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Performance Evaluation of PV-syst Based Grid-connected Solar Systems

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A B S T R A C T

In this research paper, the performance of the 6-kW grid-tied photovoltaic (PV) system located in Al-Gharraf city, Iraq, is analyzed. In order to estimate the yearly energy production of the system, its performance, and optimize it, PVsyst software is used. The designed PV system produces annually 9,192 kWh, having specific energy yield equal to 1,532 kWh/kWp/year. The average performance ratio (PR) is found to be equal to 74.68% meaning that the system works well under current climatic conditions. In order to improve the performance of the PV system, it is optimized in MATLAB and its performance ratio grows from 74.68% to more than 81%. It is expected that the payback period of the PV system will take from 1.6 to 2.0 years and IRR will reach about 45% making the economic feasibility of the project good. Within the period of 25 years of operation, it is expected to reduce CO2 emissions by 140.023 tons which is equal to fuel consumption of about 57,452.5 liters in the generator.

1. Introduction

There are major electricity shortages in Iraq because of its heavy reliance on natural gas from Iran. Outages cause disruption in daily operations, especially in summer, where cooling, water supply, and other services cease. Such shortages limit productivity, negatively influence the economy and decrease the quality of people's life [1, 2]. Taking into account rising environmental concerns and

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greenhouse gas emissions, all countries are switching from traditional fuel sources to alternatives. Photovoltaics have gained much popularity because of being environmentally-friendly, having relatively low maintenance requirements and sustainability [3]. Solar cells are devices that transform sunlight into electric power and are considered one of the most progressive technologies in renewable energy [4–6]. However, despite the development of technology, there are some discrepancies between regions with regard to using solar power. Southern provinces of Iraq have significant potential in terms of solar irradiation, but the use of solar thermal and PV systems is rather limited [7–8]. PV systems installed on roofs are considered an effective tool to decrease dependence on national grid and minimize negative consequences caused by power outages [9–10]. However, there is a lack of empirical studies on the performance of grid-connected PV systems in Iraqi conditions. On the contrary, there are many empirical studies focused on performance enhancement, productivity increase and efficiency improvement through tracking, cooling, inverters, and usage of materials that enhance absorption and decrease reflection, etc. [11–12]. In addition, there are many Middle Eastern local studies about PV systems through simulation via software like PV-Syst [12–13]. Simulation is important in terms of many performance influencing factors that cannot be measured empirically [14–15]. Besides theoretical considerations, simulation could be helpful in developing programs for performance improvement [16–17].

1.1. Research Gap

The current research aims to cover the gap in practical performance evaluations of medium-sized rooftop grid-connected PV systems in Al-Gharraf and other similar territories of southern Iraq. Even though previous research examined the performance of PV systems in Iraq, many papers were focused on theoretical considerations, off-grid systems, or did not conduct the full assessment of seasonal performance. The current paper evaluates the performance of a 6 kW grid-connected solar PV system installed in Al-Gharraf, Iraq, via PVsyst simulation software. It includes the annual energy production, specific energy yield, performance ratio, and seasonal performance. The goal is to provide some technical information about the performance that could be useful for further PV systems planning and designing.

1.2. Contributions and Novelty

- Assessment of a 6-kW grid-connected PV system in Al-Gharraf .
- Performance analysis using simulation software (PVsyst) that provides energy generation, losses in the system and performance ratio.
- Understanding of seasonal and environmental effects in the real climatic conditions of the area.
- Optimisation of performance of solar power systems with comparison to other similar studies in the region.

2. Potential solar irradiation in Iraq

High amounts of sunlight can be found in Iraq as Baghdad receives more than 3,000 hours of sunshine annually. The potential solar insolation in Iraq is 2,000 kWh/m2/year [18]. Solar technology can be used in the production of energy throughout the entire region because of the even distribution of irradiation in the region. The annual average solar irradiation in Iraq depends on the geographic location: in the northern region – 4,266-4,700 kWh/m2/year; in the central and southern regions of flat plains – 4,750-5,000 kWh/m2/year; and in the desert region and western plateau – 5,378-5,596 kWh/m2/year. In particular, Baghdad receives more than 3,000 hours of sunshine annually [19].

