

Implementation of Utility-Scale PV System to Support Power System Reliability

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Abstract: Nowadays, the Iraqi power system requires additional power due to its growing population and demands. Utility-scale photovoltaic (PV) power plants are generally feasible in geographic areas exposed to greater than 3 kWh/m²/day of solar irradiance. This study aims to analyze the possibility of expanding in use of PV systems in Iraq; thus, the main challenges facing the Iraqi electrical power system are discussed in this paper. Furthermore, the ability to implement a large-scale PV power plant in Iraq to increase the system's reliability is studied. The system advisor model (SAM) was used to achieve this analysis. As a result, based on the simulation results, the PV power plant is approved as a feasible solution in Iraq.

Keywords: photovoltaic system, system advisor model, Iraqi power system.

公用事业规模光伏系统的实施以支持电力系统的可靠性

摘要: 如今, 由于人口和需求不断增长, 伊拉克电力系统需要额外的电力。公用事业规模的光伏电站通常在太阳辐照度超过3千瓦时/平方米/天的地理区域是可行的。本研究旨在分析伊拉克扩大光伏系统使用的可能性; 因此, 本文讨论了伊拉克电力系统面临的主要挑战。此外, 还研究了在伊拉克实施大型光伏电站以提高系统可靠性的能力。系统顾问模型用于实现此分析。因此, 根据模拟结果, 光伏电站被批准为伊拉克的可行解决方案。

关键词: 光伏系统, 系统顾问模型, 伊拉克电力系统。

1. Introduction

Photovoltaic (PV) systems are a key solution for available renewable energy sources. The availability of solar power provides a better area for implementing a PV system as a potential energy resource. Furthermore, the cost of large-scale PV has decreased in recent years, carrying it far closer to the market rates set by natural gas or other power plant alternatives. Solar panels produce energy without carbon emissions, no ash or other waste materials, and no inputs other than sunshine in the environmental context.

The efficiency of most commercial PV panels ranges from 15% and 21% [1]. One of the most serious issues with PV installations is dust accumulation on solar panels [2]. It was experimentally proven that there is as much as an 11.5% decrease in the power production PV installation [3]. In China, PV technologies are rapidly developing. A PV plant was installed in china with different sizes and locations, such as small rooftops and large-scale PV plants in desert areas [4]. Furthermore, the performance of PV plants in remote desert areas was carried out in [4]. As

a result, the loss rooftop PV system is slightly higher than the desert PV system.

Practically, various PV tracking systems are available in PV power plants. Each one of those tracking systems has its characteristics and benefits. A performance comparison between those of the tracking system is presented in [5, 6]. Moreover, a comprehensive performance of operational performance and economic analysis of three PV tracking technologies which are fixed tilt (FT), single-axis tracking (SAT), and dual-axis tracking (DAT), in 3.275 MWp PV plant was presented in [7]. The authors considered the energy production, capacity factor, and levelized cost of energy (LCOE) in their study. As a result, the single-axis tracking system is the most economical system among tracking technologies.

The temperature condition plays the main role in the energy production of PV plants [8]. The floating PV plant is a new technology to decrease the temperature to maximize energy production. The PV panels are installed on water rather than a floating PV plant. Thus, the PV module would be lower due to the water-

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cooling effect [9]. In [10], the authors presented the technical analysis and economic benefits of floating PV Plant. The annual energy yield, performance ratio, capacity utilization factor, and total cost are considered indexes for comparing the floating and ground-mounted PV plants. As a result, the total efficiency increased by 2.5-3% in floating PV plants.

Several researchers have carried out the feasibility analysis of PV systems on small and utility-scale. The performance of a 200KWp grid-connected PV system in Koya city was presented in [11]. The authors concluded that the yearly average energy is 5.14 kWh/m²/day, and by installing PV Panels optimally, this becomes 5.79 kWh/m²/day. An economic feasibility study of PV installation cost in the Korean community energy system was presented in [12]; as a result, the authors indicate that the investment about 34.2% profit every year for 3,000 CES.

An economic feasibility analysis of grid-connected PV on the roof of a building was presented in [13]; the authors concrete their study to reduce the electrical demand of a small home building. As a result, the net present value (NPV) is achievable, and the payback period is less than the solar panel's life expectancy. Economic feasibility analysis PV System for a commercial building was presented in [14]. The authors dedicate their study to the head office building of Jubilee Life Insurance Company Limited, located in Karachi, Pakistan. As a result, the payback period of his project was 4.32 years, and it saved 18.3 tons of CO₂/year from being released into the atmosphere [15].

