JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2024, 25(9), 260–271
https://doi.org/10.12911/22998993/191435
ISSN 2299–8993, License CC-BY 4.0

Received: 2024.06.25
Accepted: 2024.07.22
Published: 2024.08.01

Feasibility Analysis of Grid-Connected Solar Photovoltaic Systems in Dhahran and Bisha, Saudi Arabia

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ABSTRACT

The potential for grid-connected solar photovoltaic (PV) systems to provide sustainable energy solutions across diverse climatic zones in Saudi Arabia was analyzed through a detailed feasibility study focusing on Dhahran and Bisha, representing different climatic conditions. In Dhahran, the power capacity for the six assessed PV technologies – Gintech, Jinko Solar, Apain Solar, Canadian Solar, Green Power, and Suntech-ranged from 11,970 kW to 12,012 kW, with the number of panels varying from 35,200 to 46,200. The solar collector area spanned from 61,242 m² to 88,715 m², and the electricity exported to the grid was consistent at approximately 18.770 MWh to 18,839 MWh. Initial costs were between USD 7,100,180 and USD 7,135,128, while revenue from exported electricity ranged from USD 912,378 to USD 915,079 with GHG emission reductions substantial at 9700 to 9736 tCO_2. In Bisha, power capacities ranged between 9711 kW and 9800 kW, with panel counts from 28,600 to 37,750, and solar collector areas varying from 49.774 m² to 71,721 m². The electricity exported to the grid ranged from 18,780 MWh to 18,952 MWh. Initial costs were lower, between USD 5,768,334 and USD 5,821,200 and the revenue from exported electricity ranged from USD 912,686 to USD 921,051 with GHG emission reductions between 9705 and 9794 tCO_2. These findings highlight the economic and environmental benefits of deploying grid-connected solar PV systems across different regions in Saudi Arabia, demonstrating significant potential for energy cost savings and substantial reductions in carbon emissions.

Keywords: photovoltaic systems, grid-connected, solar energy, greenhouse gas emissions, RETScreen software.

INTRODUCTION

The increasing demand for sustainable and renewable energy sources has led to significant attention being given to grid-connected solar photovoltaic (PV) energy systems, particularly in the Kingdom of Saudi Arabia. Saudi Arabia is considered an ideal location for the large-scale adoption of solar PV technology due to its abundant solar radiation and extensive arable land. Recent government initiatives, such as Vision 2030, emphasize the importance of renewable energy, showcasing the country's commitment to diversifying its energy sources and reducing its reliance on oil through the promotion of solar PV systems [1–3]. Solar PV systems convert sunlight directly into electricity using photovoltaic cells made from semiconducting materials like silicon. When sunlight strikes these cells, it generates an electric field across the layers, causing electrons to move and create an electrical current. This process, illustrated in Figure 1, allows the generated electricity to homes, businesses, and other electrical equipment [4]. The efficiency of solar PV systems depends on several factors, including the quality of photovoltaic cells, the intensity of sunlight, temperature, and shading conditions. Current commercial solar panels have an average efficiency of 15% to 22%, with advanced panels exceeding this range due to ongoing research and development [5–7].

One of the key advantages of solar PV systems is their ability to generate electricity without moving parts, resulting in low maintenance and long lifespan, often exceeding 25 years. Furthermore, solar energy is a clean and renewable

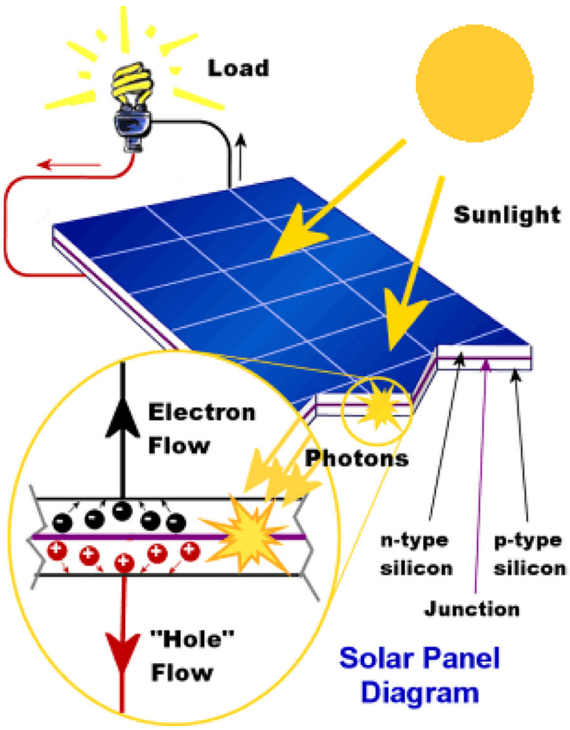

Figure 1. Solar panel diagram [6]

source, significantly reducing greenhouse gas emissions and environmental impact [8, 9]. The declining costs of solar panels and government incentives have increased the popularity of solar PV systems for residential and commercial applications, further driving demand and innovation in the sector [10–12].

