W), which is more than 50% less than the existing level of 40% recommended by multiple standards. Additionally, this study highlighted that when the efficiency of LED technologies increases, the energy demand of the building will be reduced because of lower energy usage combined with heat gain resulting from the LED efficiency.

Keywords: low energy building; efficient lighting; WWR; LED; Jordan; optimum windows size

1. Introduction

Due to the fact that the construction industry is one of the sectors that has one of the highest demands for energy, it is highly influential on energy consumption trends. Due to an expansion in the different types of buildings required, there has been significant expansion in the commercial building sector in recent years. On an annual basis, around 1.6 billion square feet of commercial buildings are constructed, which equates to 110,000 structures per annum or 500,000 every half decade [1]. Based on data from the US

Energy Information Administration (EIA), 19% of the overall amount of energy consumed within the United States is attributable to commercial structures, which produces 18% of its CO_2 emissions [2]. Most of the energy consumption by commercial structures is related to space heating/cooling and lighting, which are related to both external and internal loads. Commercial structures account for approximately 30% of the electricity consumed in the United States, where 15% of that total is used for lighting [3]. Day-lighting approaches employing windows can have a considerable effect on reducing the energy consumed for lighting, but this may lead to increased solar heat gain and loss through them. Conversely, estimations from the Lawrence Berkley National Laboratory indicate that 34% of the energy utilized by commercial structures within the United States is associated with windows, and the implementation of a fenestration strategy with enhanced energy efficiency could generate savings of 10% to 40% of overall energy consumed, depending on the local climate [4].

It has been observed in recent years that lighting technologies have rapidly improved for different types of buildings. This advancement was measured by monitoring the shift from incandescent sources of light, with limited efficiency, to compact fluorescent lamp CFL) bulbs and, recently, to energy-efficient light-emitting diodes (LEDs). Khan and Abas reported that the luminous flux produced by a 23-Watt CFL bulb was identical to that of a 100-Watt incandescent bulb. Compared with incandescent bulbs, the power consumption of CFL bulbs is two-to-five times lower and their lifetime is eight-to–ten times greater [5]. Furthermore, if the transition is made to LED luminaries, which are sources of light based on semiconductors, in the following two decades, this will lead to a reduction of around 2700 TWh of electricity as well as 1800 million metric tonnes of CO_2 emissions, while simultaneously generating savings of almost $250 billion, at the global scale [6].

A UK-based study performed by Jenkins et al. suggested that, by replacing fluorescent bulbs with LED bulbs in a standard 6-floor office structure, the energy savings achieved would be in the range of 56–62% of the cost of lighting [7]. Furthermore, the integration of lighting systems with buildings' heating, ventilation, and air conditioning (HVAC), and other systems, will be effective in reducing the dependence of the building on energy sourced from fossil fuels. Additionally, the adoption of passive strategies, including the combination of daylight with artificial light sources, can lead to significant improvements in buildings' energy performance.

Another recently and significantly developed aspect of building design is the material used for glazing. In particular, the embedding of transparent glazing substances into windows provides the dual benefits of allowing daylight to enter internal spaces and enhancing the views of building occupants. Windows that can be opened and closed enable rooms to be naturally ventilated and enhance the environmental quality of indoor spaces. Resultantly, operable windows play a critical role in enhancing the quality of spaces. They are regarded as being one of the critical factors in maintaining the physical and mental wellbeing of building occupants. Apart from the qualitative advantages, glazing systems that offer better performance with increased *R*-values (*R*-value measures resistance to heat flow through a given thickness of material, thus, higher *R*-values indicate more thermal resistance) can help improv the thermal environment and energy efficiency of a building by preventing energy transference through glazing.

The development of glazing materials with enhanced performance enables building designers to allocate more space to windows while preventing any adverse impacts on the total energy consumed by the building. As buildings are comprised of multiple interlinked systems, a change to one element of the building will influence different interconnected elements. Significantly, any changes made to such components can have a drastic impact on the energy equation for the entire building. Therefore, to optimize energy-consumption levels by meaningfully integrating such systems, it is critical that the complex interconnectivity between these systems is understood, and that strategies are used to optimize energy consumption by meaningfully integrating such systems. This is particularly exemplified by the lighting system–WWR relationship.

1.1. Low-Energy Buildings through Passive Design

Hence, this triggered the inception of the concept of 'energy-efficient' buildings, whereby thermal comfort levels are maintained in winter without the need to employ heating systems, and, in summer, without air-conditioning. Recently, several passive design strategies have been developed for the purpose of cost-effectively improving buildings' thermal performance by using energy from solar sources, which reflects the growing attention on reducing global energy-consumption levels. Simultaneously, the advancement of active-design technologies has increased the efficiency of buildings' service applications, which means that less energy is required to perform the same tasks. In building design, the accurate combination of passive strategies and active technologies can generate considerable energy savings, considering that passive strategies produce optimal results when introduced as part of the design process [8,9].

In passive-design approaches, it is necessary to determine a building's orientation and shape, the size of its windows, the kind of glazing used, the materials used to construct walls and isolate the interior section of the envelop from the outside, and the benefits from the thermal mass inside the building regarding storing thermal energy [8,10]. Conversely, active design is focused on making buildings' systems more efficient, such as ventilation and air-conditioning (HVAC), heating, lighting, and additional appliances in the building. Such approaches are significantly reliant on the climatic properties of the region, suggesting that approaches that produce results in regions characterized by hot and arid climates are not the same as those that are effective in temperate regions with increased humidity [8,11].

Practitioners and researchers in the field of architecture have increasingly focused on the passive-design approach in recent years because it does not require much additional financing. Multiple researchers have studied building design criteria that have the ability to reduce the energy necessary for cooling and heating buildings, such as a building's orientation, envelope system, shape, passive heating and cooling systems, shading, the employment of various glazing methods, mathematical equations, small-scale building modules as well as building-information modelling (BIM), and software for simulating energy in order to provide recommendations for optimizing each of the criteria utilized in passive design, based on the building's climate zone [12–15]. For example, all current studies that have employed the aforementioned methods have confirmed that it is possible to optimize the orientation of buildings by ensuring that both the long axis and largest area of glazing are north-facing, in the Southern hemisphere [11], and south-facing in the Northern hemisphere [13].

Research performed in southern Spain adopted a case-study approach, by concentrating on an energy-efficient, high-tech skyscraper that produced savings in terms of occupation hours, which reduced the use of air-conditioning by 28% and also significantly decreased the overall amount of energy consumed [16]. Research on how the adaptive thermal-comfort module on the amount of energy consumed by buildings was performed on a standard residential structure situated on the University of Newcastle campus, located in Australia, determined that the use of an adaptive strategy could generate considerable savings, related to cooling and heating energy, of up to 70% in temperate climate zones [17–21].

1.2. Standards and Codes for WWR Daylighting

Attaining the levels of light needed to efficiently and accurately complete tasks will be accomplished by utilizing daylight, artificial light, or a combination of both. Generally, windows are preferred in buildings as they allow daylight to enter, and permit occupants to view the outside. Nevertheless, it is essential that window design considers both the thermal and visual comfort of residents while also not violating their privacy. Natural light can generate energy savings and additionally has importance for the overall health and well-being of occupants.

In recent years, the CEN (European Committee for Standardization) developed standards that are applicable in countries across Europe. The first combined standard, EN

17037, was published at the end of 2018, and applicable in all European countries that engage fully the design of daylight within residential and commercial buildings. EN 17037 substitutes several standards through different European countries. Providing suitable indoor illumination from daylight to minimize the need for artificial lighting and to connect occupant's with the external environment. The EN 17037 Standard for daylight design covers four different areas: access to sunlight, prevention of glare, daylight provision, valuation of windows' views [22].

