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Assessing the impact of photovoltaic shading devices on roof heat transfer in a hot desert climate of Saudi Arabia

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Abstract

Saudi Arabia's Vision 2030 aims to significantly reduce its dependence on fossil fuels by 50%, meeting the remaining energy needs through renewable sources. Since most buildings in Saudi Arabia have unused roof space, there is a substantial opportunity for integrating sustainable energy. This paper aims to assess the shading effects of photovoltaic roof panels on roof heat transfer. The case study focuses on a higher education building located in a hot desert climate in Saudi Arabia. The calculation and assessment of the indirect shading effect were conducted using several software programs. Revit Architecture was used to create a 3D model of the building, and DesignBuilder software was utilized to estimate the building's energy consumption. The energy simulation was performed in two scenarios: one without photovoltaic panels and one with photovoltaic panels. The results indicate that installing 830 photovoltaic panels affects roof heat transfer, resulting in a 22.30% reduction in heat transfer during the summer months due to shading. Conversely, during winter, heat transfer increases by 19.64%, impacting heating demands. Statistical analysis, including t-test results, indicates a significant difference at the 95% confidence level. These findings highlight the potential of photovoltaic installations, not only for energy production but also for reducing overall energy demand.

Keywords: Design Builder, Education Building, Energy Simulation, Heat Transfer, Photovoltaic Panels, Saudi Arabia, Shading.

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1. Introduction

The building sector is one of the major contributors to nearly 40% of global carbon emissions [1]. The most significant global challenge of the 21st century is climate change, primarily driven by greenhouse gas emissions resulting from various human activities [2]. However, human activity in the building sector and the ongoing energy demand are rising due to urbanization and population growth. Furthermore, rapid shifts in climate conditions increase dependence on Heating, Ventilation, and Air Conditioning (HVAC) systems, especially in regions with extremely hot or cold climates. As a result, research focuses on energy reduction solutions for diverse climate conditions to ensure thermal comfort for building occupants [3-5].

High energy consumption is often associated with specific climate zones. Saudi Arabia is characterized by a hot and arid climate, resulting in a substantial demand for cooling in the building sector. Cooling energy use accounts for a significant portion of electricity consumption. Electricity generation in Saudi Arabia relies on fossil fuels, which increases greenhouse gas emissions and the country's carbon footprint [6, 7]. The government acknowledged the significant environmental impact and aimed to mitigate it. Integrating renewable energy technologies into the built environment thus represents a feasible strategy to lessen reliance on traditional power sources while improving energy efficiency. Saudi Arabia's Vision 2030 aspires to generate 50% of its energy consumption from renewable sources [8, 9].

One of the leading solutions and continuous development technologies over the years has been photovoltaic (PV) panels. PV can be integrated in various ways, including on building rooftops and facades [10-12]. The most economical approach is to utilize PV panels on unused building rooftops to procure energy, reduce peak electricity demand, lower carbon emissions, enhance energy self-sufficiency in urban areas, and decrease energy bills [13, 14]. In Saudi Arabia, many rooftops of buildings, including residential, educational, and commercial, remain empty and unused. In such a large area with abundant solar radiation, utilizing rooftop space with PV panels can be both economical and energy-efficient for production. When households utilize their rooftops with PV panels, they can significantly contribute to the nation’s renewable energy targets, beyond the direct energy production from using PV panels on their rooftops. The placement on building surfaces can have an indirect effect. The shading they provide can serve as a passive cooling method, reducing heat gain in underlying building structures. Such shading can help decrease cooling loads and the associated energy consumption of air conditioning systems [15-17]. The benefits of the PV shading effects highlight the importance of integrating PV technology into urban planning and building design to achieve long-term energy efficiency and sustainability.

Recent studies have investigated the impact of rooftop PV panels on building energy consumption. A study conducted by Albatayneh, et al. [18] investigated the shading effect of PV panels on building energy consumption. The case study focused on residential buildings in a humid climate. The simulation software, DesignBuilder, was used to calculate the effects of variations in energy load on a monthly basis. The results indicate a reduction in energy loads of 290 kWh/year for cooling and 30 kWh/year for heating, respectively. These findings demonstrate the potential of renewable energy to produce power, decrease the energy demands of residential buildings, and contribute to sustainable development. In a similar focus on another country, Dang and Nguyen [19] aimed to quantify the benefits of utilizing rooftop PV panels for energy efficiency by assessing their impact on energy performance. This case study examined a residential building in Vietnam. The calculations of potential energy generated by the panels revealed a decrease in roof heat transfer, leading to lower cooling loads and total energy consumption. Additionally, there was a reduction in the temperature of the roof surface, including both the inner and outer layers, as well as the attic space. The results indicate that installing rooftop solar panels not only generates energy but also lowers energy bills and reduces total energy consumption through shading effects.

