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# Investigating the Thermal and Energy Performance of Advanced Glazing Systems in the Context of Hail City, KSA

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**Abstract:** Most new housing designs in Saudi Arabia are created to meet the client's needs with minimal regard for environmental or energy-related considerations, resulting in buildings' poor thermal performance and a growing reliance on artificial means. Polycarbonate windows have recently acquired popularity. Yet, there is a rising interest in combining polycarbonate windows with nanomaterials to reduce energy consumption, especially during the summer months when air conditioning use is at its peak. To improve building insulation, this research concentrated on the use of polycarbonate windows with nanogel, which has a low U-value. This study utilized polycarbonate windows with nanogel (two layers of polycarbonate panes filled with nanogel) in Hail City, Saudi Arabia, using DesignBuilder simulation software, resulting in a 14.3% reduction in annual energy consumption. The low U-value of nanogel compared to argon or air may be the cause of these savings, which are roughly double those gained by using double-paned polycarbonate windows. The incorporated nanogel layer between two layers of argon and two layers of polycarbonate panes decreased annual energy consumption by 29% compared to utilizing only one polycarbonate layer. Moreover, compared to a single 3 mm polycarbonate pane, the nanogel layer placed between two layers of argon and two layers of single polycarbonate panes demonstrated the lowest level of $CO_2$ emissions, with an improvement of around 22.23%. This study reveals a method for insulating buildings that cuts energy use and $CO_2$ emissions. This study's conclusion supports the notion that sustainable design is the future. Sustainable construction can dramatically reduce building cooling costs and thermal loads.

**Keywords:** thermal and energy performance; advanced glazing systems; Hail city; polycarbonate windows; nanogel; nanomaterial-based insulation

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**Citation:** Abdelhafez, M.H.H.; Aldersoni, A.A.; Gomaa, M.M.; Noaime, E.; Alnaim, M.M.; Alghaseb, M.; Ragab, A. Investigating the Thermal and Energy Performance of Advanced Glazing Systems in the Context of Hail City, KSA. *Buildings* **2023**, *13*, 752. https://doi.org/10.3390/buildings13030752

Academic Editors: Cinzia Buratti and Paulo Santos

Received: 19 February 2023
Revised: 6 March 2023
Accepted: 7 March 2023
Published: 13 March 2023



## 1. Introduction

In the Kingdom of Saudi Arabia, traditional building forms have been replaced by western patterns because of the recent wave of modernization. This has resulted in debatable urban development, as western patterns have been embraced without regard for the traditional form's principles and socio-cultural background [1,2]. However, the building industry has experienced prompt expansion, increased urbanization, and significant advancements in its development, all of which have contributed to an improvement in the population's standard of living [3]. Approximately 44% of the total amount of energy generated is used for household purposes. It is anticipated that the residential sector will have a period of growth because the population is forecast to increase by 2.5% annually, and around 40% of the houses that are occupied by Saudi nationals are either rented or given to them by their employer [4]. In 2017, nearly 282,000 housing options were made available for Saudi citizens by the Saudi Ministry of Housing (M. of H.), and approximately

300,000 housing options were made available for Saudi nationals in 2018. It is anticipated that this enormous development will proceed in accordance with one of the national long-term strategy initiatives, Saudi Vision 2030, which aims to raise the percentage of people who own their own homes to 70% [5].

Most new building designs in Saudi Arabia are developed to satisfy the requirements of the client while paying little to no attention to environmental or energy-related concerns [6]. Therefore, the building industry has clearly overlooked climate as a design determinant in the process of designing building envelopes, which has led to buildings with poor thermal performance and an increasing reliance on artificial ways to offer a suitable thermal environment [7]. The hot and dry climate of Saudi Arabia, where summer temperatures can exceed 45 °C and there is a definite peak in demand for energy, makes the situation in Saudi Arabia even more difficult [8,9]. According to this, air conditioning (AC) is responsible for around half of the entire national energy demand [8]. It is projected that the demand for cooling energy will increase in tandem with the demand for housing and population growth, which will necessitate the installation of even more mechanical cooling systems, hence increasing energy consumption. Therefore, they are issues that deserve considerable consideration.

It is important to consider the thermal and energy performance of heavily glazed buildings while designing transparent building envelopes [10]. Numerous studies have investigated the use of high-tech materials for building envelopes with the goal of lowering energy consumption [10,11]. The usage of polycarbonate (PC) panels in construction has been on the rise because of these materials' light weight, durability, fire resistance, weather resistance, and ultraviolet (UV) resistance [12,13]. In addition to being more cost-effective than traditional glass, properly constructed PC panels can greatly cut down on heating and cooling expenses, especially in commercial and industrial facilities [14]. Depending on the sample characteristics, the U-values of the polycarbonate multi-sheet panels varied from 1.2 to 1.9 $W/m^2$ K, which is comparable to the values of double-glazed units. Simultaneously, the PC panels permitted a 30% reduction in light transmittance compared to standard double-glass units and an increase in solar transmittance. Nonetheless, these systems diffuse light, eliminating glare issues and enhancing visual comfort [14]. As a solution for commercial and industrial buildings, multiwall air-filled polycarbonate panels were examined. Thermal and optical performance has been evaluated [15].

In recent years, nanomaterials have garnered significant attention [16]. Nanogel is considered one of the most attractive nanomaterials for application in energy-efficient buildings and daylight systems [17]. Nanogels are nanoparticles composed of mechanically or chemically cross-linked hydrophilic polymers. With particle sizes ranging from tens to hundreds of nanometers, the soluble substances have a homogeneous and large surface area. The material has a thermal conductivity of 0.004–0.01 W/(m K) and is extremely porous and lightweight. In addition, it possesses excellent optical transparency and acoustic insulation. Nanogel is being used for fillings between double-glazed (DG) windows, multiwall polycarbonate panels, and methyl methacrylate panels in building insulation [18]. It can be used for walls, roofs, skylights, and facades [19]. Granular nanogel is employed in a variety of daylighting and thermal insulation systems (e.g., in schools, commercial and industrial buildings, airports, etc.), particularly in the United States and Europe [17]. Buratti and Moretti [20] discovered exceptional acoustic and thermal performance in an aluminum-framed window prototype with silica granular nanogel in the glazing interspace during an experimental study.

In various climatic zones with distinct weather characteristics, more research has been conducted on the impact of the glazing system and building facade design on thermal and energy performance [21]. Tsikaloudaki et al. [22] investigated how well windows in Europe's hottest area kept rooms cool by using geometrical, thermophysical, optical, and shading factors. High solar and low thermal transmittance windows improve cooling load efficiency, as they found. Transparent features in workplaces with controlled ventilation in

Mediterranean climates prevent heat dissipation to the ambient environment and increase cooling energy demands.