Presently, one standard (ISO 10916:2014) is applied for methods used for the calculation of natural light in both existing buildings and in the design of new structures or renovation projects. ISO 10916:2014 defines the technique used to calculate the amount of functional daylight that enters commercial structures through vertical facades or rooflights, monthly or annually, in addition to its effect on the need for electric lighting. It can be used for both existing buildings as well as those are being newly built or renovated. ISO 10916:2014 describes the overall energy balance equation for lighting associated with the installed power density for an electric lighting system where daylight is accessible, and lighting can be controlled (proof calculation method).

Various independent organizations have distributed guidance materials, and developed criteria and accepted techniques for practical application, including the Chartered Institution of Building Service Engineers, an organization headquartered in London that has published lighting guides for natural light, guiding building-services technicians in reducing WWR for living rooms and bedrooms to levels ranging from 15% to 50% of their prior values [23]. The Illuminating Engineering Society of North America (IESNA) released a standard for a recognized method for WWR, with a cut-off of 40%. The IES Spatial Daylight Autonomy (SDA) and Annual Sunlight Exposure (ASE) were found to restrict the Window-to-Wall ratio to 40%, which comprise a novel group of metrics used to measure the daylighting effectiveness of both existing structures and new constructions from inception to construction documentation.

A variety of approved and commonly used methods for assessing, rating and certifying the sustainability of buildings, such as LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Methodology), and DGNB (Deutsche Gesellschaft für nachhaltiges Bauen), have given recommendations for daylighting as part of their assessment approaches. In general, although natural light is an indicator that it is frequently utilized, the calculation and benchmarking techniques there used can vary. In addition to natural light, other indicators utilized to describe visual comfort are outside views, glare control, and levels of lighting [24].

1.3. LED- and Building-Design Parameters

Daylighting from the windows offsets some of the demand for artificial lighting and lowers overall energy consumed. This can be achieved using glazing to allow the entry of natural light, as well as through systems for controlling the lighting that are responsive to changing light levels. Nonetheless, if passive daylighting strategies are not implemented correctly, it can lead to increased energy consumption, particularly due to heat loss or gain heat via windows. Sunlight, or solar heat radiation, has the potential to augment a space's cooling and heating loads and can hinder the energy savings produced by daylighting. Hence, it is necessary to strike a balance between light gain and solar heat in order to fully exploit solar energy without adverse effect. Regarding this balance, recent developments in lighting technologies have led to questions regarding the efficacy of daylight in lowering the consumption of energy used by buildings.

As LED bulbs are more energy efficient, the energy consumed to power them is relatively low, even when functioning at peak levels. Hence, it remains uncertain whether solar energy derived from glazing is beneficial or disadvantageous for the overall energy consumption of buildings.

Furthermore, studies have explored the effect on reducing a building's energy demand of making active technologies, such as systems used for lighting, heating, ventilation, and air-conditioning, more efficient on the overall energy consumption of the building. For example, all previous studies that have focused on this topic have suggested that LED luminaries with enhanced efficiency should replace all compact fluorescent lamp (CFL) bulbs in buildings to reduce their total energy consumption and minimize the volume of GHS they emit into the environment [25–27].

A critical design approach involves the incorporation of natural light into building designs, the aim of which is to improve the building's aesthetic value and performance. Windows play a critical architectural role, in that they allow daylight to penetrate buildings and occupants to view the outside environment. Nevertheless, if the windows are incorrectly proportioned, this can lead to the loss or gain of heat and can therefore negatively affect the building's thermal performance. When passive design strategies such as WWR are applied, this can influence the future energy consumption of buildings, thus emphasizing the significance of studying the impact of window size on total energy consumption.

Zahra Zolfaghari recently conducted a study in which the effect of utilizing LED luminaires to optimize the WWR and total energy usage of open offices was investigated by using software-based energy simulations. The results showed how these types of lighting systems could affect general energy consumption and revealed that an optimum WWR could potentially be reduced in the range of 20–40% by installing LED over fluorescent bulbs [28].

In [29], DesignBuilder software (DesignBuilder Software Ltd.: Gloucs, UK) was used to simulate energy use for office buildings in the cities of Shiraz (hot/dry climate), Bushehr (hot/humid climate), and Tabriz (cold climate) in Iran. In each of the cities studied, it was found that the optimum WWR was 20–30% for the north facades. However, for the southern side, it was found to be 20–30%, 10–30%, and 20–50% for Shiraz, Bushehr, and Tabriz, respectively. Furthermore, it was identified to be 30–50%, 40–70%, 20–60%/40–70% for the eastern and western facades for Bushehr, Tabriz, and Shiraz, respectively. For Bushehr and Shiraz, the optimal WWR varied between 20% and 100%, whereas for Tabriz, it ranged from 16% to 25%.

Windows account for approximately 50% of lost heating in buildings [30]. As a result of the significance of window size for the level of energy consumed in buildings, their design has attracted the interest of multiple researchers. All researchers that have investigated this topic thus far have affirmed that optimal WWR is the key to reducing heat loss via windows during winter and summer heat loss/gain. Additionally, it has been consistently demonstrated that the thermal efficiency of buildings is reduced when window sizes are larger.

Ecotect and PHOENICS software (Phoenix Software Limited: Pocklington, UK) were used in [30] for the purpose of simulating typical residential buildings, where the accuracy of the simulation results was verified using two validation methods. Based on the study findings, it was suggested that north-facing glazed walls should have an optimum WWR of 0.4. Additionally, the researchers proposed that a window-to-wall ratio of 0.5 would produce optimum results, except for S-E 80. Optimum WWRs of 0.38 and 0.4 were recommended for N-W 80 and S-E, respectively. It was concluded that an increase in the window-to-wall ratio causes the mean, maximum and minimum inside natural light factors to rise.

Researchers in [31] employed EDSL TAS software to simulate an office building. The results showed that a WWR of 20% is enough to enable useful natural light for around 80% of the time, throughout the year, which would also reduce the total demand for cooling and heating from 155 kWh/m^2 per year to 25 kWh/m^2 per year. It was recommended that a WWR of 100% should not be applied, even with specialized windows. A lower WWR coupled with solar protection can increase the performance of daylighting in comparison to higher WWRs due to restricted glare. It was shown that night-time ventilation can significantly reduce the demand for cooling, by as much as 37%.

The simulation of a small office area in Tripoli, Libya was performed using the Open Studio plugin for Sketch Up and EnergyPlus software (Open Studio, Amsterdam, The Netherlands) in [32]. It was found that if windows were installed on the building's façade (with multiple WWR percentages varying between 0 and 0.9, and orientations at 45-degree intervals), the total consumption of energy increased from 6% to 181%. It was concluded that energy, WWR, and orientation were all correlated.

Some concerns have been raised on the effect of LEDs on human health, but the impacts of LEDs optical radiation have not been confirmed. It is predictable that such effects are not related to LEDs; studies have examined the exposure to light during the evening that affects the circadian system in general, and similar symptoms were obtained from studies investigating other types of circadian disturbance [33].

1.4. Advancement in Lighting Technologies

The development of light emitting diode (LED) technologies has reached the point where it is the preferred choice for virtually all lighting applications. In the last two decades, cool white LED packages have become more efficient, improving from approximately 25 lm/W (lumens per watt) to more than 160 lm/W, based on the quality of the colour and drive environment. At the same time, LED-package costs have fallen to the extent that they are comparable with traditional lighting options on a first-cost basis, while providing considerable reduced ownership costs (preliminary cost and operating cost for energy use) throughout their lifetime. Improved efficiency and lower cost have enabled bulb producers to offer enhanced colour quality, optical distribution, form factor, and control over LED lighting systems.

