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Optimization and Performance Analysis of Photovoltaic Panels for Reducing Building Energy Consumption in the Bushehr Climate: A Hybrid Study

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ABSTRACT

The global challenges posed by population growth, increasing energy demand, and the depletion of fossil fuel resources have intensified the need for sustainable energy solutions. In this context, renewable energy sources particularly solar energy have emerged as key alternatives due to their sustainability and environmental compatibility. This study analyzes and optimizes a photovoltaic (PV) system aimed at reducing building energy consumption in the hot and humid climate of Bushehr, Iran (latitude 28.92°N). Simulations were conducted using the TRNSYS software, evaluating the influence of factors such as building insulation, window-to-wall ratio, and panel tilt angle on system performance. The results indicate that south-facing PV panels installed at an optimal tilt angle of 25° can reduce building energy consumption by up to 25%. During summer months, the system decreased cooling loads by as much as 20% and partially met heating demands in winter. Additionally, the annual energy cost savings shortened the payback period to 8.33 years, while reducing annual CO₂ emissions by approximately 1.17 tons. These findings highlight the significance and effectiveness of PV systems in reducing energy consumption and environmental impact in similar climatic regions.

Keywords: Solar energy, building energy, economic analysis, payback period, photovoltaic panels, energy savings, TRNSYS software.

1 Introduction

In recent decades, rapid population growth and increasing energy demand, coupled with the depletion of fossil fuel resources, have motivated the global community to adopt renewable energy sources. Among these, solar energy has emerged as one of the most effective means for electricity generation due to its abundance, cleanliness, and potential to reduce greenhouse gas emissions [1]. Solar power has significantly contributed to reducing dependency on fossil fuels. According to the REN21 report, global solar energy capacity exceeded 1,180 GW in 2022, marking a 22% increase from the previous year. This rapid growth reflects the heightened interest of policymakers and investors in expanding solar energy deployment [2].

Buildings account for approximately one-third of global energy consumption and significantly contribute to greenhouse gas emissions, placing increasing pressure on energy systems due to urbanization and rising demands for heating and cooling. It is projected that building energy consumption will grow at an average rate of 1% annually, leading to a 35–40% increase by 2035 if no mitigation measures are implemented [3]. In this context, technologies such as photovoltaic (PV) panels, which generate electricity from solar energy, can play a crucial role in reducing energy consumption and enhancing environmental sustainability.

Recent studies conducted between 2021 and 2023 have demonstrated that rooftop PV systems not only produce clean energy but also alleviate heating and cooling demands. For instance, optimal panel orientation and tilt were found to enhance overall system efficiency by up to 25% [4]. The impact of PV panels on reducing cooling loads in hot and humid climates was investigated, reporting significant improvements in building energy performance [5]. PV systems were also shown to reduce operational costs, offering payback periods of less than 10 years [6]. Furthermore, several studies have utilized TRNSYS software to simulate PV system performance. The effects of solar radiation and temperature on panel efficiency were examined, demonstrating that proper parameter optimization could enhance annual system output by up to 18% [7]. The combined impact of thermal insulation and PV installation was evaluated using TRNSYS, resulting in a reported 22% reduction in building energy consumption in similar climates [8].

The primary objective of this study is to evaluate and optimize the performance of PV panels in reducing building energy consumption under the climatic conditions of Bushehr, a region characterized by its hot and humid environment, which presents unique challenges for solar system design and implementation. Utilizing local climatic data and TRNSYS simulations, this research examines the effects of PV panel installation on cooling and heating loads, as well as the economic and environmental impacts of such systems. The findings aim to provide practical solutions for improving energy efficiency and reducing costs in similar regions.

Moreover, policy barriers, financial uncertainties, and practical implementation challenges remain significant obstacles for expanding rooftop PV deployment in residential buildings located in hot and humid regions [9].

Recent advancements in building-integrated photovoltaics (BIPV) and passive cooling strategies have further reinforced the potential of combining architectural design with renewable energy systems to enhance energy performance in residential buildings [10], [11]. Additionally, machine learning and optimization algorithms such as genetic algorithms and particle swarm optimization are increasingly employed to determine the optimal sizing and orientation of PV systems [12], [13]. Several studies have investigated the economic and environmental trade-offs of advanced PV technologies, including bifacial and PERC modules, particularly in humid coastal regions similar to Bushehr [14], [15].