Lung Hwang et al. [23] suggested a reference map to visualize energy usage and thermal comfort by simulating glazed facade parameter compositions. They observed that to keep PMV = 0.5 without discomfort, the set air-conditioning temperature must be dropped by 2–3 °C, equating to a cooling load increase from 142.5 to 215.0 MJ/m$^2$. Lung Hwang and Chen [24] tested the distribution frequency of cooling loads and the temporal thermal comfort usefulness of simulated instances in selected cities using the MRT algorithm that incorporated sun radiation. Sensitivity analysis was utilized to rank passive solar design characteristics to determine façade design strategy priorities. Facade characteristics, energy usage, thermal comfort, and location eventually correlate. Adjusting variables in certain ranges improves energy savings and thermal comfort. In all evaluated cities, altering the glazing type had the greatest impact on improvement potential, ranging from 22.8% to 39.5% in annual cooling load and 58.6% to 87.5% in temporal thermal comfort usability. Orientation has less impact. Zhang et al. [25] examined a hot, humid building. They used sensitivity analysis and numerical simulation to look at how building orientation, depth of sunspace, type of glass, type of insulation, and thickness of exterior walls and roofs affect thermal comfort and energy use. Roof insulation thickness and density are the most important thermal comfort and energy consumption characteristics. Rammed earth should be 1.1–1.2 m thick, and thermal insulation should be 10–90 mm, preferably 10–40 mm. The adjoining sunspace is ideally oriented south, and the glazing type has no influence on thermal comfort or energy usage.

Previous studies concentrated on the thermal properties of double-glazed (DG) windows comprised of polycarbonate panes filled with nanogel, but neglected to examine their implications on indoor thermal performance, cooling energy consumption, and $CO_2$ emissions. This research contributes to the usage of modern glazing systems in the context of Hail City, Saudi Arabia, by examining the influence of advanced nanogel-filled PC systems on the thermal and energy performance and the corresponding $CO_2$ emissions of typical Saudi homes, which might be used in the building of future dwellings. The assessment process was simulated using the Design Builder 5.5.2.007 (Design Builder Software Ltd., London, UK). This research will influence the risk of thermal discomfort and high energy usage and can improve the quality of life as well, which is considered one of the main goals of the Saudi Vision 2030. Additionally, the research will encourage architects to use new architectural ideas in the next versions of modern homes.

## 2. Materials and Methods

### *2.1. Hail City Climate Analysis*

Due to the climatic dependence of the glazing system, it is crucial to consider the climatic variables while analyzing the building's performance and energy consumption. According to the Köppen–Geiger climate classification [26], the climate of Hail was categorized as BWh, being hot and dry. Hail, located at latitude 27.5° N, is approximately 600 km northwest of Riyadh, the capital city of Saudi Arabia. Summer is extremely hot and dry, with DBT exceeding 43 °C and an average maximum DBT of roughly 40 °C. The average monthly DBT and WBT are 33 and 16.5 °C, respectively. Around 19% is the average relative humidity. The big disparity between the DBT and WBT is justified by the low humidity levels. With a mean annual wind speed of 3.39 m/s, the climate may be described as quiet throughout the year.

### *2.2. Case Study*

The Hail housing project is located on the eastern of King Abdullah ring road, which is approximately 15 km away from the city center. The entire land area of the house is 500 m$^2$, and the home has two stories for a total building space of 272 m$^2$ (Figure 1). This house was built with the capability of housing six individuals. M. of H. projects were built using a concrete construction technique that adhered to the minimum required thermal insulation requirements. Table 1 provides a visual representation of the construction and thermal insulation information for the ground floor, intermediate level, roof, inner walls, and exterior walls. Additionally, a comparison to the new Saudi Building Code (SBC) is provided [27]. However, the architectural drawing makes clear that environmental implications were not considered.

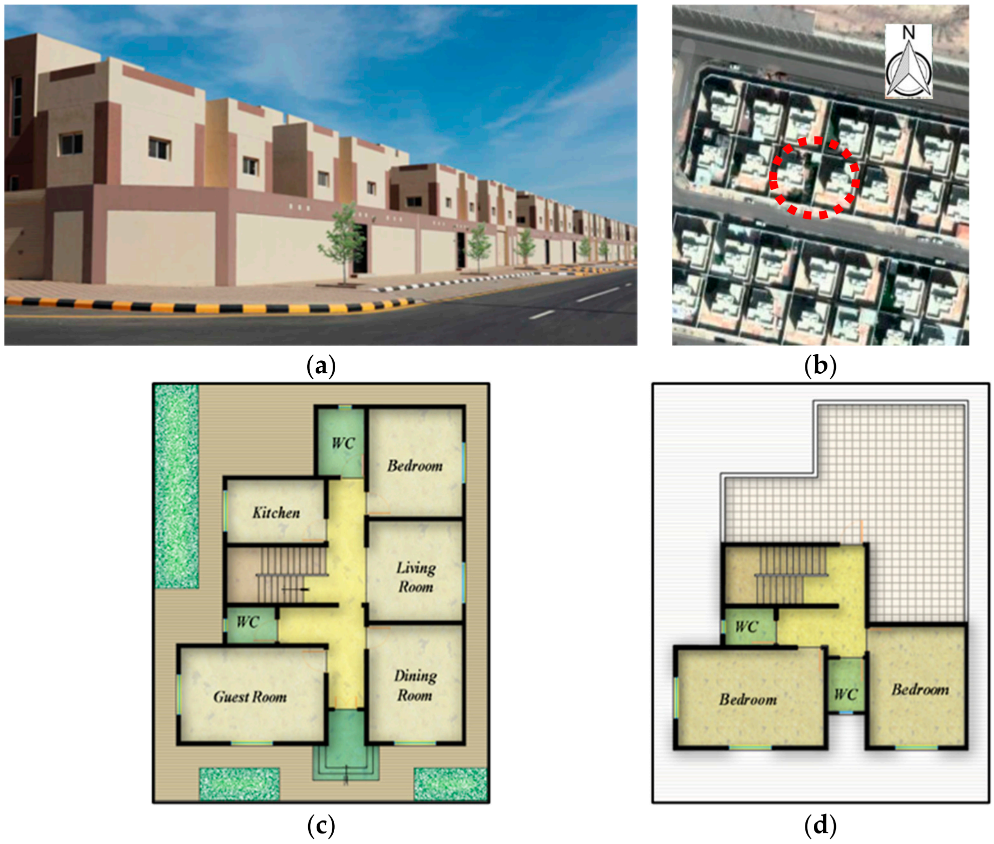



**Figure 1.** The residential building model: (**a**) external view; (**b**) satellite view; (**c**) ground floor; (**d**) first floor.