Despite these technological developments, there is still significant potential for advancement in terms of efficiency and cost, as well as in a variety of different functionalities. In combination, the increased efficiency and longer lifespan of LED technologies mean they have a lower life-ownership cost in comparison to traditional lighting technologies. Resultantly, adoption rates have increased, which has subsequently resulted in considerable energy savings, nationally and globally; as LED technologies continue to become efficient and more widely adopted, it is predicted that such energy savings will increase further. Estimations indicate that LED lighting in the United States currently produces annual energy savings of 88 TWh/year and $8.8 B/year regarding energy and cost, respectively. It is anticipated that comparable savings will be made from the adoption of LEDs in European countries, as the total consumption of energy from lighting will grow in the next 20 years. It is estimated that LED technologies will generate savings of 1500 TWh/year and $150 B/year in the immediate future [34].

A dramatic transition from traditional lighting technologies (fluorescent, incandescent, high intensity discharge) to LED technologies is now occurring. The key motivation driving this transition is the improvements in efficiency and the savings this can generate in related costs. In the near future, it is predicted that phosphor-converted LED packages will improve efficiency from the current level, of 160 lm/W, to 255 lm/W. Longer-term predictions suggest that colour-mixed packages can generate levels of efficiency reaching 330 lm/W, although for this level of performance to be achieved, technological developments are required with regard to the efficacy of amber and green LEDs [34].

Various researchers have studied building-design criteria that could potentially reduce the energy demand associated with heating and cooling structures, such as shape, orientation, envelope framework, insulation materials, glazing type, among others, and have employed various approaches, including mathematical equations or building modules using BIM and software to simulate energy, to produce recommendations that will enable each passive design criterion to be optimized based on the location of the structure and its relevant climate and micro-climate. Furthermore, researchers have investigated the effects of making active technologies more efficient on lowering buildings' energy demand from systems of heating, ventilation, lighting, and air-conditioning on overall energy consumption. However, few studies have focused on how improving the efficacy of such technology's effects optimal passive strategies [35].

Most buildings have envelopes that lose or gain heat through windows, which subsequently influences the thermal comfort of building occupants. While windowless buildings would energy savings, this is not practical in real situations as occupants need daylight to ensure they are comfortable and not physiologically impacted. Choosing appropriate window sizes is a complex process, due to the necessity of considering many factors simultaneously, including energy savings, outside views, and natural daylight [36].

It is acknowledged that the optimal passive strategies of buildings can be impacted by making active technologies more efficient. However, few studies have focused on how enhancing active technologies' efficacy can affect optimal passive strategies. Therefore, this study aims to explore the impact of improving the efficacy of lighting systems on the optimum WWR of typical Jordanian residential buildings. Furthermore, this study aims to stress the importance of these kinds of studies on improving the energy efficiency of buildings. A typical residential building in Jordan was simulated in detail by using DesignBuilder to create a model, which was used subsequently to generate results.

However, few researchers have focused on how making active technologies more efficient impacts on optimal passive strategies; thus, this research explores how increasing the efficiency of lighting systems affects the optimum WWR of typical Jordanian residential buildings. It is proposed that a residential building equipped with a highly efficient system of artificial lighting will have a lower WWR compared with structures that use solar lighting.

Future WWR optimization solutions will enable building engineers to achieve a balance when considering the different factors involved in choosing a suitable WWR according LED-efficiency levels, to ensure that residents' thermal comfort is sustained while minimizing the demand for cooling, heating, and lighting energy. However, when active technologies are made more efficient, this can affect the passive strategies adopted in buildings.

The primary objective of this research is to explore how more efficient lighting systems can impact the optimum WWR of typical Jordanian residential buildings. Furthermore, this study aims to stress the importance of such studies on making buildings more energy efficient. DesignBuilder software (DesignBuilder Software Ltd.: Gloucs, UK) is used to intricately simulate a typical Jordanian residential structure from which to generate our results.

This work is structured as follows: next, the Methodology section describes the Jordanian climate, the typical Jordanian buildings used in this analysis, and the DesignBuilder software (DesignBuilder Software Ltd.: Gloucs, UK) used to perform simulations. Then the data generated from the simulation tool are discussed in the Results and Discussion sections, to examine the impact of increasing lighting system efficiency on the optimum WWR of residential buildings in the Jordanian capital of Amman. Furthermore, the study will stress the importance of such research for increasing buildings' energy efficiency. Finally, the results from this study are summarized in the Conclusion section.

2. Methodology

As Jordan is situated between the Eastern Mediterranean and the Arabian Desert, its climate is distinguished by summers that are lengthy, hot, and dry, while winters are brief and cold. Indeed, the coldest months are December, January, and February, during which the maximum temperature is 10 °C and minimum is 5 °C. On the other hand, the hottest period of the year is from July to September, when the average maximum temperature reaches 35 °C, and the minimum, 20 °C. In the summer months, temperatures during the day can sometimes exceed 40 °C, particularly when a hot, dry wind blows from the south-easterly direction. Winter months are typically characterized by large volumes of rain (200–400 mm), which significantly reduces or stops in summer.

Jordan has various climactic regions, including some which reflect the climate of the Mediterranean and others that have desert features. Weather in Jordan can be separated into four different seasons, where spring and autumn are more conducive to human comfort. The Jordanian capital of Amman is in a zone categorized as sub-humid, in which the summers are hot and dry, and winters have increased precipitation. During winter, when the climate is cooler, the average temperature is approximately 3 °C, whereas in the dry summer period, the average temperature is 34 °C, and the hours of daylight also vary seasonally, between 7 in the winter and 13 in the summer [37], as illustrated in Figure 1.

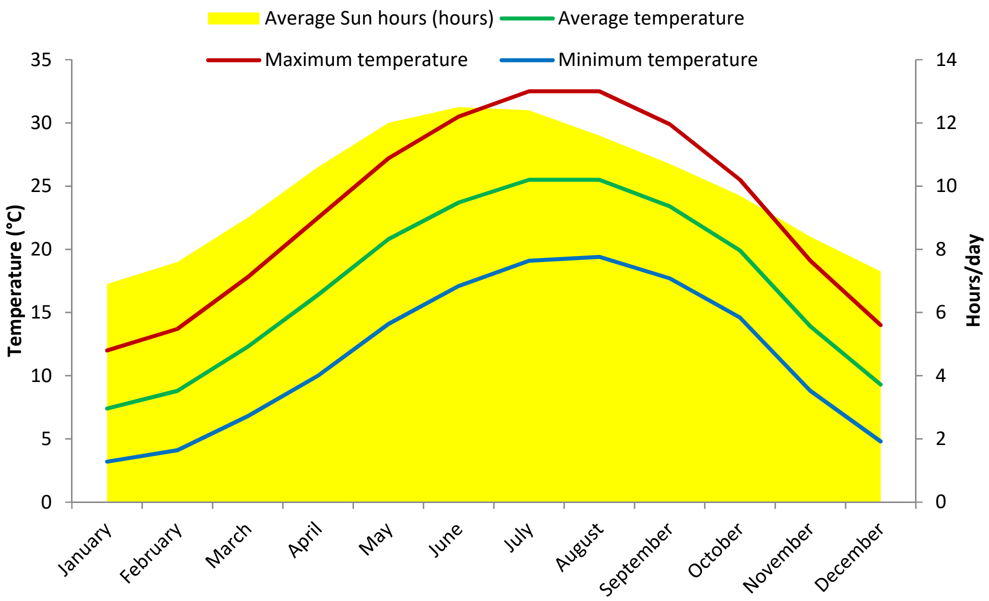


Figure 1. Average, maximum, minimum, and number of hours of sun for the city of Amman.