A utility-scale PV power plant was economically designed in [16]. The author presented an algorithm for optimum economical design. They introduced the effective levelized cost of energy index as the core of their design algorithm. As a result of their study, the economic size of inverters for 0.1–100-MW PV plants ranges from 8 to 100 kW

Nowadays, Iraq's power system is facing many challenges due to the growth of the population. Where it currently requires additional generation power to face the electrical demand. On the other hand, due to the circumstances of Iraq's wars over the past decades, the electrical system has been suffering from the low efficiency of currently old power plants. Since the development of a solar photovoltaic system surpasses any other renewable energy resources in recent years, the Iraqi Ministry of Energy aims to extend the utility scale of the photovoltaic system presently.

This paper proposes a feasibility study of constructing a utility scale photovoltaic power plant in Iraq. The PV plant's location, size, design, energy production, cost, and payback are analyzed. Furthermore, the proposed study includes technical and financial analysis. Evaluation of economic parameters including the levelized cost of energy (LCOE), cash

flow over the power plant lifecycle, net present value (NPV), and other related parameters are achieved.

The Organization of the rest of this research paper is as follow,

2. Review of Iraq Power System

The electric power sector in Iraq is managed through the Ministry of Electricity; its responsibility includes overseeing operational functions, including generating, transmitting, and distributing electrical energy. Currently, the population of Iraq will be about 32 million in 2020, and it is predicted to reach about 64 million in 2050 [17]. The maximum electricity demand in 2020, based on the Ministry of Electricity yearly report [18], was about 30 GW. On the other hand, the maximum power generation capacity in 2020 was about 19 GW. This difference between the generated power and demand began after the Gulf War. It is increasing if actions are not taken to overcome this issue Where; many power generation plans were hampered, and the operated plants became old. During the Gulf war, the total electricity generation rapidly decreases from 29GWh to about 13 GWh.

Additionally, the total technical loss in an Iraqi power system, as presented on the Iraqi Ministry of Energy website, (from electricity generation process to the customers) was about 40% in 2020, which indicates the low efficiency of the old current generation plants. Consequently, renewable energy resources are the best solution to get out of the electric power crisis in Iraq. Moreover, Political events in 2003 caused additional challenges to Iraq's power system to meet the power demand. During those events, the power demand increased, but most power plants were hampered.

The United Nations Climate Change Conference, also known as Paris Agreement, was held in Paris in 2015. The so-called Paris Agreement was ratified at that conference by the majority of the major CO₂ emitting countries. The Paris Agreement aims to reduce greenhouse gas emissions by limiting global warming to less than 2 degrees Celsius. Iraq announced its contributions to the global climate change mitigation effort at that conference [19].

The Paris Agreement, the growing Iraq population, the deficit in generation capacity, and the high technical loss motivate to expand renewable energy resources in the Iraqi power system where renewable energy resources are the best solution to get out of the electric power crisis in Iraq.

The electrical load in Iraq is classified as shown in Fig. 1, and the residual loads represent about 50% of all Iraq electrical loads. In addition, about 31% of loads were classified as government loads. From the renewable energy point of view, and since the residual load represents 50% of the total load, the PV system at home scale can be enhanced to decrease the total load in the Iraq power system. On the other hand, the

government load also can decrease by a large PV power plant.

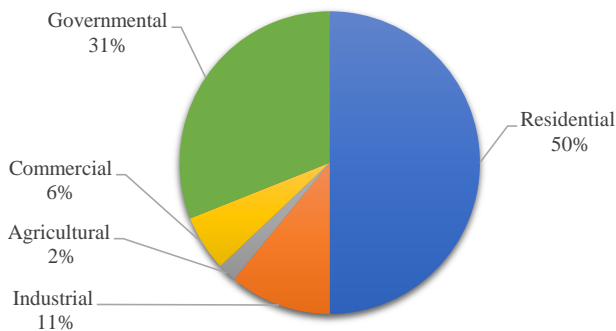


Fig. 1 The classification of electrical load in Iraq

The Iraq power system has four main power plants: steam power plants, gas power plants, hydropower plants, and diesel generators [18]. 154 Gas units generate about 42% of the total generated power, as in Fig. 2. On the other hand, the steam power plants represent about 25% of the total generated power.