**Table 1.** Specification of the thermal characteristics of building materials [27].

| | Thickness (m) | U-Value (W/m$^2$ k) | U-Value Required in SBC (W/m$^2$ k) [28] |
|---|---|---|---|
| Ground floor | 0.29 | 2.40 | — |
| Exterior walls | 0.25 | 0.82 | 0.34 |
| Interior walls | 0.25 | 1.40 | 1.26 |
| Intermediate floor | 0.36 | 2.10 | 1.14 |
| Roof | 0.48 | 0.43 | 0.20 |

### *2.3. The Modeling and Simulation Process*

Using the software DesignBuilder, the indoor air temperature, the amount of energy required for cooling, and the corresponding $CO_2$ emissions of a residential building in Hail, Saudi Arabia, were determined. Design Builder is multi-objective constrained optimization software that calculates energy, comfort, and carbon emissions using the NSGA2 algorithm and EnergyPlus simulations. Additionally, the Optimization module uses advanced evolutionary algorithms and a process called "natural selection" to help achieve the design goals by improving the performance of the building. The hot desert climate of Hail, which is designated as BWh on the Köppen–Geiger climate specification, and the location of Hail city (27.5114° N, 41.7208° E) were considered throughout the evaluation process. The simulation was modified to account for the various window layers and thermal conductivity of each material used. The simulation software imported the building's 2D drawings in dxf format to generate a model based on the building's specifications. To accurately represent the outdoor environment, the simulation software utilized weather data from Hail airport's weather station, which is affiliated with the National Center for Meteorology, from 2021. EnergyPlus's file conversion tool converted this file to epw format so that it could be used in the simulation. After that, the simulation software was modified to accommodate polycarbonate windows, and activity, heating, ventilation, and lighting system information was added. In addition to the input data used in the calculation, Table 2 contains a description of the building's attributes.

**Table 2.** Principal input and characterization of building simulation data.

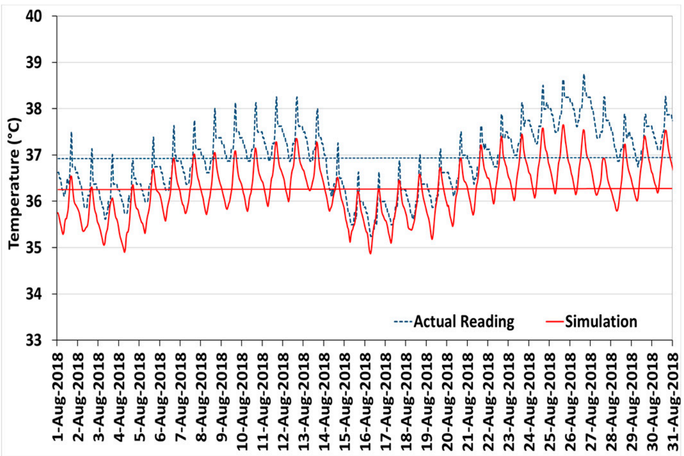
| Item | Specification |
|---|---|
| Building type | residential building |
| Location | Hail city—hot desert region |
| Floor area ($m^2$) | 272 |
| No of floors | Ground floor and first floors |
| Floor height (m) | 3.5 |
| Orientation | Northeast |
| Occupancy | 6 people |
| Window glazing | 6 mm single clear glazing |
| Window-to-wall ratio | 14% |
| Lighting (Lux) | 400 |
| HVAC | Split wall mounted |
| Lighting power (LED) | Guest room: 152 W + Living/Dining room: 200 W + Bedrooms: 152 W + Kitchen: 120 W + Toilets: 20 W |
| Equipment load (TV/VCR, PC) | Guest room: 5 $W/m^2$ + Living/Dining room: 7 $W/m^2$ + Bedrooms: 7 $W/m^2$ + Kitchen: 30 $W/m^2$ [29] |
| Cooling setpoint °C | 24 |
| Heating setpoint °C | 16 |

### *2.4. Model Validation*

Before proceeding with further development, model validation is a crucial step. The potential for discrepancies between expected and measured performance and energy consumption is referred to as the "performance gap." To ensure trust and close the performance gap, the model of the house was evaluated against actual measured data. The process of validation consisted of two phases: thermal validation and energy consumption validation. The thermal validation verifies the accuracy of the model's thermal performance by simulating the unoccupied house. The energy consumption validation, on the other hand, reflects the validity of the systems utilized in the virtual model by comparing the anticipated total energy consumption to the actual total energy consumption obtained from the electricity bills. The thermal validation was conducted in August of 2018 when the house was unoccupied. In the dining room, guest room, master bedroom, and kitchen, iButtons data loggers (DS1921H-F5 Thermochron) were utilized to capture hourly indoor temperature data, as shown in (Figure 2).


**Figure 2.** Photos of the installed data loggers in each room.

Figure 3 illustrates the comparison between the simulated indoor temperatures and the actual measurements for various rooms in the house. The charts indicated that measured and simulated data were in good agreement. A statistical study was undertaken to quantify the difference between measured and modeled data. The correlation coefficients for the dining room, guest room, master bedroom, and kitchen were 0.874, 0.872, 0.829, and 0.869, respectively, while $R^2$ for the same spaces were 0.76, 0.76, 0.69, and 0.75, respectively.

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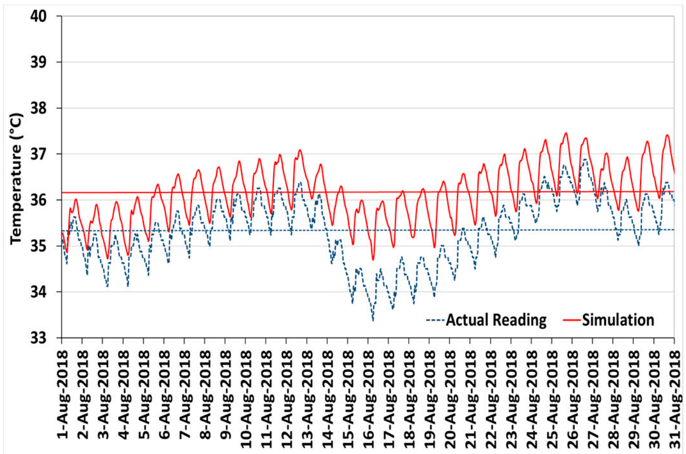


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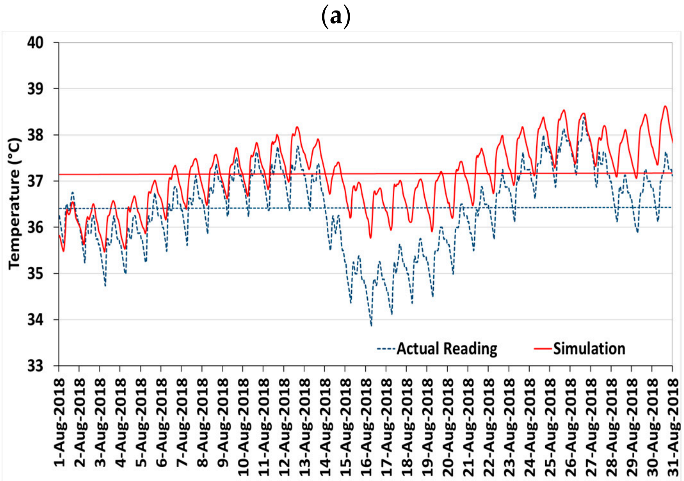


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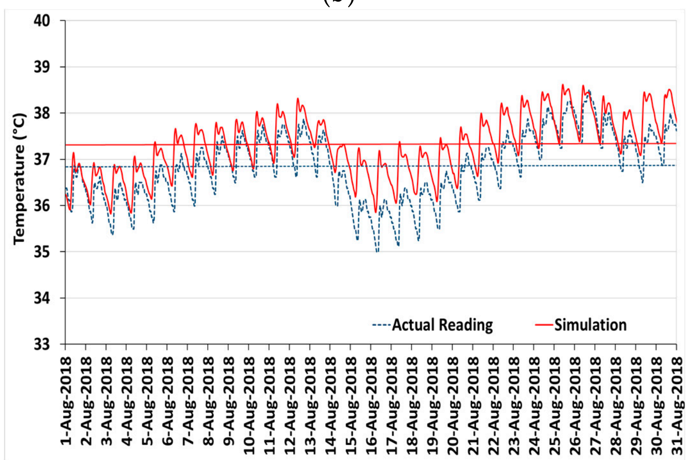



(**d**)

**Figure 3.** The comparison between the simulated and actual indoor temperatures for different rooms. (**a**) Dining room; (**b**) guest room; (**c**) master bedroom; (**d**) kitchen.

