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Field evaluation and PVsyst modelling of a mobile photovoltaic water-pumping system for smallholder irrigation in Egypt

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THE RESEARCH study was conducted at three sites in the Delta and Nile Valley to increase the sustainability of agricultural operations under arid conditions in Egypt. A mobile solar-powered irrigation pumping unit was designed and implemented, and the optimal solar panel tilt angle and azimuth were determined for the three sites to achieve high-performance and a sustainable alternative to diesel-powered water pumping. Practical trials began in early 2021 and continued for two years. The experiments were conducted in the governorates of Kafr El-Sheikh Governorate for rice irrigation, Giza Governorate for maize irrigation, and Assiut Governorate for sugarcane irrigation. The study concluded that maximum efficiency occurred when azimuth angle was 0° pointed downwards, a non-significant difference between the measured solar panel tilt angle and the results of the simulation models at a specific fixed angle for irrigating the selected crops. The most suitable tilt angle for the solar panels, which was fixed throughout the year, was 29° in Kafr El-Sheikh Governorate, 26° in Giza Governorate, and 28° in Assiut Governorate. Similarly, the solar irrigation is economical for small holdings of less than 2 acres spread over twenty (20) years with the option of cluster formation amongst farmers while a reservoir would be required for periodic irrigation to reduce operational cost. Finally, there is a necessity to have a backup diesel-powered water pump in case of a malfunction in the mobile pumping unit that operates on solar energy.

Keywords: A mobile solar-powered irrigation pumping; PV_{SYST} MODEL; Tilt angle; Azimuth angle; More water-intensive crops; Solar radiation intensity.

1. Introduction

Egypt currently faces numerous challenges in the agricultural sector, the most important of which are limited water and energy resources (Dewedar et al., 2023; Alhashimi, et al., 2023; Abdelraouf, et al., 2020). Unfortunately, as the population increases and climate change negatively impacts, irrigation water resources are declining (El-Sayed et al., 2023; Abdelraouf and Ragab, 2018; Eid et al., 2019). Despite the current difficulty of addressing limited irrigation water resources, there are solutions to mitigate the severity of this situation (Bakry et al., 2012; Abdelraouf, 2019; Abdelraouf, et al., 2021). Egypt also suffers from limited traditional energy sources and the ever-increasing rise in petroleum prices. The increasing price of traditional energy has led to a compulsory reliance on new and renewable energy sources, most notably solar energy (Ahmed et al., 2024; Abdelraouf, et al., 2019; Eid et al., 2023). To achieve the goal of getting more crop per drop per kilowatt using sustainable technologies so, these challenges have prompted us to focus on managing limited water resources for irrigation using solar energy (Abdou et al., 2024; Abdelraouf and El-Shenawy, 2018; Sabra, et al., 2023; Anter, et al., 2024; El-Shirbeny, et al., 2025)

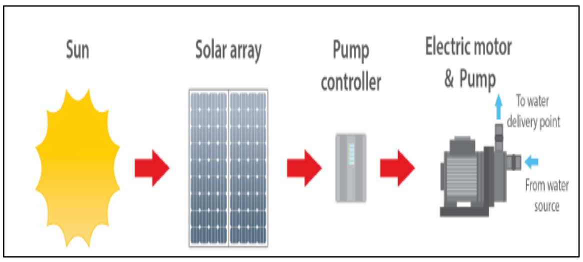

Fig. 1. Solar water pumping system.

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Diesel fuel is typically used as a power source for water pumping. In addition to requiring costly fuel, this system produces a lot of noise and contributes to air pollution due to greenhouse gas emissions. An emission-free, eco-friendly system might be created by substituting the diesel fuel with a photovoltaic array. Due to rising diesel prices and a lack of electricity, solar-powered water pumping devices have become increasingly popular in recent years. Compared to solar-powered water pumping systems, diesel-based water pumping systems have two to four times higher total capital, maintenance, and operating costs. Furthermore, solar-powered water pumping systems are widely used in irrigation applications in rural and isolated locations due to the lack of electricity in these places. (Sharma, et al., 2020: Pardo, et al., 2020; Ibrahim, et al., 2020).

Based on limited life time of the conventional energy, and negative impact on the environment, renewable energy as an alternative type of energy source and environment-friendly can contribute to fulfil the required energy demand. Several conclusions had been presented by previous researchers to highlight of providing the communities with a comprehensive awareness through training courses, seminars, and workshops presented by International Energy Authority to solve their energy problems, IEA (IEA, 2017). One of the main issues to overcome their problem, is to know the potential advantages of non-traditional energy like solar and wind energy because utilization of renewable energies contributed in cost reduction and clean the environment that mitigate the greenhouse gases that caused global warming and climatic change. Due to its importance, for the past several years on the international level, renewable energy systems are supported by several governmental policies and clean energy initiatives to improve the energy efficiency production and utilization (IEA, 2019). In additions to the environmental benefits of solar and wind energies, they played an important role from economic point of view to successfully deal with energy poverty issue by providing easily energy access. On the other hand, currently on governmental base, the construction of solar energy systems to the already installed buildings is considered one of the most important solutions to use on-grid energy system that provide sustainable buildings in additions to increase the building energy performance (Aghbashlo, *et al.*, 2018). According to Liobikienė and Butkus (2017), the usage of green energy, or ecologically friendly renewable energy sources, can help reduce greenhouse gas (GHG) emissions and so improve the climate.

This part of review presented comprehensive research studies of solar water pumping systems. The solar system consists of specified main components namely; solar panel, inverter, battery charger, a battery and controller. The performance of a PV solar water pumping system with a daily water demand of 3 m^3 and a total dynamic head of 35 m was examined. It was discovered that the pumping system was the most effective in terms of water flow, daily effort, and cost-effectiveness (Alshamani, 2018). PV pumping is regarded as one of the most promising uses of solar energy because grid electricity is unavailable in rural, isolated, and distant places. When compared to conventional pumping systems, a well-designed solar system will save money. To reduce system costs, storage tanks are a better option for storing water during night irrigation than batteries (Prosperous, 2019).

Over the past ten years, solar PV water pumping systems have demonstrated a number of advancements. Centrifugal pumps, which are typically powered by DC motors and variable frequency AC motors and have a track record of long-term dependability, were employed in the initial generation of solar PV water pumping systems. The second-generation of solar PV water pumping systems used two kinds of pumps like positive displacement pumps and diaphragm pumps. Electronic systems are used in the latest solar pumping technology, which has improved the system's performance, output power, and overall efficiency. Along with the electronic systems, the tracking system for PV arrays was improved through the use of microcontroller programming for either single or dual axis automatic tracking systems. Commercially available solar pumps have an output of up to 250 m^3/day and can lift water from 5 m to over 200 m (Alshamani, 2018). AbdulGhani and Gouda (2018) investigated the PV Pumping System's (PVPS) performance both theoretically and empirically. They discovered that the simulation and the experimental observations agreed fairly well. Less than 5% of the difference between the calculated and measured monthly flow rate was discovered. It was discovered that the amount of output water decreased with increasing temperature, indicating the significance of the cooling system for the PV modules. They also came to the conclusion that the system performs better when the MPPT (Maximum Power Point Tracking) technique is used. Their suggested system efficiency is 1.2% higher than the traditional one because MPPT is used.

Some previous reference studies (Closas and Rap, 2017; Awad, et al., 2025; Ramadan, 2016; Sahar et al., 2021) highlighted the significance of monitoring groundwater abstraction, focusing on subsidies, monitoring resource use, and enhancing knowledge by presenting policies and restrictions in the solar pumping of groundwater for irrigation from a sustainability point of view. Accordingly, if that problem is not resolved, groundwater levels may continue to decline, which may have an impact on the technology's sustainability and future reliant livelihoods. In Egypt, groundwater abstraction is a vital issue that is carried out by the irrigation and water resources ministry in order to prevent the salinity of well water from rising.

Wazed, et al., (2018) investigated sustainable irrigation techniques in Africa. They demonstrated that accurately determining the crop water demand and carrying out in-depth on-site research to examine the system's operating conditions are the best ways to reduce the cost and design of the PV power system (El Habbasha et al., 2015; El-Metwally et al., 2015; Ramadan, et al., 2020). In some situations, it has been discovered that employing a battery system really lowers costs, but in other scenarios, cost savings have been realized without the use of a battery system. Compared to diesel-powered systems, photovoltaic systems are significantly less expensive during their useful lives, but they require a larger initial investment, particularly for small rural farmers. Therefore, because of the significant carbon footprint brought on by the consequences of manufacturing and technology transfer, solar panels do not meet their intended environmental impact reduction goal.

PV pumps are often more cost-effective than diesel pumps up to roughly 3 kWp for village water delivery and 1 kWp for irrigation. PV solar arrays are a cost-effective, low-maintenance, and ecologically friendly substitute for irrigation pump assembly powered by diesel or electricity. Based on the study, it is predicted that between 9 and 70 million sets of solar PV pumps might be used in India to pump water for agriculture, saving at least 255 billion liters of diesel fuel annually. Because of this, farmers can offer a reasonably flexible and environmentally beneficial alternative energy source in rural locations where diesel fuel is costly or when dependable access to the electrical grid is unavailable. Both small-scale decentralized irrigation and large-scale irrigation systems can make use of the solar photovoltaic irrigation system (Pluschke and Hartung, 2018).