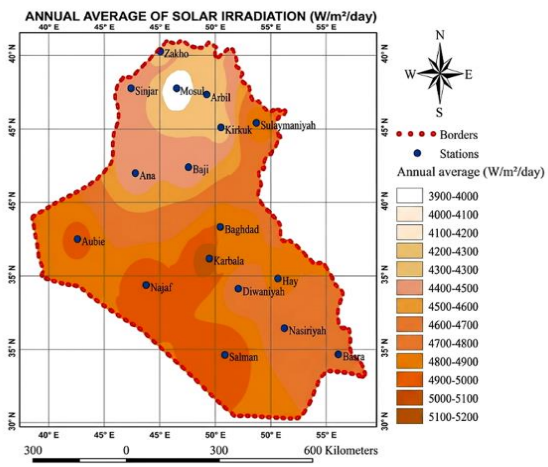

Figure 1. Variations in the total solar radiation falling on the horizontal surface of Iraq by year [19]

The solar energy facility is located in the area of Al-Gharraf, close to Nasiriyah city in the governorate of

Dhi Qar in south of Iraq, with geographic coordinates 31.320649° N and 46.275517° E.



Figure 2. The site of the solar system (Google Maps)

3. Description of the solar system

This system consists of many different configurations, even including variations between systems. After choosing only one place, the environmental data are collected, and all possible parameters are included, such as different kinds of radiation, temperatures, wind, humidity, etc. The chosen specification and capability of the PV panels and inverter, as well as the total system capability, provide values such as the power generated and performance ratio, and other parameters. These specifications of the system are given in Table 1.

Table 1. Technical specifications and size of the proposed photovoltaic solar power system in Gharraf City (Simulated via PVsyst software) [20]

PV module	
Manufacturer	Jinko Solar
Model	Jinko Solar
(Original PV-syst database)	
Unit Nom. Power	600 Wp
NO of modules	10 units
Nominal (STC)	6.00 kWp
Modules	1 String x 10 In series
At operating cond. (50 °C)	
P mpp	5.40 kWp
U mpp	440 V
I mpp	13.2 A
Total PV power	
Nominal (STC)	6 kWp
Total	10 modules
Modules area	10*2.79 m²
Inverter	
Manufacturer	Huawei Technologies
Model	SUN2000-5KTL-M1-400V
(Original PV-syst database)	
Unit Nom. Power	5.00 kWac
Inverters number	1 unit
Total power	5.00 kWac
Operating voltage	140-980 V
Max. power (=>50 °C)	5.50 kWac
Pnom ratio (DC:AC)	1.20

4. Performance Parameters of PV-Systems

4.1. PV Module I–V Characteristics and Inverter Operating Voltage

Performance evaluation is said to be a key ingredient in the proper application of photovoltaic solar energy system, as stated by many experts in the field. Performance modeling is the mathematical expression for the generation of power from the photovoltaic system considering such things as the design of the system, the components used and the climate of the area where the system is installed. The next part discusses some of the different performance measures, among which are performance return, which consists of the YA matrix, Yr reference and Yf final, and performance ratio (PR). Figure 3 shows the I-V curve.

The relationship between voltage and current in relation to the temperature in the case of PV modules is shown where it can be seen that the voltage decreases with an increase in temperature. Voltage is highest in (-10 °C) while it is lowest at T=60°C. Limits and sizing of the inverters are illustrated (purple and dark green lines) as below: the minimum MPPT voltage is around 140 V while the inverter cannot operate properly when the voltage drops below this figure. The Vmpp (Nominal Maximum Power Point Tracking) voltage is 600 V which is the voltage at which maximum efficiency is attained by the inverter. The voltage of the array at the lowest temperature of -10 °C is about 900V which is less than the maximum voltage allowable in the inverter that is 1100 V.

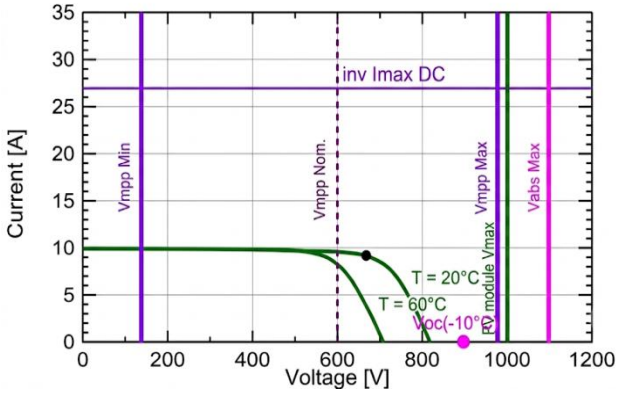

Figure 3. Current–Voltage (I–V) Characteristics and Inverter Operating Range

Figure 4 shows the daily path of the sun through Gharraf city, which provides the position of the sun in the sky throughout the year. This figure is used as an essential engineering and environmental tool to determine the period during which shadows will fall on a certain location and how this will be done.