Studies examining the effect of PV shading in various locations include the work of Albatayneh and Albadaineh [20] who evaluated the impact of PV panel shading on buildings' energy consumption. Their study involved three buildings situated in different climate zones of Jordan: Mafraq, Aqaba, and Amman, to assess the effects of PV shading. These buildings are typical low-rise residential structures, each with an area of 180 m². Additionally, the performance of three different simulation software programs, DesignBuilder, Revit, and Integrated Environmental Solution-Virtual Environment (IES-VE), was assessed. The results indicated a reduction in energy consumption across all locations, with the most significant decrease of 12.4% in Mafraq and an increase in heat of up to 15.4% in Aqaba. However, there were substantial differences among the simulation software results. Similarly, Alasadi, et al. [21] investigated the influence of PV shading on building energy consumption in three different states in the U.S.: Dayton, Boise, and Phoenix. They studied several tilt angles of the PV panels to identify the optimal shading angle. The roof area examined in all three locations was consistent at 1800 m² (30 m in width and 60 m in length). The findings revealed variations in energy savings among the locations, with the lowest savings of 2654 kWh in Dayton and the highest at 5991 kWh in Phoenix. The difference in PV effectiveness can be attributed to clear skies and high solar irradiation in the Phoenix area. The shading provided by the PV panels on building roofs reduces cooling loads during the summer, while increasing heating loads during winter.

The integration of PV with green roofs was evaluated in the study by Zheng and Weng [22]. The authors examined the effects of green roofs and photovoltaic panels on building energy consumption. The case study building is located in California, USA, with the aim of mitigating climate change. Energy modeling was conducted using EnergyPlus to analyze the impact on building energy demand. The selected building was one of the most vulnerable to climate change. Energy simulations were performed at hourly intervals, with building energy consumption analyzed on a monthly basis over a one-year period. The results revealed that all buildings in the case study experienced a reduction in energy consumption related to the integration of green roofs and PV panels. Most of the energy savings were found in the HVAC systems. Zubair, et al. [23] aimed to design a net-zero energy building. An analysis of renewable energy from PV and wind turbines was performed with various configurations. The shading effects of PV on the building roof and the associated cooling loads were studied, alongside the shading on the panels. The case study took place in a hot climate in Saudi Arabia, specifically at the College of Engineering, covering a total area of 4,859 m². SketchUp Pro and EnergyPlus were used to develop the building model and assess its associated energy consumption. The results of covering the entire building roof with PV as a shading device indicated a 12.3% reduction in the required building cooling load. Consequently, energy costs decreased, partially offsetting the initial investment in the PV system. The benefit of combining wind turbines with the PV system in the building is that PV is limited to energy production during sunlight hours. In contrast, wind turbines can generate energy throughout the day.

The energy demand was evaluated using various combinations of building energy simulation software. Jafari and Salavatian [24] studied the effects of PV shading on building energy consumption. The study was conducted in an office building located in a hot arid climate in Iran. DesignBuilder simulation software was used to develop the 3D model and estimate energy consumption. The placement of 15 PV panels on the building's roof results in reduced energy consumption. The system demonstrates an energy efficiency of 35.5% in reducing heating energy, producing energy, and controlling daylight simultaneously. In another study, Albatayneh, et al. [25] examined the impact of PV roof panel shading on building energy consumption. The case study was conducted in Jordan in a semi-arid climate. The effects of PV panels were explored using a combination of Autodesk Revit and IES-VE software. Revit was used to develop the 3D model of the residential building. At the same time, IES-VE estimated building energy consumption and evaluated the thermal impact of using PV panels as a shading device on the building's energy demand. The simulation results indicate that the PV panels provided a cumulative insolation of 1132 kWh/m2 on the rooftop, available for energy generation, and reduced the energy cooling load by 5.54%. Peres, et al. [26] aimed to study the effect of PV shading devices on building energy consumption. Several configurations of PV were explored using Rhinoceros 5.0, Honeybee, and the Ladybug plugin. The PV is positioned on building window facades as louvers. The simulation analyzed varying numbers of louvers, from one to four. The results indicate an energy generation of up to 990 kWh of electricity and a reduction in building cooling by 14-19%. Consequently, the building's energy demand decreased by 32% with the integration of the PV shading device. Understanding the behavior of occupants in higher education buildings with fixed schedules is important, as it can help utilize the building more efficiently and decrease energy consumption [27, 28]. Thus, knowing the current and future number of occupants can improve the operation of high-density buildings. Several studies have developed prediction models critical for energy estimation [29, 30].