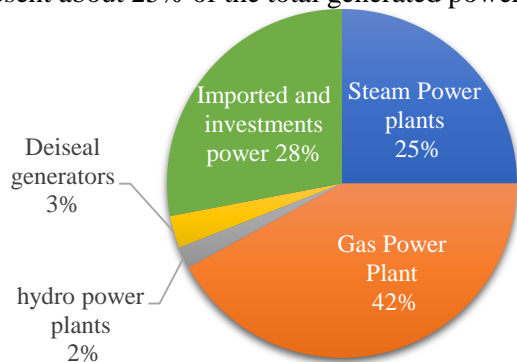


Fig. 2 Generation unit sharing in Iraq power system

Moreover, there are investment power plants and imported power from Iran power grid-connected are represent about 28% of the total generated power [18].

3. Photovoltaic Technologies

Solar cells convert sunlight into electricity. The PV cell consists of semiconductor components that directly convert sunlight into electrical energy; it does not produce noise or emissions without moving parts. It must be installed in an open area; specific mounting sites include rooftops, carports, and ground-mounted arrays. The output voltage of the PV solar cell is approximately about 0.5 V. The released current varies depending on radiation and cell area and lies between 0 and 10 A. In order to increase the voltage level to the normal usable voltage range (20–50 V), many cells are connected in series to form the solar module.

3.1. Modeling of PV Cells and Modules

The equivalent circuit of the ideal and practical model of a PV cell is presented in Fig. 3. The main equation from the theory of semiconductors that mathematically describes the I–V characteristic of the

ideal PV cell can be written as in equation (1).

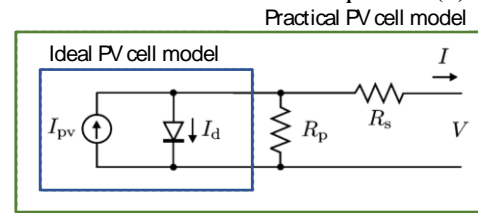


Fig. 3 Ideal and practical model of PV cell

$$I = I_{pv,cell} - I_{o,cell} \left[\exp\left(\frac{qV}{aKT}\right) - 1 \right] \quad (1)$$

Where $I_{pv,cell}$ is the PV cell current generated by the incident light. $I_{o,cell}$ is the diode's reverse saturation or leakage current. Q is the electron charge (1.6×10^{-19} Coulomb), K is the Boltzmann constant (1.38×10^{-23} J/K), T is the temperature in Kelvin, and a is the diode ideality constant, which usually ranged between $1 \leq a \leq 1.5$. PV cells are connected in series and parallel in practical applications. PV cells are coupled in series to boost the output voltage to the usable range; this is called a PV module. The fundamental equation (1) represents the fundamental equation for a single PV cell. However, PV cells are used in practical implementations, so other parameters are addressed. The equivalent circuit of a practical PV model is shown in Fig. 3, which has series and parallel resistors, R_S and R_P , respectively. The main equation of practical PV cell can be written as in equation (2).

$$I = I_{pv} - I_o \left[\exp\left(\frac{V + R_S I}{V_t a}\right) - 1 \right] - \frac{V + R_S I}{R_P} \quad (2)$$

Where I_{pv} is the PV module current. I_o is the saturation current, R_S is the equivalent series resistance of the PV module, R_P is the equivalent parallel resistance of the PV module, a is the diode ideality constant, and V_t is the thermal voltage.

The PV module/cell output depends on temperature and irradiation, so the I–V curve will change based on temperature and irradiance. The I–V curve PV module with various temperatures is shown in Fig. 4. It is observed that the temperature is inversely proportional to the open-circuit voltage V_{oc} of the module. As the temperature increases, the open-circuit voltage V_{oc} .

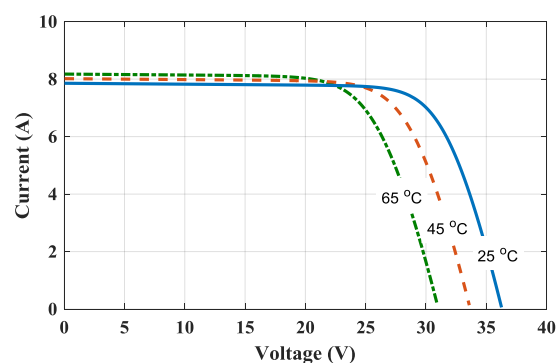


Fig. 4 Effect of temperature on I–V characteristic curve of PV module

The irradiation effect on the V-I characteristic curve of the PV module is presented in Fig. 5. It is observed that the irradiation is directly proportional to the short circuit current of the PV module. Thus, as the irradiance increases, the short-circuit current will also increase. However, solar irradiation and low ambient temperature are the best climate conditions for PV modules.