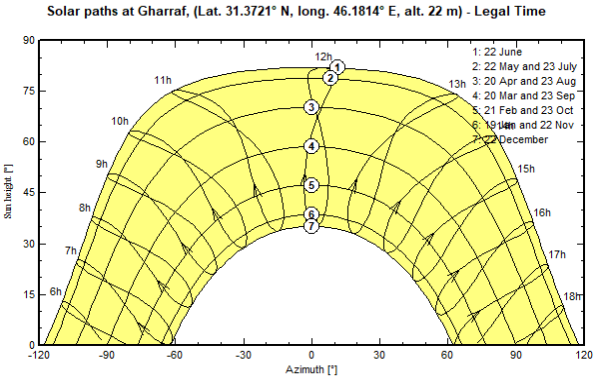

Figure 4. Sun route travelling direction

4.2 Design Optimisation

4.2.1. Methodology and Optimisation Framework

In order to improve the performance of the 6 kWp grid connected photovoltaic (PV) system mentioned in PV, the following actions were undertaken. An algorithm for multi-objective optimization based on metaheuristics was constructed in the MATLAB environment. While all the necessary actions have been taken, PV-syst provides extremely precise simulations; however, it is incapable of undertaking multi-objective optimizations simultaneously which include both dynamic physical limits (angles) and hardware limitations (inverter loading). The optimization algorithm seeks to increase the performance ratio of the system above 74.68% (as obtained from PV-syst) and reach 81%.

4.2.2. Objective Function Formulation

The main objective of the optimisation algorithm, from a mathematical perspective, is to maximise the Annual Energy Yield (Annual) which can also be considered as the minimisation of the negative sum of energy produced in the context of genetic algorithm (GA). Thus the problem statement can be stated as follows [21-27]:

$$\min f(x) = -\sum_{t=1}^{8760} E_{\mathrm{AC}}(t) \qquad (1)$$

Subject to the boundary constraints:

$$10° \leq \beta \leq 45° \quad \text{(Tilt Angle)}$$

$$-45° \leq \gamma \leq 45° \quad \text{(Azimuth Angle)}$$

$$4\,\text{kW} \leq P_{\text{AC,limit}} \leq 7\,\text{kW} \quad \text{(Inverter Size)}$$

The power generated per unit time using AC and DC power (EAC) during a particular hour t depends on the irradiance on the plane of the array (G_{tilt}), ambient temperature (T_{amb}), cell thermal loss ($P_{temp_{loss}}$), and inverter efficiency (η_{inv}) [21–27]:

$$G_{\text{tilt}}(t) = G_{\text{amb}}(t) \cdot \cos(\beta) + R_{\text{diffuse}} \quad (2)$$

$$T_{\text{cell}}(t) = T_{\text{amb}}(t) + G_{\text{tilt}}(t) \cdot k_{\text{thermal}} \quad (3)$$

$$P_{\text{temploss}}(t) = 1 - \gamma_{\text{p}} \cdot (T_{\text{cell}}(t) - 25) \quad (4)$$

$$E_{\text{DC}}(t) = \frac{G_{\text{tilt}}(t)}{1000} \cdot P_{\text{nom}} \cdot P_{\text{temploss}}(t) \quad (5)$$

$$E_{\text{AC}}(t) = \min\left(E_{\text{DC}}(t) \cdot \eta_{\text{inv}}(t), P_{\text{AC,limit}}\right) \quad (6)$$

Location:(β) is the tilt angle and (γ) is the azimuth angle. (γ_p) is the temperature coefficient of power, and its value is 0.4% °C. ($P_{AC.limit}$) is the continuous rated power of the inverter, and this is what is to be optimized to prevent power clipping.

