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Research article

Techno-enviro-economic analysis of grid-connected solar powered floating PV water pumping system for farmland applications: A numerical design model

Mohammad Al-Smairan [a], Habes Ali Khawaldeh [a], Bashar Shboul [a], Fares Almomani [b,*]

[a] Renewable Energy Engineering Department, Faculty of Engineering, Al Al-Bayt University, Mafraq, Jordan
[b] Department of Chemical Engineering, Qatar University, Qatar

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ABSTRACT

To meet the required load of a farm in the rural area in Mafraq, Jordan, the complete floating photovoltaic (FPV) water pumping sizing, modelling, and optimization of an on-grid PV system with comprehensive capacity, energy output cost, and emission estimations are outlined in this work. The novelty of this study lies in its comprehensive approach that integrates technical, environmental, and economic factors into a unified framework for designing a PV water pumping system, particularly in scenarios where grid supply is feasible or economically viable. A proposal has been made to install PV panels over the water lake to improve the overall system efficiency and to give an aesthetic appearance. The proposed system is composed of a 165 kW PV array and three 55 kW inverters, which cost 54696.92 JD as the initial cost, CO_2 emission reduction of more than 5000 tons and produce electricity at 0.028 JD/kWh. The results indicated that the FPV option demonstrates an about 5 % increase in efficiency compared to the other two scenarios. Also, the FPV option has higher costs due to a 25 % increase in system cost but results in lower CO_2 emissions compared to the other two options. Top of Form As shown from the results, the two sizing methods for solar water pumping systems, the equations-based method, and the PVsyst simulation tool give the same results. By following this methodology, one can assess the load, size the system, simulate its operation, and analyse the expected performance. Furthermore, the findings of this study could be valuable in designing a grid-connected FPV water pumping system.

1. Introduction

Globally, a substantial share of energy consumption is derived from finite fossil fuels, such as oil, gas, and coal, which are gradually depleting. Moreover, beyond their limited availability, fossil fuels also generate air pollution and release significant amounts of CO_2,

Abbreviations: PV, Photovoltaic; FPV, Floating Photovoltaic; CO_2, Carbon Dioxide; GHG, Greenhouse Gas; RESs, Renewable Energy Sources; VPP, Virtual Power Plants; CHP, Combined Heat and Power; PVC, Present Palue Cost; WPV, Water-based Photovoltaic; LPV, Land Photovoltaic; PBP, Payback Period; LCOE, Levelized Cost of Energy; TLCC, Total Life Cycle Cost; HE, Hydraulic Energy (kWh/day); V, Volume (m^3/day); H, Head (m); TDH, Total Dynamic Head; STC, Standard Test Conditions.

* Corresponding author.
E-mail address: falmomani@qu.edu.qa (F. Almomani).

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the primary driver behind global warming, which leads to climate change. For a considerable period, it has been acknowledged that the surge in fossil fuel consumption not only accelerates the depletion of fossil fuel reserves but also imposes a notable detrimental impact on the environment [1]. Using fossil fuels has an impact that includes increased health hazards in addition to the warning of global climate change. Global political acceptance of transitioning to renewable energy resources is growing, especially in developed countries [2]. Attaining a low- GHG production, which can meet the Paris Agreement and the United Nation's sustainable development goals, therefore, it needs to switch to cleaner, greener renewable energy resources [3]. RESs including solar, wind, hydropower, biomass, marine, and geothermal energies have a share of global energy capacity is about 3.38 GW, while the renewable energy share of electricity production around the world is 27.8 % [2].

While RES provides significant potential for reducing GHG emissions and meeting sustainability goals, however, effective integration into energy systems requires a robust approach. When discussing clean technologies in conjunction with renewable energy resources, two main concepts emerge within energy technologies. The first is energy supply technologies, encompassing alternative sources of renewable energy such as wind and solar power [4]. The second is energy efficiency technologies, which are employed to improve the efficiency of energy utilization [5]. Illustrative instances include VPP, CHP, and smart meters [6]. Furthermore, a significant increase in collaboration with improvements in quality of life, industrialization in developing nations, and the growth of the world population [7]. Due to the billions of dollars that have been invested in renewable energy resources, these resources now provide nearly 19 % of the world's energy demands [12].

Solar energy, in particular, has emerged as a prominent alternative due to its abundance and accessibility in various forms [8–13]. Within the context of solar energy applications, PV water pumping systems have garnered attention as a sustainable solution, especially in areas with limited grid access [14,15]. Worldwide, water pumping is typically dependent on traditional electricity sources or electricity generated from diesel. The utilization of water pumping systems dependent on fossil fuels not only entails high fuel costs but also gives rise to environmental impacts, including noise and air pollution [16]. The operational, maintenance, and replacement costs of a diesel pump are 2–4 times higher compared to a solar PV pump. In contrast, using solar water pumping reduces reliance on fossil fuel-based electricity [17]. Further, solar-powered pumping systems necessitate minimal maintenance incur no fuel costs, and are environmentally friendly [18]. PV water pumping is one of the most promising applications of solar energy, where, considering the scarcity of grid electricity in rural and remote areas across much of the world. In this context, the technology employed is related to any conventional water pumping system, with the key distinction being the utilization of solar energy as the power source [19]. The significance of PV water pumping systems has been on the rise in recent years due to the unavailability of electricity and the escalating costs of diesel [20]. The rate at which water is pumped depends on both the incident solar radiation and the size of the PV array [21]. In contrast to traditional pumping systems, a well-designed PV water pumping system yields substantial long-term cost savings. Furthermore, water storage in tanks can serve as an alternative to the need for batteries for electricity storage [22].

Typically, a pivotal factor to take into account when adopting PV systems is deciding if the array should be authorized to consistently track the sun. Passive tracking has recently gained significant interest, particularly for independent PV power applications [23]. Nevertheless, steady tracking can result in a higher daily accumulation of solar energy, although it may present maintenance challenges due to substantial wind loadings in specific regions [24]. The crucial question is whether the water pumping application requires the advantages of a 20–30 % boost in the total energy gathered by utilizing a tracker. To address this inquiry, the economic comparison between employing a tracker and increasing the number of fixed solar panels has been examined to meet the equivalent daily energy demand [24]. The technical considerations assessed for each installation included the availability of solar irradiance at the location, the well and pumping characteristics, and the configuration of the array [25].