The case study focuses on a house covering an area of 125 m^2 situated in Amman, Jordan (31.98° N latitude; 35.98° W longitude; 779 m above sea level). Amman has a Mediterranean climate. The schematic design of the selected building is shown in Figure 2.

Two entrances to the house were designed: one, through the guest room, and the other, through the main corridor. The size of the guest room window was 1.5 m × 1.5 m, while the master room's window was 1.0 m × 1.5 m window's height. In the middle of the house, the laundry and the bathroom were connected though a corridor to two bedrooms facing each other. On the western side of the house were living, dining and kitchen area, sharing one open area. All windows of the building were 1.5 m tall, but varied in width from 0.5 m to 1.5 m.

This study assumed those objects in the vicinity of the building had no thermal effect on it, and any shading effects were ignored.

DesignBuilder version (v6) was used for simulating a detailed model of a typical residential structure in Jordan, to investigate the effects of different types of LED lighting systems in optimizing the WWR of residential Jordanian buildings.

In the development of DesignBuilder, EnergyPlus software (U.S. Department of Energy's (DOE), Washington, DC, USA) was used as its basis, which was originally developed by the U.S. Department of Energy (DOE) for the purposes of evaluating current or new buildings in terms of their environmental performance. It enables the analysis of various factors, including building comfort and energy use, HVAC systems, daylighting, and design-cost optimization [38]. In the analytical process, the methodological approach begins by modelling the geometry of the building in the DesignBuilder environment. Subsequently, thermal zones are assigned, along with each of the building's fixed parameters, and lastly, simulations are run for the different WWR configurations, starting with zero glazing, and continuing, in increments of 10 percent, for distinct lighting efficiencies: 50 lm/W; 100 lm/W; 150 lm/W; 200 lm/W; 250 lm/W; 300 lm/W; 350 lm/W.

After modelling the geometry of the building using DesignBuilder, the next step involves establishing an activity template of the building. As illustrated in Figure 3, several different activity templates are available in DesignBuilder, including pre-established parameters such as the rate of metabolism, occupancy rate, and clothing worn, among others. In such simulation, the standard parameters incorporated (Residential-Dwelling unit [with kitchen]) are used apart from the set point temperatures for cooling and heating, which were modified to 27° and 19°, respectively, based on the suggestions in [39]. DesignBuilder's Occupancy functionality enables the amount of people in the family to be selected, which is a critical factor in determining the building's occupancy and there is denoted space for each family member (m^2/person); however, the default settings were maintained in the current assessment. It is important to note that the user can modify each of these parameters, which subsequently affects the outcome.

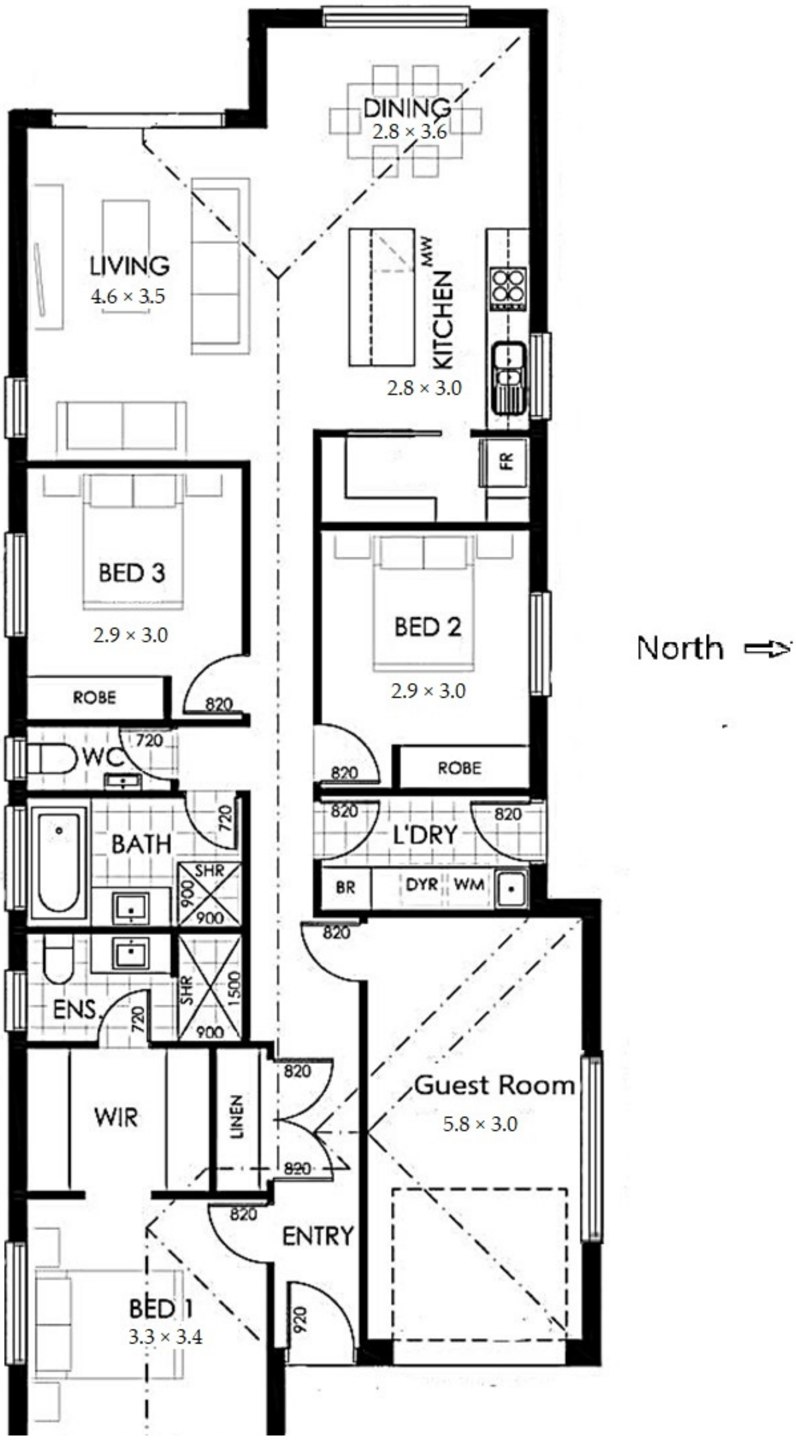


Figure 2. The schematic design of the house layout.

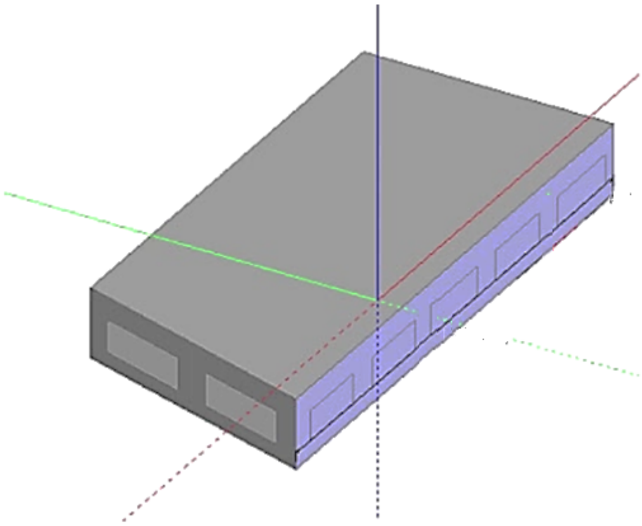


Figure 3. Modelling the geometry of the building in the DesignBuilder environment.

The building's envelope construction and materials there used have been selected such that that they are representative of standard Jordanian residential buildings.