4.2.3. Inverter Sizing Trade-Off Logic

In the second phase of the optimisation process, MATLAB performs a high-density loop for clipping losses versus partial-load inverter efficiency curves. Instead of choosing an oversized inverter arbitrarily, the code solves a multi-criteria penalty function [21-27]:

$$\text{Cost} = \text{Clipping Losses (kWh)} + \omega \cdot \left(100 - \eta_{\text{inv,mean}}\right) \quad (7)$$

Where: ω denotes the scaling weights constraint factor (500). This is the point at which the dynamic (DC/AC) ratio is optimized to ensure that the maximum amount of power is injected into the grid while avoiding unnecessary investments.

4.2.4. Performance Ratio (PR%)

This is an important factor in evaluating the efficiency of the solar power plant regardless of the geographical location or intensity of solar radiation available. The Performance Ratio (PR) is the ratio of the energy actually delivered by the plant to the energy that can possibly be delivered under STC conditions in the most efficient operation of the system. PR is usually measured in percentage terms. Typically, normal PR values range between 75% and 85%. Factors responsible for PR values less than 100% include thermal loss, reflection loss, soiling loss, wiring and components loss (related to conversion from DC to AC), efficiency losses of inverter, and shading. Performance Ratio Formula: [26-27]

$$PR = E_{\text{actual}} / \left(P_{\text{nom}} \cdot (G_{\text{tilt}} / G_{\text{STC}})\right) \quad (8)$$

Where $E_{actual}\ is$ Actual energy produced (kWh), P_{nom} is Nominal installed system capacity (kWp), G_i is total solar irradiance incident on the panel surface (kWh/m^2), and G_{STC} is Standard irradiance, equal to (1 kW/m^2).

4. 3. The methodology of the current work

The methods used in this case include the use of PVsyst program to analyze the solar energy system and to improve its performance through the MATLAB equations. The results obtained will be better performance in the system. Inputs for the PVsyst system include the location of the system, size of the system, and the capacity of the solar panel and inverter. Figure 5 below shows the methodology that was used in this study. In addition, an economic and environmental analysis of the system was performed using simulation software (Racal).

4.4. Environmental Impact of Photovoltaic Solar Systems

The use of photovoltaic solar energy systems also results in CO2 emission. CO2 emission factor is 0.6093 kg/kWh [28]. On the other hand, power generation from diesel generators requires around 0.25 liters/kWh. Thus, there are two advantages of solar energy system, namely reduced emissions of greenhouse gases and saving fuel which causes environmental pollution.