Moreover, research indicates that integrating energy storage systems with smart inverters and demand-side management significantly enhances energy resilience in residential setups [16], [17]. These technologies provide effective pathways toward achieving near-zero energy buildings in sun-rich regions through intelligent energy balancing and peak-shaving strategies [18].

A wide range of recent and domain-specific studies (2021–2023) have been reviewed in this work to support the technical, economic, and environmental analyses of rooftop PV systems in residential buildings.

The remainder of this paper is structured as follows. Section 2 presents the system and building specifications, including details of the photovoltaic system and the case study building. Section 3 outlines the modeling approach, governing equations, and simulation process using TRNSYS software. Section 4 discusses the simulation results, including system efficiency, energy savings, and economic analysis. Finally, Section 5 provides the conclusion, summarizes the key findings, and offers suggestions for future work.

2 System Description and Specifications

Figure 1 illustrates the schematic layout of the studied system. The diagram shows the interconnection between photovoltaic panels, the inverter, and battery storage, as well as the energy distribution throughout the building. The components of the system and their respective functions are as follows:

- **Photovoltaic (PV) Panels:** Generate direct current (DC) electricity from solar radiation.
- **Inverter:** Converts the DC electricity generated by the panels into alternating current (AC) electricity suitable for building use.
- **Charge Controller:** Regulates the electrical current to prevent overcharging or deep discharging of the batteries.
- **Energy Storage Batteries:** Store the generated electricity for use during low irradiance periods or nighttime.
- **Electrical Panel and Distribution System:** Distributes electrical power within the building.

- **Monitoring and Control System:** Supervises overall system performance and optimizes energy usage.

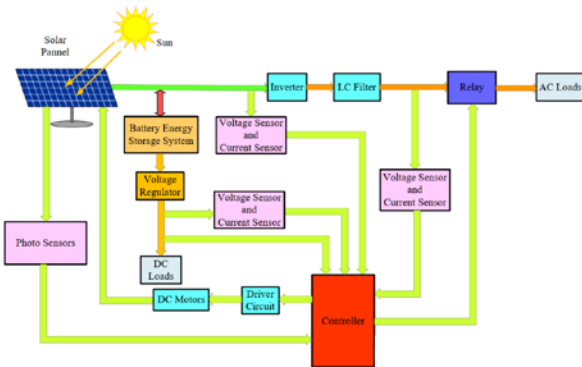


Figure 1. Schematic diagram of the photovoltaic system under study

Although the PV system is modeled as grid-connected, in the specific context of Bushehr, Iran, policies related to net metering and feed-in tariffs are still evolving. While some national incentive programs exist, their implementation and financial mechanisms vary and remain inconsistent across regions. In this study, grid interaction was simplified and no economic exchange with the utility was modeled, due to the absence of reliable and standardized regulatory frameworks. Future system deployment will benefit significantly from more stable and supportive grid policies [19].

2.1 Building Specifications

The case study focuses on a two-story residential building with a total floor area of 200 m², located in Bushehr, Iran. The building is designed with consideration for the region's hot and humid climate. To address the specific climatic challenges, the building incorporates effective thermal insulation, external shading devices, and an optimized window-to-wall ratio, all aimed at minimizing energy consumption for cooling and heating. The main features of the building are summarized in Table 1.

Table 1. Building Characteristics

Parameter	Specification
Building Type	Residential
Total Floor Area	200 m ²
Number of Floors	2
Roof Material	Reinforced concrete with thermal insulation
Wall Material	Brick with thermal insulation
Window Glazing	Double-glazed with UV-protective coating

The reinforced concrete roof is thermally insulated to minimize heat transfer into the building. The exterior walls are constructed from brick and covered with a layer of thermal insulation to reduce cooling and heating loads. All windows are fitted with double-glazed, UV-resistant glass to minimize direct solar gain and prevent energy losses. Additional features include an optimized HVAC system and external shading devices to reduce the impact of solar radiation. The overall thermal resistance of the walls is 0.45 m²·K/W, which significantly enhances the building's energy efficiency.

Detailed specifications of the roof, floor, and walls are presented in Table 2.