In Saudi Arabia, increasing solar PV electricity generation presents an opportunity to reduce dependence on fossil fuels and lower carbon emissions. The country's year-round sunshine makes it an ideal location for solar energy production. The transition to solar energy aligns with Saudi Arabia's Vision 2030, which aims to diversify the economy and enhance the private sector's role through renewable energy projects like the Sakaka Solar Power Plant, one of the world's largest solar PV initiatives [13–16]. By embracing solar PV technology, Saudi Arabia can achieve greater energy independence, reduce greenhouse gas emissions, and foster economic growth in the renewable energy sector [17, 18]. To integrate solar PV into the national grid, Saudi Arabia has developed a multi-phase strategy focusing on infrastructure, regulatory frameworks, and technological advancements. Upgrading the grid to support intermittent solar power, implementing supportive policies such as net metering and feed-in tariffs, and developing energy storage solutions are critical components of this strategy [19, 20]. Despite these efforts, challenges remain, such as high initial costs, the need for advanced energy storage technologies, and the requirement for specialized skills and infrastructure upgrades [21–24].

By addressing these challenges through innovative solutions and strategic planning, Saudi Arabia can effectively integrate solar PV systems into its energy landscape, paving the way for a more sustainable and diverse energy portfolio. This integration will not only enhance energy security and reduce environmental impact but also position Saudi Arabia as a leader in the global renewable energy transition.

The use and development of renewable energy sources in the electricity sector will provide two benefits. On the one hand, it will conserve fossil fuels for export to the world market and generate cash, while also reducing greenhouse gas emissions. Ultimately, this will protect both the local and global ecosystem. The remainder of this section presents the studies described in the literature on various aspects of grid-connected PV systems.

Pietruszko and Gradzk [25] discuss the monitoring of a roof-mounted 1-kWp grid-connected PV system in Warsaw, operational since December 2000. This system, composed of 20 Millennia MST-50 MV modules, was observed over a year to assess its performance under local climatic and solar radiation conditions. The study evaluates the system from both a component perspective (including the PV array and power conditioning unit) and a global perspective (including AC power delivered to the grid, system efficiency, and reliability). The results revealed that the system's performance surpassed initial computer simulations, yielding an annual energy output of approximately 830 kWh and a performance ratio between 0.6 and 0.8, with system efficiency ranging from 4–5%. This installation serves an essential role in both demonstration and educational purposes.

So et al. [26]. conducted an extensive study on the performance of grid-connected photovoltaic (PV) systems, focusing on four 3 kW systems installed at the Field Demonstration Test Center (FDTC) in Korea. The monitoring system, set up in November 2002, aimed to assess the impact of meteorological conditions on the operation characteristics of these systems. Over a year of monitoring, the performance and loss factors of the PV systems were evaluated both from a component and a global perspective.

Ayompe et al. [27]. validated real-time energy models for small-scale grid-connected PV systems designed for domestic use. These models predicted the AC power output of a PV system in Dublin, Ireland, using 30-minute interval performance data from April 2009 to March 2010. Statistical analysis of the predictions versus measured data revealed potential sources of error and assessed the models' ability to predict PV-cell temperature and efficiency accurately. Empirical models showed lower percentage mean absolute errors (7.9–11.7%) compared to non-empirical models (10.0–12.4%), with cumulative errors of 1.3% and 3.3%, respectively. These findings suggest that the proposed models are suitable for predicting PV-system AC output power at intervals appropriate for smart metering.

Khatib et al. [28]. conducted a field operation study of a grid-connected PV system in a tropical climate, focusing on a 5 kWp photovoltaic array paired with a 6 kW DC/AC (direct current/alternating current) inverter. The study aimed to develop accurate mathematical models and evaluate the system's productivity based on recorded performance data. Results indicated that the average PV performance ratio was 73.12%, while the inverter's efficiency ratio was 98.56%. The system's daily yield factor was 2.51 kWh/kWp, and the capacity factor stood at 10.47%. However, these findings also revealed that the system's productivity was below expectations, necessitating a thorough inspection to identify and rectify any underlying issues. Recommendations for improving the system included checking the energy source, ensuring clean PV modules, verifying system connections, validating inverter efficiency, and assessing the installation location for potential shading. This study provides valuable insights for PV system installations in Malaysia and similar regions.