This paper makes a significant contribution by thoroughly analyzing the impact of indirect shading from rooftop PV panels on roof heat transfer in a hot desert climate. A detailed 3D architectural model is created using Autodesk Revit as the basis for building energy simulations with DesignBuilder. Importantly, this work introduces an innovative approach to utilizing unused building rooftops for PV installations in Saudi Arabia, across various sectors, including residential, educational, and commercial buildings. The study carefully examines optimal panel spacing to reduce solar irradiation on surfaces and enhance shading effectiveness. The optimized PV shading significantly lowers building energy consumption, highlighting the role of solar energy in promoting sustainable building design and reducing energy demands. This research offers valuable insights for integrating solar technologies into building roofs, supporting energy efficiency and sustainable development in arid regions.

2. Methods

This section describes how to determine if shading roof PV panels benefits building energy use. It starts by converting the 2D drawing into a 3D model with Revit for the case study building. Then, the 3D model is imported into DesignBuilder simulation software for PV placement and energy analysis. The software helps to understand the thermal performance of the baseline model by calculating energy consumption with and without PV panels shading the roof. Figure 1 shows the process outlined in the paper.

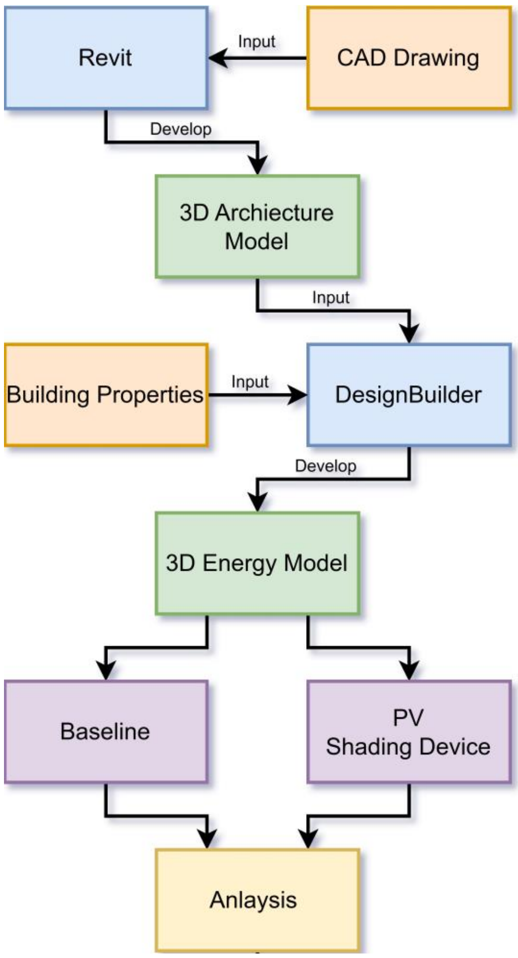

Figure 1.
Framework for analyzing the Influence of Roof PV Shading Device on Building Energy Consumption.

2.1. Case Study Building

The case study building is an educational building located on the campus of Imam Abdurrahman Bin Faisal University in Dammam, Saudi Arabia. It serves academic purposes and is occupied by students from the College of Architecture and Planning. Figure 2 illustrates the building used in the case study. The building encompasses an area of approximately 8,000 m², featuring three above-ground levels. Its dimensions are 170 meters in length, 80 meters in width, and 19 meters in height. The roof area, including stair shafts, skylight openings, and other structures, is not entirely empty. The 2D AutoCAD file was used as input in Revit software (version 25.4.0.32) to develop a 3D model of the building.

Figure 2.
Exterior Envelope of the Case Study Building.

2.2. PV Panel Specifications

The PV module used in this study is Monocrystalline (mono-Si), which produces 550 W. An important aspect of this study is the panel dimensions, as the goal is to analyze shading effects. The panel area measures 2.58 m², with dimensions of 2.28 m in length, 1.13 m in width, and 0.35 m in thickness. Sets of panels are mounted in an aluminum frame. Table 1 summarizes the manufacturing specifications of the PV panels used [31].

Table 1.
Manufacturing specifications of the photovoltaic panel.

