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Design and Economic Evaluation of a Photovoltaic Water Pumping System for Tomato Irrigation in El Oued, Algeria

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Abstract – *This paper explores the design, economic assessment, and operation of a photovoltaic water pumping system for irrigating tomatoes in Terifaoui, El Oued, Algeria. Terifaoui's desert climate and lack of grid access make it a suitable candidate for a solar-powered irrigation system. The system design, simulated using PV_{syst} software, considers El Oued's climate to ensure reliable operation. This study examines the technology, economics, and operational aspects of the system, highlighting its potential to boost agricultural output and regional economic resilience.*

Keywords: Photovoltaic, Renewable Energy, Solar-powered Sustainable, Water management.

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I. Introduction

The efficiency and effectiveness of photovoltaic (PV) systems under various conditions are well studied in research. They include analyzes of grid-connected rooftop photovoltaic systems, demonstrating the impact of optimal system design and orientation on energy efficiency. It also evaluates the performance of solar panels at different tilt angles, finding that tighter tilts are more efficient. Additionally, the group is exploring how high temperatures in desert environments affect the production of photovoltaic panels, showing significant degradation in performance. Finally, it evaluates hybrid photovoltaic/thermal (PV/T) systems, comparing different working fluids to determine which provides the best thermal and electrical efficiency [1-4].

Water is a fundamental resource essential for both human and plant life. According to NASA, every living organism on Earth depends on water for survival, from the smallest microorganisms to the largest mammals. Due to the critical importance of water and the challenges in transporting it from its source to the required destination, pumps were invented to move fluids using mechanical action, which converts electrical energy into hydraulic energy. Various techniques are used to supply the electricity needed to operate these pumps, including grid energy, generators, and even renewable energy sources [5,6].

In recent years, renewable energy has become an increasingly viable solution due to high energy prices and the decreasing costs of renewables, particularly solar PV technologies [7]. These technologies provide rural residents and farmers with environmentally friendly power sources for water pumping, offering clear competitive advantages over traditional fuel-driven generators [8]. Given the large amounts of water demanded, especially during the summer season, solar water pumping has significant potential in the agricultural sector in Lebanon. However, it remains uncommon among farmers and others involved in agriculture. Fewer than 30 projects have been implemented in Lebanon, with over 80% initiated by technology providers rather than the farmers themselves. This indicates a lack of awareness among users and highlights the need for increased efforts and incentives to make it a viable and practical solution [9].

The photovoltaic system for water pumping offers easy assembly, low maintenance and noise-free operation. This article discusses the design and control of a photovoltaic system connected to a three-phase voltage source inverter (VSI) and a motor-pump assembly, with emphasis on the effectiveness of predictive control of the assembly model finished (FS-MPC). A modified incremental conductance (InC) algorithm with flow power control optimizes power extraction and regulates flow rates. Additionally, a high gain observer (HGO) estimates mechanical and magnetic states using stator currents and control voltage. The simulation results confirm the robustness and efficiency of the system at different sunlight levels [10]. A work evaluated an integrated photovoltaic (PV) and water pumping system using Finite Set Model Predictive Control (FS-MPC) and Dead Beat Predictive Control (DB-MPC) under different insolation levels (1 000 W/m² to 700 W/m²). At 1000 W/m², the system quickly achieves maximum power point tracking (MPPT) in 0.2 seconds, with DB-MPC exhibiting faster response times than conventional methods. The high-gain interconnected observer accurately estimates motor speed, ensuring the rotor matches the desired speed. Even when sunlight drops to 700 W/m², the system maintains stability, thanks to the Incremental Conductance (InC) algorithm adjusting the photovoltaic field and output power to 2,204 W at 60% throughput. These results confirm the effectiveness of the proposed control strategies to optimize the photovoltaic water pumping system for sustainable energy applications [11].

The novelty of this work lies in its comprehensive approach to designing and optimizing a photovoltaic water pumping system specifically for tomato irrigation in El Oued, Algeria. By utilizing advanced simulation tools and conducting a detailed economic analysis, the study addresses the unique challenges posed by the desert climate and remote location, ensuring the system's efficiency and sustainability. The integration of careful component selection, loss minimization, and system configuration tailored to local conditions provides valuable insights into the practical implementation and financial viability of solar-powered irrigation in similar environments.