Sundaram and Babu [29] verified the efficiency of a 5 MWp photovoltaic (PV) plant connected to the power grid. The facility is situated in Sivagangai, Tamilnadu, India, and its yearly energy production was determined using theoretical calculations. The actual yearly average energy generated by the proposed plant was measured to be 24,116.61 kWh per day, while the estimated value was determined to be 24,055.25 kWh per day. The overall absolute average daily capture and system losses were found to be 0.384 h/day and 0.65 h/day, respectively According to Veldhuis and Reinders [30], the potential for grid-connected photovoltaic systems (GCPVS) in Indonesia is estimated at around 27 GWp, which could generate approximately 37 TWh/year-about 26% of the total electricity consumption in 2010. Mondal and Sadrul Islam [31] evaluated the potential of a 1 MW capacity GCPVS in 14 locations across Bangladesh, finding a technical potential of about 50.174 MW and assessing the financial viability of such plants.

Paudel and Sarper [32] conducted an economic analysis of a 1.2 MW grid-connected PV plant at Colorado State University-Pueblo, using array efficiency to measure performance and estimate energy yield and cash flows. Al-Sabounchi et al. [33] studied a pilot 36 kWp grid-connected PV system connected to a 0.4 kV level of the Abu Dhabi distribution network. They evaluated the system's performance under local weather conditions, focusing on energy yield, conversion efficiency, voltage and frequency consistency, the effect of dust, and ambient temperature impact. Results showed consistent operation with moderate conversion efficiency even at high temperatures, though dust accumulation significantly degraded performance. Similar studies on various aspects of GCPVS are available in the literature, such as those by Raturi et al. [34], Edalati et al. [35], Sidi et al. [36], and Bahaidarah et al. [37–39].

Methodology

This study investigates the feasibility of grid-connected PV systems in two distinct climatic zones of Saudi Arabia: Dhahran and Bisha. The selection of these cities was based on their differing climatic conditions, representing a broader range of environmental scenarios within the country.

Location details

Dhahran: Located in the Eastern Province, Dhahran is characterized by a desert climate with high temperatures and substantial sunshine throughout the year. The geographical coordinates of Dhahran are approximately 26.2361° N latitude and 50.0393° E longitude.

Bisha: Situated in the southwestern part of Saudi Arabia, Bisha experiences a drier climate with relatively lower temperatures and moderate solar radiation levels compared to Dhahran. The geographical coordinates for Bisha are around 20.0125° N latitude and 42.6052° E longitude.

Climatic zone characterization

To understand the potential and performance of solar PV systems, it is essential to characterize the climatic zones accurately. The characterization includes the assessment of solar radiation levels, temperature variations, and other relevant meteorological data.

Dhahran's climate: Dhahran has a hot desert climate with extremely high summer temperatures, often exceeding 40 °C, and mild winters. The city receives an annual average solar radiation of about 2200 kWh/m².

Bisha's climate: Bisha, on the other hand, has a semi-arid climate with cooler temperatures compared to Dhahran. The summer temperatures are typically lower, averaging around 35 °C, and the winter temperatures can drop to around 10 °C. The annual average solar radiation in Bisha is approximately 2000 kWh/m².

Table 1 shows the required data for a typical household in Saudi Arabia. The table provides detailed information on the energy consumption of various appliances, from the table it is noted that the annual energy consumption per household is approximately 18,770 kWh.

PV-module selection

Many types of photovoltaic panels with different specifications are available in the Saudi Arabia market. In this study, six different types of solar panels from different companies were selected. Table 2 shows the technical specifications of the selected photovoltaic panels.

Description of the photovoltaic panels used

Regarding the installed capacity of 1000 independent homes in the Kingdom of Saudi Arabia, in this analysis, the fixed-type installation method was chosen because it reduces cost and maintenance. The following Table 3 shows the technical specifications for all types.

RETScreen is a clean energy management software system developed by the Government of Canada through the Department of Natural Resources' Canmet ENERGY research centre. Designed to help decision-makers assess the viability and performance of renewable energy, energy efficiency, and cogeneration projects, RETScreen offers a comprehensive suite of tools for feasibility analysis, performance analysis, benchmarking, and ongoing energy management. In this study, RETScreen was used to conduct a detailed feasibility analysis of grid-connected PV systems across different climatic zones in Saudi Arabia. The software facilitated energy production and performance analysis, estimating the energy output of the solar PV systems based on solar radiation data, system configuration, and efficiency factors. Additionally, RETScreen conducted financial analysis by calculating the economic feasibility of the projects, considering capital costs, operational and maintenance costs, and potential revenue from energy production. Key financial metrics such as net present value (NPV), internal rate of return (IRR), and payback period were provided. Moreover, RETScreen estimated the reduction in greenhouse gas (GHG) emissions resulting from the solar PV systems. The software utilizes a comprehensive database that includes over 20 years of satellite-derived climate data from NASA's Surface Meteorology and Solar Energy (SSE) program, ensuring accurate energy production and performance analysis. The climate data used was averaged over a 22-year period (1983–2005), providing a robust and reliable basis for the analysis.