To formulate an efficient PV water pumping system, the designer must possess a comprehensive understanding of the well, the water requirements, the terrain of the site, and the specifics of the storage system. The designer should be familiar with dynamic and static water depths, casing diameter, and daily water needs in gallons on both a daily and seasonal basis. These parameters are critical for calculating the pumping duration, determining the pump size, assessing the power demand on the pump, and subsequently calculating the load current. This load current is then utilized to evaluate the size of the PV water pumping system [26].

Bülent [27] showed that the PV water pumping systems turn out to be more cost-competitive when fossil fuels are high. Alrefai et al. [28] noted that the designing of the solar-driven water pumping system commences with a precise identification of the pumping system and the necessary water volume across several seasons. This approach aims to attain the essential daily water discharge in cubic meters and prevent unnecessary excessive sizing of the system. The design of the solar water pumping system is outlined by considering environmental, technical, economic, and long-term operational factors. The observation distinctly revealed that the highest daily water output occurred during the summer, aligning with the increased water demands characteristic of this season. Al-Smairan [26] proved that the proposed PV water pumping system is regarded as one of the optimal solutions for providing electrical power to water pumping applications in remote areas. Almarshoud [29] suggested that the argument is made that this research puts forth a system design and conducts a comparative analysis of the PVC and cost-effectiveness for economically evaluating power supply options for pumping systems in remote areas. The study specifically examines two distinct energy supply systems: PV systems and grid networks. A financial evaluation has been undertaken for a PV pumping system, examining it as a potential substitute for the conventional electrical network. Chandel et al. [18] contended that the suggested system is well-suited for rural communities in developing countries due to its reliability, affordability, and ease of maintenance. Additionally, a significant advantage is that most of its components can be manufactured within developing countries.

Space is one of the most significant issues when installing PV systems, positioning panels at an inclined angle to prevent shading instead of placing them horizontally. Using water surfaces presents an alternative approach to implementing a PV solar energy system. The WPV system includes canal top PV, offshore PV, underwater PV, and FPV in ponds or lakes (shallow water). The presence of cooling provided naturally by the presence of the water body in an installation of WPV systems enhances the PV performance and saves agricultural or urbanization land. Further, WPV systems experience reduced dust accumulation compared with the LPV systems and encounter fewer obstructions, thus eliminating shading concerns [27,28]. Table 1 outlines a comparative overview of key aspects of typical PV and FPV systems, highlighting their differences in cost, efficiency, soiling, and shading. Fig. 1 depicts the current expansion of FPV [28].

Despite the recognized advantages of PV water pumping, key considerations regarding system design, optimization, and cost-effectiveness require further investigation, particularly, for solar-powered FPV water pumping systems. Previous studies have highlighted the potential cost competitiveness of FPV systems, especially in high fossil fuel cost scenarios. However, there remains a critical need for comprehensive analyses that integrate technical, environmental, and economic factors to optimize FPV water pumping systems for specific applications, such as agricultural settings in remote areas.

This study addresses these gaps by presenting a detailed analysis and numerical modeling of a grid-connected FPV water pumping system designed for a farm in Mafraq, Jordan. The main contributions of this research are (i) Comprehensive system sizing and design using a thorough sizing of a PV water pumping system to meet the specific load requirements of a farm in the rural area of Mafraq, Jordan, using both analytical and computational methods. This includes advanced modeling that integrates PV panels over a water lake, optimizing system efficiency and meeting the farm's energy needs. A robust modeling tool employs the PVsyst software and incorporates actual weather data. (ii) A detailed techno-enviro-economic investigation is conducted to assess the competitiveness of various system components, including PV panels, inverter, motor or pump, storage tank, and well. (iii) Environmental and economic impact are evaluated to reduce the reliance on fossil fuels such as diesel, gas, and coal for electricity production, thereby decreasing air pollution and CO_2 emissions. It also attempts to reduce the electricity bill of the farm and increase the share of renewable energy in the primary energy mix.

To sum up, this study presents a comprehensive analysis to meet the energy demands of a farm in rural Mafraq, Jordan, through the sizing, modeling, and optimization of a FPV water pumping system integrated with an on-grid PV system. Unlike previous research, which often focuses on isolated aspects of PV systems, this work provides a comprehensive analysis that integrates technical, environmental, and economic factors. The novelty lies in a holistic approach and detailed numerical modeling to designing a PV water pumping system, particularly where grid supply is feasible or viable. Installing PV panels over a water lake is proposed to enhance efficiency and provide an aesthetic benefit. The paper is structured as follows: Section 2 details the methodology, including the system description, location and load data, and the mathematical and computational modeling for system sizing using both PVsyst and an equations-based method. It also introduces water-based photovoltaic systems and outlines the economic and environmental models. Section 3 presents the results, covering system sizing, energy production, and the analysis of CO_2 emissions, energy output, and costs. Section 4 concludes by summarizing the findings and their implications for grid-connected FPV water pumping systems.

2. Methodology

This section introduces the methods, assumptions, and mathematical modelling. It is crucial to identify and analyse the geographical location of the case study. Consequently, the meteorological characteristics of the examined locations are also outlined. The model encompasses the following fully integrated subsystems: a 165 kW PV array and three 55 kW inverters. Models have been developed in the PVsyst tool and equations-based method to evaluate the size and design of the system and to guarantee the fulfilment of the electrical demand of the end-user. The authors utilized the PVsyst simulation tool in two instances. In the first case, they conducted sizing by incorporating a pump load, and in the second case, sizing was performed using electricity bills, aligning with their established methodology for sizing based on theoretical principles, as elaborated in the Appendix. The inlet system parameters are indicated in Table 2 [29–32].

The methodology employed in this work introduces several novel elements. It includes a dual approach for system sizing using both analytical methods and the PVsyst simulation tool, providing a robust framework for evaluating FPV water pumping systems. The integration of PV panels over a water lake is a key innovation, aimed at maximizing efficiency and aesthetic benefits. This research uniquely combines detailed techno-enviro-economic analyses with real-world data from Mafraq, Jordan, to provide a comprehensive assessment of system performance and cost-effectiveness. The methodology's novelty lies in its thorough consideration of various system components, including PV panels, inverters, pumps, storage tanks, and wells within a single integrated model.

A variety of techniques have been used to achieve the project's primary goals, including a literature review, the selection of an appropriate study area, on-site visits to gather relevant data, data collection that helps in the project's design, and the necessary technical, financial, and environmental calculations. Next, analytical equation techniques to build the PV water pumping system, matching the needed load with PVsyst software. There will be a couple of types of layouts: the standard one will be built on the ground, while the other one will be installed on the water lake's surface. To ascertain the electrical energy production for the two layouts, a

Table 1
Comparison of grounded PV and FPV systems [30].