II. Methodology and Experimental details

II.1. Project overview

In the arid region of El Oued in Algeria, classified among vast agricultural landscapes, lies a beacon of sustainable innovation: a photovoltaic (PV) water pumping system designed to irrigate tomato crops in isolated farmlands. This project stands as a testament to the transformative power of renewable energy in addressing water scarcity and fostering agricultural productivity in remote areas.

Driven by the region's favorable climatic conditions and strategic geographical location, the project meticulously selected a site with immense agricultural potential. The chosen farm, encompassing a sprawling expanse, employs a solar-powered pumping system to provide life-sustaining water to one hectare of plastic greenhouses dedicated to tomato cultivation.

El Oued's climate, characterized by high temperatures and significant solar irradiation, presents an ideal setting for harnessing solar energy. The system's meticulous design hinges on a comprehensive assessment of water requirements, meticulously calculated based on the region's evapotranspiration potential and the specific needs of tomato crops. To ensure the irrigation system's autonomy, a 1000 m3 reservoir serves as a crucial water storage facility.

Leveraging the power of PVsyst software, the project team meticulously simulated and optimized the photovoltaic system, meticulously factoring in the site's unique characteristics and local weather patterns as (depicted in figure.1). To maximize energy efficiency, the optimal orientation of solar panels was determined based on the site's latitude.

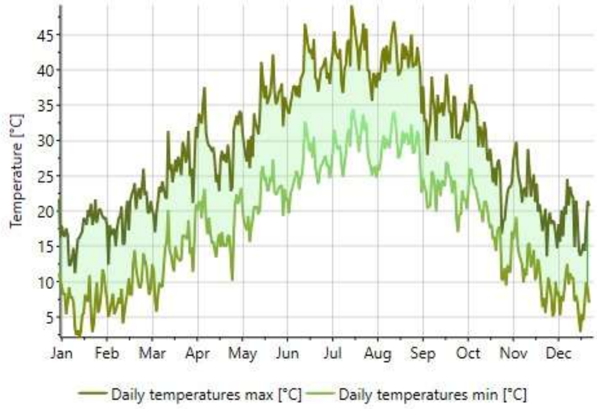
The heart of the pumping system lies in a specialized submersible pump, powered by the PV panels, meticulously designed to meet the farm's water needs. The required hydraulic power was carefully calculated based on the desired flow rate and total hydraulic head. The solar panels were meticulously sized to provide the necessary power to the pump throughout the day.

This project stands as a compelling narrative of the transformative potential of PV technology in agriculture. By harnessing the sun's abundant energy, the system not only addresses water scarcity challenges but also contributes to environmental sustainability and food security in the El Oued region. The project serves as an inspiring model for replicating sustainable agricultural practices in arid and remote areas worldwide.

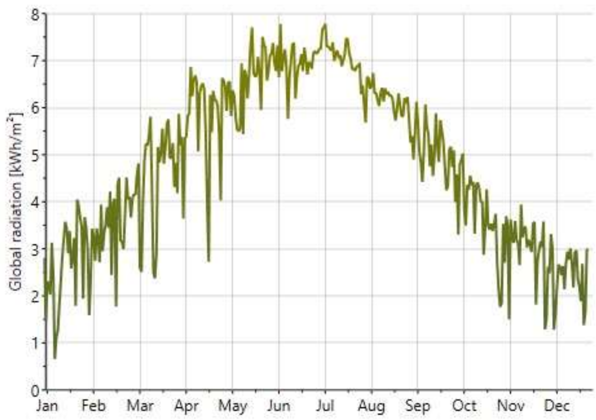
Figure 1. Project location

II.2. Annual climate averages for the el oued's region

As it shown in Figure.1, El Oued, displays a hot desert climate throughout the year. The average weather annual data of the designed site are extracted using Météonorme 8. This may include information such as temperature average, solar irradiation, wind speed, etc. Figure 1 shows also the monthly temperature and radiation of the farm lizerg region obtained by méténorme 8 software.