The outside walls were comprised of a 5 cm external layer of stone, covered by a 10 cm layer of reinforced concrete, 5 cm of extruded polystyrene, 10 cm of concrete block, and the last inside layer, consisting of 1 cm-thick cement plaster. The outside wall had an overall thermal transmittance (also known as *U*-value) of 0.55 W/m^2.K. The partition walls were constructed of concrete blocks with a thickness of 10 cm, where both sides have a 3 cm cement plaster covering with an overall *U*-Value of 2.5 W/m^2.K. A 30 cm-thick concrete later is used in the construction of the ground floor, with a covering of 10 cm of sand and 5 cm of ceramic/clay tiles, and a total *U*-value of 1.9 W/m^2.K. The roof was comprised of a 33 cm-thick layer of reinforced concrete and 2 cm layer of cement plaster, having a total *U*-value of 0.53 W/m^2.K [40].

The material used for the window frame was aluminum and its total *U*-value was 5.2 W/m^2.K. The glazing of the outside windows was comprised of Generic blue, with a thickness of 6 cm, followed by an air gap of 5 cm, and finally, a Generic clear glazing layer with a thickness of 6 cm, which has a total *U*-value of 3.1 W/m^2.K, overall solar transmission (SHGC) of 0.7, direct solar transmission of 0.6, and light transmission of 0.781. The size of the windows was modified according to 11 distinct scenarios, with a favoured height of 1.5 m [40].

A parameter that has significant importance is building air infiltration, as it refers to the volume of cold air that is carried from the external environment inside the building, which can lead to a significant rise in the heating load in the winter months. An airtight building can generate considerable savings in both energy and cost [41,42]. Based on ASHRAE codes, a value of 0.35 air changes per hour was adopted, using the updated version of the DesignBuilder software (DesignBuilder Software Ltd.: Gloucs, UK) [43].

A standard Jordanian residential building was used as the basis of the case study, wherein the selection of materials was based on the country's building codes. The house location selected for the research is representative of a standard area in which houses are situated in Jordan. Due to the fact that users may change each of DesignBuilder's parameters and so influence outcome, specific information has been provided regarding which default parameters were used, and which were altered based on the suggestions of previous researchers.

DAYSIM, one of the tools for climate-based daylighting with the use of the radiance engine and incorporating EnergyPlus (U.S. Department of Energy's (DOE), Washington, DC, USA), was used for single thermal-zone energy simulation. Nevertheless, there are strengths and weaknesses of each of these programmes caused by their usage of various simulation engines and the default inputs set by every tool [44].

Lighting in DesignBuilder

DesignBuilder's primary benefits include comprehensive HVAC design functionality with an easy-to-use graphical user interface, as well as the ability to rapidly and easily conduct single-point-in-time radiance-daylighting analysis. Conversely, in comparison to DesignBuilder, DAYSIM (National Research Council, Ottawa, Canada; Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany) does not offer state-of-the-art HVAC design and energy simulation options and does not facilitate multi-area thermal analysis.

DesignBuilder was used for the calculation of all inside gains, such as lighting, solar heat, home appliances, and occupancy. The primary lighting within the space is accounted for by General lighting (DesignBuilder Software Ltd.: Gloucs, UK). The assumption was that daylight can be used as a replacement if necessary. For the purpose of defining General lighting within DesignBuilder, W/m^2/100 lux was used, which is the default setting in versions 2.1 and above. In comparison to the use of W/m^2, this technique for defining lighting gains offers certain benefits, specifically that the real level of lighting is related to the type of lighting system with no requirement to refer to activity, and therefore illuminance needs. Hence, in situations where a building is comprehensively equipped with a specific lighting system, but a variety of different activities occur within it, it is generally feasible to enter a value of W/m^2/100 lux, once, at the building level, then select the activity for every area, and still produce plausible results for lighting gains.

W/m^2/100 lux is max lighting power (W) = lighting energy (W/m^2−100 lux) × zone floor area (m^2) × zone-illuminance requirement/100. Ultimately, the electrical input to lighting manifests as heat, which influences either zone loads or gains in return air heat. DesignBuilder separates heat into four individual fractions, where three are provided by the Return Air Fraction, Fraction Radiant and Fraction Visible input fields. The calculation of the fourth fraction, explained as the fraction of the lighting power convected to the lighting-heat gain, follows.

Convected Fraction: Convected Fraction = 1.0 − (Visible Fraction + Radiant Fraction + Return Air Fraction). Regarding return-air ducted bulbs, the return-air fraction refers to the proportion of heat produced by lighting that is convected out of the space into the zone return-air system. In situations where there is no return-air flow, this fraction will be put into the zone air by the software. Generally, the Return Air Fraction should be above zero for return-air ducted bulbs or where natural ventilation is not used for return-air ducting.

Radiant fraction: the Radiant Fraction refers to the proportion of heat generated by light that enters the space in the form of thermal radiation. DesignBuilder can calculate the amount of the resulting radiation that the zone's internal surfaces absorb by multiplying the area by the thermal absorptance produce of such surfaces.

Visible Fraction: The Visible Fraction is defined as the proportion of heat generated by lighting that enters the zone's spaces in the form of visible radiation. The software can calculate the amount of the radiation that the zone's internal surfaces absorb by multiplying its area by the solar absorptance product of such surfaces.

Convected Fraction: Convected Fraction is a calculation of the proportion of heat generated by lighting that is convected to the zone air and is made based on the fraction of the heat from lights convected to the zone air, which is calculated from: Convected Fraction = 1.0 − (Fraction Visible + Return Air Fraction + Fraction Radiant) [45].

Note: if the product of Return Fraction and Visible Fraction + Radiant Fraction + Air Fraction is greater than 1.0, an error message will be displayed.

If the drop-down list is selected, a suitable list of defaults for the type of bulb will be returned based in the table. Figure 4 shows the Return-Air Fraction, Radiant Fraction and Visible Fraction for overhead lighting, based on a recessed-bulb setup. The aforementioned values are based on the assumption that zero heat from light is returned to an adjoining area. Table 1 shows approximate values of the Radiant Fraction, Visible Fraction and Return-Air Fraction for overhead lighting for a recessed-luminaire configuration [46].

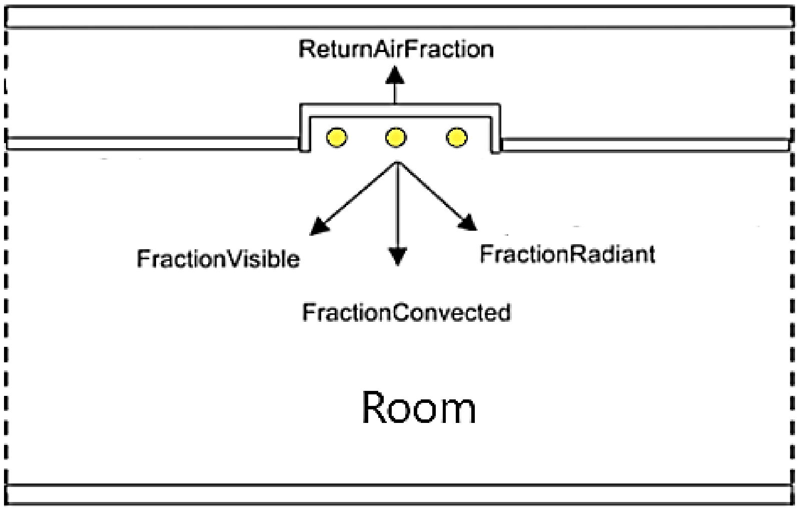


Figure 4. Recessed lighting type.

Table 1. Approximate values of the Return-Air Fraction, Radiant Fraction, Visible Fraction and Return Air Fraction for overhead lighting for a recessed-luminaire configuration.

