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Article

Clean Energy from the Sun: Design and Analysis of Solar Energy Systems

Intisar Rasheed Saleh[1,2*], Hussein Younus Razzaq[1,2]

1. Karbala Technical Institute, Karbala, Iraq
2. Al-Furat Al-Awsat Technical University, Babil, Iraq

* Correspondence: intisarkhursan@atu.edu.iq

Abstract: Solar energy has the potential to meet a substantial portion of global energy demands through effective capture and utilization of sunlight. However, economic viability, environmental sustainability, and performance optimization remain critical challenges in large-scale adoption. This study aimed to assess these factors through a photovoltaic (PV) model, considering variables like efficiency, capacity factor, degradation rate, and energy yield. Simulation methods using Matlab-Simulink incorporated local weather trends and advanced modeling tools to predict PV output based on temperature and solar radiation. Economic analyses revealed a competitive Levelized Cost of Energy (LCOE) of $6.50 per kWh, with a 7-year payback period and an 8.5-year Return on Investment (ROI). Environmentally, the PV system demonstrated a low carbon footprint (3,500 kg CO_2eq), with plans for local replanting and ongoing sustainability monitoring. Findings underscore solar energy's feasibility and its role in reducing environmental impact, supporting future clean energy initiatives.

Keywords: Simulation, Return on Investment, Levelized Cost of Energy, Photovoltaic, Efficiency, Energy system

1. Introduction

Solar energy is a type of renewable energy, and the energy is most accessible and cost-free renewable energy source for all nations [1]. Solar power is the conversion of solar energy into electrical and thermal energy [2], which are commonly uses. In general, there are two major kinds of solar energy technologies that can turn solar energy into electrical energy. The concentrating solar power (CSP) system uses hundreds of mirrors to focus sunlight to create heat or electricity at temperatures that are typically between 350 and 1000 °C [3]. Additionally, CSP as a solar energy technology may function by storage heat or by combining with coal or oil-based fueled power plants like methane gas power plant, providing electricity when the sun is not shining. The Photovoltaic (PV) power which is a solar energy system designed to generate electricity. PV cells directly convert solar radiation into electricity [4].

There are several varieties of installed systems and solar technology. Monocrystalline silicon solar cells, polycrystalline silicon (multi-crystalline) solar cells [5], microcrystalline silicon solar cells [5], cadmium telluride solar cells [6], and Copper-Indium-Gallium-Diselenide (CIGS) solar cells[7] are currently the photovoltaic modules that are mostly used in the market. Whether the usage is huge or little, this technology can provide clean energy[8]. They are placed and produce electricity on offices, public buildings, residential projects, and commercial structures all over the globe.

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The need for clean energy, especially solar energy, cannot be overstated. By lowering greenhouse gas emissions, it contributes to climate change mitigation and promotes a cleaner, healthier environment [9]. In addition to promoting energy independence, solar energy also lessens reliance on volatile fossil resources that are subject to geopolitical unrest and price swings[10]. Additionally, because solar energy depends on a plentiful and renewable resource which guarantees a more stable energy future which supports long-term sustainability.

Using concentrated solar power or photovoltaic panels, the solar energy system turns solar energy into electrical energy [11]. The most important source of energy is solar energy, which has gained appeal on a worldwide scale [12]. Due to both cost-reduction technology developments and government initiatives that encourage the production and use of renewable energy sources, solar energy has lately seen enormous growth[13]. The trend in renewable energy from 2015 to 2023 based on investment, and power conversion, the solar energy is steadily overtaking wind turbines to become the cleanest energy source[14]. The third generation solar photovoltaic (perovskites) and power conversion efficiency increase are now the hot topics in renewable energy research[15].

Due to its high absorption coefficient, remarkable carrier mobility, high dielectric constant, configurable bandgap, and availability of materials [16]. The perovskites, a third-generation solar cell, offers the highest energy conversion [17], thus, advised for use by PV designers and solar installers. The enormous quantity of solar energy and producing power would meet the energy demands, the solar photovoltaics technologies and concentrated solar power are continuously being enhanced. The highest installed capacity of solar energy helps the energy sector and sustainability of solar energy, including environmental and economic growth[18].