To increase the competitiveness of the fresh fruit business, Guzmán et al. (2018) investigated a cost-effective methodology for the sizing of solar PV systems for existing irrigation infrastructure in Chile. Four projects—two in the Maule Region and two in the Atacama Region—were analyzed in the study. In addition to the suggested features of the chosen PV system to power the irrigation systems of small fresh fruit farms, the baseline conditions of the four units were examined, along with potential energy-saving measures. Both on- and off-grid solar PV systems were examined, along with some unique aspects of Chilean laws. Additionally, the irrigation systems' necessary water demand and the pressure heads that go along with it were calculated (Okasha et al., 2013, 2016; Mansour et al., 2023; Marwa et al., 2017, 2023).

The PV system was created for an ideal irrigation system once the system's electricity demand was determined. A two-year economic study was also conducted. When the cost-effectiveness of energy-efficient measures for the irrigation system was assessed in the first year, it was discovered that the payback periods were roughly two years. Each demonstrative unit's PV system installation was assessed in the second year. With estimated payback periods of roughly 12 years, the on-grid solar PV system outperformed the off-grid system. Lastly, based on the idea that a well-designed on-grid solar PV system should endure for more than 25 years and have a sufficient plan for operation and maintenance, some recommendations were made. For PV solar pumps being used by small farmers in sub-Saharan Africa was investigated by Schmitter et al. (2018).

Two solar PV pumps were chosen for application in shallow groundwater or surface waters, and their geographic appropriateness was assessed using a multi-criteria approach. The pre-processed spatial maps were integrated with the technical specifications of small solar pump technology. The adequacy analysis was carried out in three main steps: first, areas that are not suitable for solar application were excluded; second, each factor was reclassified to the appropriate class; and third, pairs of notes that were reclassified in input maps were classified and weighted.

The main objective of the current study is to present an experimental investigation of the performance of a mobile solar-powered water pumping system at different tilt angles and directions as a sustainable and renewable alternative to the traditional, environmentally harmful and increasingly expensive diesel-fuel-based water pumping system in Giza, Kafr El-Sheikh and Assiut Governorates, Egypt.

Material and Methods

1. Solar radiation intensity levels at the study sites

The study was conducted and the solar-powered pumping unit was produced at the National Research Center in Dokki, Giza, Egypt. Under the same intense solar radiation conditions as in Giza, and with maize grown using a surface irrigation system using Gated pipes in the summer, the optimum specifications for a solar-powered irrigation pumping unit were determined using a simulation model. The optimum specifications for a solar-powered pumping unit for rice cultivation in Kafr El-Sheikh Governorate were also determined, as were the specifications for a solar-powered pumping unit for sugarcane cultivation in Assiut Governorate as shown in Figure (1). To achieve the objective of the study, it was necessary to determine and know the average incident solar radiation. Solar radiation intensity in Egypt increases from north to south.

Southern Egypt receives the highest solar intensity, with a global average horizontal irradiance (GHI) of over 7 kWh/m²/day. In northern Egypt, radiation levels are lower compared to the south, where GHI values typically range between 5.4 and 6.4 kWh/m²/day. Therefore, the differences between the average solar radiation in Kafr El-Sheikh Governorate in the Nile Delta and Giza Governorate are considered insignificant as shown in Figure (2).

2. Available facilities in the study area

The National Research Center in Dokki, Giza, Egypt, served as the site of the experiment. The PV system shown in Figure (6) designed in such a way to investigate experimentally, the effect of tilt angle and orientation on the pumped water in different seasons. To support the PV system, which included PV modules, pump, inverter, and wiring system, the system was made simply utilizing iron sheets and metallic U, T, and L sections of varying thicknesses and lengths as shown in Figure (7).

3. Measuring devices

The solar water pumping system's many parameters were measured using a variety of instruments as shown as in Figure (8):

4. Experimental design to determine the most suitable angle of inclination and angle of orientation for solar cell panels to achieve the highest intensity of solar radiation falling on them

In the experimental design, the azimuth angles of the solar panels were distributed in the main plot (90,60,30,0, -30, -60 and -90) while the tilt angles of the solar panels were distributed in the sub-main plot (0,30,50,70 and 90) in order to determine the best tilt angle and the best azimuth angle to obtain the highest intensity of solar radiation falling on the solar cell panels to obtain the highest possible energy from the sun's rays to operate the irrigation pump during summer and winter seasons.

5. Scope of the present work

The PV water pump performance mainly depends on the daily water demand and total dynamic head, Climate conditions like solar radiation and ambient temperature and pump efficiency. The lifetime and the degradation of solar panels considered one of the important factors that affect the performance of a solar pump. The performance of solar water pumping system depends on the following parameters, (1) Water flow rate, (2) Solar radiation values and (3) Total Dynamic Head (TDH): Sum of suction, discharge, and frictional heads.

6. Water flow rate

The following data was determined to estimate the required flow rate for the irrigation pump, which will be powered by solar energy as shown in Equations (1) and (2).

$$Q \times T = (A \times D_{Max.} \times F) / \eta \;\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$D_{Max.} = ET_{C\,Max.} = ETo_{Max.} \times Kc_{Max.} \;\ldots\ldots\ldots\ldots\ldots(2)$$

Denoted letters in the equations were explained in a compacted format, i.e. "Where: Q: (Water flow rate) m^3/h; T: (Irrigation time), 1 day = 6 h.; A :(Area to be irrigated), m^2; $D_{Max.}$:(Maximum depth of irrigation water required to be added), mm/day; $ET_{C\,Max}$:(Maximum evapotranspiration of maize plants, mm/day; $ETo_{Max.}$:(Maximum reference evapotranspiration during summer), mm/day; Kc_{Max} :(The highest value of the crop coefficient is during the summer season) , (FAO56); F :(Irrigation frequency); η: (Irrigation efficiency), %." Should have been presented as

Where:

Q: (Water flow rate) m^3/h; T: (Irrigation time), 1 day = 6 h.; A :(Area to be irrigated), m^2; $D_{Max.}$:(Maximum depth of irrigation water required to be added), mm/day; $ET_{C\,Max}$:(Maximum evapotranspiration of maize plants, mm/day; $ETo_{Max.}$:(Maximum reference evapotranspiration during summer), mm/day; Kc_{Max} :(The highest value of the crop coefficient is during the summer season) , (FAO56); F :(Irrigation frequency); η: (Irrigation efficiency), %."

7. Design of electric motor power

The amount of solar energy falling on the horizontal surface, the water demand, the Total Dynamic Head (TDH), the choice of a pump that will meet the required water demand and the desired pressure, the size of the PV capacity (kW) to power the required pump electric load, and the estimation of the system land requirements were all taken into consideration in order to develop the entire design process of the solar water pumping system. A site's climate, surroundings, irrigation type, and user identification (human, animal, or plant) are only a few of the many variables that affect water consumption. The sum of the friction head losses, minor head losses, and total static head is known as the Total Dynamic Head (TDH). The height differential between the water source input and the water exit level is known as the total static head. The wall shear stress experienced at the contact between the fluid in the pipes and the pipe walls is the cause of the friction head losses in the system. It is inversely proportional to the pipe's inner diameter and directly proportional to the pipe's length. Furthermore, a friction factor that depends on the flow's Reynolds number and the relative roughness of the inner pipe walls is linked to the friction head losses. Unstable turbulent flow in pipe fittings, connectors, and valves is the cause of the system's small head losses. The hydraulic Power Ph in (Watt) required to lift a volume of water over a total head, according to the following equations 3 and 4

$$P_h = Q\,\rho_w\,g\,TDH \;......(3)$$

Where: P_h = the hydraulic pump required power; Q = Flow rate or volume of water lifted per second in m3/s.; ρw = Density of water (1000 kg/m3); g = Acceleration due to gravity (9.81 m/s2), and TDH = Total dynamic head (m); The electric motor power (P_{elec})is equal to the hydraulic pump required power (P_h) divided by the pump efficiency (η):

$$P_{elec} = \frac{P_h}{\eta} \;.......(4)$$

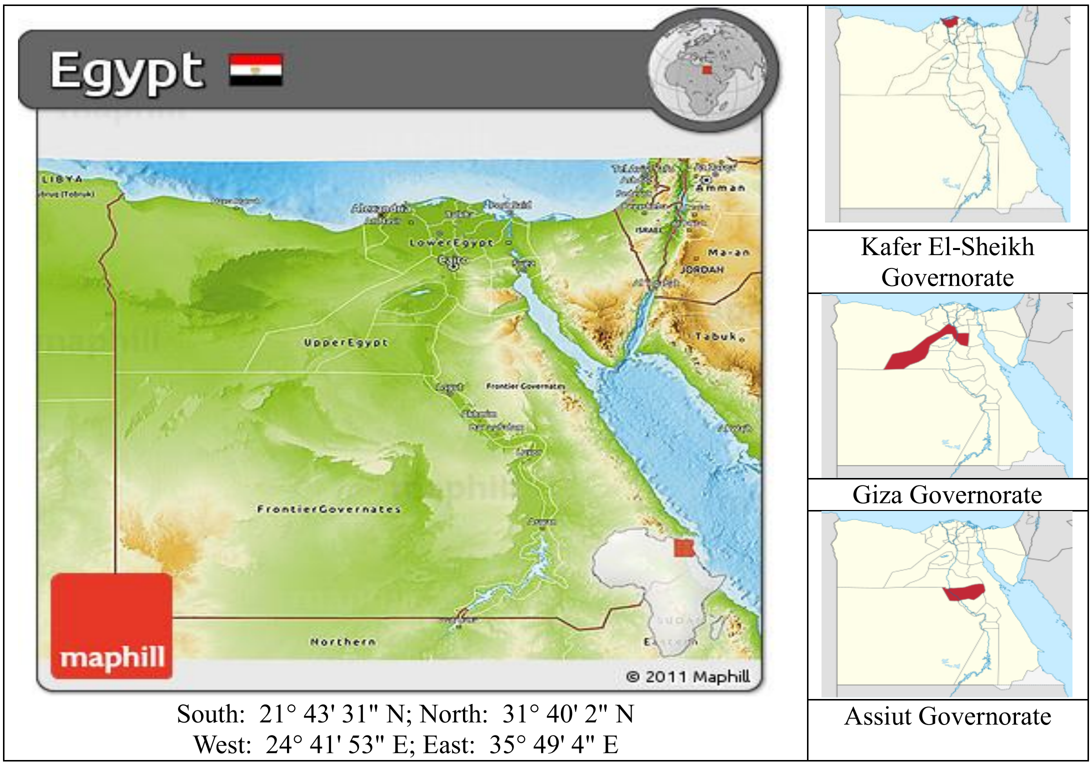


Fig. 2. Study sites in both Giza and Kafr El-Sheikh governorates in Egypt.