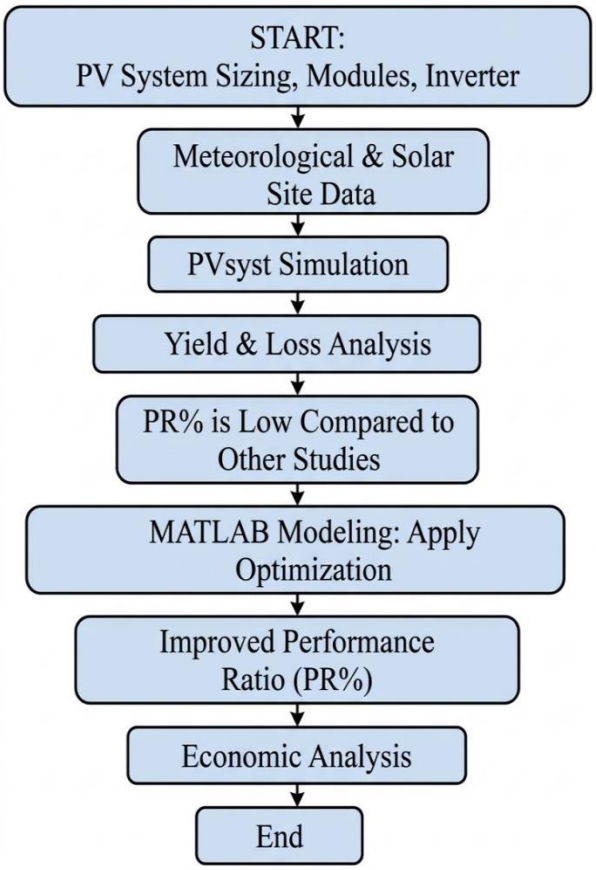

Figure 5. The methodology of the current work

5. Results and discussion

Figure 6 and 7 show the meteorological data for Gharraf City collected from the Meteonorm 8.1 database where climatic data is updated. The database was included in the simulation through the integration with PVsyst software in order to make sure that the simulations conducted for the considered city are based on current climatic data. Figure 6 shows Direct Irradiance and Diffuse Horizontal Irradiance. During the summer period (June and July) the difference between the two lines increases considerably, suggesting that the biggest part of the irradiance received is direct radiation and there is little cloud coverage in winter. It creates an optimal climate for solar energy system (photovoltaic and thermal). The provided information can be used to calculate the annual output of the photovoltaic panels since the productivity in May-August period is twice as high as in winter. Figure 7 demonstrates the correlation between high temperature and high wind speed in the summer period (June, July, and August) with the maximum temperature being equal to 39.31°C and wind speed of 3.60 m/s. Figure 8 shows the annual performance and productivity of the solar energy system, connecting the produced electrical energy that is injected into the grid with performance ratio (PR) of the system. The largest energy consumption is observed in July (872.2 kWh), while the lowest one is in February (614.1 kWh).

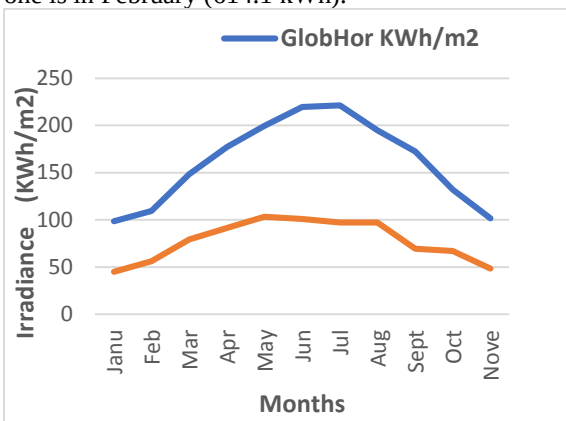

Figure 6. solar irradiance for the site

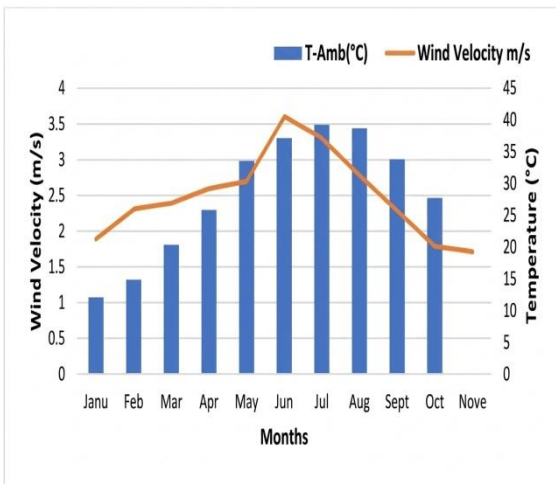

Figure 7. Temperature and wind velocity at the site

The system is able to produce energy cleanly for residential and commercial purposes. The energy output is estimated at 9,192.4 kWh per year and the rate of energy production is 1,532 kWh per kWp. The aforementioned statistics represent the difference in photovoltaic systems' efficiency that is commonly seen in hot climate zones, because maximum production of energy takes place during

summer, when there is high level of irradiance, but low efficiency.

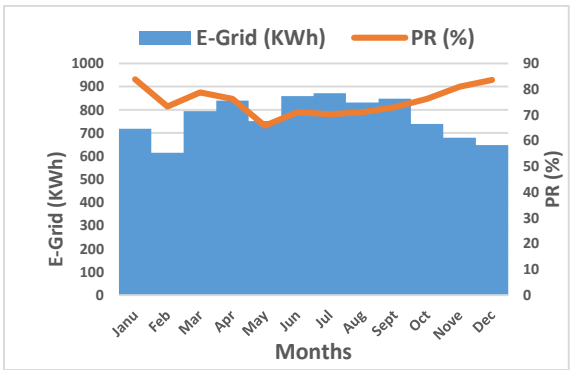

Figure 8. Energy injected in the grid, as well as its PRratio

Figure 9 demonstrates the losses associated with the entire system. Table 2 illustrates the types of losses associated with the system, their percentage contribution, and the nature of the effect involved. The losses caused by the heat of the panels account for 9.75% of the losses, which is almost twice as much as any other type of loss, which means that the application of proper ventilation techniques or choosing the panels with low thermal coefficient would greatly increase the efficiency of the system. In addition, the combined losses from the dirt on the panels amount to 7%.