Parameter	Value
Photovoltaic Type	Monocrystalline
Max Power (Pmax)	550 W
Max Power Voltage (Vmp)	41.96 V
Max Power Current (Imp)	13.11 A
Open Circuit Voltage (Voc)	49.90 V
Short Circuit Current (Isc)	14.00 A
Module Efficiency (%)	21.28%
Operating temperature	-40~+85°C
Max System Voltage	DC 1500V
Maximum Series Fuse Rating	25A
Module Efficiency	21.28%
Power Tolerance	0~+3%
Solar Cell Number	144 cells (Half-Cell)
Solar Cells Dimension	182mm x 91mm
Panel Dimension	228mm x 113mm x 35mm

2.3. Energy Simulation Model

The simulation software used in this paper was DesignBuilder (v7.3.1.003). This software, DesignBuilder, integrates with EnergyPlus as its engine. DesignBuilder is one of the most used simulation tools due to its comprehensive suite of features, including energy analysis, assessments, occupant schedule inputs, and energy modeling [32]. The DesignBuilder simulation utilized the developed 3D model in Revit to input for PV placement and to estimate building energy consumption. The estimation of building energy was conducted in two scenarios. The first scenario estimates the building's energy consumption before the placement of the PV as a baseline. The second scenario simulates the building after integrating PV panels to evaluate the shading effects on the building's roof and the associated energy demand.

2.4. Climate Zone

The case study building is located in the eastern province of Saudi Arabia. According to the Köppen climate classification, the city's climate is categorized as a hot desert climate (BWh) [33]. The seasons can be divided into three parts: hot, moderate, and cold. The hot season lasts about four and a half months, from May to September. During this season, the average daily high temperature exceeds 40 °C, with the highest temperature occurring in July and the coldest temperature dropping to 28 °C. The cold season typically lasts from December to March. During this period, the average daily high temperature is above 23.5 °C, with the lowest temperature recorded in January, which drops as low as 13 °C. Figure 3 illustrates the average high and low temperatures in Dammam City throughout the year, presented in monthly intervals [34].

The length of the day, along with sunrise and sunset times, varies depending on the month of the year. Throughout 2024, Dammam City will experience the shortest daylight period of 10 hours and 30 minutes in December and the longest daylight period of 13 hours and 50 minutes in June. The earliest sunrise falls between approximately 4:50 AM and 6:30 AM, depending on the month, while the sunset can occur as early as 4:50 PM in November and as late as 6:30 PM in July. Consequently, the extended hours of sun exposure and high solar irradiance are advantageous for solar panel energy collection. Figure 4 illustrates the daylight hours for each month [34]. The building's location and the accompanying sunlight are key factors that can influence the impact of PV shading on rooftops and their energy production. The potential excess energy generated in such areas can either be stored or sold back to the grid. However, storing electricity necessitates space, several precautions, and processors based on the available battery technology in the country [35].

The average daily solar radiation level in Saudi Arabia can reach up to 6.7 kWh/m², due to its geographic location, which experiences 80-90% clear skies throughout the year [36, 37]. Figure 5 indicates that the country receives over 2480 kWh/m² of solar radiation annually [38]. In Dammam city, the daily solar radiation is approximately 5.9 kWh/m², totaling about 2200 kWh/m² annually. The energy demand in Saudi Arabia is rapidly increasing due to extensive infrastructure projects nationwide, with an estimated annual growth rate of 19%. In line with Saudi Arabia's 2030 vision, the country aims to generate 9.5 GW of clean energy by 2030 [39].

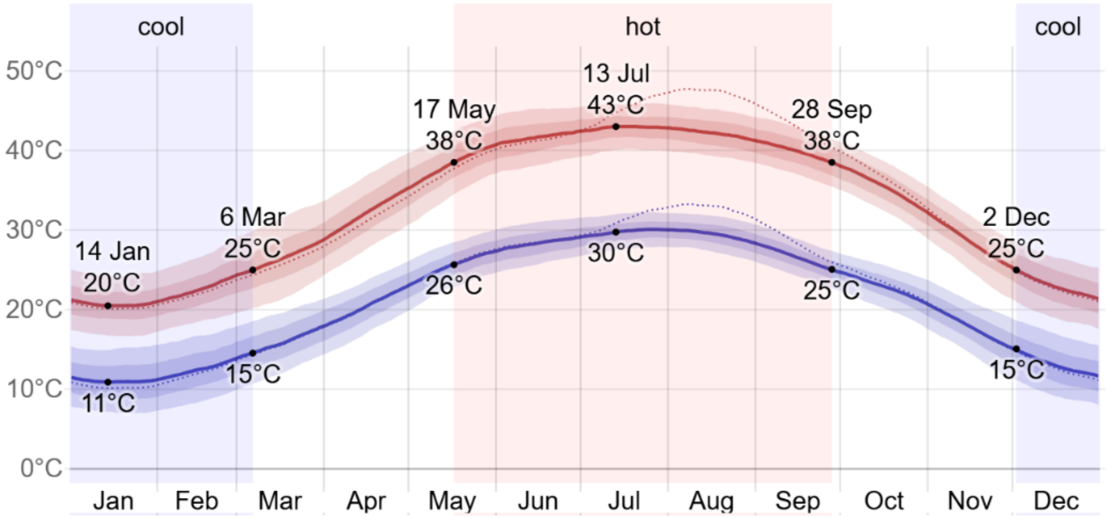

Figure 3.
The average temperature in Dammam City throughout the year is shown; the red line and blue line indicate high and low temperatures, respectively.