It should be mentioned that there was a larger difference between actual and simulated temperature results in the guest room and master bedroom than in other spaces; this could be attributed to the location of these two spaces, where they are exposed to external conditions more than other spaces. This applied to the south and west of the guest room, and the north, east, and roof of the master bedroom. It can also be noted that the actual readings are higher than the simulation in the dining room only, which may be due to the presence of only one window in the room facing south, which caused an increase in the indoor air temperature.

Next, the model's energy consumption, including HVAC, lighting, and equipment, was validated by comparing the estimated total energy consumption to the electricity bills. The energy consumption of the case study can be anticipated based on the actual research site's lighting system, building materials, and climate control settings, as well as its environmental characteristics. Then, each month's actual energy use was compared to the simulated energy consumption. The comparison findings are represented in Figure 4, which reveals an excellent correlation between the modeled and actual total energy use. The average difference between experimental data and energy model outputs was determined to be 12.4%, with $R^2$ = 0.98. The difference between the actual and simulated situation might be due to the assumptions, including the occupants' schedule, that were provided to the simulation software according to the conventional Saudi lifestyle. These assumptions may vary from the real occupants' schedule. Especially since the biggest difference occurred during the summer holidays, during which many citizens travel abroad, which is the reason for the decrease in the electric bill during this period.

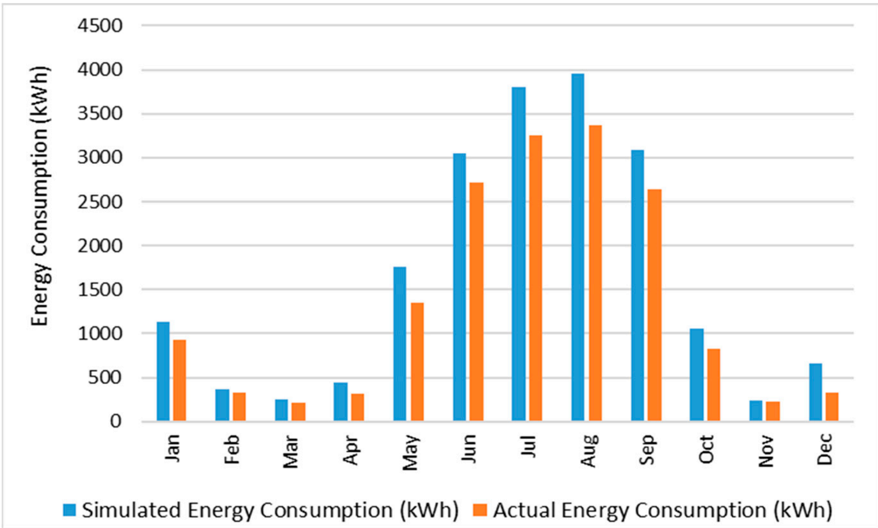



**Figure 4.** Total energy consumption comparison.

### *2.5. Polycarbonate-Based Window Scenarios*

The polycarbonate glazing system in the windows is represented in Table 3. The thermal characteristics of the building materials employed in the simulation software were extracted from the Saudi Energy Conservation Code (SBC-602) [28]. With a few adjustments, the nanogel used in this work was comparable to those described in the prior literature [30]. Figure 5 depicts six different types of polycarbonate windows' cross sections, with Sc1 and Sc2 representing the most conventional types and Sc3, Sc4, Sc5, and Sc6 representing insulated windows.

**Table 3.** Characteristics and attributes of the windows.

| Abbreviation | Window Layers and Materials | Solar Heat Gain Coefficient (SHGC) | Visible Light Transmittance | U-Value (W/m$^2$ K) |
|---|---|---|---|---|
| **Sc1** | 3 mm polycarbonate pane | 0.821 | 0.845 | 5.547 |
| **Sc2** | 6 mm polycarbonate pane | 0.779 | 0.780 | 5.115 |
| **Sc3** | 6 mm polycarbonate pane + 13 mm Air + 6 mm polycarbonate pane | 0.663 | 0.555 | 1.212 |
| **Sc4** | 6 mm polycarbonate pane + 13 mm Argon + 6 mm polycarbonate pane | 0.664 | 0.567 | 1.179 |
| **Sc5** | 6 mm polycarbonate pane + 10 mm nanogel + 6 mm polycarbonate pane | 0.48 | 0.290 | 1.088 |
| **Sc6** | 6 mm polycarbonate pane + 13 mm Argon + 10 mm nanogel + 13 mm Argon + 6 mm polycarbonate pane | 0.31 | 0.271 | 0.374 |

Sc1: Scenario 1; Sc2: Scenario 2; Sc3: Scenario 3; Sc4: Scenario 4; Sc5: Scenario 5; and Sc6: Scenario 6.