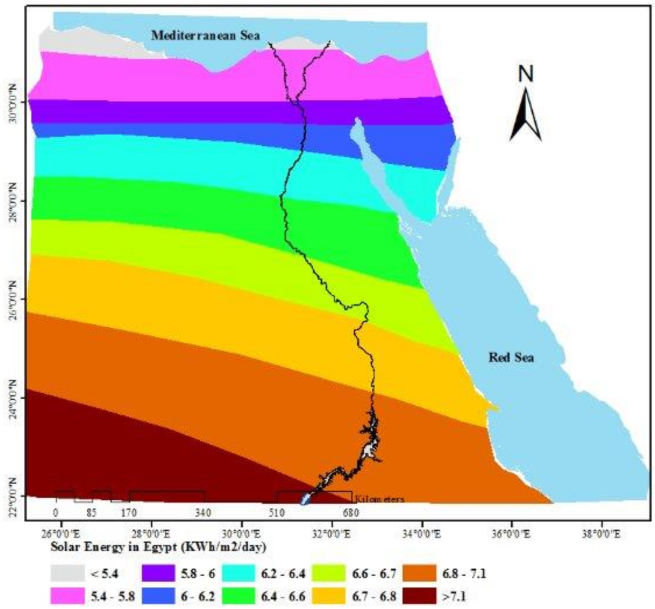
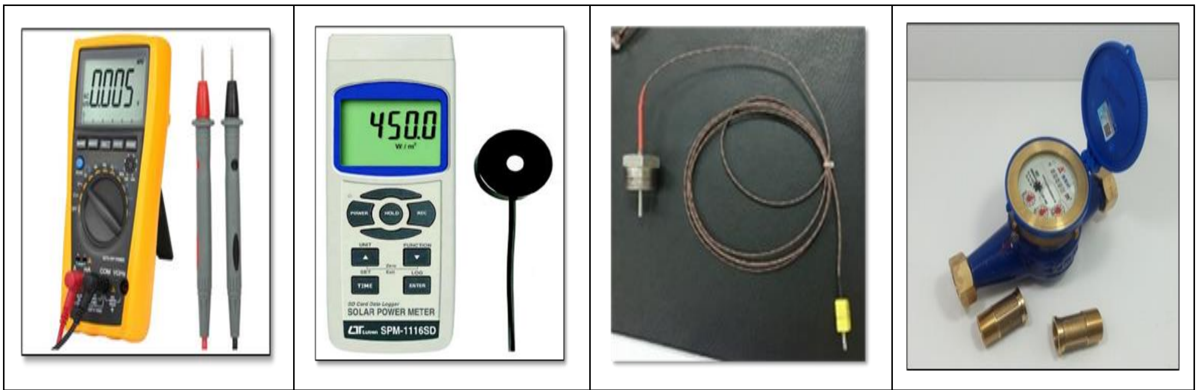


Fig. 3. Average intensity of solar radiation falling on Egypt.

Fig. 4. Photographic view of one of the solar water pump design stages.

Table 1. Photovoltaic solar panel and pump characteristics in Giza.

Photovoltaic solar panel characteristics		Pump characteristics	
Model No:	SK-280P6-60	Model	MHF - 5B
Rated Maximum Power (Pmax)	280 W	Q_{max}	383 L/min
Open – Circuit Voltage (Voc)	37.20 V	H_{max}	18 m
Short – Circuit Current (Isc)	9.92 A	Size	2``× 2``
Voltage at Pmax (Vmp)	30 V	$Suct._{max}$	8 m
Current at Pmax (Imp)	9.34 A	HP	2.5
Nominal Operating Cell Temperature (NOCT)	48 ± 2 ºC		
Maximum System Voltage	1000 VDC		
Maximum Series Fuse Rating	18 A		
Operating Temperature	-40 ºC ~ + 85 ºC		
Cell Technology	Poly-crystalline		



Multimeter	Solar Power meter	Thermocouple	Flowmeter

Fig. 5. Several devices were used to measure the different parameter in the solar water pumping system.

8. Sizing the solar system

The following formula can be used to determine the photovoltaic system's size in watts for the peak load (Ibrahim et al., 2020) was equations 5.:

$$\mathrm{Apv} = \frac{\mathrm{EL}}{\mathrm{H} \times \eta_{pv} \times \eta_{inv} \times \eta_{B} \times \eta_{cc} \times \mathrm{T_c}} \quad \ldots(5)$$

Where Apv is the total area (m^2) needed for photovoltaics; EL = The solar water pumping system's (SWPS) peak daily electrical energy requirements, expressed in Watts per day (Wh/day) and the number of running hours (6 hours); H = daily global irradiation (Wh/m^2/d); η_{pv}, η_{inv}, η_B, η_{cc} = efficiencies for photovoltaic, inverter, battery and charge controller, respectively; T_c = Temperature correction factor of the PV module.

The current system is designed to operate pump directly from the inverter without battery and charger, therefore, equation (6) can be rewritten as:

$$\mathrm{Apv} = \frac{\mathrm{EL}}{\mathrm{H} \times \eta_{pv} \times \eta_{inv} \times T_c} \dots\dots\dots\dots\dots (6)$$

The power P_{pv} in Watts (W) needed for solar modules to meet the demand for electricity can be computed as follows as equations 7:

$$P_{pv} = A_{PV} \times \mathrm{Hsc} \times \eta_{PV} \dots\dots\dots\dots\dots\dots\dots (7)$$

Where H_{sc} is equal to 1,000 W/m^2 of standard solar irradiation; The area of a single PV module that is commercially accessible can be used to estimate the number of total modules (N_m) once the total needed area of PV panels (m^2) has been determined. The following is an estimate of the number of PV modules according to equation 8:

$$N_m = \frac{P_{PV}}{P_m} \dots\dots\dots\dots\dots (8)$$

Where: The single module's power in Watts is denoted by P_m.

9. PV$_{SYST}$ Model

The solar energy industry uses PVsyst, a software tool, to design, model, and analyze all kinds of photovoltaic (PV) systems, including pumping, freestanding, and grid-connected systems. In order to assist users in optimizing system design, comparing various configurations, and precisely estimating energy yield by taking into account particular component data, weather conditions, and potential losses, it runs comprehensive hourly simulations over the course of a year.

The program PV$_{SYST}$ Model was used for its high accuracy in determining the most appropriate tilt angle and orientation angle for solar panels in three locations under study (Giza Governorate, Kafr El-Sheikh Governorate and Assiut Governorate) as shown in Figure (5).

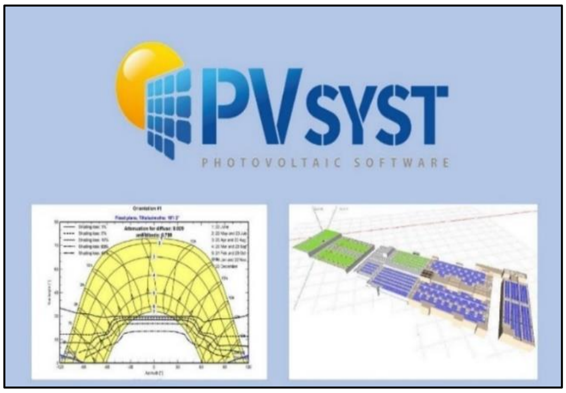


Fig. 6. Using PVSYST software to design and simulate photovoltaic (PV) systems, ensuring optimal performance and efficiency.