Data	Recessed
Convected Fraction	45%
Radiant Fraction	37%
Visible Fraction	18%
Return Air Fraction	0%

A variety of different lighting templates are available in DesignBuilder, and as demonstrated in Figure 5, the 'LED with Linear Control' template was selected for the current simulation. Users can change the parameters in each of the lighting templates, which will subsequently affect outcomes. For the current simulation, the "Linear/Off" template was selected, with minimum input and output fractions of 0.1, a working plane height of 0.8 m, a maximum permissible glare index of 22, and a duration of lighting during the day of 18 h, while the default settings were maintained from the remaining parameters. According to the "Linear/off" template, as the illuminance generated by natural light rises, continuous dimming of the overhead lights occurs in linear manner from peak electric power. After reaching their dimming points, the lights cease to function in line with the rise in illuminance caused by natural light.

In the simulation, the variety of efficiencies (lumens/Watt) for the LED lighting lamps were used including: 50 lm/W; 100 lm/W; 150 lm/W; 200 lm/W; 250 lm/W; 300 lm/W; 350 lm/W. Because multiple systems are integrated into buildings, when one element is changed, this can affect all linked elements. Hence, to identify how various efficient systems of lighting affect the window dimensions, the building parameters were all set according to the aforementioned criteria: in total, 11 different WWR scenarios were simulated starting from 10% and increasing to 100% in 10% increments. These scenarios were analyzed for different design alternatives to optimize the WWR for the LED system. In the configuration of the outside windows, the window height was set at 1.5 m.

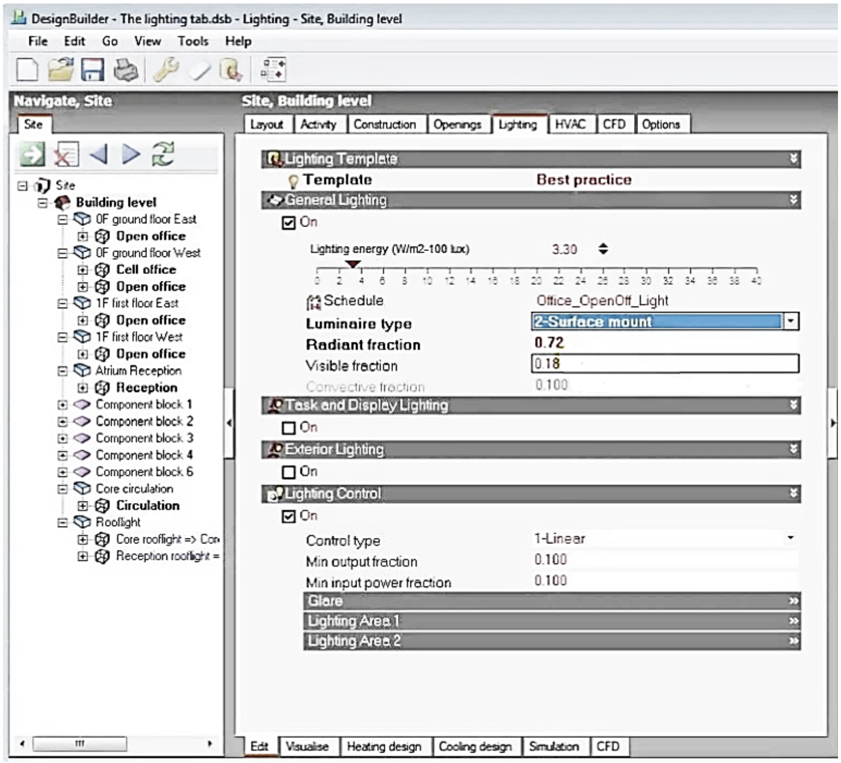


Figure 5. DesignBuilder lightning templates.

3. Results and Discussion

To ensure that future construction projects are sustainable, it is essential that recommendations are made, including the optimization of WWR, to achieve a reduction in both heating and cooling loads while ensuring that suitable lighting levels are maintained. It is possible to determine how increasing the efficiency of active technologies can affect passive approaches using various methods, including the utilization of software to run simulations.

The current research investigates the impact of using various efficient LEDs for distinct WWRs. In order to achieve this, a simulation was run, and a general report was created using DesignBuilder (DesignBuilder Software Ltd.: Gloucs, UK) for a number of WWR scenarios, as detailed in the methodology section. The findings have been shown in graphical format for ease of understanding. Subsequently, the outcomes were compared to facilitate decision-making.

The DesignBuilder software (DesignBuilder Software Ltd.: Gloucs, UK) was used to run simulations to study and examine the effects of various systems of lighting on optimizing the WWR for a typical Jordanian residential structure. The results provide useful information regarding how the systems of lighting impact the window magnitudes in addition to their combined effects on the total consumption of energy. Although the suggested optimum WWR is only related to energy consumption in the context of this research, by integrating such with the proclivities of the building residents, this can produce an acceptable WWR that satisfies both design-quality criteria and maintains the performance of the building.

Figure 6 shows that the total energy of the site in both the 0% and 8% cases was very similar. Even though an increase was observed in total site energy in the 0% scenario, it decreased significantly in the 10% scenario. Both the 20% and 30% scenarios also exhibited analogous decreases, although the total energy of the site started to decline beyond the 30% scenario, peaking at a WWR ratio of 100% (walls completely glazed). Because the region is characterized by elevated radiation and increased temperatures, there will be a significant rise in cooling demand as global temperatures rise. It is evident that, as the efficiency of LED technologies increases, buildings' energy demands will be reduced by the lower energy usage combined with the heat gain resulting from LED efficiency.

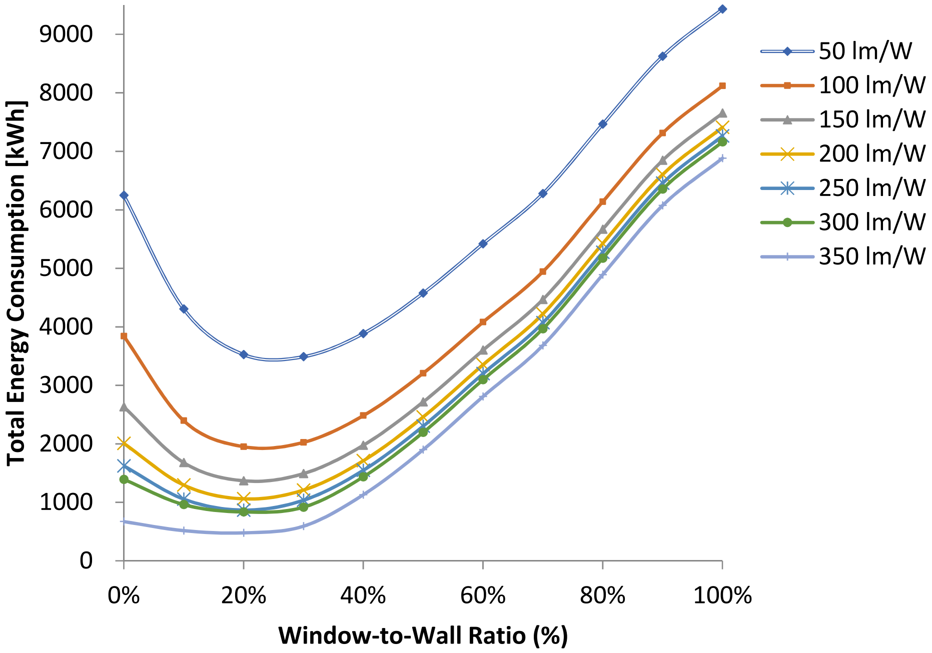


Figure 6. Overall energy consumption of the building (kWh) for a range of WWRs, as per various LED lighting efficiencies.