Table 2. Overall Thermal Resistance Values for Building Envelope Components

Component	Construction Layers	Thickness (m)	U-Value (W/m ² ·K)	R-Value (m ² ·K/W)	U-Value (W/m ² ·K)
Roof	Reinforced concrete, mortar, sand and gravel, low-density concrete, roof tiles, bitumen, plaster	0.36	2.04	0.49	0.73
Floor	Reinforced concrete with gravel, a soil layer covered with mortar and ceramic floor tiles	0.225	1.2827	0.78	0.29
External Wall	Stone, reinforced concrete, thermal insulation, plaster layer, brick layer	0.40	0.28	3.57	0.12
Internal Wall	Brick with plaster layers on both sides	0.125	1.87	0.54	0.23
Glazing (Window)	Double-glazed glass (6 mm glass layers with 13 mm air gap)	0.025	2.7834	0.36	0.07

2.2 Photovoltaic Panels

The installed photovoltaic (PV) panels consist of monocrystalline silicon modules with an efficiency of 20% and a total system capacity of 5 kW. The system is installed on the rooftop of the building, with an initial tilt angle of 25° facing south. The technical specifications of the PV system are provided in Table 3.

Table 3. Specifications of the Photovoltaic Panels

Parameter	Specification
Panel Type	Monocrystalline
Total Panel Area	25 m ²
Panel Efficiency	20%
Total System Capacity	5 kW
Installation Angle	25° South
Panel Lifespan	25 years

3 System Modeling and Simulation

This section outlines the methodology used to model and simulate the integrated photovoltaic system and its interaction with the building energy profile under the climatic conditions of Bushehr. The modeling approach incorporates physical equations governing the behavior of key system components, including photovoltaic power generation, energy storage, and building energy demand.

3.1 Governing Equations

To model and analyze the performance of the photovoltaic system integrated with building energy dynamics, the

following equations were employed. These equations describe the power generation by the PV system, energy storage in batteries, building energy consumption, overall system efficiency, and CO₂ emissions reduction. Each equation is numbered for ease of reference.

PV Output Power [20]:

$$P_{pv} = \eta_{pv} \cdot A_{pv} \cdot G \quad (1)$$

Where:

- P_{pv} is the electrical power output from the PV system (W)
- η_{pv} is the panel efficiency
- A_{pv} is the total surface area of the PV panels (m²)
- G is the solar irradiance (W/m²)

Stored Energy in Batteries [21]:

$$E_{Batt} = \eta_{Batt} \cdot \int (P_{pv} - P_{load}) dt \quad (2)$$

Where:

- E_{Batt} is the stored energy in the battery system (Wh)
- η_{Batt} is the round-trip battery efficiency
- P_{load} is the building energy demand (W)

Building Energy Demand [22]:

$$E_{load} = E_{Cooling} + E_{Heating} + E_{appliances} \quad (3)$$

Overall System Efficiency [22]:

$$\eta_{system} = \frac{E_{output}}{E_{input}} \quad (4)$$

CO₂ Emissions Reduction [23]:

$$\Delta CO_2 = EF \cdot E_{grid-offset} \quad (5)$$

3.2 System Simulation Using TRNSYS

To analyze the performance of the PV system in the studied building, the TRNSYS software was used. TRNSYS is a comprehensive energy simulation tool capable of modeling various energy system components under realistic operating conditions. This allows researchers to examine the influence of different parameters on system performance. Figure 2 presents the simulation schematic implemented in TRNSYS.

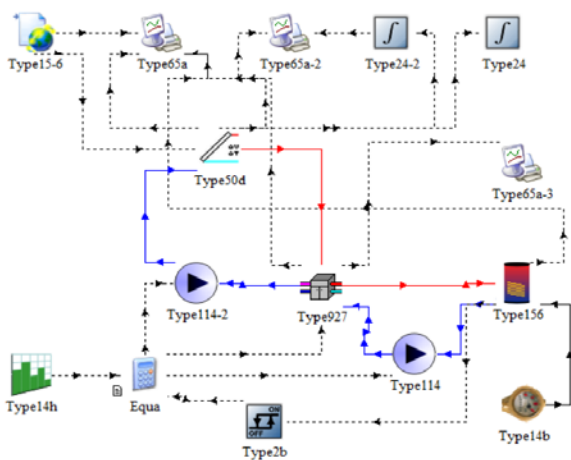


Figure 2. Simulation schematic of the system in TRNSYS software

3.3 Building Modeling

The building model was configured to closely match the actual thermal and physical properties of the structure. The specifications outlined in Tables 1 and 2 were input into the software. The HVAC system was modeled with a coefficient of performance (COP) of 3 for cooling and 2.8 for heating.

3.4 Photovoltaic Panel Modeling

The panel specifications were incorporated in detail within the model. While the nominal efficiency of the panels is 20%, this value is subject to variation due to temperature and irradiance levels. A temperature derating factor of 0.4% per degree Celsius above 25°C was included. Other parameters were modeled as listed in Table 3.