10. Cost Analysis

The experimental investigation stage, a commercial scale of mobile PV water pumping unit was designed, manufactured and tested in National Research Center, Dokki, Giza, Egypt as shown in Fig.8. Acquisition, operating, maintenance, and replacement costs are all included in the price of a stand-alone PV system. All these costs have many specifications include; the initial cost of the system is high, no fuel costs, low maintenance costs and low replacement costs. The economic analysis of the PV water pumping system is based on calculating indicators like Life Cycle Cost (LCC) (Abu-Rumman, A. K. *et al.* 2017). The LCC method is the worldwide largely used method to evaluate the economics of the PV system. LCC is applied based on the following assumptions; the lifetime of all the items is considered 20 years and the interest rate is about 10%. It can be defined as shown in equation (9)

$$LCC = C_{capital} + \sum_1^n C_{O\&M} + \sum_1^n C_{rep} - C_s \quad (9)$$

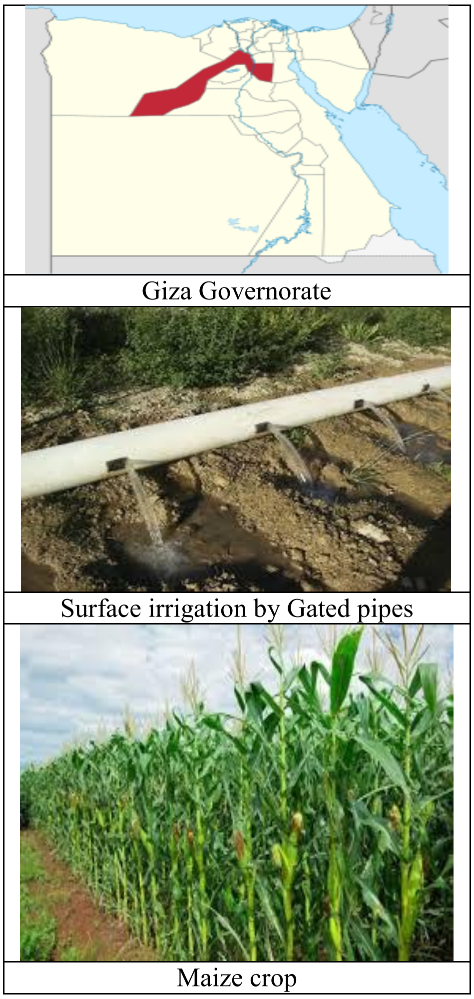
Where: $C_{capital}$: The capital cost of a project, $C_{O\&M}$; The yearly operation and maintenance costs, C_{rep} : The cost of all equipment replacement and repair, C_s : The net worth of the system at the final year of project lifetimes.

Results and Discussion

A mobile solar-powered irrigation unit was manufactured and produced under Giza Governorate conditions (Solar Energy Department, National Research Center, Dokki, Egypt) for irrigating maize, the most water-intensive crop in Giza Governorate. The optimal cell tilt angle and orientation were determined during the summer and winter seasons to maximize the use of sunlight falling on the solar panels, thus achieving maximum energy production and the highest possible irrigation discharge. The sustainable costs of this unit for pumping irrigation water were also calculated. The specifications of the mobile solar-powered water pumping unit were also designed and specified for Kafr El-Sheikh Governorate (rice irrigation) and Assiut Governorate (sugarcane irrigation). The PVSYST Model simulation program was used to determine the optimal solar panel tilt angle and azimuth angle to achieve optimal performance.

3.1. Determining the most appropriate technical specifications for a mobile solar-powered irrigation water pumping unit for small holdings in Giza Governorate.

The most important and most cultivated crops (Maize crop) in Giza Governorate and the irrigation systems applied (Surface irrigation by Gated pipes) by small-scale farmers in Giza Governorate were identified, as well as the most appropriate technical specifications for providing a mobile irrigation water pumping unit that is operated by solar energy as shown as in Figure (7).



Giza Governorate

Surface irrigation by Gated pipes

Maize crop

Figure (7): Determining the highest water-consuming crop (Maize) in Giza, along with the type of irrigation used in Giza Governorate

3.1.1. Water flow rate (Q)

To determine the irrigation pump flow rate in the Giza area, it was necessary to determine some important information related to the crops with the highest water consumption during the summer season. The maximum water requirements of the highest water-consuming crop during the summer season must be determined, i.e., the highest crop coefficient, as well as the highest reference evaporation rate. The maximum solar intensity must also be determined. The minimum area owned by most farmers was approximately 2 Feddan (8400 m^2). The most commonly used irrigation system was the surface irrigation system with gated pipe.

The research identified maize as the summer crop with the highest water demand in Giza Governorate. The maximum value of the maize crop coefficient was determined from the FAO 56, while the maximum reference evaporation rate was determined from the Central Climate Laboratory. The following data was determined to estimate the required flow rate for the irrigation pump, which will be powered by solar energy. The water flow rate (Q) was required, m^3/h

$$Q \times T = (A \times D_{Max.} \times F)/\eta$$

$$D_{Max.} = ET_{C\,Max.} = ETo_{Max.} \times Kc_{Max.}$$

Where: T (Irrigation time) = 1 day = 6 h.; A (Area to be irrigated) = 8400 m^2 = 2 Feddan;

$D_{Max.}$ (Maximum depth of irrigation water required to be added), mm/day;

$ET_{C\,Max}$ (Maximum evapotranspiration of maize plants, mm/day;

$ETo_{Max.}$ (Maximum reference evapotranspiration during summer) = 8.2 mm/day;

Kc_{Max} (The highest value of the corn crop coefficient is during the summer) = 1.2 (FAO56);

F (Irrigation frequency) = 1 day; η (Irrigation efficiency for surface irrigation by gated pipe) = 60%. by using the following equations:

$$Q \times 6 = (8400 \times 0.00984 \times 1)/0.6$$

$$Q = 22.96 = 23\ m^3/h$$

3.1.2. Design of electric motor power

After calculating the irrigation pump's flow rate, the next step is to calculate the electric motor's power. To calculate the electric motor's power, you must also calculate the total hydraulic head (T.D.H.), the pump's hydraulic power, and the pump's efficiency P_h.

Considering the design parameters as follows: Where: Q = 22.96 m^3/h = 0.00638 m^3/s; ρ (Water density) = 1000 kg/m^3; g (Gravitational Acceleration) = 9.81, m/s^2; T.D.H = 18 m; The pump hydraulic power (P_h) in Watts can be calculated as follows: $P_h = Q\,\rho_w\,g\,TDH$

$$P_h = 0.00638\ x\ 1000\ x\ 9.81\ x\ 18 = 1126.58\ W$$

The electric motor power (P_{elec}) is equal to the hydraulic pump required power divided by the pump efficiency, η (consider the pump-motor efficiency = 0.80

$$P_{elec} = \frac{P_h}{\eta}$$

$$P_{elec} = \frac{1126.58}{0.80} = 1408.225\ W = 1.89\ \text{hp} = 2\ \text{hp}$$

3.1.3. Determine the best tilt angle and orientation angle for solar panels to receive the highest solar radiation values during the summer and winter seasons: Field measurements and also using the PV_{SYST} Model

Table (5) shows the distribution of the main and sub-main parameters for the experiment to determine the best tilt angle and the best orientation angle to obtain the highest intensity of solar radiation falling on the solar cell panels to obtain the highest possible energy from the sun's rays to operate the irrigation pump. Table (5) confirms that the highest value of solar radiation intensity (5.83) falling on solar panels in the summer was when the tilt angle was 30 and the azimuth angle was zero. The results of the table also showed that the highest intensity of solar radiation falling on solar panels in the winter was when the tilt angle was 50 and the azimuth angle was zero.

In summer season: It is found that through Figure (8), the solar radiation values (kWh/m^2/day) varied with the variation of tilt angle at fixed azimuth angle (south facing). In summer season, the average daily solar radiation values south facing were 5.7, 5.8, 5.2, 4.6 and 3.7 kWh/m^2/day corresponding to tilt angles of 0,30,50,70 and 90 respectively. It has been discovered that a 30-degree tilt angle and a zero-azimuth angle (looking south) yields the most solar radiation during the summer. At a tilt angle of 30, the daily sun radiation levels are observed at various azimuth angles. The average daily amounts of solar radiation are discovered to at tilt angle equals 30 were 4.35, 4.80, 5.25, 5.83, 5.19, 4.80 and 4.74 kWh/m^2/day corresponding to azimuth angles of 90,60,30,0, -30, -60 and -90 respectively.

The maximum solar radiation value falling on the PV modules during summer season was 5.83 kWh/m^2/day at tilt angle 30 and azimuth angle zero. While the simulation model values using the program PV_{SYST} showed that the most suitable value for the solar panels' tilt angle was 15 degrees and the azimuth angle was zero.

Table 2. The highest solar radiation values (kWh/m^2/day) in the summer and winter seasons determine the most appropriate tilt angles and azimuth angles.

<table>
<tr><td rowspan="3">Seasons</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="3"></td><td colspan="7">Main Plot</td></tr>
<tr><td colspan="7">Azimuth angle</td></tr>
<tr><td>90</td><td>60</td><td>30</td><td>0</td><td>-30</td><td>-60</td><td>-90</td></tr>
<tr><td rowspan="5">Summer season</td><td rowspan="5">Sub-main plot</td><td rowspan="5">Tilt angle</td><td>0</td><td>4.11</td><td>4.65</td><td>5.02</td><td>5.70</td><td>5.11</td><td>4.75</td><td>4.18</td></tr>
<tr><td>30</td><td>4.35</td><td>4.80</td><td>5.25</td><td>5.83</td><td>5.19</td><td>4.80</td><td>4.74</td></tr>
<tr><td>50</td><td>4.17</td><td>4.57</td><td>5.15</td><td>5.20</td><td>5.03</td><td>4.68</td><td>4.62</td></tr>
<tr><td>70</td><td>4.08</td><td>4.43</td><td>4.52</td><td>4.60</td><td>4.44</td><td>4.35</td><td>4.09</td></tr>
<tr><td>90</td><td>3.34</td><td>3.52</td><td>3.61</td><td>3.70</td><td>3.56</td><td>3.28</td><td>3.19</td></tr>
<tr><td rowspan="5">Winter season</td><td rowspan="5">Sub-main plot</td><td rowspan="5">Tilt angle</td><td>0</td><td>3.42</td><td>3.47</td><td>3.52</td><td>3.55</td><td>3.51</td><td>4.48</td><td>4.07</td></tr>
<tr><td>30</td><td>4.18</td><td>4.75</td><td>4.92</td><td>4.96</td><td>4.91</td><td>4.71</td><td>4.22</td></tr>
<tr><td>50</td><td>4.25</td><td>4.79</td><td>5.21</td><td>5.66</td><td>5.06</td><td>4.76</td><td>4.33</td></tr>
<tr><td>70</td><td>4.14</td><td>4.73</td><td>5.04</td><td>5.09</td><td>5.06</td><td>4.68</td><td>4.31</td></tr>
<tr><td>90</td><td>3.59</td><td>3.88</td><td>3.94</td><td>3.98</td><td>3.87</td><td>3.80</td><td>3.54</td></tr>
</table>

In winter season: It is found that through Figure (9), the solar radiation values (kWh/m^2/day) varied with the variation of tilt angle at fixed azimuth angle (south facing). The average daily amounts of solar radiation throughout the winter south facing were 3.55, 4.96, 5.66, 5.09 and 3.98 kWh/m^2/day corresponding to tilt angles of 0,30,50,70 and 90 respectively. It is found that the maximum solar radiation in winter season obtained with zero azimuth angle (facing south) and 50-degree tilt angle. The daily solar radiation values at tilt angle equals 50 and different azimuth angles are measured. It is found that the average daily solar radiation values at tilt angle equals 50 were 4.25, 4.79, 5.21, 5.66, 5.26, 4.76 and 4.33 kWh/m^2/day corresponding to azimuth angles of 90,60,30,0, -30, -60 and -90 respectively.