(a)



(b)

Figure 2. Variation of monthly temperature and solar radiation

II.3. Sizing of case studies

The required hydraulic power depends on the system's design flow rate (Q in m³/s) and hydraulic head (H in m). This power can be expressed by the following formula

$$P_h = \rho . g. Q. H \quad (1)$$

where ρ represents the density of water (kg/m³) and g is the acceleration due to gravity (m/s²). The design flow rate (Q) and hydraulic head (H) are expressed as

$$Q = \frac{1}{n_s} \sum_{i=1}^{5} W_{Ni} \quad (2)$$

Here, W_{Ni} represents the daily water requirements of one hectare of tomato farm (m³/day), and n_s is the average number of sunny hours per day in the study region. The hydraulic head consists of three main terms:

$$H = H_s + H_{dd} + H_f \quad (3)$$

Where H_s is the static head representing the difference between the water level and the discharge level. H_{dd} is the drawdown level of water, while H_f represents friction losses in the hydraulic circuit. In this communication, the sum of static head and drawdown level is considered as 39 m.

II.4. Choice of pump model

The operating point of the pump can be determined graphically by following several steps. First, the characteristic curve of the hydraulic circuit is plotted by calculating the theoretical hydraulic head for various volumetric flow rates. Next, the pump characteristic curve is plotted, typically provided by the pump manufacturer in the form of Equation. . Finally, the intersection point, which corresponds to the operating condition being examined, is identified.

$$F (Q, H, U_P, I_p) = 0 \quad (4)$$

Here, U_p represents the applied voltage to the pump and I_p the current applied to it. Based on information from the Lawara catalog, the submersible pump type 16GS40 appears to meet our needs, displaying an hourly flow rate of 22 m³/h, a total dynamic head of 75 m, and a rated power of 3709 W. The technical specifications of both the motor pump and the controller are detailed in Figure 3 and Figure 4.

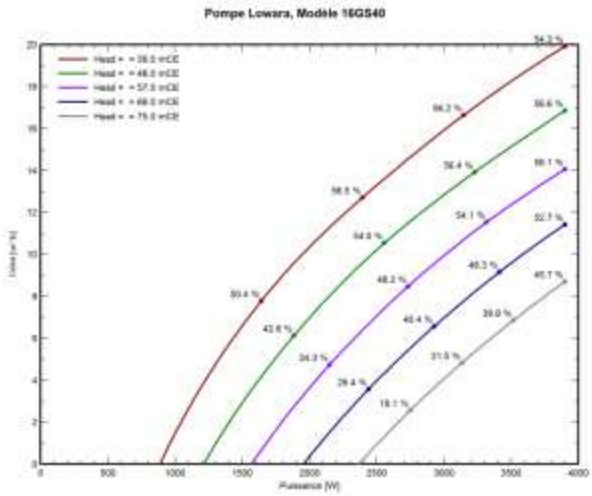


Figure 3. Flow rate as a function of power

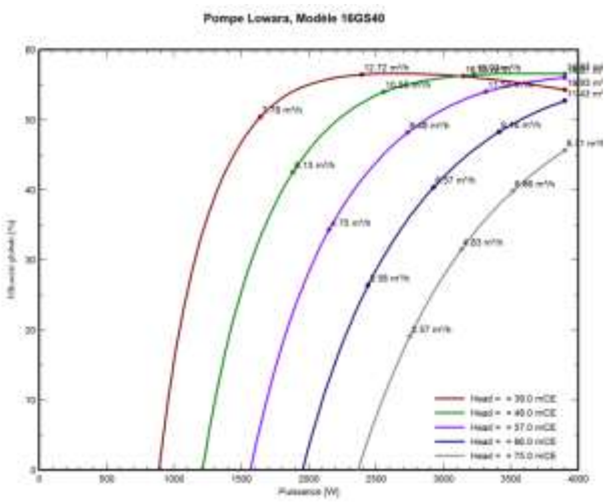


Figure 4. Overall efficiency as a function of power

II.5. Sizing of photovoltaic (pv) panels

The PV modules generate direct current (DC) power to supply an AC motor and drive the pump. The required electrical rated capacity (CR) can be expressed as follows:

$$CR = \frac{\eta_p \times \eta_m \times \eta_{sys} \times P_h}{h_p} \quad (5)$$

Where η_p is the pump efficiency, η_m is the motor efficiency, η_{sys} is the pumping system efficiency, P_h is the hydraulic power, and h_p is the daily irrigation period.