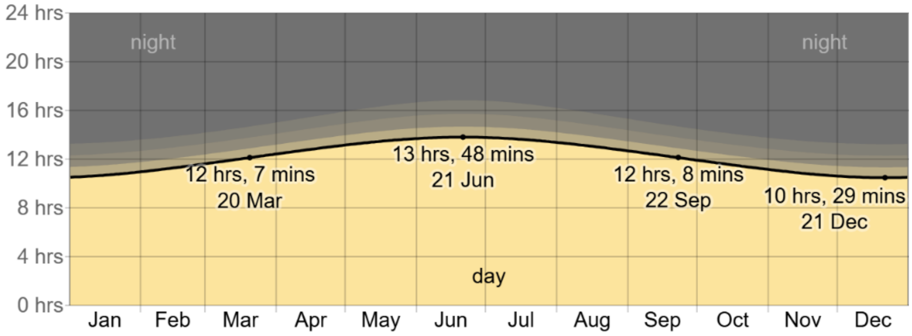

Figure 4.
Daylight hours in Dammam city by month.

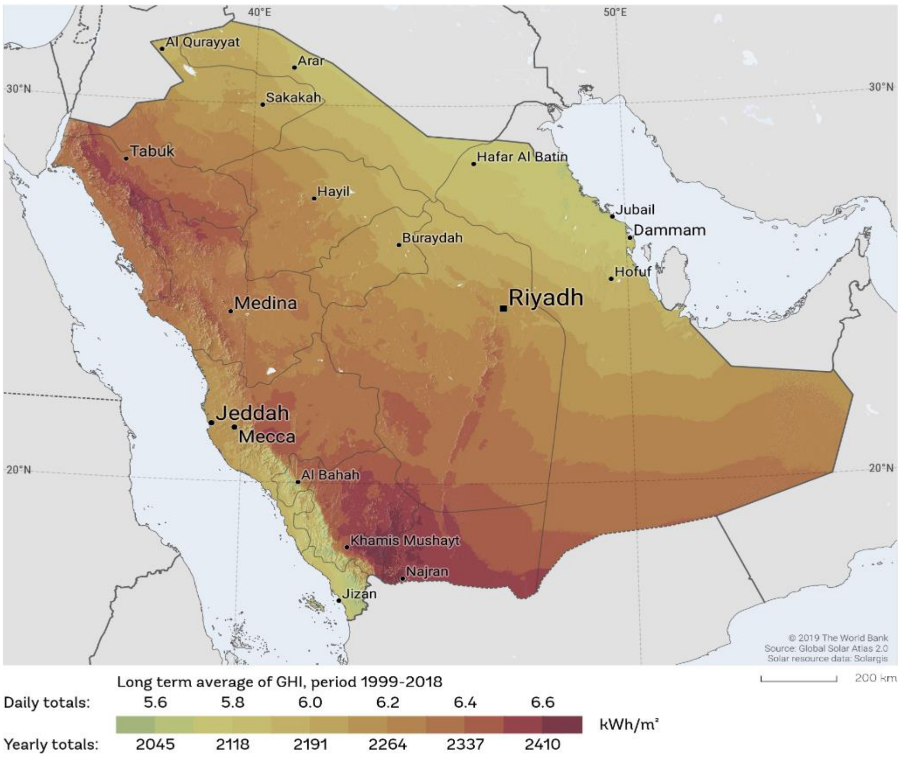

Figure 5.
Horizontal irradiation across Saudi Arabia.

3. Results

This section outlines the processes leading to the study results. It includes an analysis of the building roof to identify the optimal space for placing the PV panels, followed by the development of a 3D model in Revit, which is then used as input in DesignBuilder for the placement of PV panels. Finally, an analysis of the heat transfer from the building roof assesses the impact of PV shading on building energy consumption.