3.5 Climatic Conditions in Bushehr

Climatic data significantly affect the performance of PV panels and the building's energy consumption. Weather input data were sourced from the Meteorom database. Average daily temperatures are 35°C in summer and 25°C in winter. The annual average relative humidity is 70%, with annual solar irradiation around 2000 kWh/m² and an average wind speed of 3 m/s.

3.6 Energy Storage

The energy storage system employs lithium-ion batteries with a capacity of 10 kWh and a round-trip efficiency of 90%. The system stores excess solar energy during peak irradiance hours and discharges at night to meet building loads. The depth of discharge is set to 80% to enhance battery lifespan.

4 Results and Discussion

4.1 Model Validation

Final yield ($Y_{f,m}$) results obtained in this study were compared with experimental data reported by Hashim et al. (2022) [24]. The reference system was a 5 kWp rooftop grid-connected PV system installed at the Energy Research Center of the University of Khartoum, Sudan, where measured data were collected from April 2017 to March 2018.

As shown in Figure 3, the simulation results demonstrate good agreement with the measured values, with an average deviation of approximately 8.7%. The simulation consistently overestimated the energy output compared to the experimental data. This discrepancy can be attributed to several factors. First, the meteorological data used in the TRNSYS simulation are based on a 30-year average (typical meteorological year, TMY), which may not accurately reflect the specific weather conditions during the measurement period in 2017–2018. In contrast, the experimental study utilized real-time climate data

for that specific year, including short-term variations in irradiation, temperature, and dust accumulation.

Second, the actual PV system is subject to real-world energy losses such as soiling, inverter mismatch, wiring losses, and temporary shading, which are difficult to fully account for in simulation environments. These losses may result in lower real output compared to the idealized performance assumed in the software. Overall, the observed deviation of less than 10% falls within an acceptable range for PV system modeling, confirming the validity and robustness of the simulation approach applied in this study.

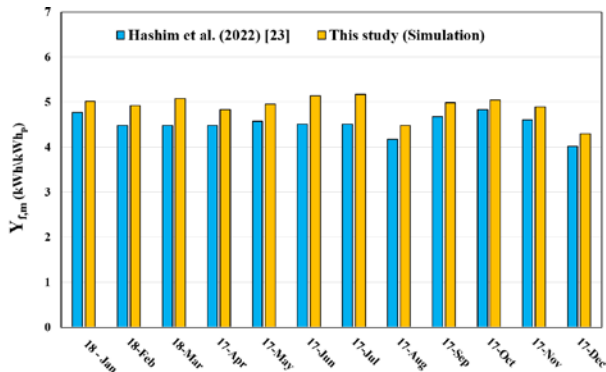


Figure 3. Validation of simulation results against experimental data from Hashim et al. (2022) [24]

4.2 Climate Data and Seasonal Considerations

The simulation in this study was conducted using a Typical Meteorological Year (TMY) file for the city of Bushehr, which includes hourly values for solar radiation, ambient temperature, humidity, and wind speed. This dataset represents average climatic conditions based on 30 years of historical weather records and was sourced from Meteonorm 8.0. Seasonal variations are clearly represented in the model and reflected in both the energy output of the PV system and the building's thermal loads. For example, maximum solar radiation and ambient temperatures occur during the summer months (June to August), leading to higher electricity generation and cooling demand. Conversely, during the winter months, solar radiation and temperature drop, reducing cooling loads while PV output also declines slightly.

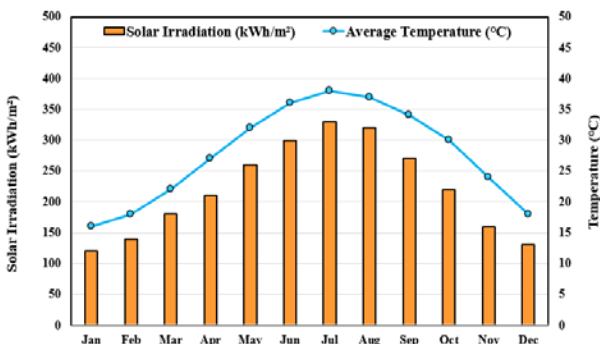


Figure 4. Solar irradiation and temperature levels in Bushehr city

These seasonal patterns are illustrated in Figure 4, which shows the monthly average ambient temperature and global horizontal irradiation (GHI) for Bushehr. The alignment of these variations with simulation outputs confirms that seasonal climatic dynamics were adequately captured in the modeling process [25].