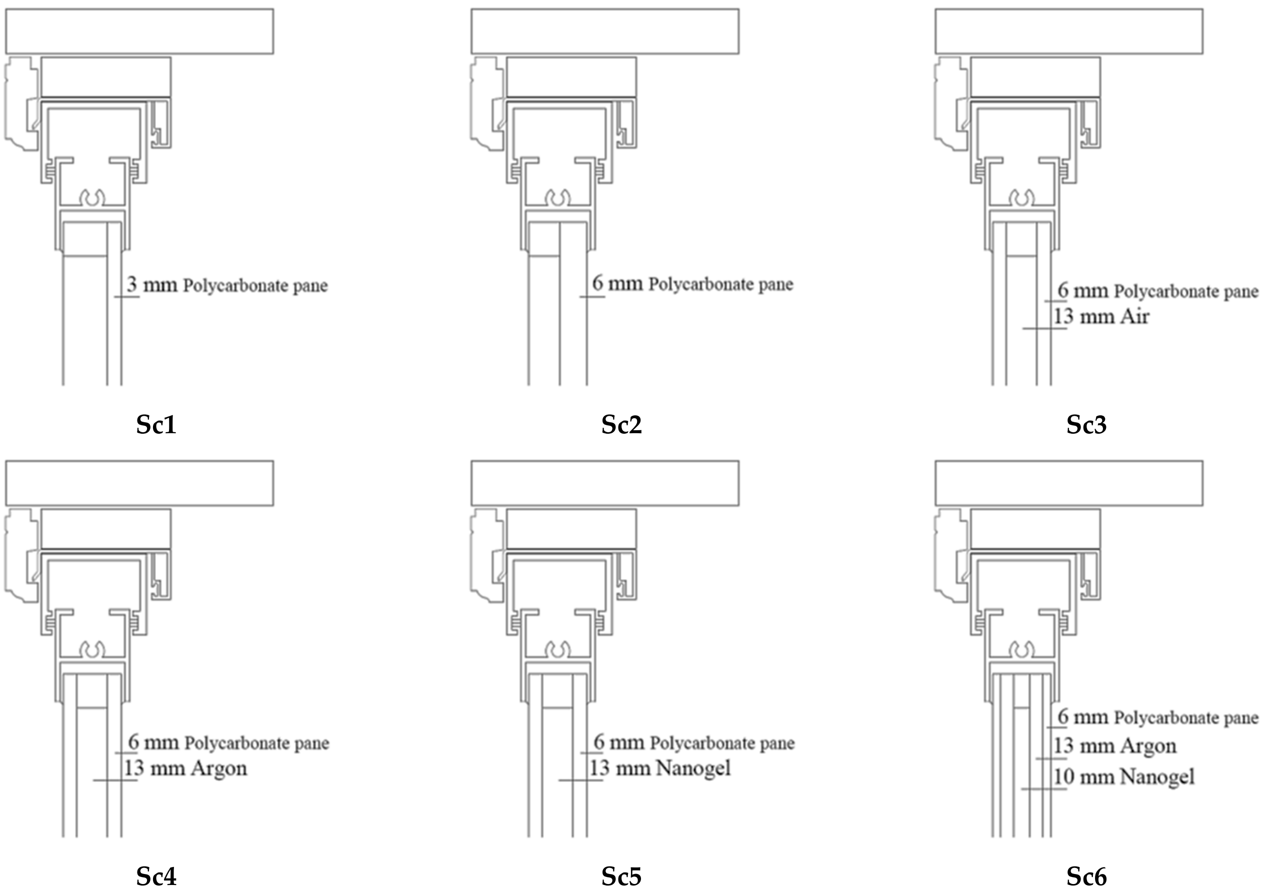



**Figure 5.** Cross sections of windows.

## 3. Results and Discussion

It is worth mentioning that, to demonstrate the impact that polycarbonate (PC) window glazing has on thermal performance in the context of the local environment, an investigation was conducted on a typical Saudi residential building located in Hail City (as evaluated by the indoor air temperature, monthly and annual energy consumption for cooling, and $CO_2$ emissions). Scenario Sc1, which was referred to as the "base scenario" and was used to analyze all the other scenarios, was chosen to represent a polycarbonate sheet that had a thickness of 3 mm. This choice was made because scenario Sc1 was used to evaluate the other options.

### *3.1. The Effect of the Investigated Polycarbonate Windows on the Indoor Air Temperature*

It was determined how successful various settings are at providing thermal insulation for polycarbonate windows. The temperature of the air inside the building that was being investigated was measured and recorded for Sc1, which was a conventional polycarbonate window, as well as for the other window scenarios. Comparisons were made between the suggested scenarios for polycarbonate windows and the base scenario for polycarbonate windows Sc1. The 21st of June was the day that this research was conducted, which is officially considered to be the longest day of the year in the Northern Hemisphere.

The findings revealed that the conditions in which polycarbonate windows were installed influenced the indoor air temperature. The thermal performance of the suggested scenarios with polycarbonate windows is shown in Figure 6a. Furthermore, this figure displays the reductions that could be observed in comparison to the scenario that served as the base case, Sc1. Using high-tech polycarbonate windows was shown to significantly lower indoor air temperatures throughout the day.

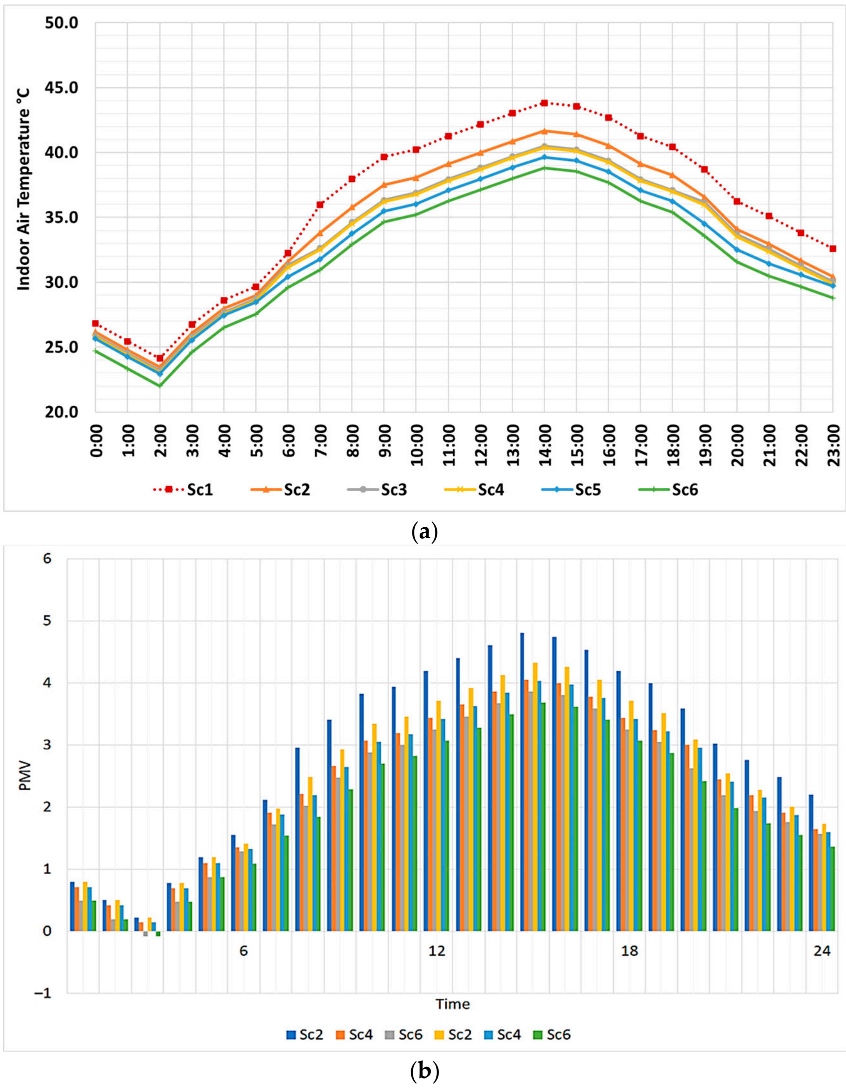



**Figure 6.** The thermal condition in the investigated building. (**a**) Indoor air temperature using varied polycarbonate windows; (**b**) thermal comfort using PMV index.

Despite the obvious distinctions that exist between them, the polycarbonate windows that were examined all displayed patterns that were extremely similar to one another in terms of the thermal performance that they offered. When compared to Sc1, Sc6 has the capacity to bring the temperature of the indoor air down by between 2.12 and 5.14 kelvin. Sc2 is the least preferred scenario because it only reduces the air temperature by 0.66 K to 2.16 K on average. Because of this, it is the scenario with the fewest advantages. The rate at which indoor air temperatures are lowering in Sc3 and Sc4 is approximately the same, which may be related to the fact that their values for thermal conductivity are growing closer to being identical to each other.