Table 1. Electrical load calculation for a typical building

Appliance	Power (W)	Units	Usage duration (h/day)	Average daily consumption (kWh/day)
Lightning	25/60/100	3/3/2	8	3.64
Television	200	2	4	1.6
Air heater	700	1	4	2.8
HVAC	1100	4	8	35.2
Fridge	150	1	24	3.6
Laundry	300	2	1	0.6
Geyser	1500	1	1	1.5
Miscellaneous	100	1	24	2.4

Table 2. Technical specifications of the five selected photovoltaic panels

Company	Maximum power (Watt)	Efficiency (%)	Module area (m^2)
Gintech	280	17.24	1.623
Jinko Solar	330	19.56	1.687
Apain Solar	280	14.4	1.94
Canadian Solar	320	19	1.686
Green Power	260	13.54	1.92
Suntech	340	17.49	1.944

Table 3. Technical specifications for all types

Parameter	Gintech	Jinko Solar	Apain Solar	Canadian Solar	Green Power	Suntech
Type	Mono-Si	Mono-Si	Mono-Si	Mono-Si	Mono-Si	Mono-Si
Nominal operating cell temperature (°C)	45	45	45	45	45	45
Temperature coefficient (%/°C)	-0.4%	-0.4%	-0.4%	-0.4%	-0.4%	-0.4%
Miscellaneous losses (%)	10%	10%	10%	10%	10%	10%

DESIGN AND ANALYSIS

Design of grid-connected solar PV system for 1000 homes

This paper presents the design of a grid-connected PV system intended to supply the average annual energy requirements for 1000 homes. In this study, we aim to design a grid-connected solar photovoltaic (PV) system to meet the energy needs of 1000 homes. The calculation of the required system capacity and configuration is based on a thorough analysis of household energy consumption patterns. Our preliminary analysis determined that the annual energy consumption per household is approximately 18,770 kWh. Consequently, for 1000 homes, the total annual energy consumption amounts to 18,770 MWh. The design process involves several critical considerations to ensure the system's efficiency and reliability in meeting the energy needs of the specified number of households. These considerations include:

- Location and solar irradiance: The first consideration for designing a grid-connected solar PV system is the location of the homes and the solar irradiance at that location. Different regions receive different amounts of sunlight, and this will impact the potential energy production of the solar PV system. This information can be obtained from solar irradiance maps or databases for the specific location.
- System capacity: The second consideration is determining the system capacity needed to meet the average annual energy needs of 1000 homes. To calculate the system capacity, the average annual energy consumption of a single home needs to be known. Once the average annual energy consumption of a single home is known, it can be multiplied by the number of homes (1000 in this case) to determine the total energy requirement. This value will then be used to size the grid-connected solar PV system accordingly.
- System configuration: The third consideration is determining the system configuration for the grid-connected solar PV system. This can include deciding on the type of solar panels to be used (crystalline silicon vs. thin-film technology), whether to use microinverters or a central inverter, and the arrangement of the panels (roof-mounted or ground-mounted).
- Integration with the grid: The fourth consideration is the integration of the grid-connected solar PV system with the existing electrical grid. This involves ensuring that the system meets all the necessary technical requirements and regulations for grid interconnection.
- System monitoring and maintenance: The final consideration is the implementation of a monitoring and maintenance plan for the grid-connected solar PV system.

Grid-connected PV system configurations

Grid-connected PV systems use solar panels to provide the majority of the energy required during system depletion and are connected to the local electrical grid to acquire electricity at night.

Due to ample solar radiation, photovoltaic panels occasionally create more electricity than the needed load during the day, and the excess power is sent back into the grid. When solar panels fail to generate enough electricity to satisfy the needed demand, the grid compensates for the power shortage. In general, power flows to and from the grid based on the availability of solar radiation and the actual load demand in the grid-connected PV system. Grid-connected PV systems are extremely simple, with minimal operating and maintenance expenses. A grid-tied PV system sends power directly into the grid, eliminating the need for expensive backup batteries. Grid-connected PV systems consist primarily of PV panels, an inverter, an electricity meter, an AC breaker panel and fuses, safety switches and cables, a power grid, and domestic plugs. Figure 2 depicts the layout of a grid-connected PV system without batteries. To get the most energy out of PV arrays, choose panels with good cell efficiency and operating temperatures. The inverter is the most critical component of any grid-connected system. It takes DC electricity from the PV array and transforms it to (AC) electricity at the proper voltage and frequency to feed the grid or power domestic loads. Kilowatt hours (kWh) or electricity meters are used to measure the flow of power to and from the grid. Two types of meters can be used: one for incoming power and one for departing electricity.