4.3 Simulation Results

This section presents the results of the PV system simulation for reducing building energy consumption under the hot and humid climate of Bushehr. Solar irradiance reaches its peak in summer due to higher solar altitude and longer daylight hours, which also causes a corresponding rise in ambient temperature. Consequently, the cooling demand significantly increases during summer months. In contrast, lower irradiance and cooler temperatures in winter increase the heating load. Figure 5 demonstrates the impact of building insulation. The results clearly show a significant reduction in building load during both hot and cold months, attributed to reduced heat exchange through insulated walls, roofs, and floors. Insulation reduced annual energy consumption by approximately 30%–40%, yielding substantial cost savings and environmental benefits.

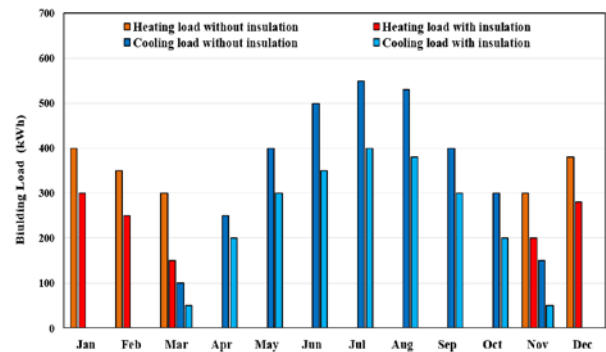


Figure 5. Effect of building insulation on building energy load

In addition to insulation, the window-to-wall ratio was examined (Figure 6).

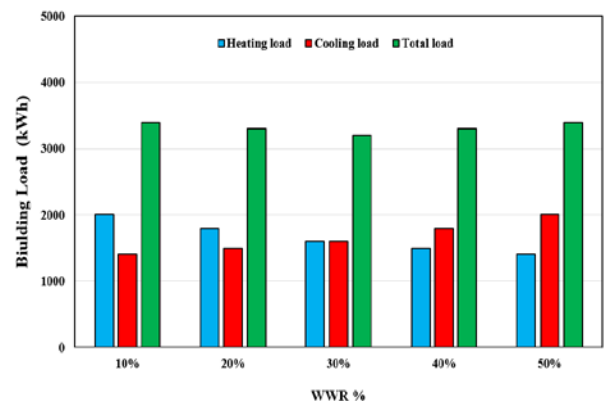


Figure 6. Impact of window-to-wall ratio on building energy load

Increasing this ratio led to higher cooling loads in summer due to enhanced solar heat gain, but slightly reduced heating loads

in winter by allowing more solar radiation to enter the interior space. The optimal window-to-wall ratio was determined to be around 30% to balance these seasonal effects.

Using the optimized window-to-wall ratio and insulated envelope, the heating and cooling loads were simulated (Figure 7). From May to September, cooling loads peaked exceeding 400 kWh in July and August. Heating loads rose from December to February, reaching up to 300 kWh in January. The significant summer cooling load emphasizes the need for sufficient energy generation. Rooftop PV panels help mitigate this load by acting as thermal shades and reducing heat gain.

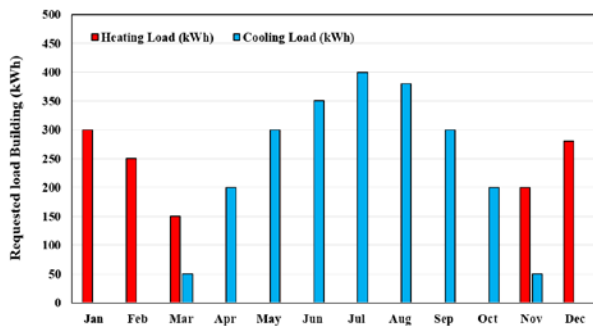


Figure 7. Heating and cooling load of the building

The tilt angle of PV panels significantly influences annual energy output. Figure 8 shows the energy production at various tilt angles. For the climate of Bushehr, a 25° tilt angle provides optimal year-round performance. In summer, a lower tilt angle increases vertical irradiance capture, while in winter, a steeper tilt helps maximize energy absorption from the low-angle sun. A fixed 25° tilt offers a good compromise, minimizing the need for seasonal adjustments and ensuring stable output.