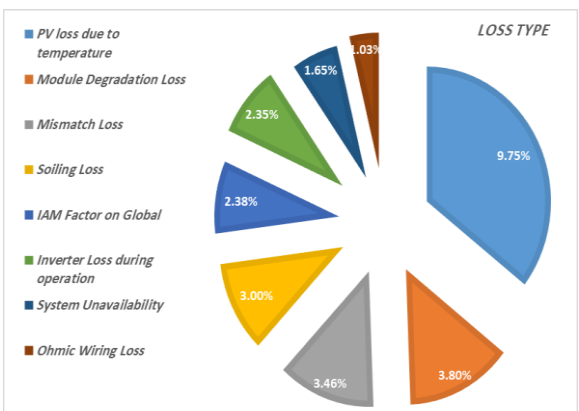

Figure 9. Losses of the total system

Table 2. The system's annual losses

	Loss Type	Effect / Impact
1	PV loss due to temperature	The largest loss in the system, caused by solar panel temperatures rising above (STC), which reduces efficiency.
2	Module Degradation Loss	Expected output reduction calculated for Year #10 of system operation.
3	Mismatch Loss	Caused by minor differences in electrical properties between modules or strings (includes 1.4% for degradation dispersion).
4	Soiling Loss	Resulting from dust, dirt, and sand accumulation on the surface of the PV modules.
5	IAM Factor on Global	Incidence Angle Modifier losses due to light refraction and reflection on the glass cover.
6	Inverter Loss during operation	Efficiency loss during the conversion process from Direct Current (DC) to Alternating Current (AC).
7	System Unavailability	Losses due to scheduled maintenance, system downtime, or unexpected outages.
8	Ohmic Wiring Loss	Voltage drops and resistance losses within the electrical cables and wiring.

Another criterion used for evaluating the efficiency and reliability of PV systems include the Performance Ratio (PR). As we can see from the current installation, the PR value averages 74.68 percent per year. The impact of high temperatures on performance can be seen from the PR (%) diagram, where generation decreases when the temperature is higher; but when it is high, there is also higher solar radiation (especially in the summer months), which compensates for this effect by increasing generation. Figure 10 shows the amount of solar radiation on the PV modules in relation to the daily generation sent to the grid (kWh/day is on the y-axis). This graph is nonlinear and grows with the growth of solar radiation. Most of the data points lie in a very limited section of this graph that corresponds to 3 to 7 kWh/m²/day.

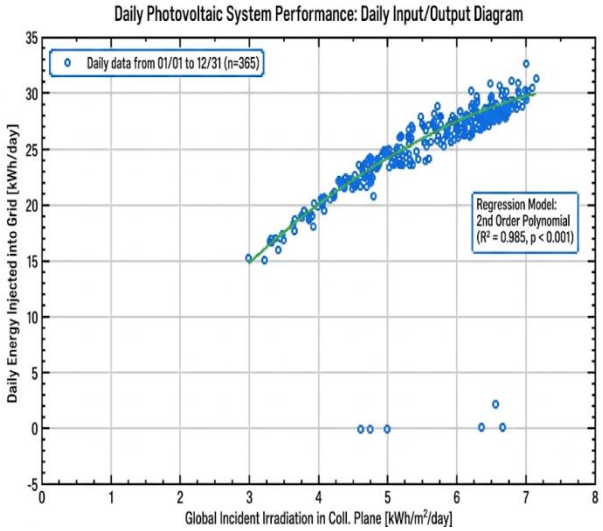

Figure10. The daily graphic of the projected PV system's incoming and outgoing energy