The maximum solar radiation value falling on the PV modules during winter season was 5.66 kWh/m^2/day at tilt angle 50 and azimuth angle zero. While the simulation model values using the program PV_{SYST} showed that the most suitable value for the solar panels' tilt angle was 46 degrees and the azimuth angle was zero.

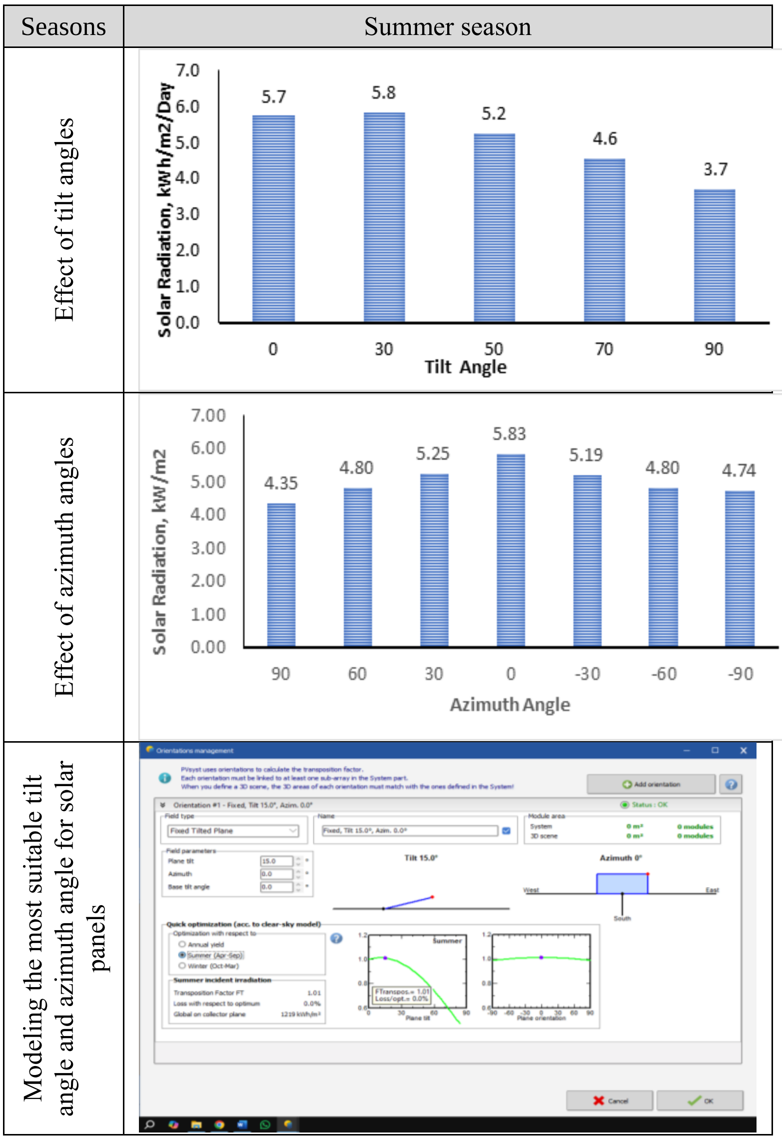


Fig. 8. Determine the most appropriate tilt angle and azimuth angle for solar panels during the summer using actual measurements and simulation models.

Comparing the field and actual results measured at the experimental site with the simulation results, it was found that they agreed on the azimuth angle being zero, at which the highest values were achieved. However, there were differences in the solar panel tilt angle values. The actual estimated solar panel tilt angle in the summer was 30 degrees, while the simulation program estimated it to be 15 degrees. This is acceptable and confirms the accuracy of the simulation results (between zero and 30 degrees). This is also due to the specific tilt angles for the solar panels being specified, and the incident solar radiation intensity at each degree was not measured. In winter, there were no significant differences between the actually measured solar panel tilt angle (50 degrees) and its value using the simulation program (46 degrees).

When it comes to actual implementation, farmers who will use the solar-powered water pumping unit year-round, i.e. during all agricultural seasons for irrigating crops, particularly the summer and winter, have two installation options. The first option is to have the solar panels tilted at a variable angle according to the irrigation season to achieve the highest position for receiving the sun's rays falling on the solar panels. However, this variable option is vulnerable to tampering and difficult to adjust by untrained farmers who cannot protect it from tampering, as shown in Figure (10). The second option is to have the solar panels at a fixed position (at a tilt angle of 26 degrees) as shown as Figure (11). Even so, the intensity of the solar radiation striking the solar panels is not at its maximum. throughout the year, the differences are insignificant compared to the values of the first option, which varies in position each season.

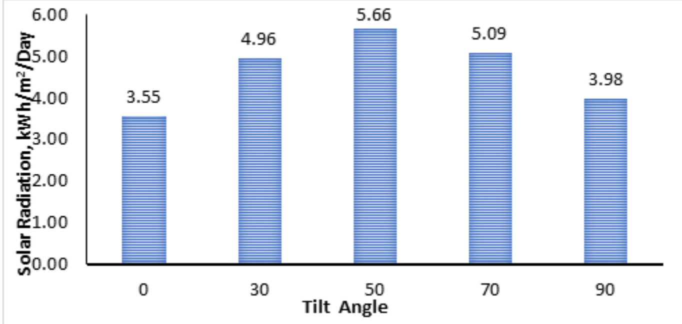
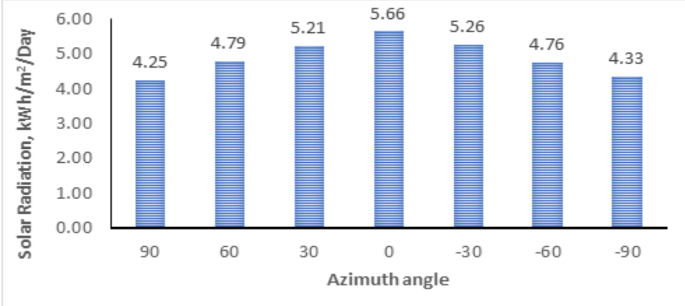
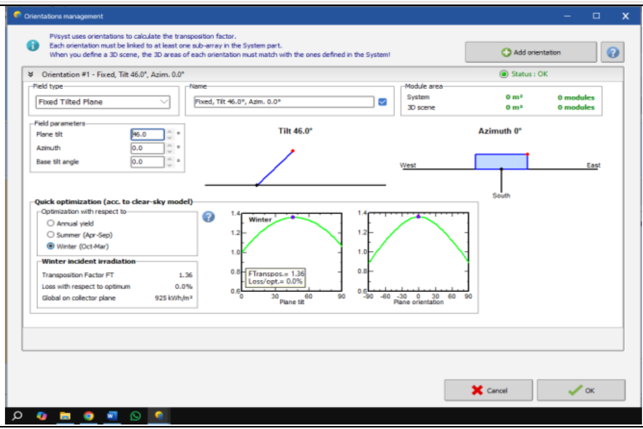
Seasons	Winter season
Effect of tilt angles	
Effect of azimuth angles	
Modeling the most suitable tilt angle and azimuth angle for solar panels	

Fig. 9. Determine the most appropriate tilt angle and azimuth angle for solar panels during the winter using actual measurements and simulation models.

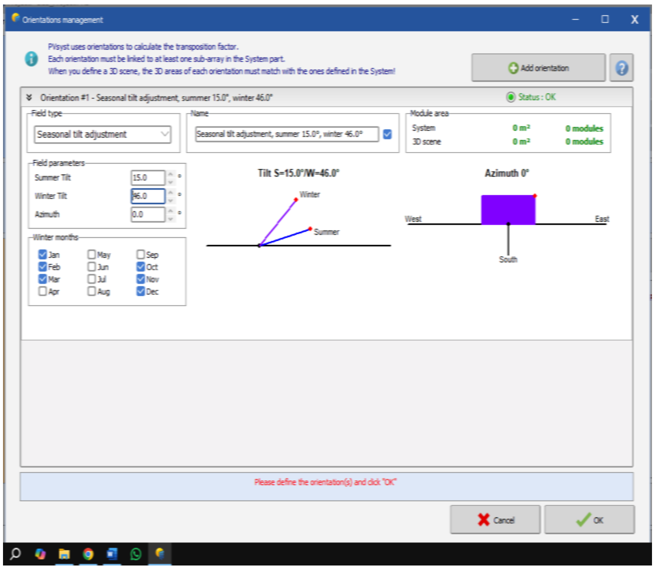


Fig. 10. Seasonal tilt adjustment according to summer season and winter season.