Aspects	Grounded PV	FPV
Cost	High land costs.	Increased cost due to floats, anchoring, mooring, and plant design.
Cost trend	Dropping costs.	Higher perceived risk due to technology maturity.
Efficiency	Lower than FPV.	Increased efficiency due to cooling.
Soiling	Depends on the surrounding land.	Lowered soiling compared to GPV.
Shading	Depends on the surrounding landscape.	Limited shading.

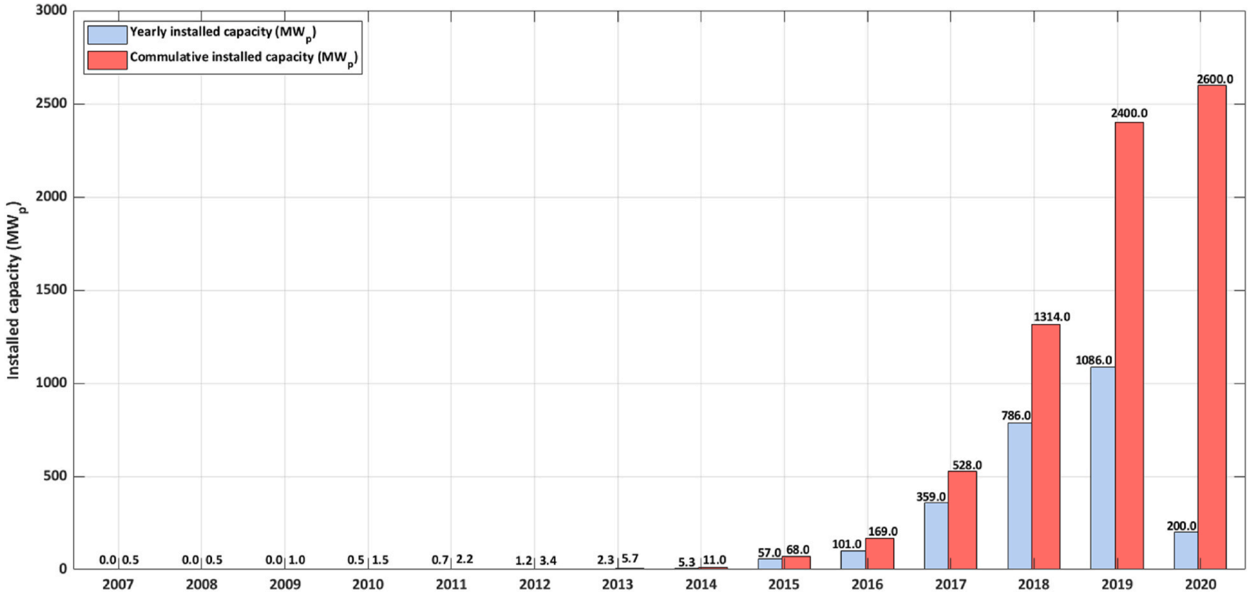

Fig. 1. Worldwide installed capacity of FPV and yearly augmentation [28].

Table 2
Technical and cost data inputs of the installed PV water pumping system.

Specifications	Unit	Quantity
Technical data		
PV module type	PS-P72-345W	
Inverter model type	PVI-33-TL	
PV rated power	W_p	345
Motor-driven pump system efficiency	%	88
Global solar irradiance	W/m^2	100–280
Hourly discharge	m^3/h	15
Minimum sun hour for one day	h	4.33
Economic data		
PV price	$/W	0.26
Price for one Inverter	$	4367
Plant lifetime	year	20
Operation and maintenance cost	$	2–2.5 % of IC
Replacement cost	$	2–16 % of IC

technical study will be done. Additionally, a cost analysis will be performed to calculate the PBP, LCOE, and TLCC. GHG Emissions Analysis will also be performed because, in addition to energy security, one of the primary motivating factors for the worldwide deployment of renewable energy resources is mitigating climate change. Technical, financial, and environmental indicator criteria will all be compared in detail between the two systems. Finally, solar water pumping systems could potentially be designed in rural locations worldwide using this technology.

2.1. System description

The PV pumping system comprises a conventional pump integrated with an electric motor, powered by electrical energy supplied by PV panels assembled in the area. The purpose of this pump is to lift water from the basement, making it accessible to users [33].

Chains and solar panels, as shown in Fig. 2, were installed over the water pond for several purposes that were studied and one of the best solutions to provide the possible space for the system on the farm, we found several advantages and a few disadvantages, including: (i) The solar lake installation serves to shade bodies of water, reducing evaporation in ponds, reservoirs, and lakes. (ii) The improved efficiency of solar panels, resulting from temperature reduction and shading, can play a role in reducing the occurrence of algae blooms in freshwater. (iii) The presence of algae in drinking water sources can pose risks to human health. Moreover, it has the potential to harm aquatic plants and animals, potentially resulting in their death. However, the drawbacks include difficulty in conducting maintenance operations due to the difficulty of accessing the deep panels (good design and maintenance areas can be applied for) and the installation cost of the PV structure will be increased. Fig. 2a shows the solar energy system above the pond and Fig. 2b represents the location of the system and pond with the farmer.

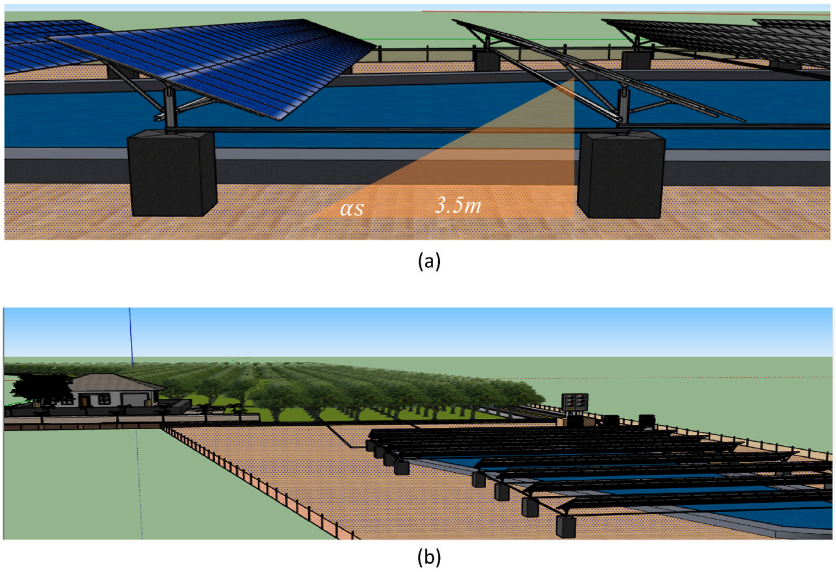

Fig. 2. Side view created with SketchUp: (a) the solar energy system above the pond, and (b) the configuration of the system and the pond's placement relative to the farmer.