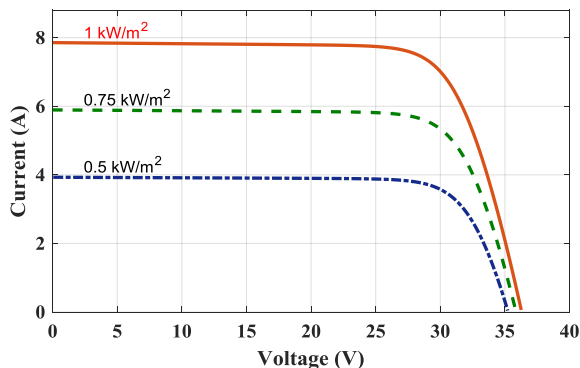


Fig. 5 Effect of irradiation on I-V characteristic curve of PV module

3.2. Design Consideration of PV Power Plant

Many essential considerations must be considered in the PV power plant design process. These include site selection, module selection, inverter selection and configuration, PV array configuration, and step-up transformer selection.

The site area of the PV plant mainly depends on the plant capacity and its layout. Practically, there is no direct formula between the capacity of the PV plant and the required area due to some reasons. For example, the technologies applied in each power plant of photovoltaic modules and inverter are different from one plant to another. Moreover, the PV modules and inverters manufacturers are also different from one PV plant and others. The radiation data play an important factor in selecting the PV plant site. Thus, Iraq's direct normal irradiation (DNI) is presented in Fig. 6, indicating the highest solar radiation values in Iraq's southern and western regions. The total daily DNI reaches more than 6 kWh/m².

Another parameter that must be considered is the albedo factor, defined as the ground reflectance. It is highly dependent on the site's nature. The grass has an albedo factor of about 0.26, asphalt has a value albedo factor between 0.09 and 0.15, and snow has about 0.8. With an albedo factor of 0.8, the earth will reflect 80% of the direct radiation.

Neighboring buildings, trees, and even tall buildings can shade the PV array, so it must be considered that the system could be shaded only in a couple of years due to the growth of trees. Shading resulting from the building involves natural shading, which should be considered a critical shading component. Some shading can be prevented in practice by shifting the PV modules or the shading-causing object.

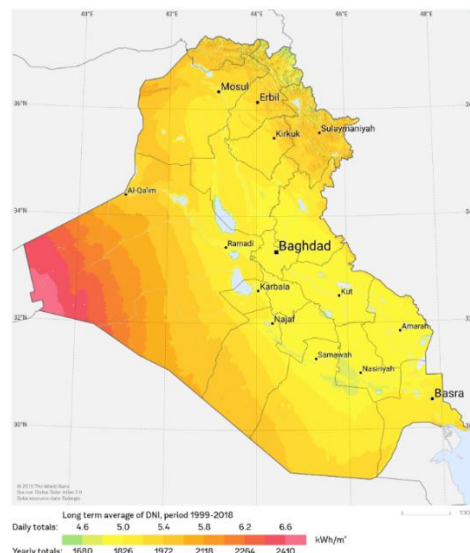


Fig. 6 Direct normal irradiation of Iraq

Connecting a large PV system to the electricity grid may impact the power grid operation during both steady-state and dynamic operations. Thus, the grid code requirements for connecting PV plants to the electricity system should be considered in the PV power plant design process.

3.3. Quantifying PV plant performance

PV power plant energy output is expected to deteriorate over time, especially after ten or fifteen years of service. The efficiency of the original installation is crucial for future performance, but operations and maintenance activities also heavily influence PV performance. Several performance indicators are presented in the literature to measure the expected performance of the plant, which are listed as follow:

1) *The performance ratio (PR)*: is a performance index that is often used to quantify the performance of PV plants when it commercially operates. This indicator compares actual energy yield to theoretical energy yield during the design process. Thus, it shows the percentage of the available energy exported to the grid after subtracting energy loss.

2) *The capacity factor (CF)*: is the ratio of the actual energy yield annually to the maximum possible energy yield. The maximum possible energy yield can be obtained by multiplying the installed PV inverter by several hours in a year. In contrast, the actual energy yield is the energy delivered annually to the grid.

3) *Levelized cost of energy (LCOE)*: this is another parameter to measure the performance of PV plants in a financial manner; it considers the energy yield over the lifetime of the plant and the life cycle cost [21]. For evaluating the LCOE, the lifetime cost of the project must be calculated firstly, including PV module cost, converters cost, transformer cost, and maintenance of fixed annual cost.