The PV power at Standard Test Conditions (STC) should slightly exceed the rated power of the pump. It should be noted that when using a DC-AC MPPT regulator, the PV solar capacity may be reduced compared to direct coupling configuration.

Various technologies are available for photovoltaic (PV) modules. The sizing of these modules depends on several criteria, such as the electrical requirements of the installation and choosing a technology that aims to minimize battery usage while avoiding energy shortage. As illustrated in Figure 5, the module selected for this study is the Jinkosolar.

Figure 5. Selection of PV Arrays

II.6. Choice of Inverter

The Maximum Power Point Tracking (MPPT) is widely employed in photovoltaic technology as a predominant regulator [12]. Figure.8 presents the specific electrical characteristics of this regulator. This illustration suggests that the control device used is a generic model, but it has been specifically tailored to the photovoltaic system it belongs to. Optimization implies that it has been designed to interact efficiently with the associated components and configurations.

The system configuration includes an MPPT-AC inverter (Maximum Power Point Tracking - DC to AC conversion), playing a crucial role in optimizing the energy production from solar panels. The reference to an AC inverter also indicates that the system likely converts the energy generated in DC by the solar panels into AC, suitable for use with AC electric motors or within premises as shown in Figure 6.

Figure 6. Characteristics of the MPPT Inverter

II.7. Water storage

The storage volume heavily depends on the total daily water demand and the required autonomy (Au in days), assuming no production, it can be expressed as:

$$V_s = \sum_i W_i \cdot A_u \qquad (6)$$

Where W_i represents the daily water demand for each component of the system.

The pumping technique selected for our study is known as "solar-powered pumping." The hydraulic reservoir is used to store water, and the choice of its capacity is crucial to meet water needs during autonomous periods. We have sized the reservoir for a four-day autonomy period, with a height of 3.1 meters. Thus, the resulting reservoir has a usable capacity of 100 m³.

III. Simulation results

III.1. Distant shadows

Figure 7 illustrates the sun's path throughout the day across various months of the year, detailing both azimuth (the angle relative to the south, measured negatively towards the east) and solar elevation (the angle between the sun and the horizontal plane of the location) at each hour. The term "distant shading" refers to objects such as structures, trees, or hills located at a distance from the site that cast shadows.

In the context of photovoltaic installations, distant shading can significantly affect solar panel performance by reducing the amount of direct sunlight they receive. It is therefore essential to consider these factors during the design and placement of solar panels to minimize their impact on energy production. Advanced modeling tools can assess the potential impact of distant shading and optimize the orientation and arrangement of solar panels accordingly. It's important to note that this simulation does not account for specific shading instances.

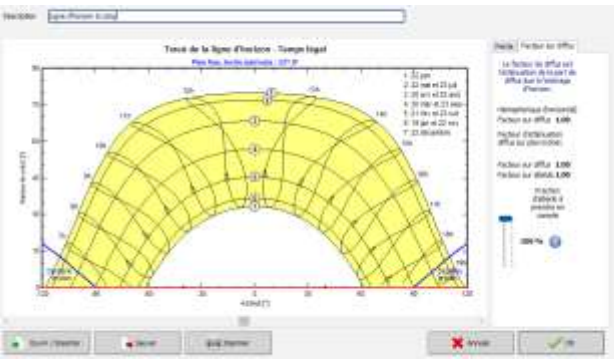


Figure 7. Sun Path Diagram

III.2. Simulation report

Figure 8 below provides the following information:

PV Field: Comprising eight modules in series forming two strings, totaling 16 modules, with a total area of 35 m² and a power of 5 kWc at 50°C (under operating conditions).