2.2. Single-line diagram

A single-line diagram (see Fig. 3) is the representation of a power system using a simple symbol for each component. The single-line diagram of a power system is the network which shows the main connections and arrangement of the system components along with their data.

2.3. Location data

This work will be carried out in the Mafraq area. The Mafraq is located in the northern part of Jordan. The Mafraq area has a cold semi-arid climate [34]. The majority of rainfall occurs during the winter [35]. Mafraq experiences an average annual temperature of 16.6 °C (61.9 °F), with approximately 184 mm (7.24 in) of precipitation annually [36]. The average annual solar irradiance in the Mafraq area is around 5.84 kWh/m^2/day [37].

2.4. Load data

In this section, the load data for the farm is presented in Table 3, detailing the monthly electricity consumption for the year 2019. The table provides a comprehensive overview of the monthly consumption in kWh, showing the variations in the usage patterns throughout the year. The sum and average consumption for the entire year are calculated, amounting to 255760 kWh and 21313 kWh,

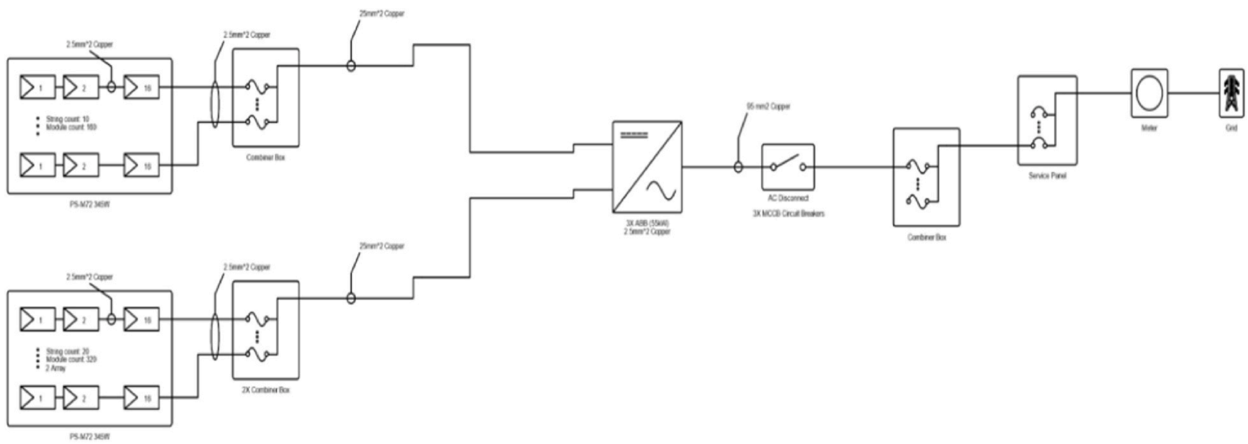

Fig. 3. Single line diagram of PV system.

respectively. In addition, the table includes the specified capacity, set at 165 kWh, serving as a crucial reference for the farm design and optimization process.

2.5. Mathematical and computational modelling

2.5.1. Sizing land photovoltaic water pumping system using PVsyst simulation tool

Here, we have been sizing using the PVsyst simulation tool in two cases, the first one using pump load and the second one using electricity bills as we have done in sizing using theory. The simulation results for the two cases are shown in Tables 8 and 9 in the results section. PVsyst is specifically designed for architects, engineers, and researchers, which introduces significant utility and a user-friendly interface as an educational tool. It contains a comprehensive contextual Help menu that elaborates the models and procedures utilized, thus providing a user-friendly strategy along with a guide for project development. PVsyst's ability to import meteorological and personal data from a variety of sources further enhances its applicability in the present study. This feature allows the designers to integrate real-world data into the adopted simulations, ensuring accuracy and reliability in assessing the performance of the grid-connected PV water pumping system integrated with PV panels over a water lake [38].

2.5.2. Sizing land photovoltaic water pumping system using equations-based method

The most important aspect of designing a PV pumping system is the rigorous analysis of the electrical loads. The models are designed according to the proposed configurations. The developed model is formulated using the design calculation methodology. The design constraints and input parameters for the proposed units are presented in Table 4.

The electricity demand can be evaluated as [39]:

$$\mathrm{HE} = \frac{\mathrm{V} \times \mathrm{H} \times \rho_w \times \mathrm{g}}{\left(3.6 \times 10^6\right)} \tag{1}$$

in water pumping systems, the term "head" denotes the vertical distance that water needs to be pumped from its standard level, for example, underground. The TDH or the total pumping head is the aggregate of three elements, as represented [40]:

$$\mathrm{TDH} = \mathrm{S}_{WL} + \mathrm{S}_{DL} + f_l + D_h + P_h \tag{2}$$

where S_{WL} is the static water level (m), S_{DL} is the dynamic water level (m), f_l is the friction losses (m), D_h is the discharge head (m), and P_h is the pressure head (m).

To calculate water demand accurately, it is crucial to factor in the ultimate purpose of water and/or user needs. When dealing with crop irrigation, it is important to consider local conditions and the specific requirements of the crops being cultivated. The water requirements of the crop are primarily influenced by the irrigated area, the developmental stage, and the efficiency of the irrigation process [26].

The hydraulic power denoted as P_H (W), needed to deliver a specific water flow rate (Q) at a given TDH, is determined by an equation that takes into account the intended utilization of the water and/or user demands [41]:

$$\mathrm{P_H}\ (\mathrm{W}) = \frac{\mathrm{Q} \times \rho_w \times \mathrm{g} \times \mathrm{TDH}}{3600} \tag{3}$$

where: Q represents the water flow rate (m^3/h).

Calculation of the electric power needed to the input of the motor-pump unit, $\mathrm{P_{El}}$ [kW], is illustrated by the equation [42]:

Table 3
The sum and average for monthly electricity bills for 2019.

Month	Consumption (kWh)
January	6240
February	2480
March	7200
April	30240
May	37120
June	39280
July	37600
August	38000
September	32320
October	22880
November	1680
December	720
Sum	**255760 kWh**
Average	**21313 kWh**
Capacity	**165 kWh**

Table 4
Design specifications of the proposed FPV system.

