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Review Article

Optimization of Solar Water Pumping Systems for Agricultural Irrigation: Comparative Analysis and Design of an Ideal Solution

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Abstract

This study details the optimal characteristics of these systems to design an ideal pumping solution that maximizes agricultural productivity while reducing costs and ecological footprint. The designed system is an off-grid solar pump control device equipped with an MPPT controller for 24V DC photovoltaic panels operating within a 30-48V range. This system operates directly under solar irradiation, eliminating the need for energy storage. A major innovation of this system is its ability to regulate the filling of the water tank based on the measured water flow. When sensors detect low flow, the system automatically activates the water tank recharge and stops its activity when the flow reaches a predetermined threshold, thus optimizing the efficiency of water use for irrigation. The advanced architecture of the system integrates controllers capable of compensating for solar power fluctuations and intelligent sensors to automate the pumping process according to crop water needs. This systemic approach offers a robust and sustainable method to improve water management in agricultural operations, contributing to sustainable development goals and resilience to climate change.

Keywords: Solar Water Pumping Systems, Environmental Impact, Agricultural Irrigation, Climate Resilience.

I. INTRODUCTION

In arid and semi-arid regions, agriculture faces numerous challenges exacerbated by climate variability and climate change. These areas, characterized by a chronic lack of water, heavily depend on irrigation systems that are often inefficient and costly. These challenges are particularly acute in Africa, where food insecurity and water resource degradation pose serious threats to sustainable development and the socio-economic stability of communities (Mekonnen & Hoekstra 2016; Rockström *et al.*, 2010).

Agricultural irrigation in these regions has traditionally relied on fossil fuels, leading to high costs and significant environmental impacts, notably greenhouse gas emissions. Additionally, traditional irrigation systems are often inefficient, with substantial water losses due to evaporation and misalignment of irrigation periods with actual crop needs (Barron *et al.*, 2013).

Solar water pumping systems represent a promising solution to these challenges. Utilizing solar energy, an abundant, renewable, and largely underutilized resource, especially in Africa, these systems offer an ecological and economical alternative. Unlike conventional methods, solar water pumping systems do not use fossil fuels and, in their most ecological form, avoid the use of batteries for energy storage, further reducing their environmental impact and associated costs (Kumar & Kandpal 2015; Li *et al.*, 2023).

Solar pumping technology is particularly suited for irrigation due to its ability to provide water directly in response to solar availability, which often corresponds to the periods of highest water demand by crops. This synchronization optimizes energy efficiency and improves water resource management. Battery-less solar pumping systems maximize the use of direct solar energy through Maximum Power Point Tracking (MPPT), which adjusts the pump load to maximize the use of available energy, offering a particularly sustainable and efficient solution (Fonteh 2017; Rodriquez *et al*., 2020).

Recent analyses indicate that these systems can significantly reduce operational costs compared to thermal systems, with savings up to 75% on fuel and maintenance costs (Mekonnen & Hoekstra 2016). Moreover, the automation of pumping processes based on solar availability cycles and water needs contributes to more rational water use, reducing losses and increasing irrigation efficiency (Serote *et al*., 2023).

However, the decision to choose between a system with or without batteries depends on several factors, including solar irradiation variability, water demand patterns, and initial economic considerations. Batteries can offer greater flexibility and autonomy but introduce additional costs and environmental concerns related to their production, use, and end-of-life (Schäfer *et al*., 2018).

This study aims to comparatively analyze these systems against traditional options and design an optimal solution based on the results of this analysis (Kumar & Kandpal 2015; Fonteh 2017; Serote *et al.*, 2023).

II. Comparative Analysis of Pumping Systems

The adoption of solar water pumping systems for agricultural irrigation in arid and semi-arid regions presents a major opportunity to improve water resource efficiency while minimizing environmental impacts and associated costs. This section provides a detailed comparative analysis of the three main pumping systems: solar systems without batteries, solar systems with batteries, and thermal gasoline systems, focusing on aspects of energy efficiency, maintenance costs, and environmental and social impacts.

1. Battery-less Solar Pumping Systems

Characteristics and Advantages

a) Energy and Operational Efficiency. These systems maximize the direct use of solar energy through Maximum Power Point Tracking (MPPT), which dynamically adjusts the pump load to best exploit the available solar energy. The simplicity of these systems reduces energy losses, with efficiency rates reaching up to 85% under optimal conditions.
b) Maintenance and Operational Costs. Very low, mainly for cleaning solar panels and periodic pump maintenance, estimated at about $20 per year. No battery replacement or fuel costs, significantly reducing long-term operational expenses.
c) Environmental Impact. Minimal, with no CO2 emissions and no battery waste, contributing significantly to environmental sustainability. Use of renewable energy decreases the ecological footprint of irrigated agriculture.
d) Social Impact. Very positive, as these systems improve water access without increasing costs for local communities. Ease of maintenance and the absence of dependence on fossil fuels or batteries enhance the autonomy of farmers and the resilience of rural communities.