The analysis of the building's roof area reveals several points. The main issue is that the roof cannot be fully occupied with PV panels. This limitation is due to the space required for circulation and walking to and around the existing structure. Approximately 60% of the roof area can be utilized for placing the PV panels, which is equivalent to 4,305 m^2 out of the total roof area of 7,175 m^2. Figure 6 illustrates the designated area for PV panels, highlighted in blue. The developed 3D model at Level 3 of detail used Revit for greater accuracy and reliability of the associated results. The model was then utilized as input in DesignBuilder to place the PV panels on the building's roof, followed by an analysis of the effect of PV shading on the building's energy consumption. A total of 830 panels were placed, covering an area of 2,141.4 m^2. Figure 7 shows the 3D model of the case study with the integrated PV on the roof.

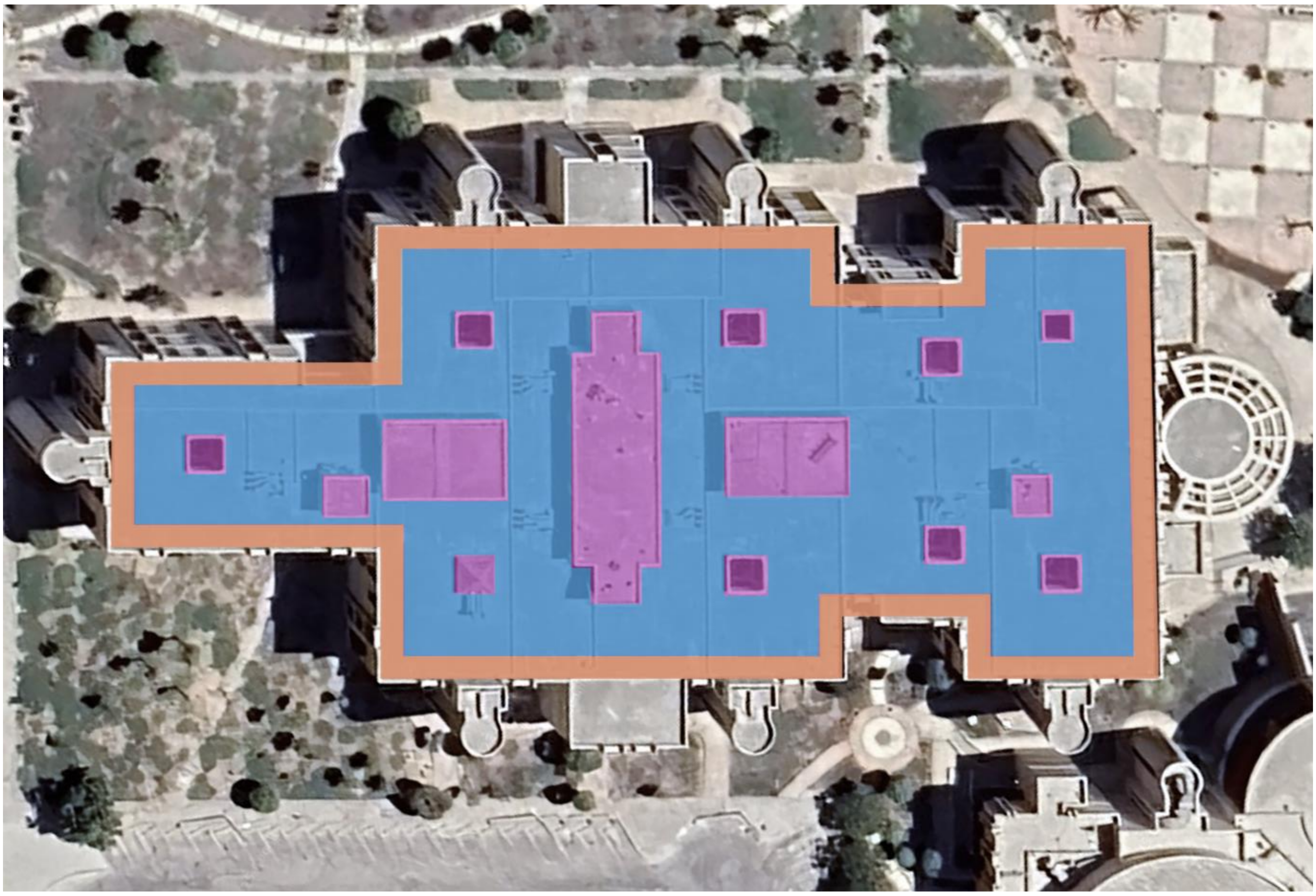

Figure 6.
Highlighting different areas on the roof. The orange color indicates circulation, the pink color designates existing structures, the gray color represents the shadow cast by the structure, and the blue color is specified for placing the PV panels.