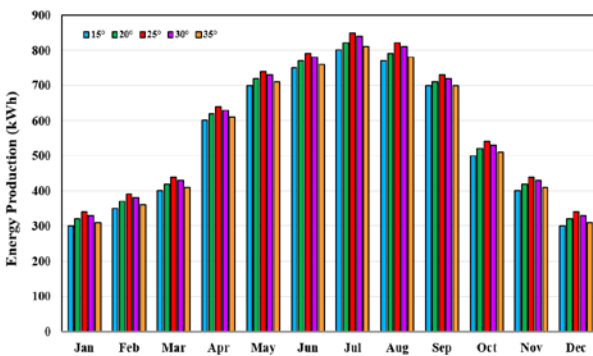


Figure 8. Effect of different tilt angles on energy production

System efficiency, which reflects the effectiveness of energy conversion under varying conditions, is shown in Figure 9. The PV system's monthly efficiency varied from 40%–50% in the winter to 70%–80% in the summer. The drop in winter efficiency is attributed to shorter days and lower sun angles, while increased irradiance and daylight hours enhance summer performance. The system peaked at around 80% efficiency during June to August, indicating optimal operation during this period.

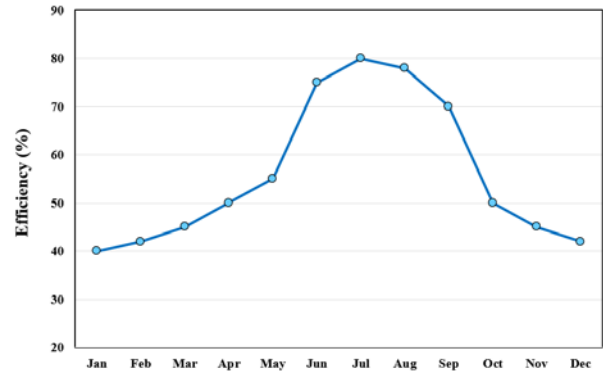


Figure 9. Photovoltaic system efficiency across different months of the year

Figure 10 illustrates the amount of energy stored in the batteries, which reflects the system's capability to retain surplus energy generated and utilize it when needed. The analysis shows that energy storage is significantly influenced by solar irradiance levels and the building's energy consumption. Results indicate that battery performance is particularly effective during the summer months, when a major portion of the building's energy demand is met through stored solar energy. However, during the winter season, due to reduced energy generation, the batteries are unable to fully meet the building's energy needs, necessitating reliance on auxiliary energy sources.

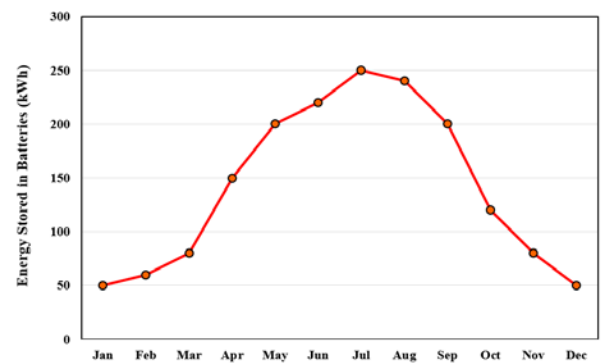


Figure 10. Energy stored in the batteries

Figure 11 presents the monthly energy produced by the photovoltaic (PV) system alongside the building's energy consumption.

During summer months, the PV system reaches its peak annual production due to high solar irradiance and extended daylight hours. In June and July, the system is capable of supplying up to 90% of the building's energy needs. This high production enables surplus energy to be stored for nighttime use. Conversely, from October to March, energy production declines due to lower solar irradiance, reduced sun angles, and shorter days. In January, the system reaches its lowest output, supplying only about 40% of the building's energy demand.

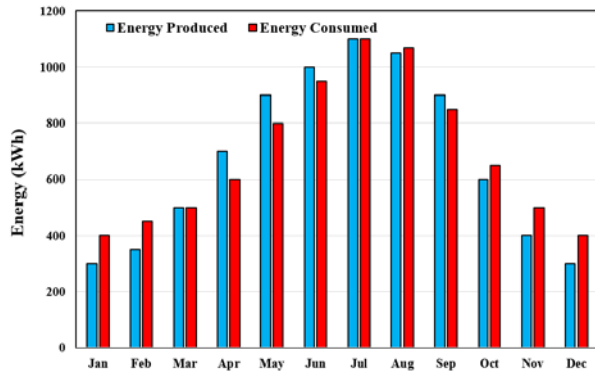


Figure 11. Energy generated by the photovoltaic system and building energy consumption

Figure 12 compares the building's performance in two scenarios: with and without the PV system. The results reveal notable differences in grid energy consumption, energy demand reduction, and heating/cooling loads. The analysis highlights the substantial impact of PV installation on energy cost reduction and building energy efficiency improvement.