Costs and Disadvantages

Dependence on Solar Irradiation: their performance is directly linked to sun availability, which can be a challenge during periods of low sunlight or cloudy days. This factor requires careful water resource management, especially in areas with significant climatic variations.

2. Systèmes de Pompage Solaire Avec Batteries

Characteristics and Advantages

a) Autonomy and Flexibility. Batteries allow solar energy storage, enabling pumping even in the absence of direct sunlight, and ensuring a more regular and reliable water supply. This feature is particularly useful for crops requiring regular and precise watering, regardless of daily sunlight variations.
b) Adaptability to Variable Demands. Facilitates better water management by adjusting pumping to the specific needs of crops at different stages of their development. Batteries facilitate the integration of sensors and automated systems to optimize water usage based on weather conditions and soil moisture.

Costs and Disadvantages

a) Initial and Maintenance Costs. Higher due to the batteries, with initial costs potentially exceeding those of battery-less systems by 30-50%. Batteries require periodic replacement every 5 to 7 years, with replacement costs estimated at $600 for two batteries.
b) Environmental and Social Impact. More significant due to battery production and recycling, raising concerns related to material extraction and waste management. Environmental and social issues arise concerning the extraction of lithium, cobalt, and other minerals needed for batteries.

3. Thermal (Gasoline) Pumping Systems

Characteristics and Advantages

a) High Power and Flow Rate. Capable of pumping large quantities of water up to 45 m³/h, independent of solar conditions. Useful for large agricultural operations requiring rapid and large water supplies.
b) Robustness and Reliability. Less dependent on climatic conditions for operation, offering a reliable solution where sunlight is insufficient or highly variable.

Costs and Disadvantages

a) High Operational Costs. Fuel use entails continuous expenses, with operational costs significantly higher than solar systems, around $127.41 annually in fuel. Regular maintenance required for combustion engines increases costs and technical expertise needs.

b) Environmental Impact. CO2 emissions and other atmospheric pollutants contribute to climate change and air quality degradation. Use of non-renewable resources contradicts sustainable development principles.

c) Social Impact. Dependence on fossil fuels can increase farmers' economic vulnerability to oil price fluctuations. Noise pollution and hydrocarbon contamination risks affect the quality of life of local communities.

4. Conclusion of the Analysis

The detailed comparative analysis reveals that battery-less solar pumping systems are the most suitable for well-sunned regions, offering high efficiency, reduced operational costs, and minimal environmental and social impact. Systems with batteries, although initially more expensive, offer greater flexibility and better adaptability to variable water needs of crops. In contrast, thermal gasoline systems, despite their robustness and power, are the least recommended due to high operational costs, negative environmental impact, and unfavorable social implications.

III. Design of ideal solar water pumping

1. Design Pumping system

Building on the results of the previous comparative analysis, to maximize efficiency, minimize costs and reduce environmental impact in arid and semi-arid regions, particularly in Africa. The design of this optimal system takes into account technical, economic, environmental and social characteristics to meet the specific needs of users in these regions.

To develop an ideal solar water pumping system, several key criteria have been identified:

a) Maximum Energy Efficiency: Optimal use of solar energy to maximize water flow according to actual needs.

b) Minimized Total Cost in the Long Term: Includes initial costs, and reduced operational and maintenance costs.

c) Low and Easy Maintenance: Ensuring that the system is simple to maintain, with minimal costs and technical skills required.

d) Minimal Environmental Impact: Use of environmentally friendly technologies and practices.

e) Reliability and Autonomy: Capable of operating autonomously, with maximum reliability to meet water needs.

The pumping system mainly includes energy system, power system, control and detection system, water management system, and user interface. Each part is described in detail below.

Energy system

Solar without battery system is selected as the energy system because of its high efficiency, low maintenance, and lower environmental impact. This choice is strategic for areas with sufficient and regular solar irradiation, typical of the target regions. High-efficiency solar panels, optimized to capture solar energy even during low irradiation. designed to be robust and resistant to extreme climatic conditions in arid regions.