- Loss Factors: A detailed list of various system losses, which will be examined in more detail in the following figure. Each parameter has specific significance and importance in our study.
- Water Needs: The average daily consumption of the pumps is 52.08 m³/day.
- Regulator: An MPPT regulator with a maximum efficiency of 96%.

The normalized system forecasts (post-storage: Yf) include the equivalent losses in the photovoltaic field (Lc), the storage system (Ls), and the unused energy (Lu). The losses in the solar energy collection process amount to 0.93 kWh/day, while the system losses are approximately 1.05 kWh/day. Ultimately, the energy produced at the pump output reaches 3.37 kWh/day.

During the summer season, energy consumption is generally reduced, while in winter, it tends to increase. From January to February and from November to December, solar collection losses and system losses were minimal but saw an increase during the other months of the year. Notably, during the summer, losses related to module quality are more frequent. This observation is understandable given the higher temperatures during this period of the year. The performance ratio (PR), as illustrated in Figure 9, represents the overall efficiency of the system. It is calculated by dividing the actual yield by the nominal yield of the system.

Figure 8. Simulation Parameter Analysis

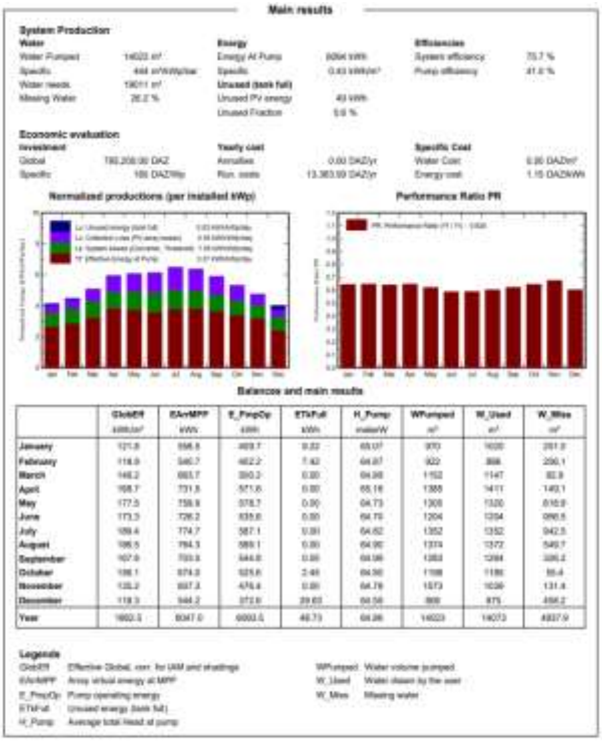


Figure 9. Summary of Main Finding

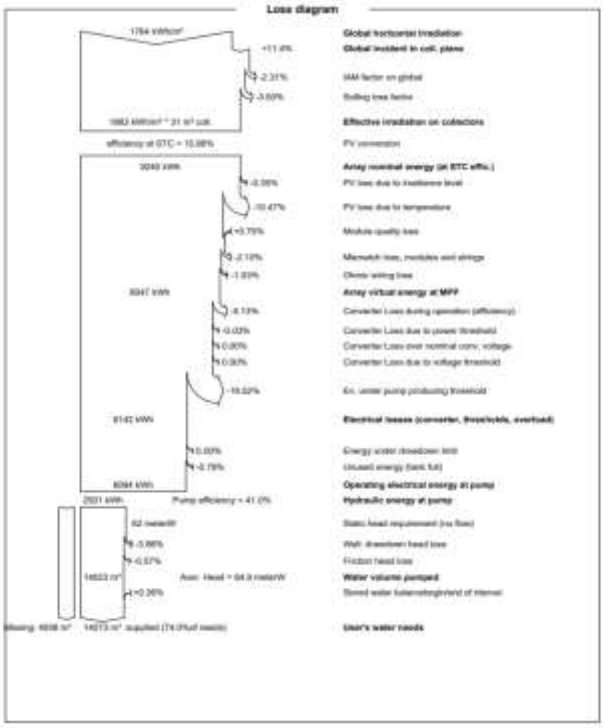


Figure 10. Annual Loss Diagram

III.3. Loss diagram

The initiation of the simulation provides access to the detailed results of our photovoltaic system design, which has a capacity of 1764 Wc at a temperature of 50°C.