The changes observed in the total energy of the building in the various WWR cases suggest that without installed glazing, heat and light cannot be transferred, and the amount of energy consumed by the residential building is elevated because of the higher window-to-wall ratio; however, if the WWR percentage is reduced, this can lead to a decrease in the total site energy.

Figure 7 shows that an increase in the WWR percentage causes the cooling load to raise. In the 0% scenario, the annual consumption of energy increased, although this decreased in the 10–20% WWR scenarios. However, after this point, there are minimal differences in all the LED lighting scenarios between 20% and 100%.

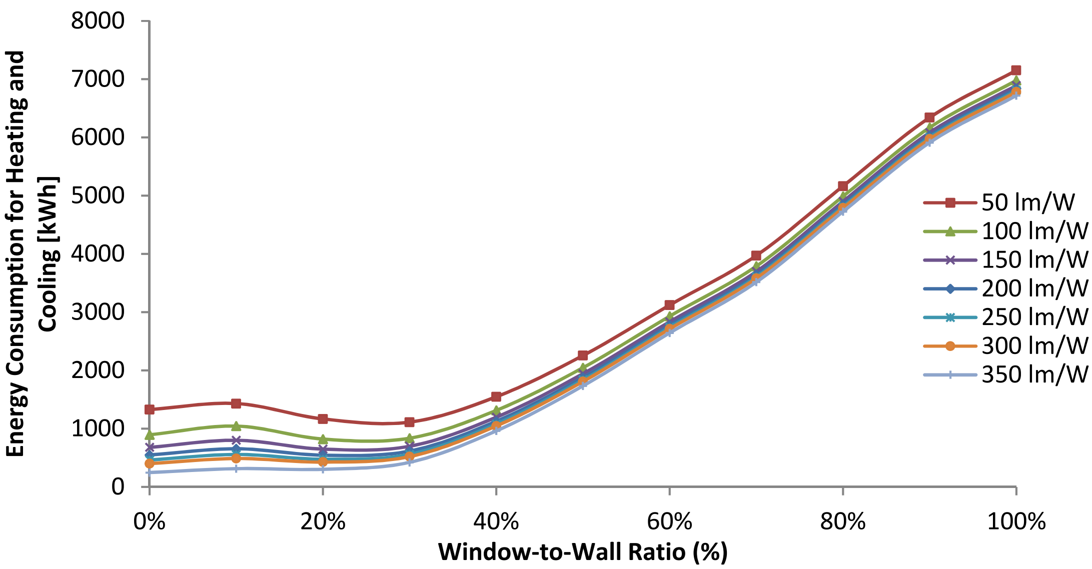
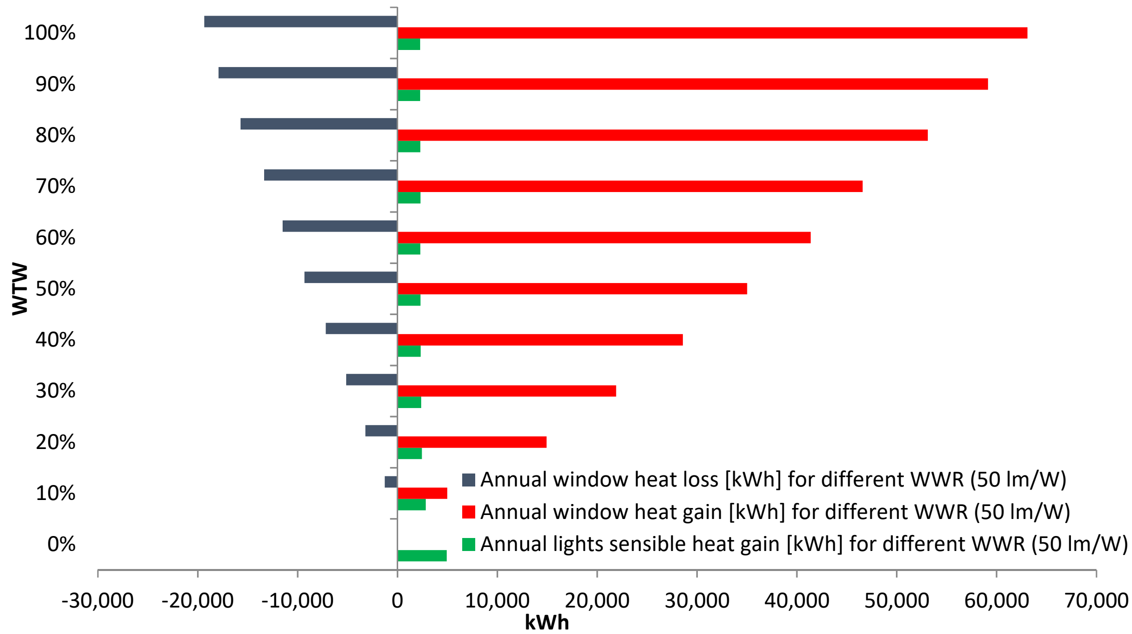
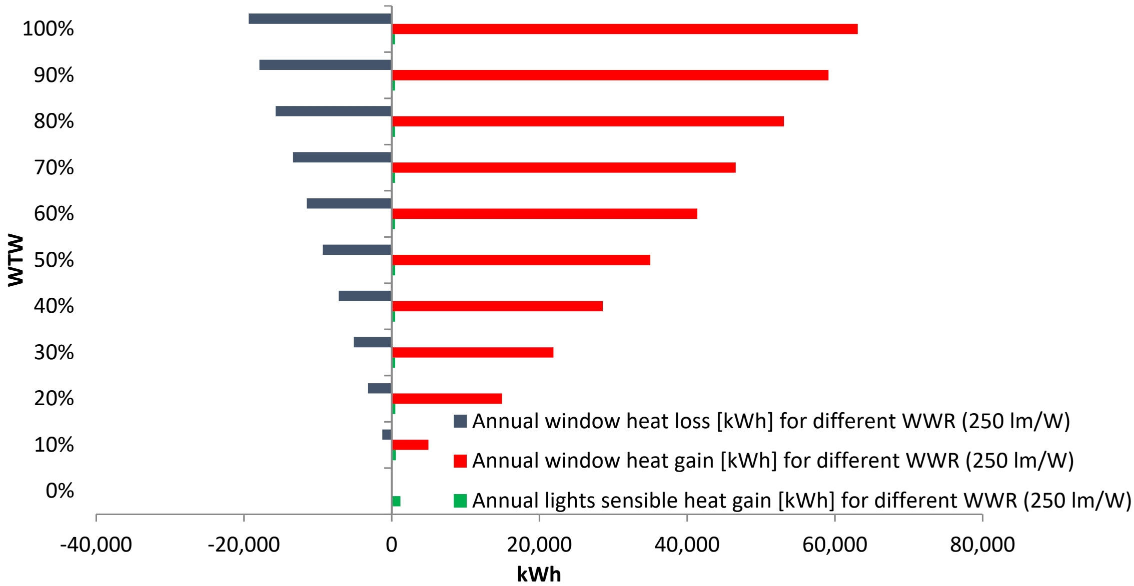


Figure 7. Annual space heating- and cooling-energy consumption (kWh) for different WWR.

Generally, some heat gain occurs as glazing allows light and solar radiation to enter the building, but some of this heat is lost as result of conduction heat losses via the same glazing. Figure 8 summarizes the overall gains and losses in heat on a yearly basis, where the annual heat gain from lighting and windows is depicted by the green and red bars, respectively, and blue bars show the annual heat loss through windows.



(**a**) LED with 50 lm/W



(**b**) 350 lm/W efficiency

Figure 8. Annual heat gain vs. annual heat loss (kWh) for different WWRs.