Data	Symbol	Unit	Value
Hydraulic energy	HE	kWh/day	454.7
Volume	V	m^3/day	360
Total dynamic head	TDH	m	463
Water density	ρ_w	kg/m^3	1000
Gravity	g	m/s^2	9.81
Hydraulic power	P_H	kW	19
Solar irradiance at STC condition	G_{REF}	W/m^2	1000
Global solar radiance	G_{Glob}	W/m^2	175
Motor's efficiency	η_{MP}	%	88

$$P_{El} = \frac{P_H}{\eta_{MP}} \tag{4}$$

where: η_{MP} is the efficiency of the motor-driven pump system.

A basic approach introduces a straightforward mathematical equation. This expression allows for the approximation of the rated power of the PV panel, as indicated by the provided formula [43].

$$P_{PV} = \frac{P_{El} \times G_{REF}}{G_{Glob} \times F_Q} \tag{5}$$

where: P_{PV} refers to the maximum power output of the PV array under Standard Test Conditions (STC: radiance = 1000 W/m^2, AM 1.5, cell temperature = 25 °C) [kW], G_{REF} it represents the solar radiation intensity incident on a surface under STC [1 kW/m^2], G_{Glob} it signifies the net solar radiation received on a horizontal surface [kW/m^2], F_Q is the quality factor of the system, as shown in Table 5.

2.6. Water-based photovoltaic systems

2.6.1. Floating photovoltaic water pumping system

Solar panels positioned on water surfaces are called FPV systems. Now, FPV is emerging. To substitute costly land expenses, FPV systems are preferable. FPV comprises five primary key elements, including solar PV panels, inverter, mooring system, pontoon, connections, and cable. Regarding the technical performance, three parameters have been discussed through a literature review. These parameters are the effects of wind loading, the impact of albedo, and the impact of temperature. In practical applications, solar cells do not operate under standard conditions. The two most important factors that affect the PV module output that must be taken into account are temperature and irradiance [44]. Ghosh [27] showed that by increasing wind speed to 15 km/h, a reduction of approximately 17 % in both LCOE and global CO_2 emissions of 69.51 kg was achievable. Solar radiation incident on a surface encompasses three primary components: direct, diffuse, and reflected radiation (Albedo). It is thought that FPV systems can generate considerable power output as a result of the strong reflection from the surface of the water. PV panels, or solar cells, exhibit a negative temperature coefficient, implying that as temperatures rise, the efficiency of solar energy conversion to electrical energy in PV systems decreases. WPV systems provide the opportunity to lower the temperature of the PV system due to the presence of water and wind. The ambient temperature above water can be lower compared to that above rooftops or land because water has a higher specific heat than land or building materials. The anticipated outcome of the WPV system is that PV panels will experience cooler temperatures. Water's ability to freely circulate allows incoming solar radiation on its surface to mix with large depths of cooler water, a feature not feasible for rooftops or land. Moreover, transparent natural water transmits solar energy differently compared to land or roof-based surfaces. Further, while net radiation heats the surroundings for roofs or land, water serves the purpose of evaporation. Ghosh [27] noted that LPV systems can reach temperatures above 40 °C on sunny days, varying with location, while water temperature seldom surpasses 20–25 °C. Therefore, a WPV scheme experiences at least less temperature than an LPV. A temperature increases of 20 °C enhances the efficiency by 4 %. Also, Liu et al. [43] highlighted that the module temperature of FPV systems can be 5–10 °C lower than that of roof-mounted modules. Trapani and Millar [44] stated that a comparative analysis between FPV and LPV revealed a 5 % increase in electrical yield, attributed to the cooling effect of the water. The cell temperature characteristics of a typical PV module are shown in

Table 5
Factors related to the quality of components and various PV systems [42].

Component/system	F_Q
PV array	0.80 … 0.90
PV module (crystalline)	0.85 … 0.95
PV system (Off-grid)	0.10 … 0.40
PV system (On-grid)	0.60 … 0.75
Hybrid system (PV & Diesel)	0.40 … 0.60

Table 6 [45]. In this work, the impact of temperature has been taken into account only.

2.7. Economic model

In this research, a projected system lifespan (n) of 20 years for components is assumed, along with an annual inflation rate of 0 % and an internal rate of interest (r) of 6 %. As mentioned above, Table 2 outlines the economic indices adopted in this study.

The initial investment is calculated using the following equation [46]:

$$\text{Initial investment} = \text{Modules cost} + \text{Structure cost} + \text{Inverters cost} + \text{Auxiliary cost} \tag{6}$$

The annual cost savings can be given as follows [26]:

$$[(\text{AVG. Consumption per month })\text{x12 month (kWh)}] \times 0.06\ \text{JD/kWh} \tag{7}$$

The payback period is estimated based on the expression below [47]:

$$\text{PbP} = \frac{\text{Initial investment}}{\text{Annual saving}} \tag{8}$$

Life-cycle costing stands as the most robust analysis and is typically the method employed to assess the economic feasibility of an application. This approach considers not only the capital costs (overall initial expenses for purchasing and installing the system) but also all future expenses (operation and maintenance, replacement) for the entire operational lifespan of the PV system, taking into account the discount rate (the rate at which money's value would grow if invested) and the inflation rate (the rate at which the price of a component increases above or below general inflation) [44].

The total life cycle cost is given as the following formula:

$$\text{TLCC} = \text{IC} + \text{OMC} + \text{RC} \tag{9}$$

Where: IC is the initial cost, OMC denotes operating & maintenance cost (2−2.5 %/year of IC), RC illustrates replacement cost (2–16 % of IC for total lifetime) [43].

Arguably, the most critical figure in comparing two electricity-generating systems is the net cost of generating each kilowatt-hour over the lifetime of each system [44].

The cost of energy can be determined via Equation (10), as depicted below [48]:

$$\text{LCOE} = \frac{\text{Total life cycle cost}}{\text{Total life time energy produced}} \tag{10}$$

The cost of WPV systems remains a somewhat ambiguous factor. There is a scarcity of reported studies based on WPV. FPV systems typically incur a cost approximately 25 % higher than LPV systems, yet the payback period for FPV is generally no more than 6 years [47]. Regarding the cost of energy, Uddin et al. [48] indicated that the LCOE from the FPV generation facility is elevated at 0.1829 $/kWh.

2.8. Environmental model

PV solar-assisted-electric technology uniquely meets the demands of the three key drivers of the evolving power generation landscape: premium power for enhanced reliability, distributed generation for economical point-of-use applications, and renewable energy for environmental benefits and energy security [44].