RESULTS AND DISCUSSION

In this study, which looks at the feasibility of grid-connected solar PV systems in Saudi Arabia, we chose two Saudi cities to explore and analyze: Dhahran and Bisha. These cities were chosen for their diverse geographical positions and levels of solar radiation, which represent the many climatic conditions prevalent across the country. Dhahran, located in the Eastern Province, experiences a desert environment with high temperatures and plenty of sunshine all year. Bisha, located in the southwest, has a drier climate with lower temperatures and somewhat lower amounts of sun radiation. By picking these two towns, we hope to represent the diversity of Saudi Arabia's solar energy potential and assess the viability of grid-connected solar PV systems under various environmental circumstances.

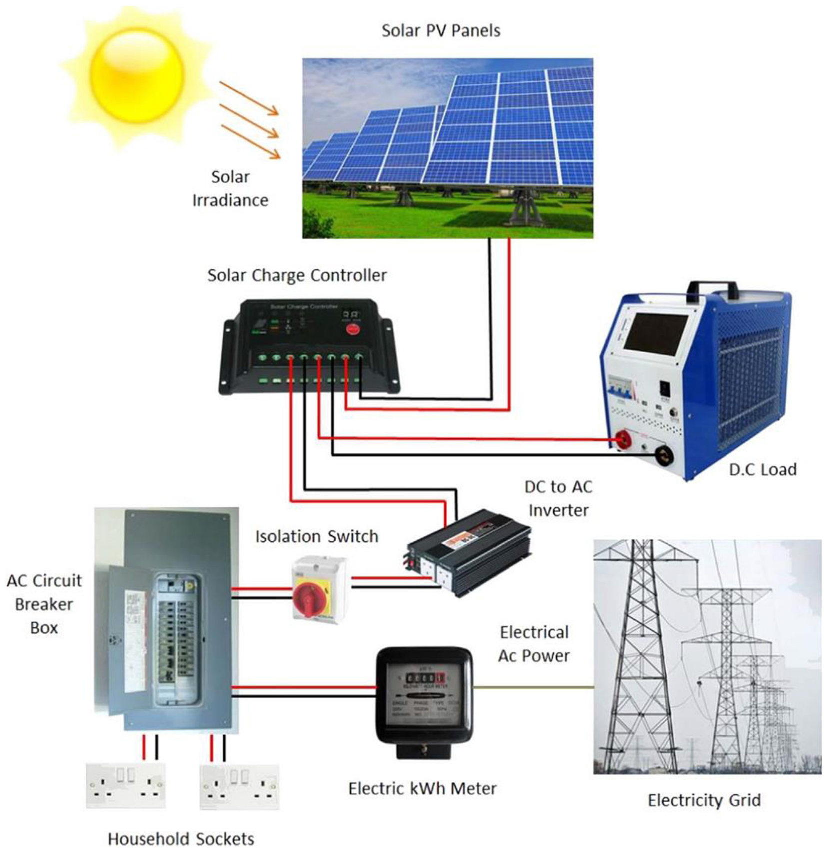

Figure 2. The primary components of a grid-connected PV system without battery backup [25]

Results for Dahran City

When analyzing the city of Dhahran using RETScreen software, two important graphs were created to understand site reference conditions and daily solar radiation along with air temperature trends throughout the year. Figure 3 illustrating the site's terms of reference, provides insight into the city's typical longitude, latitude, elevation and time zone which are important parameters for analysis. The Figure 4 displays monthly solar radiation levels in conjunction with average monthly air temperatures throughout the year. This graph allows you to determine the amounts of solar radiation and temperature fluctuations on a daily basis in the region. It shows a clear pattern of rising solar radiation and temperatures in the summer, followed by a decrease in both during the winter months. Understanding these trends is essential to evaluate the feasibility and performance of solar PV systems in Dhahran.

To design the photovoltaic system for the city of Dhahran using different selected solar panels that are usually common in Saudi Arabia, Table 4 presents the most important results obtained from the analysis. The table shows the main factors to consider are power capacity, number of modules (panels), solar collection area, upfront costs, electricity exported to the grid, revenue from electricity exported, and greenhouse gas emissions reduction.

From the table above we can conclude that the power capacity of the system varies slightly among the different solar panels, with Canadian Solar having the highest capacity at 12,000 kW and Jinko Solar having the lowest at 11,979 kW.