4. The Proposed PV Plant

The design process of the PV power plant is faced with many steps. Before any necessary calculations for PV power plant design, it is important to choose the PV plant's location. The daily average of direct, global, and diffusion radiation of the proposed site (Latitude: 33.05°, Longitude: 40.74°) for one year are gathered from NSRDB and presented in. The maximum daily average global radiation was about 450 W/m².

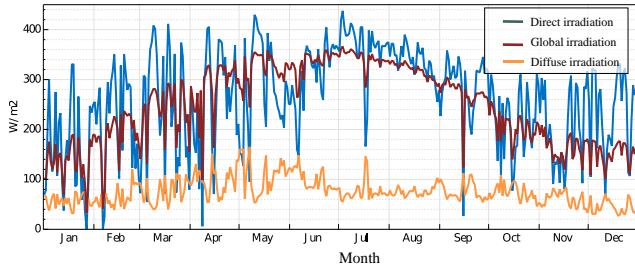


Fig. 7 Daily average of Direct, global, and diffusion radiation of proposed PV plant location

In a PV power plant, the electrical power is generated by PV modules. It is a converter through a series of transformations before it reaches the grid at the point of common coupling (PCC). For completing the PV plant designing process, it is essential to select at least the main components of the plant, which may include PV modules, inverters, transformers, and cables. Large types of PV modules and inverters are available and can be used. The PV module and inverters' main technical and physical specifications are listed in Table 1 and

Table 2, respectively.

Table 1 PV module technical and physical specifications

Specifications	Value	Temperature coefficient
Nominal efficiency	22.237%	-
Maximum power	480 W	-1.691 W/oC
Maximum power voltage	79.0 V	-
Maximum power current	6.1 A	-
Open circuit voltage	92.9 V	-0.272 V/oC
Short circuit current	6.5 A	0.002 A/oC
Module area	2.16 m ²	-
Module length	2.16 m	-
Module width	1 m	-
Number of cells	128 cells	-

Table 2 Inverter specifications

Specifications	Value
Maximum output power	1 MWAC
Maximum input power	1.03 MWDC
Nominal AC voltage	690 VAC
Maximum DC voltage	800 VDC
Maximum DC current	1389.95A
MPPT range	585– 800 VDC
Power use during operation	4451.37 WDC

The PV module of this study is arranged to be as in

Table 3. Where in the proposed design, there are 100x1Mw PV inverters. Each inverter is connected with many PV strings. The entire PV string is 26,024 strings. It is essential to ensure that the String VOC at reference condition (STC) must be less than the maximum DC input of the PV inverter. Additionally, String VMPP at reference condition (STC) must be in the range of MPPT of the PV inverter for proper operation and maximum power point tracking.

Table 3 The proposed design of 100MW PV power plant

The proposed design of 100MW PV power plant		
The items	Value	Comments
No. of inverters	100	Power = 1MW/inverter
No. of modules	208,192	480 W/module
No. of strings	26,024	These strings are divided over all inverters
No. of modules in series/string	8	-
String VOC	743.2 V	Maximum VDC of inverter 800V
String VMPP	632.0	The inverter MPPT range is: (585– 800) V

The single-line diagram of the PV power plant is presented in Fig. 8. It consists of four main power transformers to connect the PV inverter with a high voltage power grid.

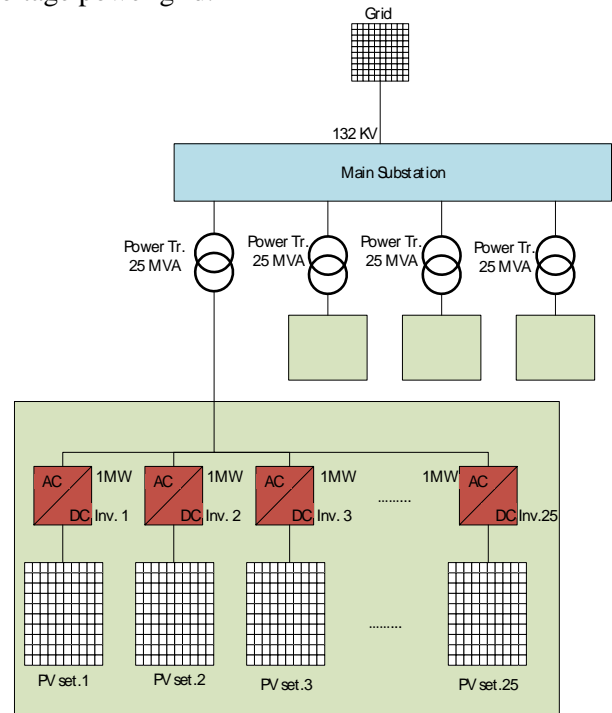


Fig. 8 Single line diagram of the proposed PV power plant

The rated power of each power transformer is 25 MVA; more rates can be used. Each transformer is connected with 25 PV inverter packages at the low voltage side. Some PV plants can be designed using two steps up transformer level (from LV to 11k and 11kv to 132kv). The main substation that collects all power transformers represents the point of common coupling (PCC), where it is the connection point

between the plant the utility grid.