An accurate and dependable model is essential for evaluating thermal comfort. This research used Fanger's predicted mean vote (PMV) to evaluate the thermal performance of the building under investigation. In thermal environment modeling, design, evaluation, and control research, the predicted mean vote (PMV) is commonly used.

The findings demonstrate that the PMV prediction varies considerably across all tested scenarios. In the studied settings, PMV tends to display the same behavior as interior air temperature. Figure 6b shows a comparison of the examined polycarbonate windows with respect to PMV. Sc6 was determined to be the most successful scenario with the lowest PMV values when compared to the other scenarios studied. Sc6 recorded PMV values ranging from −0.08 to 3.68 at 3:00 AM and 3:00 PM, respectively. Sc5 is the second most-preferable option after Sc6 in terms of establishing optimal temperature conditions, with PMV values ranging from 0.11 to 3.86. These results provide support for the building's environment and demonstrate that it meets the requirements of the Saudi rating system for the interior environment (MOSTADAM).

### *3.2. Assessing the Cooling Energy Consumption of Proposed Polycarbonate Windows*

The results of the simulation for each of the six window configurations are displayed in Figure 7a–c. Compared to the other window scenarios, the Sc6 window (with nanogel and argon layers mixed with polycarbonate panels) produced the best monthly and annual energy consumption, annual energy savings, and annual energy costs. Compared to the Sc1 window, this window decreased annual energy use by about 29%. The nanogel layer of the Sc5 window was responsible for around 14.3% of the overall annual energy savings achieved. This percentage of savings exceeds the savings achievable by installing double-paned polycarbonate windows with an air (Sc3) or argon (Sc4) layer between the panes. These annual savings range from 8.7% to 8.8%. Compared to the baseline scenario, the Sc2 window has a negligible impact on energy savings of 3.8% (Sc1). As nanogel's thermal conductivity is far lower than that of argon or air, windows constructed with it may provide exceptional thermal insulation. In addition, nanogel's nano-porous nature has the effect of dramatically lowering airflow volume. The thermal conductivity of air encased in nanopores of nanogel is lower than that of air at ambient pressure [13]. This is due to the action of condensation within the nanopores of the nanogel.

In addition to this, it was discovered that the heat transfer through the nanogel was noticeably lower than that of the other double-polycarbonate fillers. When compared to conventional double polycarbonate, nanogel has a lower solar heat gain coefficient and a lower U-value (0.31 and 0.374 W/m$^2$ K, respectively) than conventional double polycarbonate (0.663 and 1.212 W/m$^2$ K, respectively). This may be attributed to the fact that nanogel has a lower thermal conductivity. However, the visual transmittance of the double-polycarbonate layer was much higher than that of the nanogel (0.555 against 0.271). Even though lighting load has a negligible effect on overall energy consumption, it is conceivable that this factor, in addition to the low value of optical transmittance that polycarbonate panes have, contributes to a higher lighting load's energy consumption [31]. Even though the average amount of energy needed for lighting decreased by 27%, this reduction is still nowhere near as significant as the decrease in the amount of energy required to maintain the climate of the building, which decreased by 29%. As a result of this, total energy consumption decreased by 22%. It is possible that the low thermal conductivity of argon and nanogel is what allowed the Sc6 window to obtain the best energy-saving result, which was 29%. Sc6 is a thicker window than the other windows that were examined in the research, yet it weighs less than 0.7 kg, which indicates that it may have a broader range of applications.

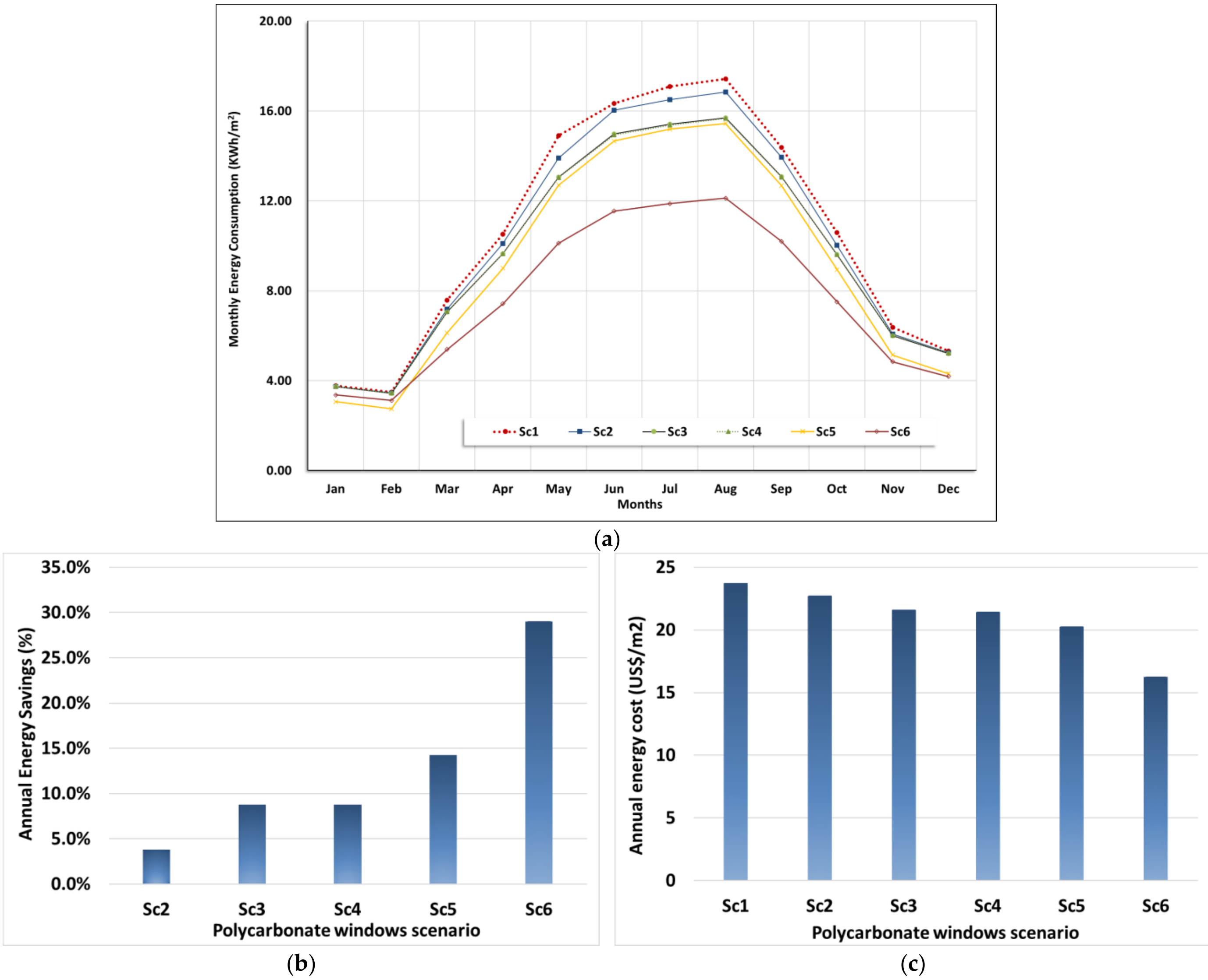



**Figure 7.** Simulation results for energy consumption attributed to the scenarios of polycarbonate windows: (**a**) monthly energy consumption; (**b**) annual savings; and (**c**) annual costs.