To find the total energy production per year, MWh, the relation is given as [49]:

$$\text{Specific yearly energy production} = \frac{\text{Yearly energy production}}{\text{Total lifetime}} \tag{11}$$

The overall CO_2 emissions from gas-fired plant, Kg/y, is calculated as [50]:

$$\text{Gas fired plant}_{CO_2} = \text{Spesfic yearly energy production} \times 1.915 \times 0.454 \tag{12}$$

The overall CO_2 emissions from PV plant, Kg/y, is calculated as:

$$\text{PV}_{CO_2} = \text{Spesfic yearly energy production} \times 0.2204 \times 0.454 \tag{13}$$

Table 6
Cell temperature characteristics of a typical PV module [45].

Typical cell temperature coefficient		
Power	T(P)	−0.47 %/Co
Open-circuit voltage	T (V_{oc})	−0.38 %/Co
Short-circuit current	T (I_{sc})	0.10 %/Co

The net CO_2 emission reduction can be estimated as [51]:

$$\text{Gas fired plant}_{reduction} = \text{Total lifetime} \times \text{Gas fired plant}_{CO_2} - \text{PV}_{CO_2} \quad (14)$$

3. Results and discussion

3.1. System sizing for solar water pumps

Sizing solar water pumping systems has been carried out using two techniques, the first one was done using theory (pump load and electricity bills), and the second one was using PVsyst (pump load and electricity bills). Two layouts have been compared, the first one is on land (LPV), and the second one is on a lake (FPV). Based on the impact of temperature on the energy output. Trapani and Millar [43] stated that a comparative investigation between FPV and LPV demonstrated a 5 % electrical capacity enhancement due to the cooling effect of the water. Table 7 compares yearly energy production estimates over 20 years using an equations-based method (LPV) and the PVsyst simulator LPV and FPV system. The equations-based method (LPV) with a capacity of 164 kW yields values ranging from 293.9000 to 257.1789, resulting in a cumulative total of 5503.0525, the PVsyst simulator (LPV) with a capacity of 166 kW predicts slightly higher figures, with values ranging from 295.4 to 258.4915 and a cumulative total of 5531.1389. In contrast, (FPV) with a capacity of 158 kW yields values ranging from 298.8000 to 258.0000 and a cumulative total of 5527 MWh. The differences indicate variations between the mathematical model and simulation algorithm employed via the adopted method. Further analysis is justified to assess the accuracy and reliability of these estimates and understand the fundamental elements that share the observed differences.

3.2. A yearly PV system energy production utilizing three distinct methods

Fig. 4 presents a comparison of the annual energy production of a PV system using three different approaches: an equations-based method (LPV), the PVsyst simulator LPV and FPV. These methods illustrate an incremental reduction in energy production across the 20 years and therefore reflect the impact of degradation on the PV performance. However, the equations-based method forecasts a considerable drop than the PVsyst simulator, hence, suggesting a potential overestimation of the degradation rate. Moreover, the PVsyst simulator results exhibit slight annual fluctuations in energy production, a detail missed by the equations-based method could be associated with unconsidered elements, such as the variations in solar irradiance or temperature. While the FPV system estimates the same energy output as the PVsyst simulator, but with less capacity, due to the cooling effect of water.

3.3. The results of CO_2 emissions, energy, and economy

Table 8 shows the energy, economic, and CO_2 emission results. The required capacity to meet the pump load is 164 kW, the capacity needed to meet the annual electricity bills is 166 kW, while the required capacity to meet the annual electricity bill using (FPV) is 158 kW. The cumulative total energy output over 20 years is very close to 5503, 5531, and 5527 MWh for pump load, electricity bills, and (FPV) respectively. The economic parameters for pump load sizing are slightly more than for electricity bill sizing. This is because electricity bills are more accurate than pump load calculations. Regarding the CO_2 emissions, as shown in Table 8 the pump load sizing

Table 7
Yearly energy production using the equations-based method and PVsyst simulator.

Year	Yearly energy production using equations-based method (LPV) (MWh)	Yearly energy production based on PVsyst simulator (LPV) (MWh)	Yearly energy production based on PVsyst simulator (FPV) (MWh)
1	293.9000	295.4000	294.8000
2	291.8427	293.3322	292.7000
3	289.7998	291.2789	290.7000
4	287.7712	289.2399	288.7000
5	285.7568	287.2152	286.7000
6	283.7565	285.2047	284.7000
7	281.7702	283.2083	282.7100
8	279.7978	281.2258	280.7200
9	277.8392	279.2573	278.7200
10	275.8944	277.3025	276.7200
11	273.9631	275.3613	274.7200
12	272.0454	273.4338	272.7200
13	270.1410	271.5198	270.7000
14	268.2501	269.6191	268.7300
15	266.3723	267.7318	266.7300
16	264.5077	265.8577	264.7300
17	262.6561	263.9967	263.7300
18	260.8175	262.1487	261.7400
19	258.9918	260.3137	259.7400
20	257.1789	258.4915	258.2400
Total	**5503.0525**	**5531.1389**	**5527.0000**

Table 8
Energy, economic and CO_2 emission results based on theoretical analysis.

System	Pump (LPV)	Electricity Bills (LPV)	Electricity Bills (FPV)
Size of the system (KW)	164	166	158
Energy output (MWh)	5503	5531	5527
TLCC (JD)	134417	131273	156183
LCOE (JD/kWh)	0.0240	0.0230	0.0280
PBP (Years)	5	4	4
Net CO_2 (kg/20years)	4781034	4756831	4527586

Table 9
Energy, economic and CO_2 emission results using PVsyst simulation tool.