In addition to the number of units required for each panel also varies, with Green Power requiring the highest number of panels at 46,200 and Jinko Solar requiring the lowest at 36,300. On the other hand, The solar PV module area is an important factor in determining the space required

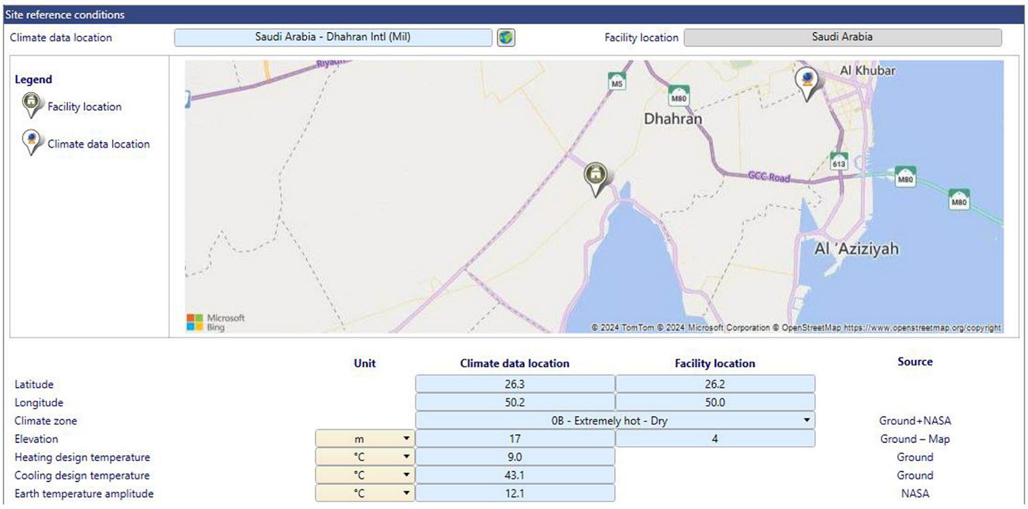

Figure 3. Site reference conditions

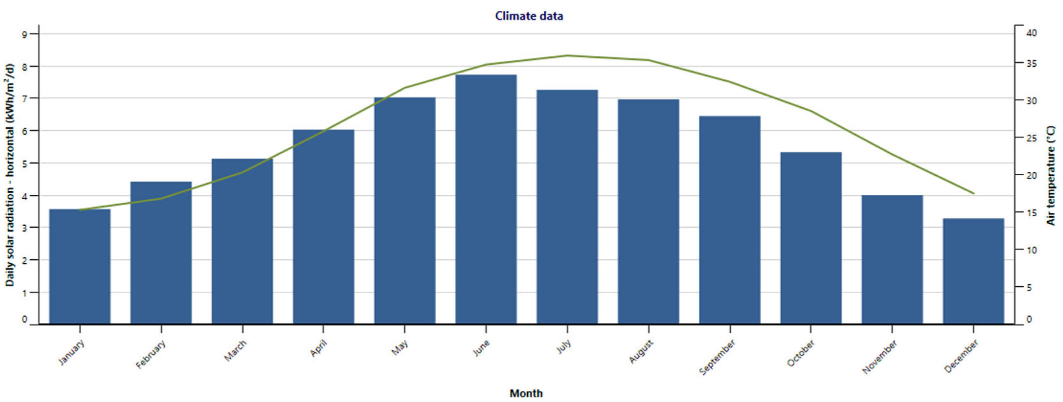

Figure 4. Climate data for Dahran City

for the PV system. Apain Solar has the largest area requirement at 83,125 m^2, while Jinko Solar has the smallest at 61,242 m^2.While The initial costs of the PV system vary among the different panels, with Green Power being the most expensive at USD 7,135,128 and Suntech being the least expensive at USD 7,099,992.

It is observed from the Table 4 that The amount of electricity exported to the grid is relatively consistent among the panels, ranging from 18,770 MWh to 18,839 MWh. Revenue from exported electricity: The revenue from exported electricity is directly related to the amount of electricity exported and the selling price. Apain solar has the highest revenue at SAR 3,391,034, while Gintech has the lowest at SAR 3,379,177.

Figure 5 shows the GHG emission reduction we notice that all panels contribute to reducing GHG emissions, with Canadian solar having the highest reduction at 9726 tCO_2 and Green power having the lowest at 9700 tCO_2. Based on these results, the choice of solar panel for the PV system design would depend on factors such as cost, space availability, and environmental impact. Panels with higher power capacity and lower initial costs may be more attractive, but other factors such as reliability and efficiency should also be considered in the final decision.

Results for Bisha

Similarly, we analyzed the city of Bisha using RETScreen software to compare it with Dahran city, Figure 6 and Figure 7 show the Site reference conditions and Climate data for Bisha City.