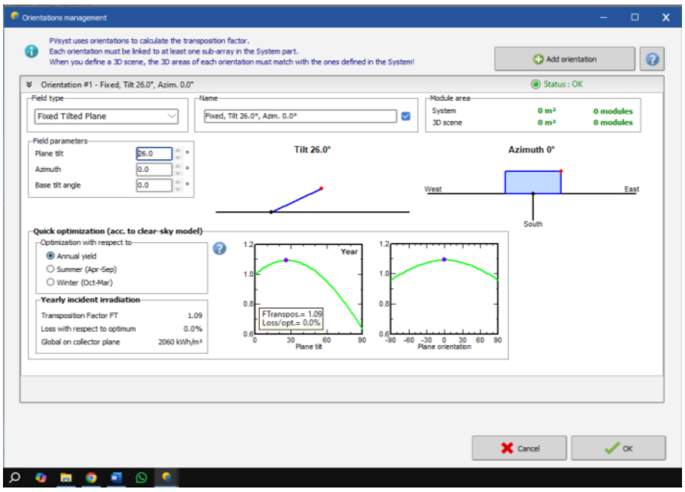


Fig. 11. Fixed tilted plane during annual yield.

3.1.4. System Sizing Calculation

Electric motor power = 2 hp = 2 x 746= 1492 W
Daily electric energy consumed (EL) = 1492W x 6 h = 8952 Wh =8.952 kWh

$$\mathrm{Apv} = \frac{\mathrm{EL}}{\mathrm{H} \times \eta_{\mathrm{pv}} \times \eta_{\mathrm{inv}} \times \mathrm{T_c}}$$

$$\mathrm{Apv} = \frac{8.952}{5.8 \times 0.90 \times 0.90 \times 0.21} = 9.07\ m^2$$

$$\mathrm{P_{pv}} = \mathrm{A_{PV}} \times \mathrm{Hsc} \times \eta_{\mathrm{PV}}$$

$$\mathrm{P_{pv}} = 9.07 \times 1000 \times 0.21 = 1904.7\ \mathrm{W}$$

$$\mathrm{N_m} = \frac{\mathrm{P}_{PV}}{\mathrm{P_m}}$$

The number of modules (Nm)= 1904.7 W / 333 W = 5.72 = 6 Modules

3.1.5. Cost Analysis

Acquisition, operating, maintenance, and replacement costs are all included in the price of a stand-alone PV system. Among the various features of these prices are the system's high initial cost, fuel-free operation, low maintenance costs, and inexpensive replacement costs. The economic analysis of the PV water pumping system is based on calculating indicators like Life Cycle Cost (LCC) as shown as in Table (3). The LCC method is the worldwide largely used method to evaluate the economics of the PV system. LCC is applied based on the following assumptions; the lifetime of all the items is considered 20 years and the interest rate is about 10%. It can be defined as shown in equation (7)

$$LCC = C_{capital} + \sum_1^n C_{O\&M} + \sum_1^n C_{rep} - C_s$$

Where: $C_{capital}$: The capital cost of a project, $C_{O\&M}$; The yearly operation and maintenance costs, C_{rep} : The cost of all equipment replacement and repair, C_s: The net worth of the system at the final year of project lifetimes. The total cost of a solar water pumping unit in 2021, to suit the conditions of the study area, for a period of 20 years, was approximately $4,442.5 as shown in detail in Table (3).

Table 3. The cost analysis for the solar water pumping system according to 2021 prices .

		Components	Quantity	Unit price ($)	Total price ($)
$C_{capital}$	Capital Cost	PV module 333 W	6	80	480
		Controller	1	45	45
		Inverter (2 kW)	1	160	160
		Installations	1	95	95
		Mobile Metallic frame	1	1100	1100
		Hydraulic system	1	350	350
		Water Pump (2.5 hp)	1	300	300
		Total			2530
		Inflation Rate			5%
		Capital Cost with inflation Rate			2656.5
$C_{O\&M}$	O&M Cost	Operation and maintenance costs for 20 years	20	40	800
C_{rep}	Replacement Cost	Replacement of pump and inverter	2	240	480
C_s	Salvage Value	Salvage Value = 20% from Capital Cost	1	506	506
LCC	Cycle Cost	Life Cycle Cost (LCC)			4442.5

3.2. Specifications for a solar-powered water pumping unit in Kafr El-Sheikh Governorate Using PV_{SYST} Model to determine the best tilt angle and direction for the solar panels.

The most important and most cultivated crops (Rice crop) in Kafr El-Sheikh Governorate and the irrigation systems applied (Basin surface irrigation) by small-scale farmers in Kafr El-Sheikh Governorate were identified, as well as the most appropriate technical specifications for providing a mobile irrigation water pumping unit that is operated by solar energy as shown as in Figure (12).

Kafer El-Sheikh Governorate

Basin surface irrigation

Rice crop

Fig. 12. Determining the highest water-consuming crop (Rice) in Kafer El-Sheikh, along with the type of irrigation used in Kafer El-Sheikh Governorate.

3.2.1. Water flow rate (Q)

To determine the irrigation pump flow rate in Kafr El-Sheikh farm, the highest water consumption during the summer season was rice. The minimum area owned by most farmers was approximately 2 Feddan (8400 m^2). The most commonly used irrigation system was the surface irrigation system.

The research identified rice as the summer crop with the highest water demand in Kafr El-Sheikh Governorate. The maximum value of the rice crop coefficient was determined from the FAO 56, while the maximum reference evaporation rate was determined from the Central Climate Laboratory. The following data was determined to estimate the required flow rate for the irrigation pump, which will be powered by solar energy. The water flow rate (Q) was required, m^3/h

$$Q \times T = (A \times D_{Max.} \times F) / \eta$$
$$D_{Max.} = ET_{C\,Max.} = ETo_{Max.} \times Kc_{Max.}$$

Where: T (Irrigation time) = 1 day = 6 h.; A (Area to be irrigated) = 8400 m^2 = 2 Feddan

$D_{Max.}$ (Maximum depth of irrigation water required to be added), mm/day

$ET_{C\,Max}$ (Maximum evapotranspiration of maize plants, mm/day

$ETo_{Max.}$ (Maximum reference evapotranspiration during summer) = 7.8 mm/day

Kc_{Max} (The highest value of the corn crop coefficient is during the summer) = 1.2 (FAO56)

F (Irrigation frequency) = 1 day; η (Irrigation efficiency for surface irrigation by gated pipe) = 50%.

by using the equations (1), (2) as follow

$$Q \times 6 = (8400 \times 0.00936 \times 1)/0.5$$
$$Q = 26.21\ m^3/h$$

3.2.2. Design of electric motor power

After calculating the irrigation pump's flow rate, the next step is to calculate the electric motor's power. To calculate the electric motor's power, you must also calculate the total hydraulic head (T.D.H.), the pump's hydraulic power, and the pump's efficiency P_h.

Considering the design parameters as follows: Where: Q = 26.21 m^3/h = 0.00728 m^3/s; ρ (Water density) = 1000 kg/m^3; g (Gravitational Acceleration) = 9.81, m/s^2; T.D.H = 15 m

The pump hydraulic power P(h) in Watts can be calculated as follows:

$$P_h = Q\, \rho_w\, g\, TDH$$

$$P_h = 0.00728\ x\ 1000\ x\ 9.81\ x\ 15 = 1071.252\ W$$

The electric motor power (P_{elec}) is equal to the hydraulic pump required power divided by the pump efficiency, η (consider the pump-motor efficiency = 0.80)

$$P_{elec} = \frac{P_h}{\eta}$$

$$P_{elec} = \frac{1071.252}{0.80} = 1339.065\ W = 1.79\ 5hp = 2\ hp$$

3.2.3. Determine the best tilt angle and orientation angle for solar panels to receive the highest solar radiation values during the summer and winter seasons using the PV_{SYST} Model

Due to the high accuracy of the simulation program, it was relied upon to determine the most appropriate tilt angle for the solar panels and the most appropriate azimuth angle during the summer and winter seasons. The actual value of the maximum solar radiation intensity falling on the solar panels was then measured.

Figure (13) shows the most appropriate tilt angle for the solar panels, which was 15 degrees at the azimuth angle of zero degree during the summer, when the highest radiation intensity falling on the solar panels was 5.6 kWh/m^2/day. Figure (14) shows the most appropriate tilt angle for the solar panels, which was 47 degrees at the azimuth angle of zero degree during the winter, when the highest solar radiation intensity falling on the solar panels was 5.02 kWh/m^2/day.

Figure (15) and Figure (16) illustrate the method of installing solar panels on agricultural land that needs to be irrigated using solar energy. Figure 10 shows the variable position of the solar panels, where the farmer can change the tilt of the panels to suit the season. Figure 16 shows the fixed position of the solar panels at a constant tilt angle (29 degree) throughout the year. The fixed position of the solar panels is the best, although it does not achieve the highest intensity of solar radiation falling on them. However, it is characterized by stability and safety throughout the year. In addition, the difference between it and the variable position is insignificant in the value of the intensity of light falling on the solar panels.