Item	Pump (LPV)	Electricity Bills (LPV)	Electricity Bills (FPV)
Size of the system (KW)	164	166	158
Energy output (MWh)	5503	5531	5527
TLCC (JD)	134417	131273	156183
LCOE (JD/kWh)	0.0230	0.0220	0.0280
PBP (Years)	4.1000	3.9000	4.000
Net CO_2 (kg/20years)	4508646	5111468	4527586

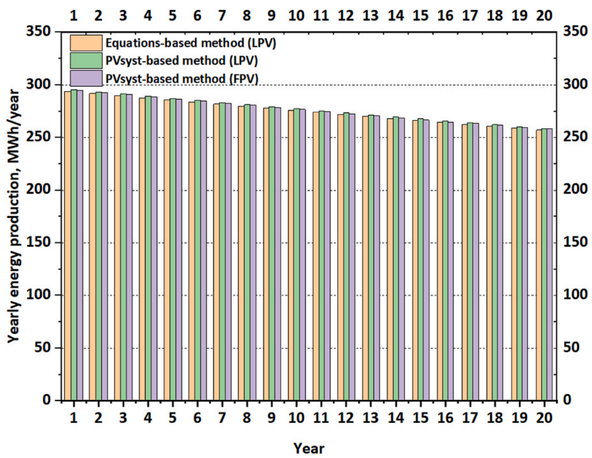

Fig. 4. Yearly energy is affected by degradation using the equations-based method (LPV) and the PVsyst simulator LPV and FPV, respectively.

method has slightly more CO_2 emissions than the electricity bills option. The economic parameters for the FPV option are more than the other two options, where the cost of the FPV system is increased by 25 % as mentioned before. While CO_2 emissions are less than the other two options.

Table 9 shows the energy, economic, and CO_2 emission results for sizing the solar water pumping system using the PVsyst tool (pump load, electricity bills, and FPV). The required capacity to meet the pump load is 164 kW, the capacity needed to meet the annual electricity bills is 166 kW, while the required capacity to meet the electricity bills using FPV is 158 kW. The cumulative total energy output over 20 years is very close to 5503, 5531, and 5527 MWh for pump load, electricity bills, and FPV respectively. The economic parameters for pump load sizing are slightly more than for electricity bill sizing. This is because electricity bills are more accurate than pump load calculations. Regarding the CO_2 emissions, as shown in Table 9 the pump load sizing method has less CO_2 emissions than the electricity bills option. The economic parameters for the FPV option are more than the other two options, where the cost of the FPV system is increased by 25 % as mentioned before. As shown in Tables 8 and 9, the energy, economic, and environmental results for the two sizing methods and the two layout methods LPV or FPV are very close to each other, which means that the solar water pumping sizing by theory matches very well with the PVsyst simulation tool and is the same for the two layouts of system. These results apply to small systems. For MW systems the results will differ.

Fig. 5 shows the production cost of energy for FPV systems in different locations in the northern hemisphere [27]. From the figure, we notice that the production cost of energy for FPV systems in Cairo (Egypt) and Dubai (UAE) are 30 $/MWh (0.0300 $/kWh) and 25 $/MWh (0.0250 $/kWh) respectively. The previously calculated LCOE matches the cost of energy for the FPV system calculated here in this work (0.0280 $/kWh). In addition, from the literature review, the payback period for FPV systems is not more than 6 years. In this work, the payback period is about 4 years.

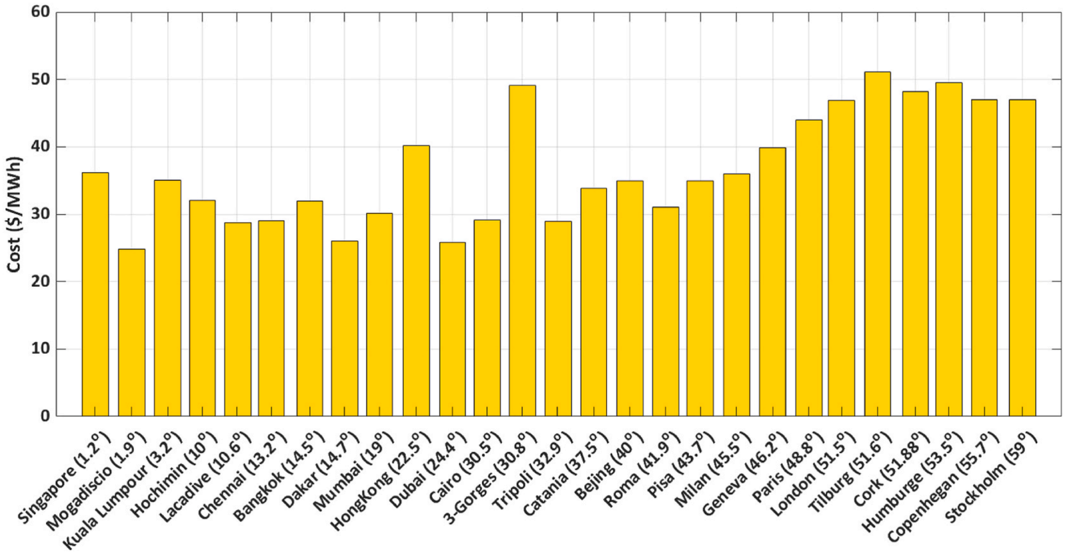

Fig. 5. The cost of producing FPV across 27 diverse locations in the northern hemisphere, is denoted in $/MWh [27].

4. Conclusion

In this paper, the complete FPV water pumping modelling, sizing, and optimization of a grid-connected PV system with detailed capacity, energy output, cost, cost of energy, payback period, and emission calculations have been presented for a typical farm in the rural area in Mafraq. The designed system consists of a 165 kW PV array and three 55 kW inverters, and overall, it costs 54696.9200 JD as the initial cost and produces electricity at 0.0280 JD/kWh. A proposal has been made to install the PV panels over the water lake to increase the efficiency of the system and to give an aesthetic appearance. This research presents a detailed procedure to design an FPV water pumping system where grid supply is possible or economically viable. As shown from the results, the two sizing methods for solar water pumping systems, the mathematical method, and the PVsyst simulator give the same results. The research paper gives a guideline for the designer to estimate the load, and system size and simulate the expected performance for on-grid PV systems. The main results drawn from this study are:

- The LPV method, with a capacity of 164 kW, gives values between 293.9000 and 257.1789, totalling 5503.0525. For the same method but with a capacity of 166 kW, values range slightly higher, from 295.4000 to 258.4915, totalling 5531.1389. Conversely, the FPV method, with a capacity of 158 kW, produces values ranging from 298.8000 to 258, totalling 5527 MWh.
- To meet the pump load, 164 kW is required, while 166 kW is needed for annual electricity bills. Using FPV for the annual electricity bill requires a capacity of 158 kW.
- The total energy output over 20 years is nearly identical for the pump load (5503 MWh), electricity bills (5531 MWh), and FPV (5527 MWh).
- The FPV option has higher economic parameters compared to the other two options due to a 25 % increase in the cost of the FPV system. However, it results in lower CO_2 emissions compared to the other two options.

In addition, to future investigations, the following are the subjects and paths for floating photovoltaics: evaluation of the environmental impact, technological developments and efficiency enhancements, economic feasibility and cost-benefit analysis, integration with current power grids and infrastructure, and long-term performance and maintenance measures.