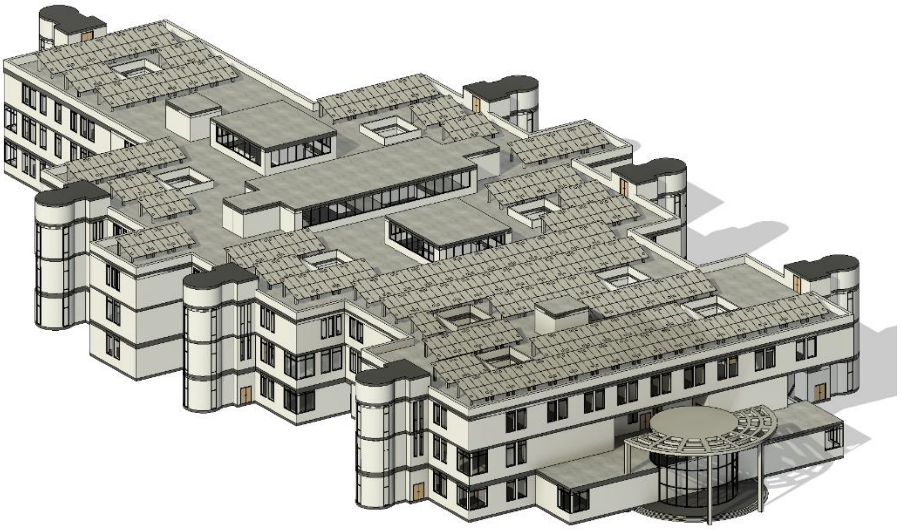

Figure 7.
3D model featuring integrated PV panels on the roof of the case study building.

The calculation and analysis of roof surface heat transfer were conducted in two distinct scenarios to understand the passive effect of PV roof shading on building energy consumption. In the first scenario, a baseline was established by estimating the heat transfer from the roof surface before installing the PV. This baseline measurement is crucial for evaluating the subsequent effects of the PV panel installation. The simulation results during cold weather months, January, February, March, April, November, and December, were recorded. The heat transfer from the roof surface during cold weather stood at –38,741.72 kWh, indicating a significant outflow of heat from the building. During the hot weather months of June, July, August, September, and October, the roof heat transfer was 61,167.52 kWh, indicating that considerable heat was entering the building through the roof surface. The second scenario involved integrating the PV panels on the case study building roof, aiming to explore their shading effects on surface heat transfer and the associated building energy consumption. This scenario is important as it assesses how the addition of roof PV panels not only impacts energy generation but also influences thermal dynamics within the building. The simulation results indicate that with the PV panels in place, the heat transfer from the roof surface was –48,212.00 kWh during cold weather (January, February, March, April, November, and December) and 47,525.97 kWh of heat gain entering the building during hot weather (June, July, August, September, and October).

Figure 8 shows the roof heat transfer data from the case study building at monthly intervals. These values are significant as they indicate the thermal dynamics of the building's surfaces over one year. The positive value indicates that heat is entering the building through the roof surface, primarily during periods of hot weather. Conversely, negative values reveal that heat is exiting the building through the surface; this is most prevalent during colder weather conditions. This phenomenon occurs particularly when the temperature inside the building exceeds that of the outside environment, thus creating a gradient for heat transfer.

The results of analyzing the heat transfer data for both the baseline and simulated PV shading device reveal several insights, shown in Table 2. During hot weather, the total heat transfer in the baseline building through the roof was 61,167.52 kWh, which is higher than the simulation results with PV panels installed on the roof. The placement of the PV panels demonstrates a reduction in heat transfer to the building by 22.30%, which is equivalent to 13,641.55 kWh. However, the analysis revealed a contrasting outcome during cold weather; in this case, the heat loss from the building was greater with the PV panels installed on the roof. The total heat transfer through the roof in the scenario without PV was 38,741.72 kWh. When PV panels were present, heat loss increased by 19.64%, resulting in an additional loss of 9,470.28 kWh. This dichotomy in performance underscores the nuanced effects of PV installations on building energy dynamics, highlighting the need for careful consideration in both the design and implementation phases.