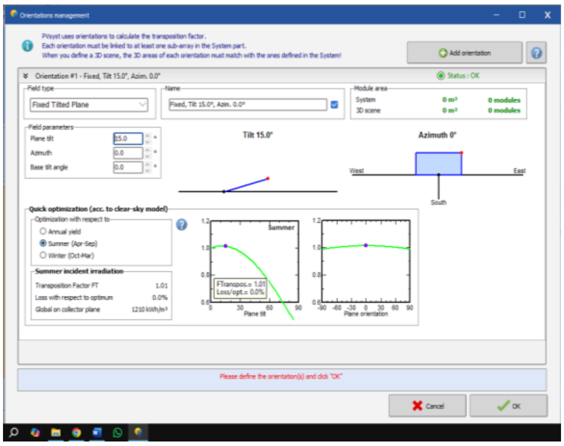


Fig. 13. Modeling the most suitable tilt angle and azimuth angle for solar panels in summer season.

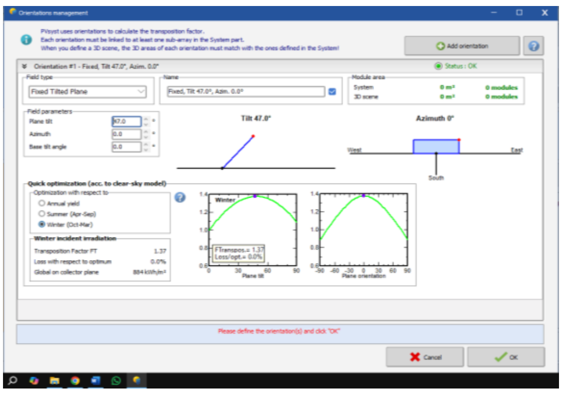


Fig. 14. Modeling the most suitable tilt angle and azimuth angle for solar panels in winter season.

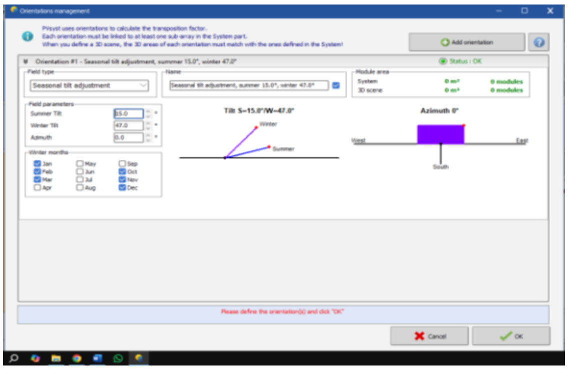


Fig. 15. Seasonal tilt adjustment according to summer season and winter season.

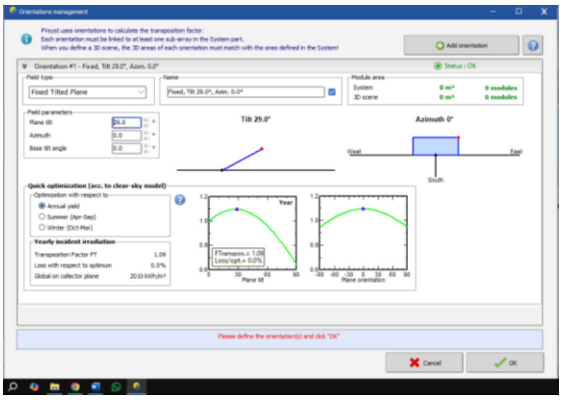


Fig. 16. Fixed tilted plane during annual yield.

3.2.4. System Sizing Calculation

Electric motor power = 2 hp = 2 x 746= 1492 W

Daily electric energy consumed, (EL) = 1492W x 6 h = 8952 Wh =8.952 kWh

$$\mathrm{Apv} = \frac{\mathrm{EL}}{\mathrm{H} \times \eta_{pv} \times \eta_{inv} \times \mathrm{T_c}}$$

$$\mathrm{Apv} = \frac{8.952}{5.6 \times 0.90 \times 0.90 \times 0.21} = 9.4\ m^2$$

$$\mathrm{P_{pv}} = \mathrm{A_{PV}} \times \mathrm{Hsc} \times \eta_{PV}$$

$$\mathrm{P_{pv}} = 9.4 \times 1000 \times 0.21 = 1974\ \mathrm{W}$$

$$\mathrm{N_m} = \frac{P_{PV}}{\mathrm{P_m}}$$

The number of modules (Nm)= 1974 W / 333 W = 5.93 = 6 Modules

3.2.5. Cost Analysis

Table (4) shows the detailed and total costs of designing a solar unit for pumping irrigation water in Kafr El Sheikh Governorate for small holdings not exceeding 2 acres (8400 square meters), which is slightly less than the costs of the unit designed for Giza Governorate, as the total costs for Kafr El Sheikh Governorate amounted to $4337.5 due to the low motor capacity to only 2 horsepower.

Table 4. The cost analysis for the solar water pumping system according to 2021 prices .

		Components	Quantity	Unit price, ($)	Total price ($)
$C_{capital}$	Capital Cost	PV module 333 W	6	80	480
		Controller	1	45	45
		Inverter (2 kW)	1	160	160
		Installations	1	95	95
		Mobile Metallic frame	1	1100	1100
		Hydraulic system	1	350	350
		Water Pump (2 hp)	1	200	200
		Total			2430
		Inflation Rate			5%
		Capital Cost with inflation Rate			2551.5
$C_{O\&M}$	O&M Cost	Operation and maintenance costs for 20 years	20	40	800
C_{rep}	Replacement Cost	Replacement of pump and inverter	2	240	480
C_s	Salvage Value	Salvage Value = 20% from Capital Cost	1	506	506
LCC	Life Cycle Cost LCC)	Life Cycle Cost (LCC)			4337.5

3.3. Specifications for a solar-powered water pumping unit in Assiut Governorate: Using PV_{SYST} Model to determine the best tilt angle and direction for the solar panels.

The most important and most cultivated crops (Sugarcane crop) in Assiut Governorate and the irrigation systems applied (Furrow Surface Irrigation) by small-scale farmers in Kafr El-Sheikh Governorate were identified, as well as the most appropriate technical specifications for providing a mobile irrigation water pumping unit that is operated by solar energy as shown as in Figure (17).

3.3.1. Water flow rate (Q)

To determine the irrigation pump flow rate in the Assiut Governorate, it was necessary to determine some important information related to the crops with the highest water consumption during the summer season. The maximum water requirements of the highest water-consuming crop during the summer season must be determined, i.e., the highest crop coefficient, as well as the highest reference evaporation rate. The maximum solar intensity must also be determined. The minimum area owned by most farmers was approximately 2 Feddan (8400 m^2). The most commonly used irrigation system was the surface irrigation system with gated pipe.

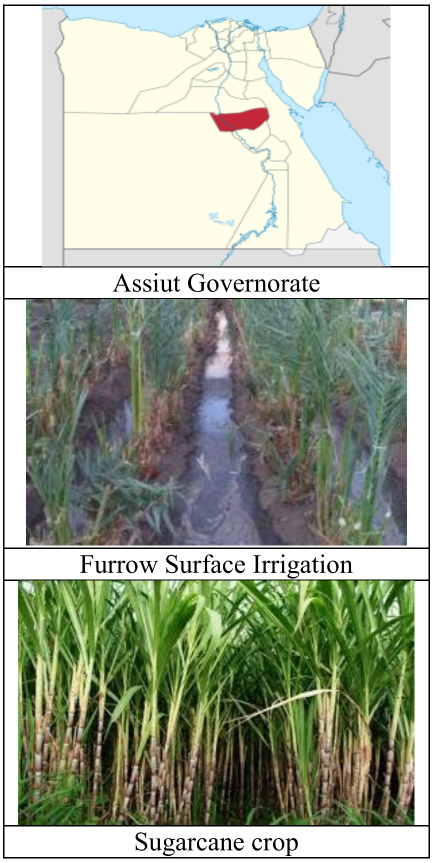


Fig. 17. Determining the highest water-consuming crop (Sugarcane) in Assiut, along with the type of irrigation used in Assiut Governorate.

The research identified corn as the summer crop with the highest water demand in Giza Governorate. The maximum value of the sugar-cane crop coefficient was determined from the FAO 56, while the maximum reference evaporation rate was determined from the Central Climate Laboratory. The following data was determined to estimate the required flow rate for the irrigation pump, which will be powered by solar energy.

$$Q \times T = (A \times D_{Max.} \times F)/\ \eta$$
$$D_{Max.} = ET_{C\ Max.} = ETo_{Max.} \times Kc_{Max.}$$

Where:

Q (Water flow rate) = ? m^3/h

T (Irrigation time) = 1 day = 6 h.; A (Area to be irrigated) = 8400 m^2 = 2 Feddan

$D_{Max.}$ (Maximum depth of irrigation water required to be added), mm/day

$ET_{C\ Max}$ (Maximum evapotranspiration of maize plants, mm/day
$ETo_{Max.}$ (Maximum reference evapotranspiration during summer) = 10.5 mm/day
Kc_{Max} (The highest value of the sugar-cane crop coefficient is during the summer) = 1.25 (FAO56)
F (Irrigation frequency) = 1 day; η (Irrigation efficiency for surface irrigation by gated pipe) = 60%.

$$Q \times 6 = (8400 \times 0.013 \times 1)/0.6$$
$$Q = 30.33\ m^3/h$$

3.3.2. Design of electric motor power

After calculating the irrigation pump's flow rate, the next step is to calculate the electric motor's power. To calculate the electric motor's power, you must also calculate the total hydraulic head (T.D.H.), the pump's hydraulic power, and the pump's efficiency P_h.