In the 0%-to-20% scenarios, the amount of energy used for cooling purposes was negligible. Nevertheless, from the 30% scenario onwards, it began to increase in a linear manner, peaking at the 100% scenario. On the other hand, a linear decrease was observed in energy consumption regarding WWR percentage, except for the 10% scenario. However, this decrease became negligible beyond the 40% scenario.

It can be clearly observed that the energy utilized for cooling purposes showed a more significant change compared with the consumption of energy for heating and lighting. On the other hand, the lighting energy only changed significantly within the range of the 0% scenario to the 20% scenario, and then mostly remained the same for the rest of the cases.

The energy saving from LED due to minimized heat loss in winter, and heat gain, in summer, through the heat generated by lights and solar radiation penetrating the building through glass, in addition to the building's loss of some of heat by conduction through glass. In this study, efficient lighting reduced total heating and cooling by 9%, 21%, 31%, 38%, 44%, 42%, and 58% when using 50 lm/W, 100 lm/W, 150 lm/W, 200 lm/W, 250 lm/W, 300 lm/W, and 350 lm/W, respectively.

A significant increase was observed in the annual heat gain from windows when moving between the 0% scenario and the 100% scenario, whereas the annual sensible heat gain via light decreased. However, from the 20% scenario onwards, the changes in the reduction in energy caused by light efficiency were negligible. Conversely, the annual heat loss through windows increased linearly with window-to-wall ratio. Because an increase in heat loss does not equate to an increase in heat gain, solar heat-and-light gain must be balanced to fully take advantage of solar energy sources while avoiding effects reverse of those intended.

Electric lighting demand can be partially offset by taking advantage of natural light through windows, which can also reduce the total amount of energy that the building consumes. It is possible to achieve this by using glazing types that permit natural light to penetrate the building, in addition to controllable lighting systems that can dynamically respond to changing light levels. However, in situations where passive daylighting strategies are incorrectly applied, an increase in the consumption of energy can result. Sunlight is accompanied by solar heat radiation, which has the potential to raise the HVAC load of a space and offset the savings in energy produced by natural light.

Hence, it is important that solar and light gains are balanced so that solar energy can be effectively exploited while avoiding inverse effects. Regarding this balance, due to advancements made in lighting technologies, questions have emerged as to whether daylighting can effectively reduce a building's total energy consumption. As LED bulbs have become increasingly efficient, the amount of energy consumed for lighting has reduced significantly, even in cases where the lighting system is working at full capacity. Therefore, it remains unclear whether the solar energy that penetrates buildings through glazing is beneficial or detrimental for the total energy consumption of the building.

In Figure 9, the relationship between the efficiency of LED lamps (lm/W) for various WWRs is represented graphically. It is evident that, as the LED efficiency increases, a lower windows-to-wall ratio is needed; as can be observed, the WWR decreased to 29%, 24%, 22%, 20%, 19%, 18%, and 17% when the efficiency of the LED lighting lamps rose to 50, 100, 150, 200, 250, 300, and 350, respectively. It is possible to express the relation among the efficiency of the LED lighting lamps (lm/W) and the various WWRs as follows:

$$\text{Window-to-Wall Ratio (\%)} = 0.836 \times (\text{LED Lighting lamps efficiency (lm/W)})^{-0.27}$$

It is therefore proposed that in general, the WWR for residential structures equipped with LED lighting systems can be reduced to 17%, which is less than the WWR threshold of 40% recommended in the ASHRAE standard, as well as other building codes [40,47]. Additionally, it is recommended that energy simulation software should be employed when designing future residential buildings in order to optimize the WWR, because changes made to one element have the potential to impact various other interconnected elements. Even though the optimum WWR can range between 17% and 29%, it still effectively represents a decrease that can be accomplished by enhancing the efficiency of the lighting system.

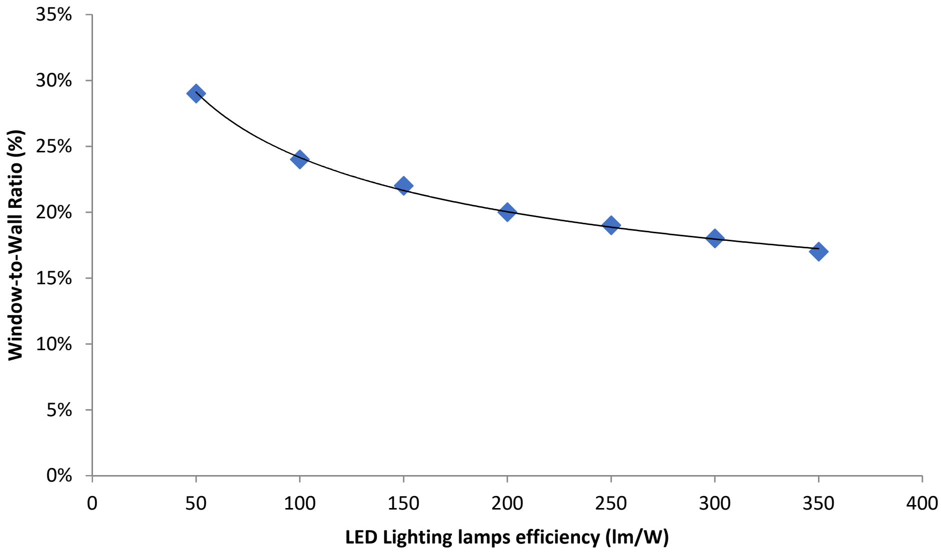


Figure 9. Graphical representation of the relationship between the efficiency of LED lamps (lm/W) and different WWR.

4. Conclusions

Optimizing the WWR enables building engineers to strike a balance between the different factors involved in choosing a suitable WWR when designing new buildings with the aim of minimizing the energy used to heat, cool, and light the buildings. Even though it is recognized that making active technologies more efficient affects the passive strategies employed in buildings, few studies in the literature have focused on this area. Therefore, this study aimed to examine the impact of increasing lighting-system efficiency on the optimum WWR of residential buildings in the Jordanian capital of Amman. Furthermore, the study sought to stress the importance of such study on increasing the efficiency of buildings. The findings were drawn from data generated by intricately simulating a typical Jordanian dwelling, using the energy simulation programme DesignBuilder.

Simulations were run for 11 different WWRs starting from 10% and increasing in 10% increments to 100% for various LED lighting-lamp efficiencies that produced different lm/W outputs. The simulation outcomes showed the effect of rendering the lighting system was more efficient on the tested window dimensions and stressed the importance of integrating optimum passive approaches with active technologies that are the most efficient in the building-design stage to achieve maximum energy savings.

Our results disprove the common misconception that window sizes should increase and affirm that our experimental building had enough lighting, and used solar radiation to lower overall energy consumption. However, when a small percentage of WWR is included, this leads to an increase in the total energy demand up to the 30% WWR scenario. The results provide beneficial information that emphasizes the importance of making lighting systems more efficient by decreasing window size.

This research suggests that the WWR for a standard residential structure with an installed efficient LED lighting system could be reduced to approximately 17%, which is less than the WWR threshold proposed in the ASHRAE standard and other building codes. This suggests that when setting future WWR standards, it is important that new LED-lighting technologies are considered. Additionally, the study proposes that software should be employed to simulate energy use when designing buildings, to accurately identify their WWRs. When a single element is modified, this can impact other connected elements. This study was limited in the settings and assumed properties of the models here used, using local construction materials and software settings appropriate to the Jordanian climate.

Lastly, while the optimum WWR can vary from 17% to 30%, it still provides an effective insight into the extent to which effective lighting systems can produce reductions, as it is essential to provide recommendations on how the optimal WWR can be determined to minimize both heating and cooling loads, as well as to maintain suitable lighting levels, which will enhance the sustainability of projects in the future. Furthermore, the study aimed to stress the importance of this kind of research into making buildings more energy efficient in the future.

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