Power system

New generation DC 24V vertical water pump, chosen for its high efficiency and ability to operate under various flow conditions, up to 3.5 m³/h. Integration of an MPPT controller to adjust the pump speed and maximize the use of available solar energy, thereby improving the overall system efficiency.

Control and Monitoring System

Automation and Sensors are core components of the Control and Monitoring System. Use of water level, pressure, and flow sensors to automate pump operation, adjusting pumping according to actual needs.

Water management system

Storage Tank with capacity of 7.5 m³ is selected to store sufficient water during periods of solar peak, thus ensuring regular distribution throughout the day, even during peaks in demand.

User Interface

A user-friendly control system to easily monitor and adjust system parameters for optimal water management.

2. Design of the solar pumping system

The designed system is an off-grid solar pump controller equipped with an MPPT controller for 24V DC photovoltaic panels, operating in the range of 30-48V, the specific parameters are shown in Table I. This system operates directly under solar irradiation, eliminating the need for energy storage. A major innovation of this system is its ability to regulate the filling of the water tank according to the measured water flow. When the sensors detect a low flow, the system automatically activates the recharging of the water tank and ceases its activity when the flow reaches a pre-established threshold, thus optimizing the efficiency of water use for irrigation. The overall structure of the control system is shown in Fig 1. The circuit diagram of the control board is shown in Fig 2.

Table I: The specific parameters

Name	Value
Equipment	24v Solar Pump
Contrôller model	DC24V
Max Open Circuit Voltage	50V
MPPT Voltage Rage	30-48V
Solar panel Connection	450W

Fig 1: The overall structure of the control system

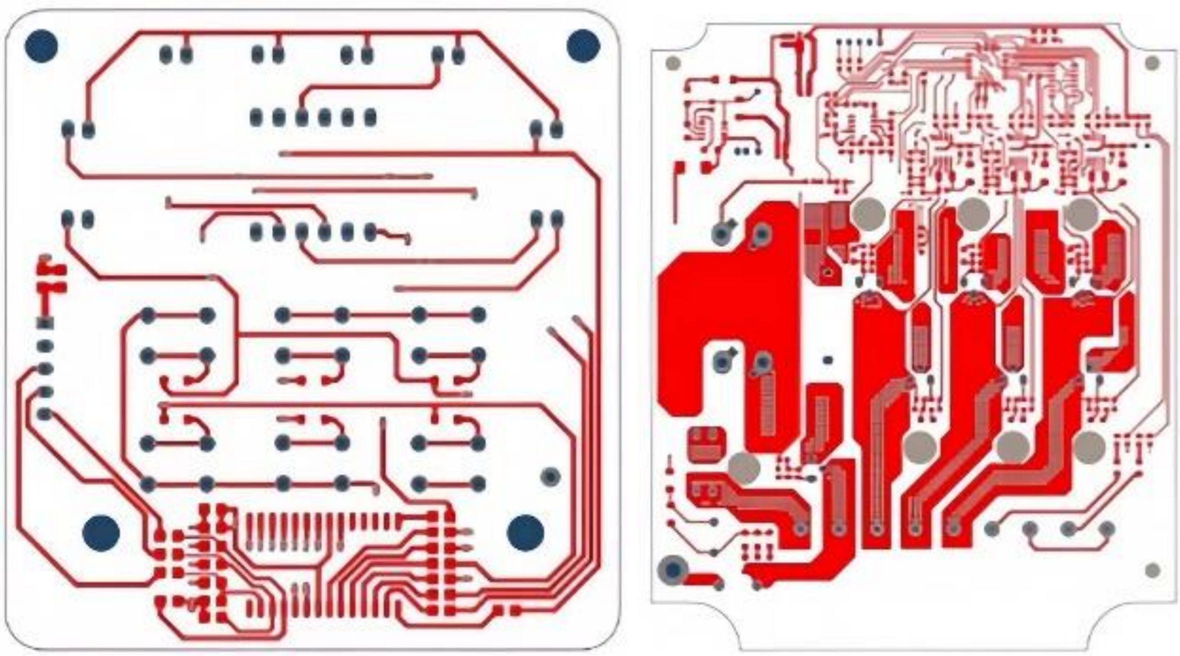

Fig 2: The circuit diagram of the control board

The comparative analysis of battery-less solar pumping systems, battery-included systems, and thermal gasoline systems revealed that battery-less solar systems are most suitable for well-sunlit regions. They offer high efficiency, require low maintenance, and have a minimal environmental and social impact. These systems maximize the direct use of solar energy, avoid the costs and environmental impacts associated with batteries, and reduce dependence on fossil fuels.