5. Results and Discussion

The proposed system has been modeled and simulated in a system advisor model (SAM) simulation environment, applicable for PV power plant and wind farms simulation. All required data, including metrological data, module inverters types, and any other related parameter, are used to build the complete PV model. The simulation results consist of four subsections: monthly and annual energy production, the DC power and AC generated power, the power losses and the system efficiency, and the performance results.

5.1. Monthly and Annual Energy Production

The total produced energy of the proposed PV power plant for each month in the first year of the project life is presented in Fig. 9. It is observed that the maximum energy produced was in May, Jun, July, and August, which are the summer months. The maximum energy was in July, reaching about 17 GWh.

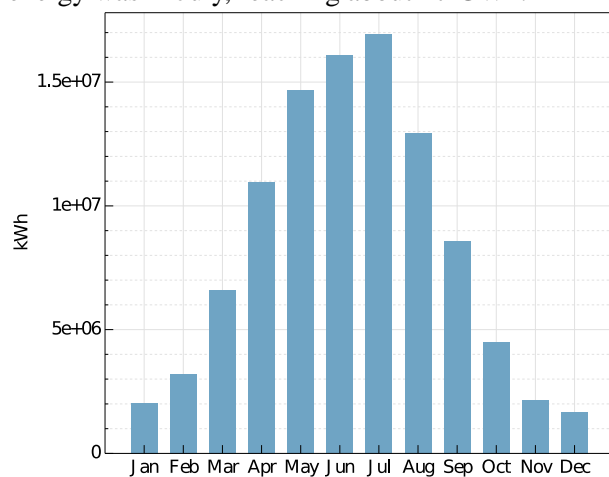


Fig. 9 Energy produced in each month

As shown in Fig. 9, January and December have the lowest produced energy where it reaches about 2GWh and 1.6GWh, respectively.

The produced energy for all project lifetime (25 years) is presented in Fig. 10. The energy production was decreasing by project lifetime. The total produced energy in the first year is about 100.3GWh, but in the fifth year, it was about 98.2GWh due to the degradation rate. Generally, the degradation of the PV plant is about 0.5%/year. However, the energy produced by the last year of the project (after 25 years) was about 88.7 GWh.

5.2. The DC array power and AC generated power

Fig. 11 presents a time-series data of the output DC array power and the inverter-generated AC power as an average daily profile for May, June, July, and August.

It is observed that the output array DC power is almost lower than the inverter output AC power.