Data availability statement

Data will be made available upon request.

CRediT authorship contribution statement

Mohammad Al-Smairan: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Habes Ali Khawaldeh:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bashar Shboul:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fares Almomani:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

A. Sizing solar water pumping system using theory based on pump load

I. **Type of module:** Philadelphia Solar's Poly-Crystalline modules (PS-P72-345W) is used with power up to 345W, and the price is 0.18 JD/Watt, then the price for the one panel equals to 0.18 JD/W × 345W = 62 JD for one module.
II. **Inverter**: PVI-33-TL – Price for one Inverter = 3057JD.
III Energy analysis

Based on well data and equations (1)–(5), the following calculations have been done:

$$\text{Total dynamic head} = 463m$$

$$\text{Hydraulic energy, HE} = \frac{454.7\text{kWh}}{\text{day}}$$

$$\text{Where : } 360 = 15\,m^3/\text{h} \times 24\text{h, hourly discharge} = 15\,m^3/\text{h}$$

$$\text{Hydraulic power, P}_\text{H}\ (\text{W}) \cong 19\ \text{kW}$$

$$\text{The electric power, P}_\text{El} = \frac{\text{P}_\text{H}}{\eta_\text{MP}} = \frac{19}{0.88} = 21.50\ \text{kW}$$

$$\text{Rated power of the PV panel, P}_\text{PV} = \frac{\text{P}_\text{El} \times \text{G}_\text{REF}}{\text{G}_\text{Glob} \times \text{F}_\text{Q}} = \frac{21.50 \times 1}{0.175 \times 0.75} = 164\ \text{kWp}$$

where: G_{REF} is a solar irradiance at STC condition (1000 W/m^2), and G_{Glob} is a global solar radiance on horizontal surface KW/m^2 (100 W/m^2 - 280 W/m^2).

IV Economics analysis

$$\begin{aligned}\text{Initial investment} &= \text{Cost of modules} + \text{Cost of structure} + \text{Cost of inverters} + \text{Auxiliary cost} = (62 \times 475) + (60 \times 164)\\ &+ (3057 \times 5) + [\ (0.14 \times 55) + (0.35 \times 55) + (106.35 \times 5) + (4.25 \times 5) + (80 \times 6.38) + (341.73)\\ &= 56007.08\ \text{JD}\end{aligned}$$

$$\begin{aligned}\text{Annual Saving} &= ((\text{AVG. Consumption per month })*12\text{ month })(\text{kWh})] \times 0.06\text{JD/kWh}\\ &= (21.5 \times 24 \times 30 \times 12\ )\ \text{kWh}] \times 0.06\text{JD/kWh} = 11145.6\text{JD/year}\end{aligned}$$

$$\text{Payback Period} = \frac{\text{Initial investment}}{\text{Annual saving}} = \frac{56007.08}{11145.6} = 5.02 \cong 5\ \ \text{years}$$

$$\begin{aligned}&\text{Total life cycle cost (TLCC)} = \text{IC} + \text{OMC} + \text{RC}\\ &= 56007.08 + (56007.08 \times 0.02 \times 20) + (56007.08 \times 0.05 \times 20) = 134416.992 \cong 134417\ \text{JD}\end{aligned}$$

$$\text{LCOE} = \frac{\text{Total life cycle cost}}{\text{Total life time enrgy produced}} = \frac{134417}{5503.053 \times 10^3} = 0.024\ \text{JD}\Big/\text{kWh}$$

V. CO_2 emissions calculations:

$$\text{Spesfic yearly energy production} = \frac{5503.053}{20} = 275.15\ \text{MWh}$$

$$\text{From gas fired plant : } = 275.15 \times 10^3 \times 1.915 \times 0.454 = 239218.1615\frac{\text{Kg}}{\text{year}}$$

$$\text{From PV}: \ = 275.15 \times 10^3 \times 0.2204 \times 0.454 = 27531.94924 \frac{\text{Kg}}{\text{year}}$$

VI. Net CO_2 emission reduction:

Gas fired plant:

$$= 20 \times 239218.1615 - 27531.94924 = 4756831.281 \frac{\text{Kg}}{\text{life time}}$$

B. Sizing solar water pumping system based on electricity bills

$$\text{Capacity for one year} = \frac{\text{AVG}}{4.33 \times 30} = \frac{21313.33}{130} = 165 \text{ KWp}$$

where: 4.33 is the minimum sun hour for one day, 30 number of days/month and 130 kWh/month.

I Energy analysis

$$\text{Spesfic yearly energy production} = \frac{5531.139}{20} = 276.55 \text{ MWh}$$

where: 20 years, lifetime of project.

II Economic analysis

$$\text{Initial Investment} = \text{Cost of modules} + \text{Cost of structure} + \text{Cost of inverter} + \text{Auxiliary cost} = 54696.92\text{JD}$$

$$\text{Annual Saving} = [((\text{AVG. Consumption per month })*12 \text{ month (kWh)}] \times 0.06\text{JDkWh} = [\ (225760\text{kWh})] \times \frac{0.06\text{JD}}{\text{kWh}} = 13545.6 \frac{\text{JD}}{\text{year}}$$

$$\text{Payback Period} = \frac{\text{Initial investment}}{\text{Annual saving}} = \frac{54696.92}{13545.6} = 4.03 \approx 4 \text{ years}$$

$$\text{Total life cycle cost (TLCC)} = \text{IC} + \text{OMC} + \text{RC TLCC} = 54696.92 + 0.02 \times 54696.92 \times 20 + 0.05 \times 54696.92 \times 20 = 131272.608 \cong 131273 \text{ JD}$$

$$\text{LCOE} = \frac{\text{Total life cycle cost}}{\text{Total life time enrgy produced}} = \frac{131273}{5531.139 \times 10^3} = 0.023\text{JD}\Big/\text{kWh}$$

III $\boldsymbol{CO_2}$ emission calculations

$$\text{From gas fired plant}: \ = 276.55 \times 10^3 \times 1.915 \times 0.454 = 240435.3355 \frac{\text{Kg}}{\text{year}}$$

$$\text{From PV}: \ = 276.55 \times 10^3 \times 0.2204 \times 0.454 = 27672.03548 \frac{\text{Kg}}{\text{year}}$$

IV Net $\boldsymbol{CO_2}$ emission reduction

From gas fired plant:

$$= 20 \times 240435.3355 - 27672.03548 = 4781034.675 \frac{\text{Kg}}{\text{life time}}$$

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