All offered scenarios' energy costs were calculated using USD/m$^2$. Sc6 exhibited the lowest cost per square meter at USD 16.3. Sc5, which followed it, was around 20.3 USD/m$^2$ more expensive. Sc1, Sc2, Sc3, and Sc4 all come in at 23.7, 22.8, 21.6, and 21.5 USD/m$^2$ for their respective total energy costs. These results are consistent with the findings of prior studies [32], which placed the total expenses at between USD 20.02 and USD 24.57/m$^2$. Sc6, on the other hand, showed a significant decrease in energy cost relative to earlier studies.

This study's findings are consistent with those of similar research, all of which contribute to lowering energy use significantly as well as achieving the best internal thermal conditions. For instance, Schultz and Jensen [33] reduced energy use in a Danish family home by around 1200 kWh annually, which is equivalent to a 19% decrease in yearly heating needs. To carry this out, aerogel glazing was used in place of the conventional triple-paned argon-filled glass. Using silica aerogel sandwiched between two layers of standard single transparent glass, Huang and Niu [34] demonstrated a 4% yearly decrease in the space cooling of commercial buildings in the humid subtropical area. Mujeebu and Ashraf [35] found that double-paned glass windows increased heat gain much more than nanogel glazing. They claimed that double-glazed windows decreased the heating burden in the winter and increased the cooling load in the summer. Abdel Monteleb et al. [36] studied the effect of several glazing types based on nanogel on the energy needed for cooling in Egyptian residential buildings; they achieved a significant reduction of 26% in the case of using nanogel combined with traditional glazing. Rashwan and Farag [37], who examined the impact of the wall-, window-, and coating-based nano-insulating materials on heat transmission through the fabric of buildings, noted the significant contribution of nanogel glazing in comparison to wall-based nano VIPs. Additionally, other studies [38–40] showed that adding aerogel grains to the cavity between two panes of glass significantly decreased the U-value. When compared to conventional double-glazing units with the same air-gap thickness, they reduced heat loss by 63%. This research showed that window-based nanomaterials fared better than traditional insulating options. Furthermore, it demonstrated the potential benefits of using both traditional polystyrene and nano-VIPs in construction projects to improve energy efficiency. Using these materials in the future would reduce costs and energy use.

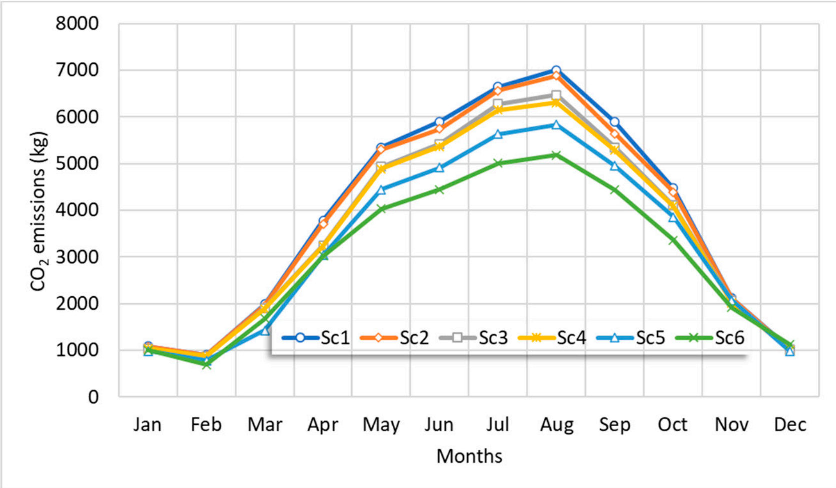
### *3.3. Investigating the Effects of Proposed Polycarbonate Windows on the $CO_2$ Emissions*

While new technologies have helped to reduce carbon dioxide emissions from building operations, the amount of carbon dioxide that is "embodied" in a building during its entire life cycle has been steadily increasing over the last few years. Heating, air conditioning, ventilation, and lighting are all factors that contribute to operational carbon dioxide emissions [41]. On the other hand, material extraction, fabrication, transportation, construction, maintenance, and demolition are all factors that contribute to embodied carbon dioxide [42]. According to this previous work, the operating carbon dioxide ($CO_2$) emissions have been linked to the growing use of air conditioning in studied buildings, which are in a hot desert environment. It is not unreasonable to assume that the components of a building, such as its components and its materials, are responsible for a portion of the ever-increasing amount of carbon dioxide that is released into the atmosphere. Building materials, such as window configurations, roofing tiles, and wall bricks, have been the focus of several studies that have resulted in significant advancements in thermal performance, decreased requirements for cooling energy, and significant reductions in operating carbon dioxide ($CO_2$) emissions. This research led to the finding that the use of polycarbonate panels combined with nanogel materials has the potential to improve both the thermal comfort of buildings and human health within them. This could be accomplished by reducing the need for buildings to have air conditioning and the rate at which heat is transferred through windows and other architectural elements. Furthermore, this could improve the thermal comfort of buildings. In addition, the installation of windows made of polycarbonate may minimize the quantity of carbon dioxide ($CO_2$) and other gases that contribute to the warming of the planet caused by human activity.

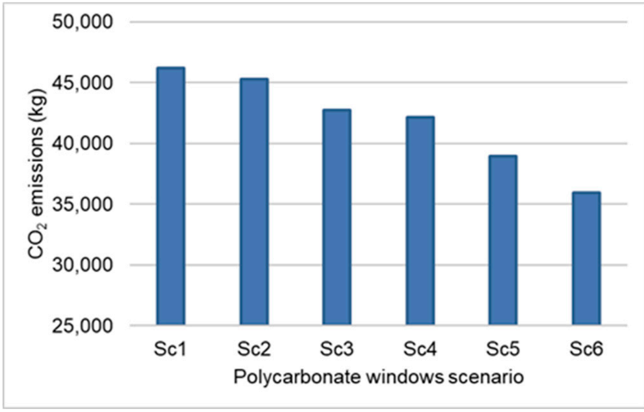
When compared to the other window scenarios, the Sc6 window recorded the lowest monthly and annual $CO_2$ emissions (Figure 8). These findings are in line with the findings regarding energy usage. While Sc2 logs the highest amount of emissions, Sc3, Sc4, and Sc5 come in second, third, and fourth place, respectively.