Table 5 shows that the power capacity of the solar panels varies, with Gintech having the highest capacity at 9800 kW and Jinko Solar the lowest at 9735 kW. The number of units required also varies, with Green Power needing the most at 37,750 panels and Jinko Solar

Table 4. Summary of main results for Dharan city

Parameter	Gintech	Jinko Solar	Apain Solar	Canadian Solar	Green Power	Suntech
Power capacity (KW)	11,970	11,979	11,970	12,000	12,012	11,986
Number of unit (panel)	42,750	36,300	42,750	37,500	46,200	35,200
Solar collector area (m^2)	69,432	61,242	83,125	63,158	88,715	68,428
Electricity exported to grid (MWh)	18,773	18,778	18,773	18,820	18,839	18,770
Initial costs (USD)	7,100,180	7,106,526	7,100,180	7,128,000	7,135,128	7,099,992
Electricity exported revenue (USD)	912,378	912,944	912,378	914,645	915.079	912,222
GHG emission reduction (tCO_2)	9702	9709	9702	9726	9736	9700

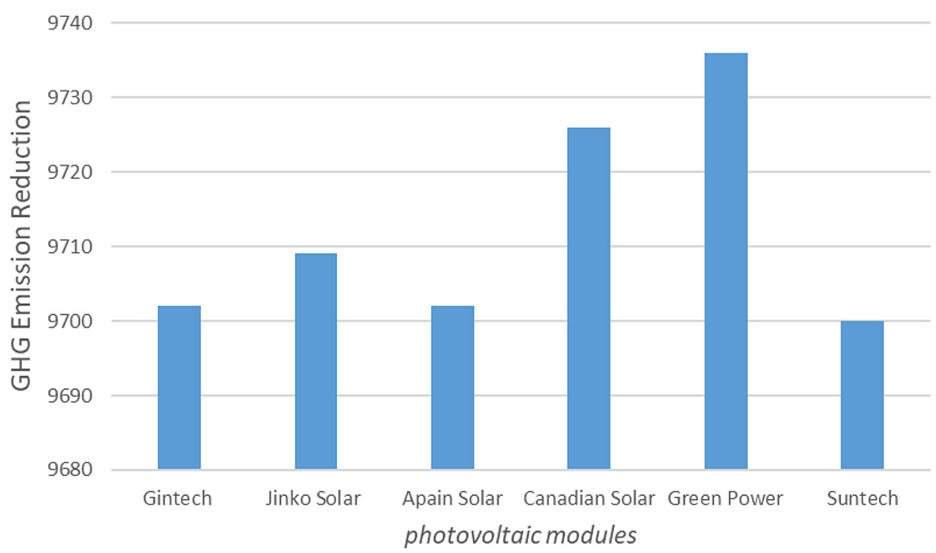

Figure 5. GHG emission reduction in Dahran City

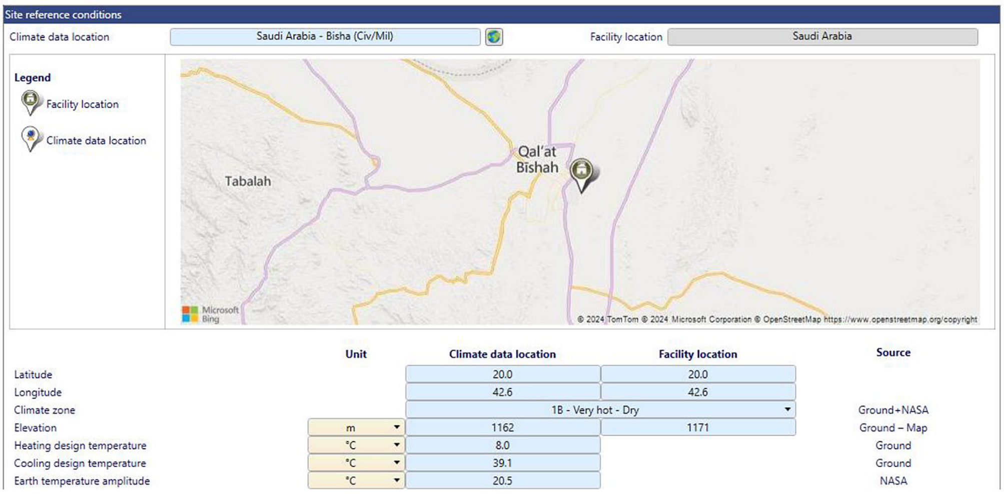

Figure 6. Site reference conditions for Bisha City

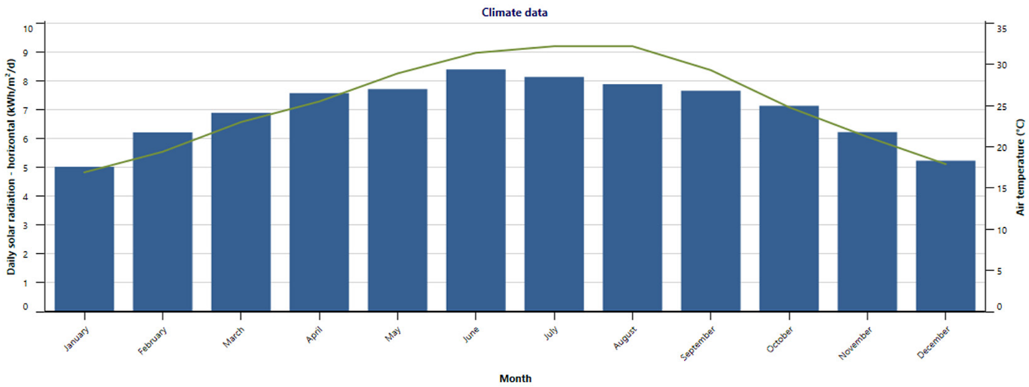

Figure 7. Climate data for Bisha City

Table 5. Summary of main results for Bisha city

Parameter	Gintech	Jinko Solar	Apain Solar	Canadian Solar	Green Power	Suntech
Power capacity (KW)	9800	9735	9800	9760	9711	9724
Number of unit (panel)	35,000	29,500	35,000	30,500	37,750	28,600
Solar collector area (m^2)	56,845	49,774	68,056	51,386	71,721	55,597
Electricity exported to grid (MWh)	18,952	18,826	18,952	18,874	18,780	18,805
Initial Costs (USD)	5,821,200	5,782,590	5,821,200	5,798,440	5,768,334	5,776,800
Electricity exported revenue (USD)	921,051	914,942	921,051	917,292	912,686	913,908
GHG emission reduction (tCO_2)	9794	9729	9794	9754	9705	9718