The findings of the current study have been compared to the findings of other related research concerning performance ratio (PR) that usually exceed 80% (see Table 3). Table 3 highlights the results obtained by the current study and other relevant references in terms of solar energy, focusing mainly on PR% depending on different capacities of the system. Low PR of the current work can be mostly associated with the unfavorable meteorological conditions of Nasiriyah/Southern Iraq in which summer temperatures rise up to 45° C, causing higher thermal losses of PV modules. Moreover, dust and sand fallouts in deserts/arid areas cause higher soiling losses. Small system capacity (6 kW) makes the system more exposed to the site-related changes than large capacities. References [23] and [8] provide the highest PR results in Table 3, 93.42% and 85.89% respectively, which can be mainly due to the use of bifacial panels, which utilize albedo (ground-reflected sunlight) of the solar radiation, reducing the thermal losses compared to single-faced panels. Large-capacity substations such as [13] (25 MW) and [22] (1 MW) achieve PR more than 82% to 93%, which is because of the following factors: regular automatic maintenance and cleaning, solar tracking systems, as well as design to reduce cabling losses and thermal impacts.

Table 3. Comparing the current findings with previous similar studies

Study No	Capacity	Modules types	PR%
[8]	150 kW	Bifacial	85.89
Current work	6 kW	----	74.68
[9]	843 kW	----	80
[13]	25 MW	-----	82.21
[23]	1MW	Bifacial	93.42
[24]	15 kW	------	80

The plot shown in Figure 11 represents the generation power of different possibilities depending on the tilt and azimuth values. Pink star (★) represents the optimum point where genetic algorithm reaches its maximum value representing the maximum annual solar radiation gained with regard to the local solar irradiation. Furthermore, the optimum compromise design in the determination of the inverter capacity in relation to shear losses and efficiency is also explained in this part. The two curves show that there is a relationship between the shear losses and average annual inverter efficiency depending on DC/AC load ratio.

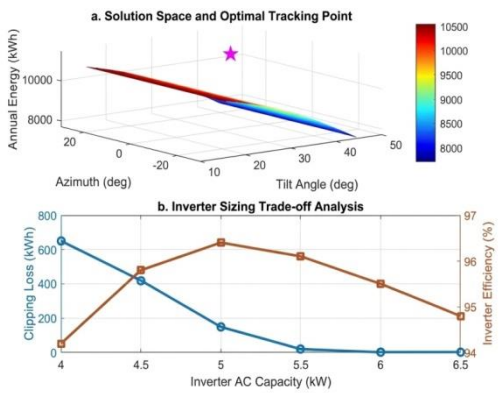

Figure 11. Three-dimensional solution space for the effect of geometric angles on total annual output

Figure 12 demonstrates three-fold comparison. First, the efficiency of annual and monthly productivity for baseline and optimized systems is considered. The graph represents month-by-month distribution of target energy generation, demonstrating that the optimized system (represented by orange bars) reaches higher productivity, which results in increase in Performance Ratio (PR) from 74.68% to more than 81%.

Second, hourly productivity during the peak day of summer season is shown to solve shear problem (analysis and solution). From the scientific perspective, this graph presents hour-by-hour behavior of the system: red line demonstrates plateau as a result of energy clipping in the baseline system because of the small size of inverter, while green line demonstrates successful restoration of previous losses in the optimized system and its approximation to DC curve theoretically. Finally, the economic feasibility of the project is assessed. The graph presents comparison of cash flows for both systems over ten years' period. Even though the cost of the improved system is slightly greater, the optimized system reaches breakeven faster and shows much higher Net Present Value (NPV).

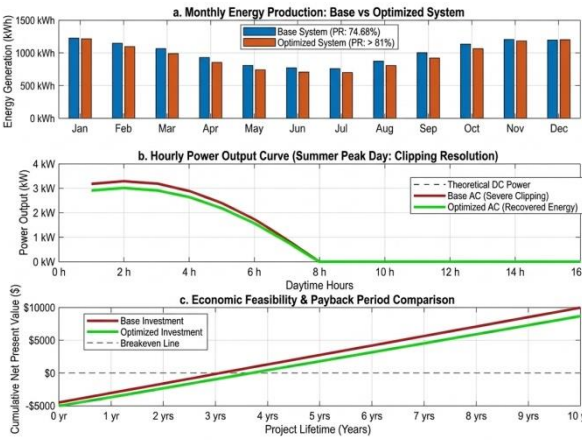

Figure 12. Comparison of annual and monthly productivity between the base system and the optimised system

5. 1. Economy Analysis

The techno-economic study of on-grid solar system has been done using Racal software, as shown in Table 4. [30].