### *3.4. Evaluating the Effectiveness of Advanced Glazing Systems*

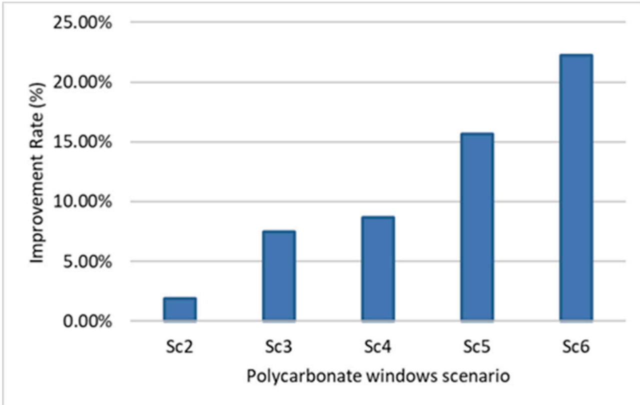
Comparing the amount of energy that was saved due to the utilization of Sc6 to the amount of energy that was saved due to the utilization of insulation systems for walls and roofs was performed in order to verify the glazing systems that employ polycarbonate and nanogels. Comparisons were drawn between three different thicknesses of wall insulation, namely Siporixe 20 cm, Siporixe 25 cm, and Siporixe 30 cm, as well as three different thicknesses of roof insulation, namely 11 cm, 13 cm, and 15 cm insulation. The findings of the investigation into all of the cases are presented in Figure 9.




(**a**)




(**b**)




(**c**)

**Figure 8.** The simulation outcomes for each proposed polycarbonate window scenario in terms of (**a**) monthly $CO_2$ emissions, (**b**) annual $CO_2$ emissions, and (**c**) the improvement rate.

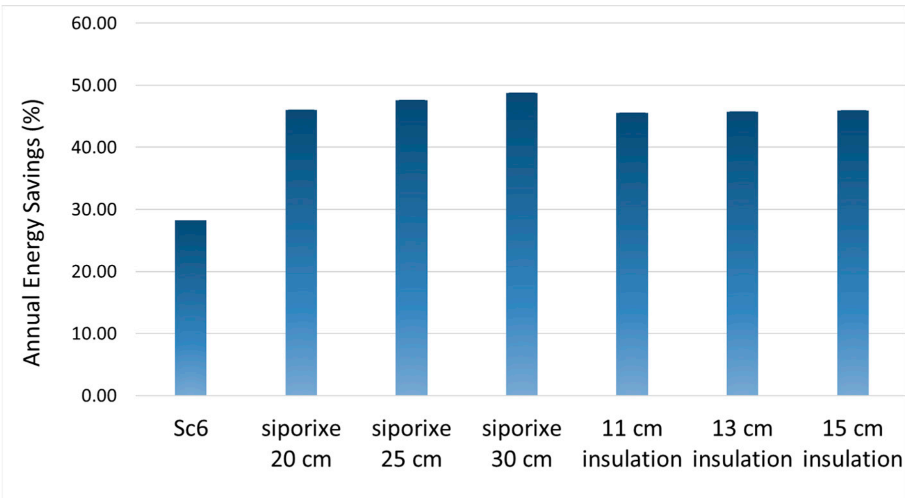



**Figure 9.** The comparison between Sc6 and wall and roof insulation in terms of annual energy consumption saving.

However, considering the window area, which made up 14% of the wall area, it was possible to generate energy savings that were more than twice as high as those that might have been obtained by the use of wall or ceiling insulation. This demonstrates the remarkable efficiency of glazing systems that are composed of polycarbonate packed with nanogels. This study was expanded to provide further explanations for the main causes of the influence of the analyzed window scenarios on internal thermal conditions and cooling energy demand. Therefore, a novel scenario was presented to investigate the impact of increasing the thickness of argon as a filler material between polycarbonate panes. The suggested new window consists of 6 mm of polycarbonate, 36 mm of argon, and 6 mm of polycarbonate. The suggested new window scenario has the same thickness as Sc6, which is the most successful scenario in terms of cooling energy requirements. It was discovered that the cooling energy needed (Kwh/m$^2$) for two panes of polycarbonate filled with argon is greater than that for Sc6 throughout the year, with a difference between 0.14 Kwh/m$^2$ and 0.88 Kwh/m$^2$. Due to its low thermal conductivity (0.004 W/(m K)), nanogel material is more efficient than increasing the thickness of argon.

## 4. Conclusions

Using field measurements and Design Builder simulation software, this study looked at how adding nanogel to polycarbonate windows changed the temperature of the air inside, the amount of energy needed to cool the air, and the amount of $CO_2$ produced. This study is not without limitations. First, this study was only conducted in Hail City, Saudi Arabia, which is in a hot desert; thus, it may not be applicable in other locations. Owing to the greater surface of the facade area compared to the roof, the investigation only examined the building facades rather than their roofs. Additionally, due to the high rate of heat transmission through the windows, this study mainly examines windows with polycarbonate panes and nanogel filling. On the other side, the daily occupants' schedule for the study model was assumed to be compatible with the Saudi lifestyle, which could be different from the occupants' schedule of other similar hot arid regions.

As a result, in this study, indoor air temperature, annual energy consumption, energy cost, energy savings, and $CO_2$ emissions were measured in order to assess the effects of polycarbonate windows, including nanogel, in a hot desert setting (Hail City, Saudi Arabia). Compared to the single polycarbonate pane with a thickness of 3 mm (the reference window), the indoor air temperature was reduced by 4.20 k, and approximately 14.3% of energy was saved, which is twice as much as that produced by double glazing filled with argon. When a nanogel layer was positioned between two layers of argon and two layers of polycarbonate panes, the annual energy consumption decreased by 29%, and the indoor air temperature decreased by 5.14 k. Further investigation was conducted to determine how much energy was required for cooling and how much carbon dioxide was emitted. Compared to a standard window, it was revealed that a nanogel filler sandwiched between two layers of polycarbonate windows could reduce $CO_2$ emissions by 15.65%. The nanogel layer filled between two layers of argon and two layers of polycarbonate panes might lower $CO_2$ emissions by 22.23% to the equivalent reference window. In other words, polycarbonate windows incorporating insulating elements as nanoparticles may be utilized more frequently in the construction of energy-efficient buildings, resulting in a 31.4% reduction in running expenses for building owners. Noting the window area, which comprised 14% of the wall area, it was possible to realize energy savings that were more than twice as large as those that might have been achieved by utilizing wall or roof insulation. Incorporating nanoparticles into polycarbonate windows could be refined with additional studies examining the economic viability of adopting these windows. This study helps our understanding of the incorporation of advanced glazing systems into buildings in Hail City. Researchers and policymakers can utilize the findings of this study. In conclusion, the incorporation of advanced glazing systems into residential buildings offers a substantial amount of thermal comfort and energy-saving potential, which could contribute to the achievement of the quality of life in residential buildings and the reduction in $CO_2$ emissions, which is one of the most important goals of Saudi Arabia's Vision 2030.

**Author Contributions:** Conceptualization, M.H.H.A. and A.R.; methodology, M.H.H.A.; software, A.R.; validation, M.H.H.A. and A.A.A.; formal analysis, A.R.; investigation, M.M.G.; resources, E.N. and M.A.; data curation, M.M.A. and M.A.; writing—original draft preparation, M.H.H.A.; writing—review and editing, A.R.; visualization, M.M.G.; supervision, A.R.; project administration, M.H.H.A.; funding acquisition, M.H.H.A. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research has been funded by the Scientific Research Deanship at the University of Ha'il, Saudi Arabia, through project number "RD-21 075".

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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