Accordingly, the solar energy systems' viability and efficiency in supplying sustainable energy demands, to improve the effectiveness of solar energy systems and their design for greater efficiency. The study challenge was to evaluate the economic feasibility and environmental advantages of using solar energy and investigate grid integration and energy storage option. The result would be useful suggestions for putting solar energy systems into practice, as well as case study thorough examination of the possible effects of solar energy includes grid integration and energy storage options. The novelty of this study lies in its comprehensive examination of solar energy systems, covering multiple aspects including modelling, economic analysis, performance measurements, and environmental effect assessment. Although each of these aspects has been individually studied before, this study brings them together in a holistic approach towards solar energy system evaluation.

Whereas economic viability and environmental sustainability are commonly considered factors, this study investigated the maximize energy system performance, which is a key goal. By integrating performance measures such as efficiency, capacity factor, degradation rate, and energy yield assessment, the study provides a thorough understanding of the system performance of economic and environmental factors. The study employs various methods to reach its objectives. It utilizes real-world data and trends by simulating weather and local weather information. Advanced modelling tools are used for precise predictions and evaluations. The economic analysis encompasses factors such as capital costs, operating costs, ROI, payback time, and LCOE. The environmental impact assessment considered the factors of life cycle analysis, carbon footprint analysis, habitat disturbance, sustainability monitoring, and mitigation methods.

2. Materials and Methods

Approach and methodology

The study used quantitative and qualitative methodologies methods and the performance metrics and economic evaluation. The direct measurements of energy production data integration were used to evaluate performance measures, whilst environmental assessment fell under the purview of qualitative analysis. The financial model and cost-benefit analyses were employed in economic analysis, and the life cycle assessment was analyzed to comprehend the environmental effect.

The performance metrics through on-site measurements and system monitoring, data on solar panel efficiency, capacity factor, degradation rate, and energy production were gathered. The economic analysis was integrated the financial data to compile information on capital costs and operating costs based on the governmental organizations and financial entities tariff were provided. The environmental assessment utilized the literature reviews, environmental reports, and regional ecosystem studies data were gathered for the life cycle assessment, carbon footprint analysis, and habitat disturbance evaluation for sustainability monitoring.

Tools and Software

The Performance metrics were measured using digital multimeters, data recording tools, and sun irradiance sensors. The economic Analysis was used to determine the cost-benefit analyses, return on investment (ROI) estimation [19], and Levelized Cost of Energy (LCOE) evaluations utilized Eqs. 1 and 2 respectively, financial modeling was achieved using software tool. The formula for calculating LCOE is based on total cost of production and total expected energy generation [20]. Where the It defines as investment expenditures in the year t, Mt is the operation and maintenance expenditures in the year t, while Ft is the fuel expenditures in the year t, Et is the electrical energy generated in the year t, r is the discount rate, and n is the expected lifetime of system or power station. The environmental assessment applied latest tools of SimaPro and OpenLCA [21], life cycle assessment and carbon footprint analysis were carried out. The evaluation of habitat damage was made easier by Geographic Information Systems (GIS) software [22]. Environmental monitoring tools specifically designed for sustainability were used.

$$ROI = \frac{Cost\ of\ Investment}{Net\ Return\ on\ Investment} \times 100\% \quad (1)$$

$$\text{LCOE} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \times 100\% \quad (2)$$

By investigating voltage-current (V-I) and Power-voltage (P-V) output characteristics, Matlab-Simulink and utilized to construct a PV model. The experiment was carried out using Matlab-Simulink to solve the mathematical equations of the PV model. Likewise, the model was modeled as a subsystem with electrical characteristics. Both the constant and variable parameters were used in the simulation. The experiment has typically been carried out under specific thermal conditions (STC) of 25 °C and 1000W/m2. Subsequent steps have included experimenting with different levels of sun irradiation and temperature.

Solar Energy System Design

Solar Panel Selection and Configuration

Deciding the kind, brand, and size of solar panels were included into a solar energy system, accordingly, considering elements including effectiveness, cost, and suitability for the particular use. The configuration and wiring were chosen for the solar panels within the solar array. To improve energy output, choices were made regarding tilt angles, orientation, series or parallel connections. The efficiency of a solar panel may be defined as the proportion of electrical energy generated by the panel in relation to the amount of solar energy it receives as input[23]. The concept may be articulated as: $\eta = (Pout \div Pin) \times 100\%$. The η is the solar panel efficiency (%), Pout is the Electrical Power Output (W) and the Pin is the Solar Power Input (W).