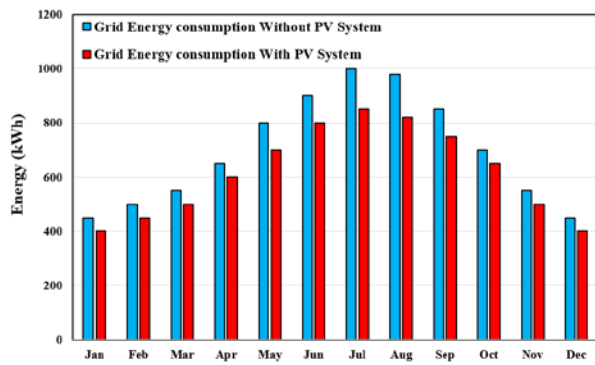


Figure 12. Comparison of building performance with and without PV panels

As illustrated, installing PV panels significantly decreases grid dependency and enhances overall energy efficiency. Without PV panels, the building is fully reliant on the grid, with energy demand peaking in summer due to high cooling loads. In winter, heating loads similarly increase grid demand, leading to elevated costs and greenhouse gas emissions. In contrast, with the PV system, a large portion of cooling demand is met during summer, and surplus energy can be stored or exported to the grid. This reduces grid consumption by up to 70%. In winter, despite lower production, the system still offsets part of the heating load, reducing grid consumption by approximately 30%.

4.4 Environmental Impact

The PV system notably decreases the building's carbon footprint by reducing reliance on grid electricity and replacing it with clean solar energy. Figure 13 shows the reduction in greenhouse gas emissions. The PV system reduces CO₂ emissions by approximately 1170 kg annually, with the highest

monthly reduction in summer (140–160 kg). Even in winter, the system prevents 40–50 kg of CO₂ emissions per month.

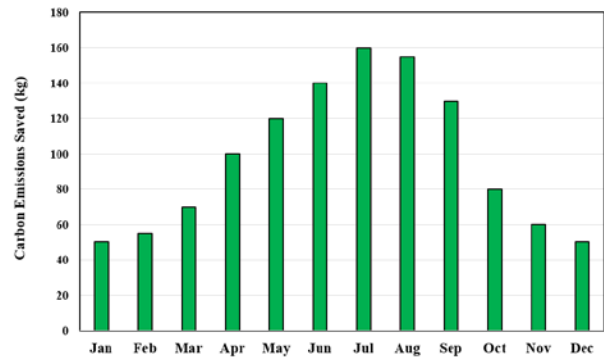


Figure 13. Reduction in greenhouse gas emissions

While this analysis focuses on operational CO₂ savings, a complete evaluation of the system's environmental impact requires a **life-cycle assessment (LCA)** of the photovoltaic panels and insulation materials. This includes their **embodied energy**, emissions during manufacturing, transportation, installation, and end-of-life processes. Although such analysis was beyond the scope of this study, future research is encouraged to apply LCA methodologies such as **ISO 14040/44**, utilizing material-specific and region-specific environmental data to better understand the system's long-term sustainability.

4.5 Economic Analysis

The greatest savings occur during summer, reaching 70–80% of monthly energy expenses, due to high solar generation and reduced grid dependency. Although savings are lower in winter, they still amount to 20–30%. Based on the economic parameters listed in Table 5, the payback period of the PV system is calculated at 8.33 years, and the return on investment (ROI) is 100%, indicating that over its 25-year lifespan, the system will yield cost savings equal to twice the total installation and maintenance expenses.

Table 5. Economic Assumptions

Parameter	Value	Unit
Installation Cost	5000	\$
Annual Maintenance Cost	100	\$
Annual Energy Production	8100	kWh
Electricity Price	0.15	\$/kWh
Annual Cost Savings	600	\$
Discount Rate	5	%
System Lifespan	25	years

These findings confirm that PV systems are not only environmentally beneficial but also economically viable for residential buildings in regions with high solar radiation. Reduced grid dependency and significant annual cost savings further reinforce the financial feasibility of such systems. Figure 14 demonstrates the cost savings achieved through PV system installation.