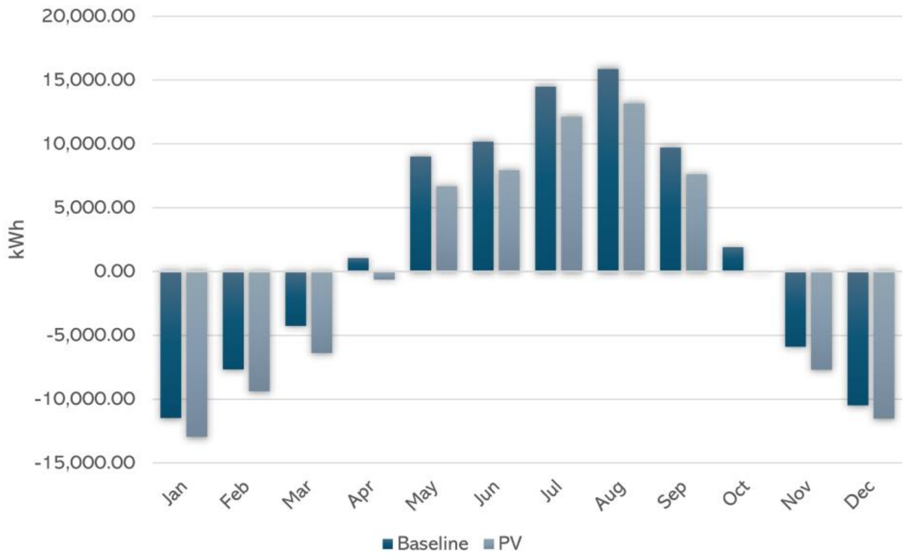

Figure 8.
Monthly heat transfer data for both the baseline and simulated PV shading device.

Table 2.
Roof heat transfer of the building with and without PV over one year.

Month	Baseline	PV Shading Device	Difference
January	– 11,478.22	– 12,946.49	1,468.27
February	– 7,680.56	– 9,382.69	1,702.13
March	– 4,265.49	– 6,391.18	2,125.69
April	1,060.25	– 634.12	754.89
May	9,013.92	6,680.86	2,333.06
June	10,178.67	7,929.84	2,248.83
July	14,481.33	12,126.29	2,355.04
August	15,866.93	13,164.76	2,702.17
September	9,721.87	7,609.33	2,112.54
October	1,904.79	14.89	1,889.90
November	– 5,893.38	– 7,696.13	1,802.75
December	– 10,484.33	– 11,531.39	1,047.06

Another statistical analysis, a paired t-test, was performed to confirm the robustness of the observed differences in thermal performance. A t-test was conducted to compare monthly roof heat transfer values before and after the installation of PV panels. Two hypotheses were tested: H0 (the null hypothesis) and H1 (the alternative hypothesis). H0 indicated no difference between the two variables, while H1 indicated a significant difference in heat transfer when installing the roof PV panels. Using formula (1), where d is the mean of the difference between the two observations, Sd is the standard deviation of those differences, and n is the number of pairs (12 months).

$$t = d / (Sd / \sqrt{n}) \qquad (1)$$

The result of the analysis yielded a t-value and a p-value. The t-value is 4.34, and the p-value is 0.0012. Since the p-value is smaller than 0.05, the difference is statistically significant at the 95% confidence level. The results support the descriptive analysis that rooftop PV alters the thermal behavior of the roof, which validates the effectiveness of the passive shading strategy.

4. Conclusion

This study comprehensively analyzed the influence of rooftop PV panels on the thermal performance of an educational building located in Dammam, Saudi Arabia, with a particular focus on their passive shading effects within a harsh, hot desert climate characterized by extremely high temperatures and intense solar radiation. Utilizing advanced 3D modeling techniques via Revit software combined with dynamic energy simulations through DesignBuilder, the study conducted a detailed comparative assessment of roof heat transfer processes under two scenarios: with and without PV panel installations.

The results demonstrated that PV panels significantly reduced roof heat gain by approximately 22.30% during the peak summer months, thus decreasing the cooling loads necessary to maintain indoor thermal comfort. In contrast, during the winter season, the presence of PV panels contributed to a 19.64% increase in heat loss, leading to higher heating demands. Statistical analysis, including a t-test, confirmed the significance of these seasonal variations at the 95% confidence level, underscoring the dual functionality of PV panels not only as renewable electricity generators but also as passive shading devices that influence thermal dynamics. These findings highlight the importance of incorporating seasonal and climate-specific variables into building design to maximize overall energy efficiency. The research highlights that PV shading can serve as a highly effective passive strategy for enhancing energy performance in buildings located in arid, hot environments, such as Dammam City, Saudi Arabia. Such insights align with Saudi Arabia's Vision 2030 objectives to promote dual-function renewable energy systems that generate electricity while simultaneously improving thermal performance. Recommendations for future research include examining the effects of different panel tilt angles and configurations to optimize both energy production and shading efficacy across seasons. Additionally, integrating rooftop PV panels with other passive cooling measures, such as green roofs, reflective surfaces, or shading devices, may further enhance heat reduction and energy savings in hot climates. Overall, the findings highlight the crucial role of climate-sensitive, tailored design strategies in maximizing the benefits of renewable energy infrastructure in arid regions, thereby contributing to sustainable building practices and advancements in energy efficiency.

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