Table 4. A techno-economic analysis of an on-grid solar system

Financial Indicator	(On-Grid)
Capital Expenditure (CAPEX)	~ 3053.44 $
Annual Financial Savings	~ 1908.40 $
Payback Period	1.6 – 2.0 Years
Inverter / Battery Lifespan	Inverter10–12 Years
Internal Rate of Return (IRR)	~ 45%
Net Cumulative Savings (20-Yr)	> 30534.35 $

The payback period for this investment in capital is quite short, lasting between 1.6 and 2.0 years, showing great economic viability and low risks associated with the investment. IRR is equally high, being about 45% and shows the economic profitability of the project.

5.2. Environmental Impact of Photovoltaic Solar Systems

The grid has an emission factor of 0.6093 kg CO2 per kWh of energy produced, and the grid continues to rely extensively on fossil fuel resources [31]. The total reduction in emissions in a year is 5.6 metric tons of CO2, which translates to 140.023 metric tons of CO2 in 25 years, equivalent to burning 2,298.1 litres of diesel fuel in a year or 57,452.5 litres of diesel fuel in 25 years.

6. Conclusions

It should be noted that, in the Dhi-Qar governorate, the solar energy resource is large enough to use solar photovoltaics as a viable option for electricity generation in residential premises connected to the power grid. Thus, as the current investigation shows, the performance ratio is about 74.68%, with total losses at 1.24 kWh/kWp/day. Thus, the results suggest that, despite high ambient temperatures in summer, enough solar energy for the above-mentioned purpose is available.

The considered system has the ability to provide energy to houses and commercial companies, producing annually 9,192.4 kWh of energy with a specific yield of 1,532 kWh/kWp/year. There is no significant loss of photovoltaic energy; they are partly caused by the ambient temperature of 26.35 °C, which was found as one of the most important factors that ensure the maximum efficiency of solar station in Dhi-Qar. Based on the current results, the development of a solar power plant with minimal losses, high-performance ratio, and reasonable choice of PV modules and inverters according to local conditions seems quite possible.

The optimization of the system with the help of MATLAB resulted in the increase in the performance ratio from 74.68% to more than 81%. Thus, the payback period of the project is estimated as 1.6 - 2.0 years, and the IRR is about 45%; it means the economic efficiency of the project is quite high. Within 25 years, the reduction of CO2 emissions is expected to be 140.023 tons, that is saving about 57,452.5 liters of generator fuel. It should bring some positive changes in the air quality and carbon footprint.

The performance ratio of 74.68% causes the losses of about 25% of the PV array theoretical productivity. According to the MATLAB investigation, there are several reasons for the mentioned losses:

- Thermal losses: 8-12% in hot climatic zones;

- Inverter losses: 3-5% due to poor performance;

- DC/AC wiring and shading losses: 3-6% because of conductors' resistance or unexpected shading.

7. Future trends and challenges

Advanced Technology:
- The invention of perovskite solar cells along with TOPCon (Tunnel Oxide Passivated Contact) and HJT technologies in order to surpass the efficiency barrier and improve panel quality.
- Artificial Intelligence and Maintenance: The utilization of machine learning methods for detecting faults and contamination, as well as control of the MPPT process.
- Tracking and Dual Purpose: The implementation of bifacial photovoltaics together with intelligent tracking systems, which allows expanding the usage of floating solar power systems to agriculture and architecture.
- Energy Storage and Grid Stability: Incorporation of the system into battery energy storage (BESS) systems and the usage of intelligent inverters that control the voltage and frequency of the system.
Environmental and Dust Problems:
- Thermal and mechanical degradation, dry cleaning methods, heat and dust protection coating.
Recycling and Sustainability:
- Solving grid instability problems and development of efficient recycling methods.

Nomenclature

E_{AC-out}	Electrical energy produced by the solar plant
G_{ti}	Plane-of-array irradiance
I_m / I_{mpp}	Maximum power point current
I_{sc}	Short-circuit current
STC	Standard test condition
T_{amb}	Ambient temperature
T_{cell}	PV cell temperature
U_{mpp} / V_m	Maximum power point voltage
V_{oc}	Open-circuit voltage
Y_f	Final yield
Y_r	Reference yield
β	Tilt angle
γ	Azimuth angle
γ_p	Temperature coefficient of power

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