Energy storage, Tracking Systems

The inverter design used for solar power system to convert solar power produced from Alternating Current (AC) energy. While the battery system used as energy storage from surplus solar power. The capacity, and its interaction with the solar system are all considered in this design. The mounting systems utilized the actual parts and pieces attached with solar panels to the roofs, ground mounts, or other surfaces. The stability and lifespan of the solar array were ensured by proper installation. The tracking systems of solar panels had specialized technologies that enable them to track the sun course throughout the day to maximize their exposure to sunlight. Depending on whether they can move in one or two directions, tracking systems may be either single-axis or dual-axis. The electrical system integration linked with every component of a solar energy system, from the solar panels, inverters, batteries, and related electrical equipment. The effective and secure functioning of the system is ensured by this integration.

Performance Metrics and Evaluation Criteria

The efficiency of solar panel is rated 19.5% expected to convert sunlight into power. The higher efficiency implies that more energy can be produced with the same quantity of sunshine, which translates into greater performance. Accordingly, the efficiency (η) of energy conversion is a measure of the effectiveness with which energy is converted from one form to another. The efficiency of an energy conversion process, such as a machine or system, may be determined using the following equation (3):

$$\eta = (\text{output energy or power} \div \text{input energy of power}) \times 100\% \quad (3)$$

However, the capacity factor of the solar system applied in this study is functioning of its maximal capability, with a capacity factor of 0.22 (or 22%) [24]. A greater capacity factor indicates that a larger share of the system potential output is consistently produced. In addition, the degradation Rate (% per year) of solar panels contributed to lose efficiency at a reasonably gradual pace, and the degradation rate of 0.5% per year [25], which is advantageous for a longer system lifetime. Therefore, the Energy Yield (MWh/yr.) was applied to estimate the system yearly produces 1,250 megawatt-hours of power. Economic benefits result from increased energy output, which is indicated by a greater energy yield. Similarly, the reliability (%) is considered which is a high degree of uptime and resilience to faults were shown by the system's 98% [26] dependability, which is crucial for reliable energy production. Table 1 shows the evaluation criteria of solar panels performance.

Table 1. Solar panels evaluation parameters

Metric	Value	Evaluation Criteria
Efficiency (%)	19.5%	Higher is better.
Capacity Factor	0.22	Closer to 1 is better.
Degradation Rate (% per year)	0.5%	Lower is better.
Energy Yield (MWh/yr.)	1,250	Higher is better.
Reliability (%)	98%	Higher is better.

Simulation and Modeling of Solar Energy Generation

Accurate forecasts and efficient modelling of system performance were considered by utilizing local weather station data and sophisticated modelling tools, such as PVsyst, a sophisticated tool known for detailed PV system analysis with quick simulation times, SAM and HOMER have both recognized tools for modeling the solar system and simulating power plants [27]. The simulation model has ability to simulate the past weather patterns aimed to improve the accuracy of predictions for energy production [28]. While the predicted yearly output found to be a useful measure tool of the system and it projected the performance and financial advantages. The selected system design, a 3-kW rooftop system, is well-suited for the intended use. Table 2 lists the main factors and methods used to forecast the solar system.

Table 2. Factors and Methods Evaluation for Predicting Output of Solar System

Aspect	Value/Method Used
Solar Resource Data	Local weather station data
Modelling Software	PVsyst, SAM, or HOMER
Weather Patterns	Historical weather patterns
System Configuration	3 kW rooftop system
Output Predictions	Predicted annual output

Circuit Modeling for Solar PV Cell Efficiency

Figure 1 shows a more accurate circuit model of a solar PV cell, consisted of a genuine single diode type, and its series and parallel resistance values are specified. The Rs and Rp are disregard due to a direct impact on the PV solar cell's efficiency. The current source (Iph) is placed in parallel with the diode to the solar PV device, which theoretically profound a perfect solar cell, with an output current determined by Kirchhoff's first law. Accordingly, when Id is substituted into Eq. (4), the ideal solar cell's output current I is calculated as shown in Eq. (6).