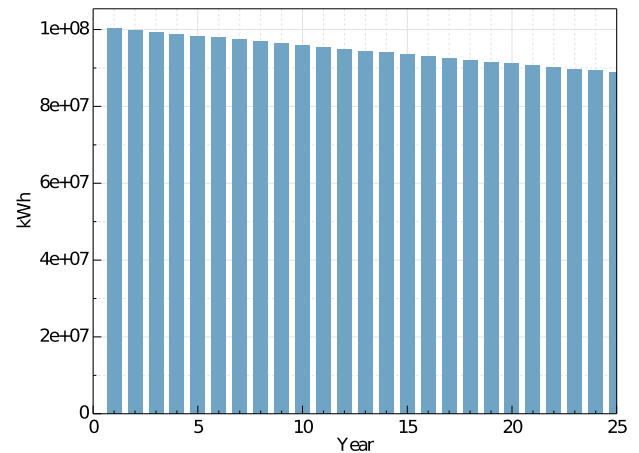


Fig. 10 Annually energy produced

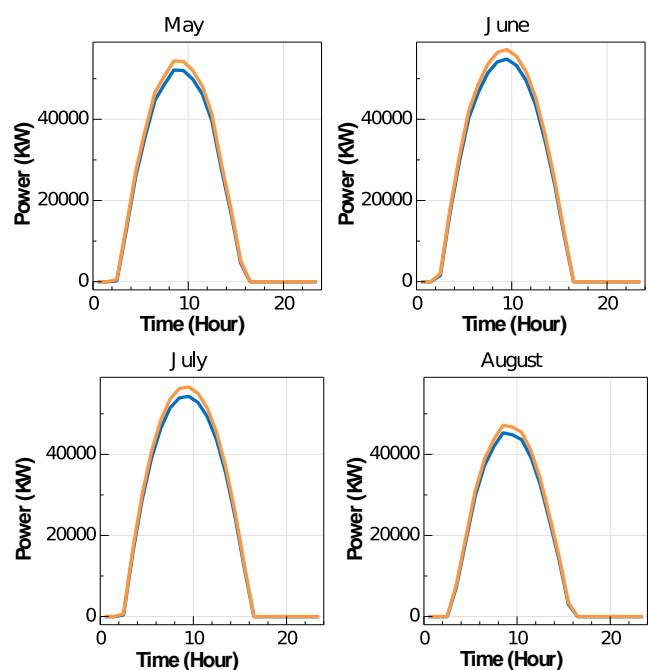


Fig. 11 Hourly profiles of DC and AC power for May, June, July, and August

5.3. Power Loss and System Efficiency

Many losses can affect a PV power plant, including natural losses such as soiling, shading, reflection, DC losses such as DC wiring and module losses, and inverter and AC system losses. The losses in the PV power plant are present each month throughout the year. The average daily profile of AC power wiring loss is presented in Fig. 12. In terms of clipping loss in the PV inverters occurs when the DC input power is larger than the inverter's rated power.

This phenomenon occurs in the summer season only as in May, June, July, and August. Thus, the daily profile clipping losses in the PV inverter for May, June, July, and August are presented in Fig. 13. It is observed that the maximum average daily clipping loss occurred in July which about 1.7 MW.

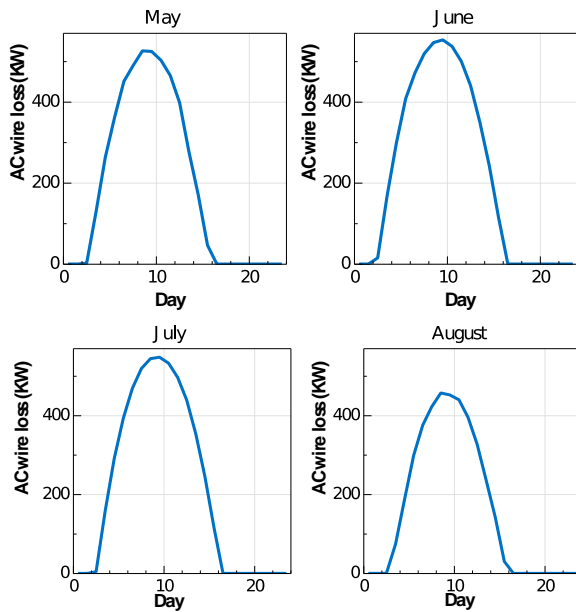


Fig. 12 Hourly profiles of AC power loss for May, June, July, and August

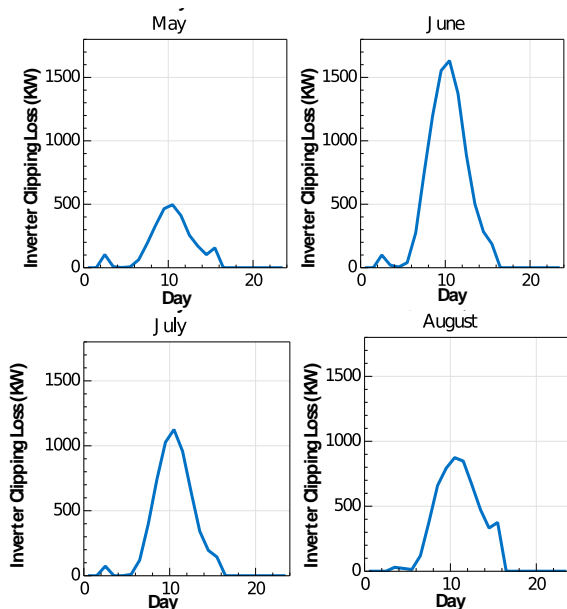


Fig. 13 The average daily profile clipping loss in May, June, July, and August

5.4. Performance Results

The performance results include the financial and technical performance metrics. As described in previous sections, this LOE is a financial metric representing the total PV plant lifecycle cost expressed in cents per kilowatt-hour of energy generated over its life. The capacity factor is the ratio of the predicted energy output during the first year of operation to the rated output, equivalent to the PV plant energy that may generate if it operated at its nameplate capacity for every hour since the system rated power is available. The predicted energy is calculated the capacity factor can be calculated.