The design of an ideal solar water pumping system, based on these observations, integrates a holistic approach that combines technical efficiency, economic viability, and environmental and social responsibility. This optimized system uses high-efficiency solar panels with an advanced MPPT system to maximize captured energy. A next-generation water pump ensures optimal flow suited to the actual needs of crops, while a water management system, including a storage tank and a drip distribution network, optimizes water use.

This solution offers not only a significant reduction in operational costs compared to traditional methods but also an improvement in agricultural productivity. By avoiding the use of batteries and fossil fuels, the system reduces its ecological footprint and strengthens the autonomy of rural communities. Farmers benefit from a reliable and regular source of water for irrigation, which improves food security and resilience against the impacts of climate change.

In conclusion, the adoption of this battery-less solar water pumping system can play a transformational role in agriculture in arid and semi-arid regions. It offers a sustainable and economically advantageous approach, aligned with sustainable development goals and capable of effectively responding to future challenges in water management and food security.

The design of this battery-less solar water pumping system reflects an integrated approach to meet the irrigation needs in arid and semi-arid regions. By maximizing energy efficiency, minimizing costs and environmental impact, and enhancing the autonomy of communities, this system offers a sustainable and economically viable solution to improve agricultural productivity and food security. The implementation of this system should serve as a model for sustainable irrigation initiatives across similar regions, thereby contributing to the achievement of global sustainable development goals.

IV. CONCLUSION

The research and analysis conducted in this study highlight the crucial importance of solar water pumping systems for agricultural irrigation, especially in the contexts of arid and semi-arid regions. The challenges posed by climate variability and the need for sustainable water resource management demand innovative and efficient solutions. Among these, solar water pumping systems stand out as particularly promising alternatives due to their ability to optimize the use of solar energy, an abundant resource in these regions.

This study confirms that, to maximize benefits while minimizing costs and negative impacts, the battery-less solar pumping system represents the future of agricultural irrigation in regions critically in need of water management innovations. By continuing to develop and implement these technologies, we can hope for a greener and more productive future for global agriculture, especially in areas most vulnerable to climate variations and drought.

RECOMMENDATION

Awareness and Training: Organize awareness and training programs for farmers and policymakers on the benefits of battery-less solar pumping systems, including their energy efficiency, low maintenance, and environmental benefits.

Grants and Incentives: Encourage governments and international organizations to offer grants or low-interest loans for the purchase and installation of battery-less solar pumping systems, thus reducing the financial barriers to their adoption.

Technical Optimization of Installed Systems:

Monitoring and Evaluation: Implement real-time monitoring systems to assess the performance of the pumping systems and quickly identify any needs for maintenance or adjustment.

Continuous Improvement: Encourage ongoing research and development to improve the technology of pumps, solar panels, and MPPT controllers, to further increase the efficiency and durability of the systems.

Integrated Water Resource Management:

Data-Based Planning: Use meteorological and hydrological data to proactively plan water use, adjusting pumping schedules to match the crop demand cycles and water availability forecasts.

Precision Irrigation: Develop and use precision irrigation systems, including drip irrigation and automated irrigation, to optimize water use and minimize losses.

Sustainability and Environmental Impact:

Reducing the Ecological Footprint: Promote the use of eco-friendly and recyclable materials in the manufacturing of solar pumping system components.

Protecting Local Ecosystems: Ensure that the installation and operation of solar pumping systems do not disrupt local ecosystems, implementing measures to protect biodiversity and water resources.

Strengthening Community Capacity and Autonomy:

Technical Training: Offer regular training to farmers and local technicians on the maintenance and troubleshooting of solar pumping systems, strengthening local autonomy and capacity.

Local Cooperatives: Encourage the formation of cooperatives or associations of farmers to collectively manage the solar pumping systems, sharing knowledge and resources for mutual benefit.

Integration into Rural Development Policies:

National and Regional Strategies: Integrate solar pumping technology into national and regional strategies for rural development and food security, recognizing its role in promoting sustainable agriculture.

Public-Private Partnerships: Encourage partnerships between the public sector, private companies, and research institutions to finance, develop, and deploy solar pumping technologies tailored to the specific needs of different regions.

By following these recommendations, it is possible to maximize the benefits of solar water pumping systems for agricultural irrigation, thus contributing to more sustainable water resource management, increased agricultural productivity, and a significant improvement in food security and the economic well-being of rural communities in arid and semi-arid regions.

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