$$I = I_{ph} - I_d \quad \dots (4)$$

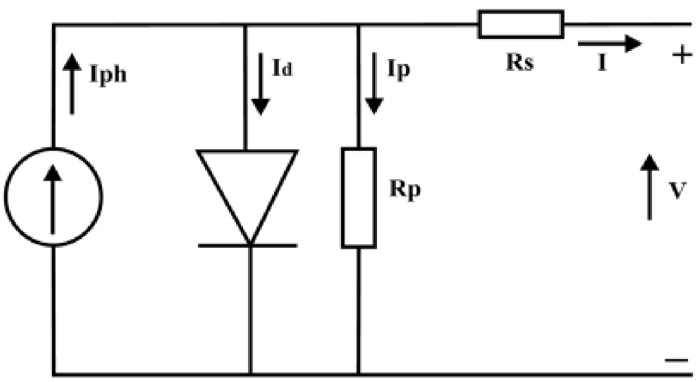


Figure 1. Model equivalent circuit for a PV panel

In the Eq. (5), the diode current is adjusted to Eq. (7) while the Rs is included but the Rp is assumed to be infinite.

$$I_d = I_s\left[\exp\left(\frac{qV_{oc}}{N_sKAT_o}\right) - 1\right] \quad \ldots (5)$$

$$I = Iph - I_s\left[\exp\left(\frac{qV_{oc}}{N_sKAT_o}\right) - 1\right] \quad \ldots (6)$$

$$I_d = I_s\left[\exp\left(\frac{q\,(V + IRs)}{N_sKAT_o}\right) - 1\right] \quad (7)$$

The presence of Rs is altered Eq. (6) and controlled Eq. (8). While the output current I is calculated when the PV cells are connected in a series-parallel configuration, that would revise Eq. (7) as shown in Eq. (9).

$$I = Iph - I_s\left[\exp\left(\frac{q(V + IRs)}{N_sKAT_o}\right) - 1\right] \quad (8)$$

$$I = Np * Iph - Np * I_s\left[\exp\left(\frac{q(V + IRs)}{N_sKAT_o}\right) - 1\right] \quad (9)$$

The values for the above-mentioned PV cell modeling equations must be specified for modeling, and these values vary depending on the selected type of PV module. The following equation provides the information needed to calculate Iph, Irs and Is for this model. Accordingly, the Iph of photocurrent is relative to the incoming flux and independent of V or Rs. Predominantly, it dependent on radiation of the solar, its impacted by weather temperature given to the equation (7) which Iph is presented.

$$Iph = [I_{sc} + Ki\,(T_o - T_r)] * \frac{G}{G_{ref}} \quad (10)$$

The saturation current (Is), Imax or Irs reverse saturation current are estimated by applying Eqs. (11) and (12). Using the model and data provided by the manufacturer module, calculate the factor A and energy band gap Eg.

$$I_{rs} = I_{sc}/\left[\exp\left(\frac{qV_{oc}}{N_sKAT_o}\right) - 1\right] \quad \ldots (11)$$

$$I_s = I_{rs}\,[T_o/T_r]^3 \exp\left[\left(\frac{qEg}{AK}\right)\left(\frac{1}{T_r} - \frac{1}{T_o}\right)\right] \quad \ldots (12)$$

Environmental Impact Assessment

Table 3 shows the environmental impact assessment. The life cycle assessment indicated that a thorough analysis of the environmental effects of the solar energy system, including the stages of manufacture, usage, and disposal, were evaluated to understand the system comprehensive environmental consequences. Likewise, the carbon footprint (kg CO2eq) of the system designated as 3,500 kilos of CO2 equivalent [29]. The sum of the greenhouse gas emissions throughout the course of the system life-term were estimated. While a value of 3,500 kg indicated that the system emits this much CO2eq yearly and has a modest carbon footprint. The land and habitat disruption of the system environmental are considered to be "Minimal"[29]. This indicates that the local ecosystems and animal habitats are not significantly harmed by the installation or operation of the solar energy system.

While the sustainability is continuous monitoring and sustainability issues are being actively considered. This implies that actions are being taken to continuously monitor, control, and minimize the system for long-term environmental effects with an emphasis on fostering sustainability. In addition, the mitigation strategies at phase of "Local reforestation" are implied that steps being made to minimize any unfavorable environmental effects. Thus, the environmental restoration and the disturbance that the solar system installation causes may both be mitigated by reforestation activities.