For obtaining the proposed design's financial results, a financial parameter must be provided, and system cost must be calculated. Table 4 presents the

total cost analysis of the proposed system. The total installation cost is categorized into direct and non-direct capital costs.

Table 4 Cost analysis of the proposed pv plant

Direct capital cost			
PV Modules			
No.	KW _{DC}	\$/W _{DC}	Total price (\$)
208,192	99,998.78	0.38	37,999,536.00
PV Inverter			
No.	MW _{AC}	\$/W _{AC}	Total price (\$)
100	100	0.06	5,999,927.00
Other equipment			
\$/W _{DC}			Total Price (\$)
(0.2/W _{DC})			19,999,756.00
Insulation labor			
\$/W _{CD}			Total Price (\$)
(0.05/W _{DC})			12,999,842.00
Installer margin and overhead			
\$/W _{DC}			Total price (\$)
0.05/W _{DC}			12,999,842.00
Total of Direct cost			74,999,088.00
Non-Direct capital cost			
Permitting and environment studies			
\$/W _{DC}			Total Price
(0.08/W _{DC})			\$ 7,999,902.50
Engineering and developer overhead			
\$/W _{DC}			Total Price (\$)
(0.05/W _{DC})			12,999,842.00
Grid interconnected			
\$/W _{DC}			Total Price (\$)
(0.03/W _{DC})			2,999,963.50
Land purchase			
\$/W _{DC}			Total Price (\$)
(0.03/W _{DC})			2,999,963.50
Land preparation and transmission			
\$/W _{DC}			Total Price (\$)
(0.02/W _{DC})			1,999,975.62
Total of Non-direct cost			16,999,792.00
Total installation cost (Direct and non-direct cost)			91,998,880.00
Operation and maintenance 13			1,299,984.4
\$/KW_{DC} per year			

The direct cost refers to the cost and installation of the main component labor cost, which represents the PV module, inverter, insulation labor cost, and Installer margin and overhead cost. The total direct capital cost was about 75 million dollars.

On the other hand, the non-direct capital cost includes permitting and environmental studies, which represent 0.08/WDC, Engineering, and developer overhead, which represent 0.05/WDC; Grid interconnected, which represent 0.03/WDC, Land purchase which represents 0.03/WDC, and Land preparation and transmission which represent 0.02/WDC. The total non-direct capital cost was about 17 million dollars. Thus, the total installation cost (direct and non-direct) was 92 million dollars. During the lifetime of the PV plant, the operation and maintenance cost can be estimated as 13KWDC/year, which results in about 1.29 million dollars.

The total electrical energy generated by the PV plant in year one of the project and more performance

metrics is presented in Table 5. The capacity factor of the project was about 11.5%. The energy yield, the ratio of the system's annual AC-generated energy in year one to its nameplate DC capacity, was about 1,004 kWh/kW.

Table 5 Performance metrics

Performance metric	Value
Annual energy (year 1)	100,394,936 kWh
Capacity factor (year 1)	11.50%
Energy yield (year 1)	1,004 kWh/kW
LCOE	10.73 ¢/kWh
Net present value (NPV)	\$7,364,392

The levelized energy (LOE) cost of energy was about 10.73 ¢/kWh. The net present value (NPV) measures a project's economic feasibility, including revenue and cost. In general, a positive NPV indicates an economically feasible project, while a negative NPV indicates an economically infeasible project. NPV of the proposed project was \$7,364,392.

6. Conclusions

The main challenges facing the Iraqi electrical power system are presented in this paper, which include the power demand, power loss, and the performance of old generation power plants. This research study aims to present a preliminary study to implement a utility scale photovoltaic power plant in Iraq where the PV plant's location, size, design, energy production, and cost were analyzed.

The proposed design was modeled in a system advisor model (SAM) simulation environment. As a result, the total produced DC energy in the first year by the proposed 100MVA PV plant was about 105.438 GWh. On the other hand, the total AC energy generated by the system was about 100.302 GWh, which means more than 95% of the DC energy is successfully converted to AC energy. The total installation cost of the project was about 92 million dollars, the capacity factor was 11.5%, and LCOE was about 10.73 ¢/kWh.

In order to develop the proposed study, an optimization technique can be used as follow:

- An optimization technique can be used to select the optimum PV plant location in Iraq to produce the maximum energy.
- An optimization technique can develop the optimum PV plant design to produce the maximum energy with lower installation costs.
- A tracking system PV power plant can be developed to increase the total produced energy.

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