The various energy losses are observed in the photovoltaic system. These significant losses are due to the system's exposure to various degradation factors, which are represented as loss factors, as shown in Figure 10:

1. Losses at the photovoltaic fields:
    - Temperature
    - Module quality
    - Resistance, and others
2. Overall losses at the inverter level.
3. Losses related to the storage system.
4. Losses related to usage, particularly the pump with the storage system (reservoir).

The analysis of the loss diagram over the entire year reveals that the global incident irradiation cannot be fully exploited due to the various factors and losses in different parts of the system. Consequently, the total amount of energy obtained is 6094 kWh. These results highlight the importance of considering and minimizing these losses to optimize the overall efficiency of the photovoltaic system

III.4. Performance evaluation

According to the configuration, the energy and economic analysis of the designed PVWP system should be conducted based on simulation data. The economic analysis aims to thoroughly evaluate the total cost associated with implementing the photovoltaic pumping system that operates on solar energy. This economic estimate is meticulously configured within PV_{syst} and incorporates the individual costs of each component used in the studied system. Consequently, an automated calculation process is initiated, generating a detailed display as shown in Figure 11. This visual representation provides a comprehensive view of the costs incurred for each component, thus offering a solid basis for the overall economic evaluation of the project. It is essential to emphasize that this approach is part of a genuine financial analysis specific to this project.

Figure 11 presents a comprehensive assessment of the costs associated with the installation components, amounting to approximately 795,200.00 DAZ, excluding annual maintenance labor costs.

Based on the data in Figure 11, it is clear that the energy production by the photovoltaic panel is directly linked to the incident energy, thus ensuring the satisfaction of the energy needs of the residence throughout the year. The results indicate that the pump energy is evaluated at 6094 kWh/kW/year. This production exceeds the total energy need of the residence, set at 49 kWh/year.

Cost of the system

Installation costs

Item	Quantity units	Cost DAZ	Total DAZ
PV modules			
JKM 315PP-72 (Plus)	16	18,000.00	288,000.00
Supports for modules	16	5,000.00	80,000.00
Pumps			98,300.00
Controllers			93,000.00
Tank			22,500.00
Hydraulic circuit	250	180.00	45,000.00
Other components			
Accessories, fasteners	10	800.00	8,000.00
Wiring	150	240.00	36,000.00
Combiner box	2	2,050.00	4,100.00
Studies and analysis			
Engineering	2	50,000.00	100,000.00
Installation			
Global installation cost per module	16	200.00	3,200.00
Global installation cost per inverter	1	600.00	600.00
Transport	1	15,000.00	15,000.00
Total			795,200.00
Depreciable asset			566,800.00

Operating costs

Item	Total DAZ/year
Maintenance	
Cleaning	2,000.00
Total (OPEX)	2,000.00
Including inflation (5.00%)	3,819.17

System summary - Water and Energy cost

Total installation cost	795,200.00 DAZ
Operating costs (incl. inflation 5.00%/year)	3,819.17 DAZ/year
Energy used for pumping	8084 kWh/year
Excess energy (tank full)	48.7 kWh/year
Water Pumped	14023 m³
Cost of pumped water	15.4 DAZ/m³

Figure 11. Economic evaluation

IV. Conclusion

This article explored two approaches, namely analysis and graphical method, for the design of photovoltaic pumping systems. These approaches aim to develop a system meeting the irrigation requirements in the liquefied zone. The process mainly relies on assessing water needs, calculating the required hydraulic power, identifying the available solar energy, and finally, selecting the appropriate components. In summary, this article offers a summary of the results of the study, integrates the observations from the experiment, and presents conclusions resulting from the techno-economic analysis. This information could also serve as a basis for future recommendations and proposals for improvements with a view to more efficient and sustainable operation of the system.

Declaration

- The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.
- The authors declare that this article has not been published before and is not in the process of being published in any other journal.
- The authors confirmed that the paper was free of plagiarism.

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