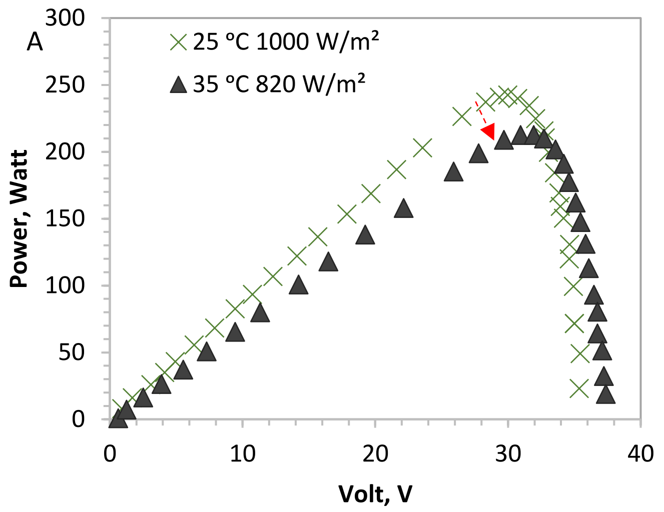
Table 3. Evaluation of Environmental Aspects and Mitigation Strategies[30]

Aspect	Value (Example)
Life Cycle Assessment	Assessment in progress
Carbon Footprint (kg CO_2eq)	3,500
Land and Habitat Disruption	Minimal
Sustainability	Ongoing monitoring
Mitigation Strategies	Local reforestation

3. Results and Discussion

The PV model simulation results were sensitive to the climatic conditions in Miskolc[31], which are characterized by highly changeable solar radiation and temperature values. To understand how the PV module responds to changes in the I-V and P-V values, as outlined in the datasheet of the model under (STC). Figure 2 shows that, despite a decrease in solar radiation, the PV model current has been influenced and marginally affected by power production as increasing PV temperatures. This phenomenon aligns with findings by other researchers[32], indicating that the model considers both constant solar irradiation across various temperatures and varying levels of solar exposure were considered in this work.

The first scenario involves a constant temperature of 25 °C and solar radiation levels below 1000 W/m2. The PV model output current decreased from 8.75 A to about 7.2 A; on the other hand, the output power of the PV modules remained relatively same at 250 W to around 220 W, as compared to the standard case of STC at 25 °C, 820 W/m2.



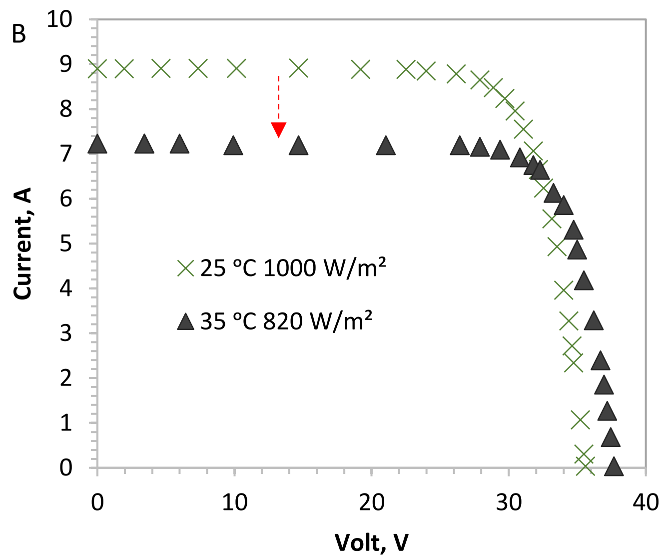


Figure 2. Characteristics of PV model under STC at 25 °C and 820 W/m2 (A) power vs voltage, (B) Current vs. voltage.

The sun radiation is vital over PV related to the ionisation and reduction of transmittance, PV model output current and power were decreased from 8.75 A to around 4.8 A, and the output power value dropped from 250 W to around 140 W, while the temperature and solar radiation were 25 °C and 535 W/m2. A considerable reduction from 8.75 A to around 1.7 A in the PV panel output current was caused by the ongoing decrease in the solar irradiation value at 25 °C, which is 185 W/m2. As seen in Figure 3, the PV model's output voltage decreased from 250 W to about 45 W when compared to the datasheet of the model under STC.