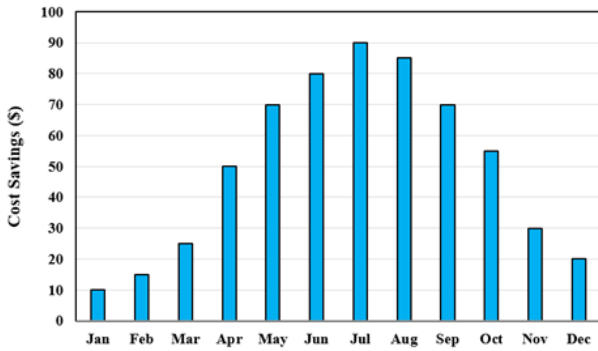


Figure 14. Monthly energy cost savings of the building

The economic analysis in this study was based on fixed assumptions for installation cost, operation and maintenance (O&M) cost, electricity tariffs, and system lifetime. It is acknowledged that these factors can significantly influence key economic indicators such as payback period and net savings. For instance, higher electricity prices can accelerate cost recovery, while fluctuations in system component prices or inflation may increase the investment burden.

4.6 Sensitivity Considerations

Based on preliminary assessments, system performance was found to be highly influenced by the panel tilt angle, ambient temperature, and the quality of solar radiation data. A formal sensitivity analysis was not conducted in this study; however, literature indicates that small changes in these inputs can result in noticeable variations in energy output and performance ratio [26]. Further simulation studies are required to quantify the degree of impact and support optimal system design for different climatic scenarios.

4.7 Practical Feasibility and Implementation Challenges

From a practical standpoint, the implementation of rooftop PV systems in hot and humid regions such as Bushehr presents both opportunities and challenges. The abundant solar radiation makes the region highly suitable for PV deployment; however, high humidity and dust accumulation may reduce panel efficiency over time. Additionally, technical issues such as roof space limitations, structural load capacity, and the need for regular cleaning and maintenance must be considered.

On the policy and market side, initial investment costs remain a barrier for many homeowners, especially in the absence of financial incentives or net-metering regulations. Despite these challenges, advances in PV module durability, falling component prices, and growing public awareness are steadily improving the feasibility of such systems in residential applications.

5 Conclusion

This study analyzed and optimized a photovoltaic system to reduce building energy consumption in the hot and humid climate of Bushehr. The findings showed that installing PV panels at an optimal tilt angle of 25° significantly reduced heating and cooling loads and enhanced overall energy efficiency. From an energy performance perspective, the PV system reduced the building's annual energy consumption by an average of 25%. During summer, solar generation was sufficient to reduce cooling loads by up to 20%, with surplus energy available for storage or grid injection. In winter, while production decreased, the system still contributed to heating demand reduction.

Economically, the system achieved annual savings of \$600, resulting in a payback period of 8.33 years. This confirms the PV system's financial viability for residential applications in this region. Moreover, the system reduced annual CO₂ emissions by 1.17 tons, significantly mitigating environmental impact and contributing to climate change mitigation efforts. Additional optimization parameters were also examined. Proper insulation was shown to reduce annual energy consumption by up to 40%, and an optimal window-to-wall ratio of 30% was identified to balance cooling load reduction and energy efficiency.

Overall, the study emphasizes that combining PV systems with energy-efficient building design such as thermal insulation and optimized window sizing can significantly enhance energy performance and reduce operating costs. To further improve system performance during low-irradiance periods, it is recommended to either increase battery storage capacity or integrate the PV system with other renewable energy sources. These approaches not only improve energy resilience but also reduce grid dependency and enhance environmental sustainability.

Building upon the results of this study, several directions are recommended for future research. First, experimental validation through field measurements in different seasons can help improve the accuracy of simulation outputs and provide real-world insights into system behavior. Second, integrating hybrid renewable energy systems, such as photovoltaic-thermal or PV-wind configurations, could help ensure more stable and reliable power generation for residential buildings. Third, the implementation of real-time control algorithms and smart energy management systems can optimize load balancing, enhance self-consumption, and increase overall system efficiency. In addition, future studies should consider life-cycle cost analyses and environmental assessments for various PV module types and insulation materials under different climatic conditions. Exploring local policy incentives, dynamic electricity pricing models, and economic feasibility will also be essential for large-scale adoption. Finally, investigating the long-term degradation performance of PV modules and energy storage systems in humid coastal climates can help designers and policymakers develop better maintenance and replacement strategies. These research

avenues will contribute to more robust, resilient, and cost-effective photovoltaic applications for sustainable buildings.

Disclosure of Potential Conflicts of Interest

The Authors declare that there is no conflict of interest

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