the least at 29,500. Solar collector area ranges from 49,774 m^2 for Jinko Solar to 68.056 m^2 for Apain solar. Initial costs vary, with Apain Solar being the most expensive at USD 5,821,200 and Green Power the least at USD 5,768,334. Electricity exported to the grid ranges from 18,780 MWh to 18,952 MWh, while revenue from exported electricity varies from USD 912,686 for green power to USD 921,051 for Apain solar. Figure 8 shows the GHG emission reduction. We notice that all panels contribute to reducing GHG emissions. We notice that all panels contribute to reducing GHG emissions, with Apain Solar having the highest reduction at 9794 tCO_2 and Green Power having the lowest at 9705 tCO_2.

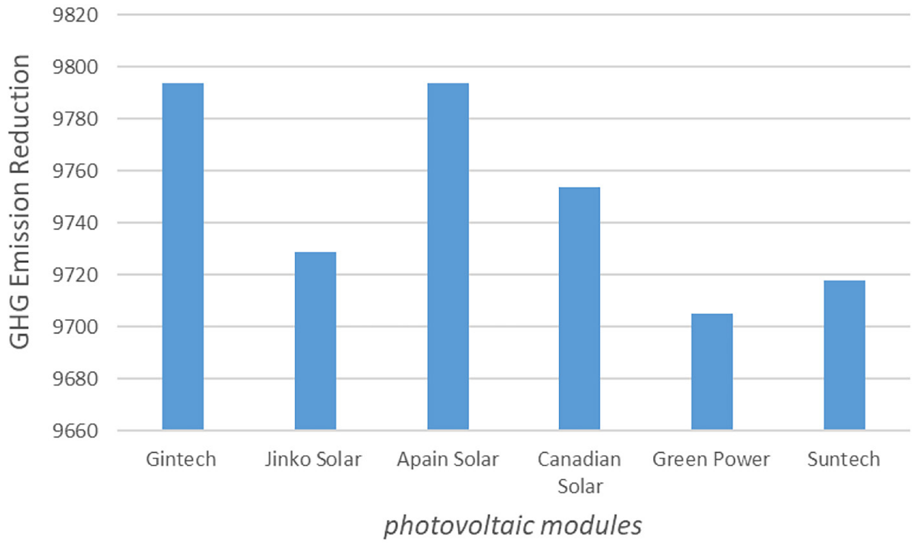

Figure 8. GHG emission reduction in Bisha City

Table 6. Summarize the most relevant results

Location	Best panel	Payback time (years)	Solar collector area (m^2)
Dhahran City	Jinko Solar	7.78	61,242
Bisha City	Jinko Solar	6.64	49,774

To compare the findings to acquire the best panel for each location in terms of the lowest recovery time and the smallest required solar energy collection area, and to recommend the best place for solar PV installation, we may summarize the most relevant results in Table 6.

CONCLUSION

Based on the data obtained in the analysis, Bisha City is suggested to build solar PV systems due to the lower payback time and smaller space requirement for solar energy gathering. Jinko Solar panels are the ideal choice for Bisha, as they give a payback period of 6.64 years and require a solar collector area of 49,774 m^2. This implies that the city of Bisha has superior solar potential and economic feasibility for installing solar photovoltaic electricity compared to the city of Dhahran which reach the payback period to 7.8 years.

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