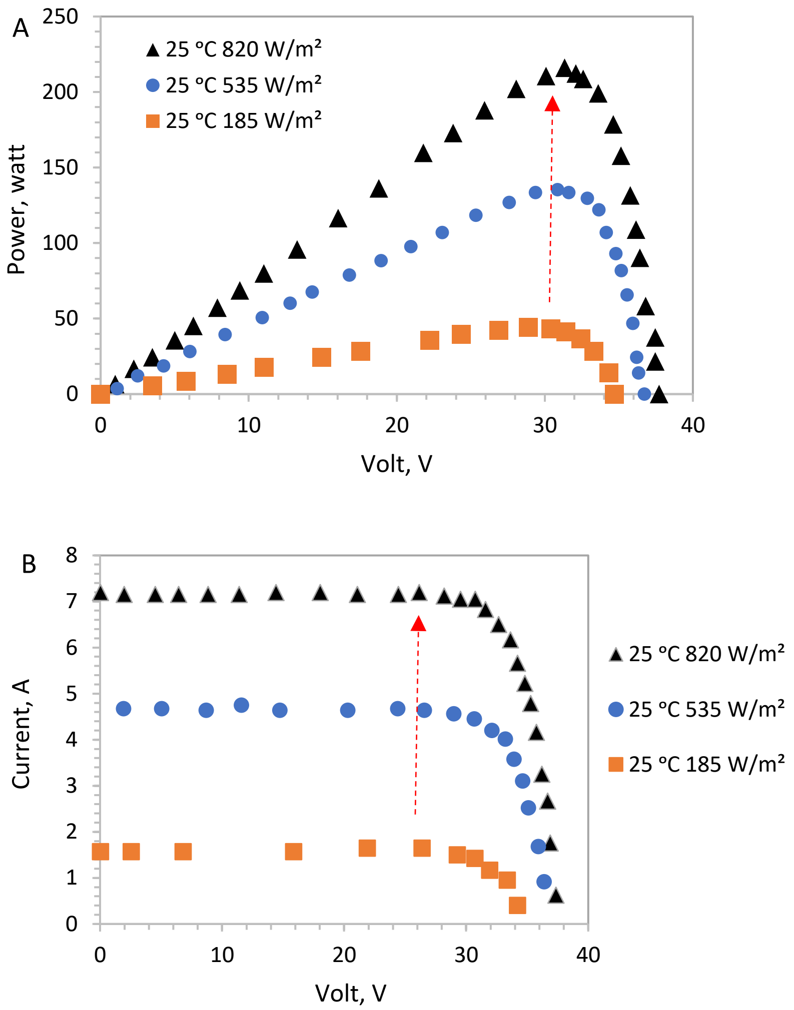


Figure 3. Characteristics of the PV model at 25 °C with various radiation (A) power vs voltage, (B) Current vs. voltage.

In the second scenario, we have a fixed sun irradiation value of 1000 W/m2 and a range of temperatures of 35, 24, and 18 °C. The model performance was impacted by the high temperatures, which caused the PV cells to rise. The output current of the PV model declined somewhat to 8.75 - 7.75 A and the output power dropped to about 210 W when compared to the datasheet of the PV model under STC at 35 °C and 1000 W/m2. Figure 4 shows the increased output current and power of the PV model at 24 C° and 1000 W/m2. Because the radiation and temperature figures in the standard operating datasheet for PV models are so close. Figure 4 shows that even with 1000 W/m2 of solar radiation, the PV model's output current and power consistently rise with a 10 °C temperature drop compared to the values when the temperature was high.