Considering the design parameters as follows: Q = 30.33 m^3/h = 0.008425 m^3/s; ρ (Water density) = 1000 kg/m^3; g (Gravitational Acceleration) = 9.81, m/s^2; T.D.H = 19 m

The pump hydraulic power (P_h) in Watts can be calculated as follows:

$$P_h = Q\, \rho_w\, g\, TDH$$

$$P_h = 0.008425\ x\ 1000\ x\ 9.81\ x\ 19 = 1570.34\ W$$

The electric motor power is equal to the hydraulic pump required power divided by the pump efficiency, η (consider the pump-motor efficiency = 0.80)

$$P_{elec} = \frac{P_h}{\eta}$$

$$P_{elec} = \frac{1570.34}{0.80} = 1962.93\ W = 2.63\ hp = 3\ hp$$

3.3.3. Determine the best tilt angle and orientation angle for solar panels to receive the highest solar radiation values during the summer and winter seasons using the PV_{SYST} Model

Due to the high accuracy of the simulation program, it was relied upon to determine the most appropriate tilt angle for the solar panels and the most appropriate azimuth angle during the summer and winter seasons. The actual value of the maximum solar radiation intensity falling on the solar panels was then measured.

Figure (18) shows the most appropriate tilt angle for the solar panels, which was 15 degrees at the azimuth angle of zero degree during the summer, when the highest radiation intensity falling on the solar panels was 6.5 $kWh/m^2/day$. Figure (19) shows the most appropriate tilt angle for the solar panels, which was 45 degrees at the azimuth angle of zero degree during the winter, when the highest solar radiation intensity falling on the solar panels was 5.91 $kWh/m^2/day$.

Figure (20) and Figure (21) illustrate the method of installing solar panels on agricultural land that needs to be irrigated using solar energy. Figure 20 shows the variable position of the solar panels, where the farmer can change the tilt of the panels to suit the season. Figure 21 shows the fixed position of the solar panels at a constant tilt angle (28 degree) throughout the year. The fixed position of the solar panels is the best, although it does not achieve the highest intensity of solar radiation falling on them. However, it is characterized by stability and safety throughout the year. In addition, the difference between it and the variable position is insignificant in the value of the intensity of light falling on the solar panels.

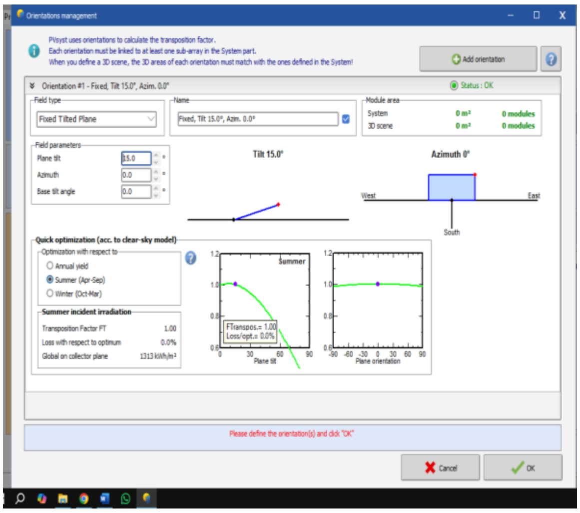


Fig. 18. Modeling the most suitable tilt angle and azimuth angle for solar panels in summer season.

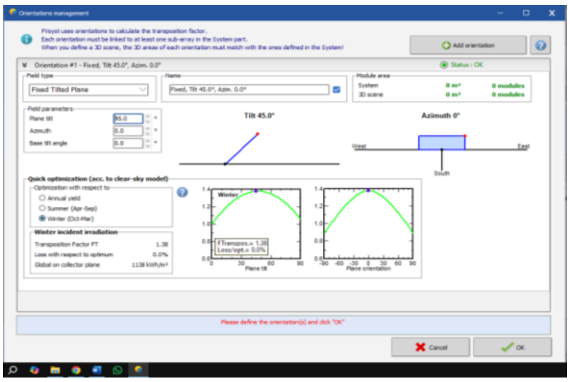


Fig. 19. Modeling the most suitable tilt angle and azimuth angle for solar panels in winter season.

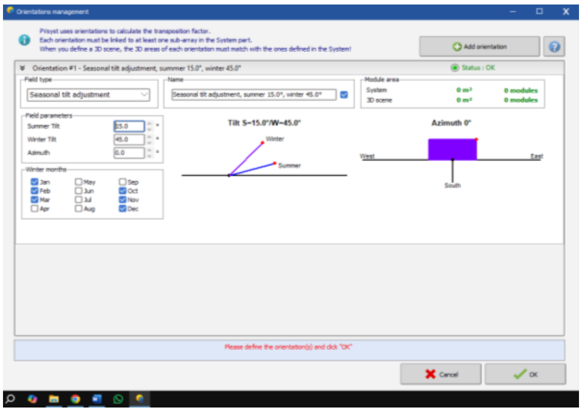


Fig. 20. Seasonal tilt adjustment according to summer season and winter season.

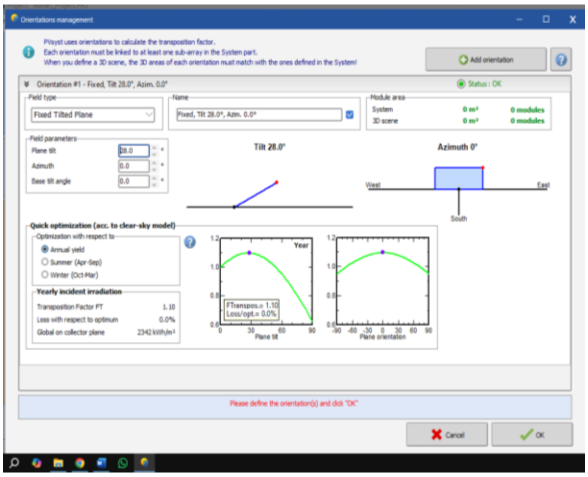


Fig. 21. Fixed tilted plane during annual yield.

3.3.4. System Sizing Calculation

Electric motor power = 3 hp = 3 x 746= 2238 W
Daily electric energy consumed, (EL) = 2238 W x 6 h = 13428 Wh =13.428 kWh

$$\text{Apv} = \frac{\text{EL}}{\text{H} \times \eta_{pv} \times \eta_{inv} \times \text{T}_c}$$

$$\text{Apv} = \frac{13.428}{6.5 \times 0.90 \times 0.90 \times 0.21} = 12.145\ m^2$$

$$\text{P}_{pv} = \text{A}_{PV} \times \text{Hsc} \times \eta_{PV}$$

$$\text{P}_{pv} = 12.145 \times 1000 \times 0.21 = 2550.45\ \text{W}$$

$$\text{N}_m = \frac{\text{P}_{PV}}{\text{P}_m}$$

The number of modules (Nm)= 2550.45 W / 333 W = 7.659 = 8 Modules

3.3.5. Cost Analysis

Table (5) shows the detailed and total costs for designing a solar unit for pumping irrigation water in Assiut Governorate for small holdings with an area not exceeding 2 acres (8400 square meters), where the total costs for Assiut Governorate amounted to 4663 US dollars to increase the number of solar modules and increase the horsepower of the engine to 3 horsepower.

Table 5. The cost analysis for the solar water pumping system according to 2021 prices .

		Components	**Quantity**	**Unit price ($)**	**Total price ($)**
$C_{capital}$	Capital Cost	PV module 333 W	8	80	640
		Controller	1	45	45
		Inverter (2 kW)	1	160	160
		Installations	1	95	95
		Mobile Metallic frame	1	1100	1100
		Hydraulic system	1	350	350
		Water Pump (3 hp)	1	350	350
		Total			2740
		Inflation Rate			5%
		Capital Cost with inflation Rate			2877
$C_{O\&M}$	O&M Cost	Operation and maintenance costs for 20 years	20	40	800
C_{rep}	Replacement Cost	Replacement of pump and inverter	2	240	480
C_s	Salvage Value	Salvage Value = 20% from Capital Cost	1	506	506
LCC	Life Cycle Cost ,(LCC)	Life Cycle Cost (LCC)			4663

Conclusions

The rising cost of conventional electricity sources has led to a general and urgent shift toward the design and installation of mobile solar-powered irrigation pumping units as a sustainable alternative to diesel-powered irrigation pumping units. To achieve the highest possible performance of solar-powered irrigation pumping units, this pilot project was conducted in three different locations in Egypt: Kafr El-Sheikh Governorate for rice irrigation, Giza Governorate for corn irrigation, and Assiut Governorate for sugarcane irrigation.

The study concluded that:

1. To achieve the highest performance for a mobile solar-powered irrigation water pumping unit, the

azimuth angle of the solar panels should be southward and equal to zero. This was confirmed by the actual results measured at the three experimental sites in this study, the results of simulation modeling, and previous studies.

2. The results indicated a non-significant difference between the measured solar panel tilt angle and the results of the simulation models, especially when choosing a fixed angle throughout the agricultural seasons for irrigating the selected crops.

3. The most suitable tilt angle for the solar panels, which was fixed throughout the year, was 29 degree in Kafr El-Sheikh Governorate, 26 degree in Giza Governorate, and 28 degree in Assiut Governorate.

4. The study was based on daily irrigation. However, if there is a period between irrigations, a reservoir must be built for this purpose, as the cost would be very high if the period between irrigations were included and the lack of a reservoir was absent.

5. The cost is very economical for small holdings of no more than two acres, spread over twenty years, with the possibility of cooperation between farmers to establish a single unit serving more than one farm.

6 - In all cases, to increase the safety factor, it is necessary to have a backup diesel-powered water pumping unit in case of a malfunction in the mobile pumping unit that operates on solar energy.

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