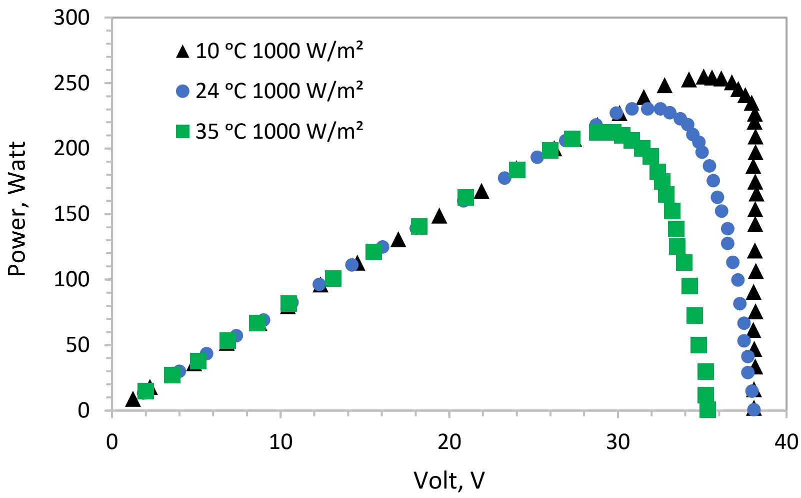


Figure 4. Properties of the P-V pair Various temperatures and constant radiation conditions for PV model

The solar panel with high efficiency suggested that the system expected to capable of efficiently converting sunlight into power. This is in line with the goal of the study to increase the production of renewable energy by improving system performance. Table 4 shows the annual energy yield and the system estimated about 1,250 MWh yearly energy production which it satisfied the research objective of generating a significant quantity of renewable energy for both supplying energy demand and reducing environmental effect. Accordingly, the economics payback period for five-year was estimated and it is consistent with the study goal of determining economic feasibility.

Thus, the method was more financially appealing since the payback time is shorter and the original expenditure possible recovered very soon. The carbon footprint of the system showed a noticeable but not too negative environmental effect, as seen by its modest carbon footprint contributed about 3,500 kg CO2eq. Considering the study goals, a carbon footprint assessment is crucial since it informs sustainability and environmental concerns.

Table 5. Evaluation of metrics and interpretation for solar system performance

Metric	Value	Interpretation output
Solar Panel Efficiency (%)	19.5%	The solar panels demonstrate good efficiency, converting nearly 20% of sunlight into electricity. This aligns with the research objective of optimizing system performance.
Annual Energy Yield (MWh/yr.)	1,250	The system generates 1,250 MWh of electricity per year, meeting the research goal of producing a substantial amount of clean energy.
Economic Payback Period (years)	5	Achieving a payback period of 5 years signifies a rapid return on investment, which aligns with the research objective of assessing economic viability.
Carbon Footprint (kg CO_2eq)	3,500	The system's carbon footprint of 3,500 kg CO_2eq indicates moderate environmental impact, which is a factor considered in the research objectives.

The study emphasized influence renewable energy policy by emphasizing the need of financial incentives, grid connectivity, and environmental laws. They eventually support the expansion of the solar energy sector by guiding industry standards and financial viability. Before installing a solar photovoltaic (PV) system in any given location, it was crucial to model, simulate, and analyzed the generator to get insight into its behavior and features under the actual weather conditions of that area. The impact on renewable energy policy is by highlighting the need of financial incentives, grid connection, and environmental legislation. They ultimately encourage the growth of the solar energy sector by setting standards for the sector and ensuring its profitability.

4. Conclusion

In conclusion, this study on solar panels demonstrated significant advancements in renewable energy technology and sustainable practices. The solar panels had 19.5% efficiency rate effectively converted sunlight into power, while the system made 22% capacity factor ensured consistent energy production. With a low annual deterioration rate of 0.5%, the system longevity was promising. The energy output of 1,250 MWh/yr. Aligned with the goal of producing clean energy, and the system of 98% reliability meant minimal downtime and failures. The sophisticated modeling tools, enhanced by historical weather patterns and regional data, yielded accurate energy forecasts. The successful simulation of a 3-kW rooftop system and extensive modeling predicted the annual energy production accurately. Financially, the system presented a viable investment with an initial capital cost of $1,000,000 and a reasonable 7-year payback period. Maintenance was efficiently managed within a budget of $6,000 annually. A positive financial return was indicated by an 8.5 year of ROI, and the Levelized Cost of Energy (LCOE) was economically set at 6.50 cents per kWh. Environmental considerations were paramount, as evidenced by a current life cycle assessment to gauge broader ecological impacts. The system's carbon footprint was relatively modest at 3,500 kg CO2eq, underscoring its minimal environmental impact. Eco-friendly installation practices further reduced ecological disruption and supported ongoing sustainability initiatives focused on long-term environmental stewardship. Local replanting as part of mitigation strategies effectively countered environmental changes, highlighting a commitment to ecological balance and sustainability.

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