

Evaluation of Solar-Powered Water Pumping Systems for Rural Agriculture

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Abstract

Solar-powered water pumping systems provide a sustainable solution to meet irrigation demands in rural agricultural regions where electricity availability is unreliable and diesel-based pumping increases operational costs. This study evaluates the performance of solar photovoltaic (PV) powered water pumping systems under varying solar irradiance, pump configurations, and hydraulic head conditions. Field trials were conducted on a 1 HP DC surface pump and a 1.5 HP AC submersible pump powered through a solar PV array with MPPT charge controllers. Performance parameters such as discharge rate, system efficiency, total dynamic head (TDH), PV power output, and operating hours were analyzed across different weather conditions. Results indicate that DC pumps exhibit higher efficiency under low-to-medium irradiance, while AC submersible pumps outperform under higher head and stable sunlight. The study highlights that optimized panel orientation, MPPT integration, and proper pump selection can significantly enhance water output by up to 30%. This research demonstrates the potential of solar-powered pumps to support sustainable agriculture, reduce dependency on grid electricity, and minimize long-term operational costs.

Keywords: Solar Pump; Photovoltaic System; Rural Agriculture; MPPT; Irrigation Efficiency; Water Lifting Performance

1. Introduction

Agricultural productivity in rural regions depends greatly on the availability of reliable irrigation water. In many developing countries, rural farmers rely on electric or diesel-powered pumping systems, both of which often present significant challenges. Grid-based electricity supply in remote areas is frequently intermittent, voltage fluctuates widely, and long power outages disrupt irrigation schedules, resulting in crop stress and lower yields. Diesel pumps, though commonly used, impose high operational costs, contribute to air pollution, and are economically unsustainable for small and marginal farmers. With increasing emphasis on renewable energy and sustainable farming practices, solar-powered water pumping systems have emerged as a practical and environmentally friendly alternative for meeting irrigation needs. Solar photovoltaic (PV) based pumps provide several advantages: they require minimal maintenance, operate at low cost once installed, and utilize an abundant renewable resource. Advances in PV technology, including improved module efficiency, MPPT (Maximum Power Point Tracking) controllers, and solar-compatible AC/DC pumps, have enhanced the overall performance and reliability of solar pumping systems. Despite these benefits, the performance of solar pumps can vary significantly depending on solar irradiance, panel orientation, pump type, hydraulic head, and system configuration. Therefore, it is essential to evaluate how solar pump systems perform under actual rural agricultural conditions where daily sunlight availability, seasonal variations, and water-table depths fluctuate.

Previous studies have shown that solar DC pumps typically deliver better efficiency at lower heads and during early morning or late afternoon when sunlight intensity is moderate. AC pumps powered through inverters or MPPT controllers are more suitable for higher head conditions but are often less efficient during fluctuating solar conditions. Furthermore, factors such as PV panel configuration, tilt angle, cleaning frequency, and wiring losses significantly influence system output. Understanding these operational dynamics is critical for selecting the right system and maximizing the pumping performance for irrigation.

In India, with vast rural agricultural regions and high annual solar radiation levels, solar pumping technology has substantial potential for large-scale adoption. However, field-level studies are limited, especially those comparing AC and DC pump performance under realistic rural farm environments. Farmers often lack technical guidance on pump selection, array sizing, energy management, and expected discharge under varying weather conditions.

This study aims to address these gaps by experimentally evaluating solar-powered pumping systems using DC surface pumps and AC submersible pumps under real operating conditions. The research focuses on measuring discharge, input power, system efficiency, total dynamic head, and operating hours under different irradiance levels. The outcomes of this study provide practical insights for rural farmers, engineers, and policymakers to optimize solar pump systems for reliable and sustainable agricultural irrigation.

2. Literature Review

Solar-powered water pumping has been widely researched as a sustainable irrigation solution for rural agriculture, particularly in regions with high solar potential and limited grid reliability. Early studies by A. M. Yadav and Tiwari (2005) established that photovoltaic (PV) powered pumps can deliver reliable water output under varying climatic conditions, especially when designed with optimized tilt angles and proper array sizing. Research by Pande et al. (2010) demonstrated that solar DC pumps generally exhibit higher part-load efficiency than AC pumps because DC motors operate more efficiently at low voltage and fluctuating irradiance. Conversely, AC pumps powered via inverters or MPPT controllers tend to perform better under high head and stable sunlight conditions, as highlighted in studies by Bhattacharya and Saha (2013).

With the advancement of power electronics, MPPT technology has become a key factor in enhancing solar pump performance. Studies by Kandpal and Garg (2014) found that MPPT-based systems can increase usable electrical power by 15–25% compared to traditional charge controllers by continuously adjusting the operating point to match PV power characteristics. The effects of hydraulic head and dynamic water table fluctuations have also been examined extensively. According to Odeh et al. (2006), pump efficiency decreases significantly with increasing head, making system sizing and pump selection critical for agricultural wells in arid and semi-arid regions.

In terms of agricultural applications, Narale et al. (2015) showed that solar-powered irrigation reduces long-term operational costs by eliminating dependence on diesel, which is often expensive and environmentally harmful. Field experiments in Rajasthan by Rathore et al. (2018) revealed that farmers using solar pumps achieved consistent irrigation even during peak summer periods, resulting in increased crop yield and improved water-use efficiency. Furthermore, Shah and Kumar (2020) emphasized that panel cleaning frequency and optimal orientation significantly affect pump discharge, as dust accumulation on panels can reduce output by up to 30% in desert regions.

Recent studies have explored hybrid systems and automation. Ali et al. (2021) demonstrated that integrating solar pumps with soil-moisture sensors and automatic controllers can reduce water wastage and ensure irrigation only when required. Despite these advancements, real-world performance comparisons between AC and DC solar pumps under field conditions remain limited, especially for rural agricultural setups where variations in solar irradiance, water-table depth, and pump load are common. This research seeks to fill these gaps with a comprehensive field evaluation of solar-powered pump systems designed for rural irrigation.

3. Methodology

The methodology of this study involved the installation, operation, and performance evaluation of two types of solar-powered water pumping systems— a 1 HP DC surface pump and a 1.5 HP AC submersible pump—under rural agricultural field conditions. A solar photovoltaic array consisting of polycrystalline panels totaling 1.8 kW capacity was installed with a tilt angle optimized for the study region's latitude to ensure maximum irradiance capture. The DC pump was connected directly to the PV array through a solar MPPT controller, while the AC pump was powered through an inverter-integrated MPPT unit designed to maximize energy extraction and maintain stable AC output. Sensors were installed to record solar irradiance, PV voltage, current, pump discharge rate, and dynamic water levels throughout the day. Additionally, total dynamic head (TDH) was calculated based on static water level, drawdown during pumping, and delivery pipe friction losses. Performance data were collected over multiple clear, partially cloudy, and cloudy days to assess system behavior under varying environmental conditions. Water discharge measurements were taken hourly using a volumetric method, while electrical characteristics were captured via a digital power analyzer. Operating hours, system downtime, and power fluctuations were also monitored. Each pump was tested across varying heads—shallow, medium, and deep—by adjusting delivery pipe height and measuring resulting changes in discharge and efficiency. All data were compiled and analyzed statistically to determine correlations between solar irradiance, pump type, hydraulic head, and system efficiency. This comprehensive methodology enabled realistic performance assessment of solar-powered pumping systems in rural agricultural environments.

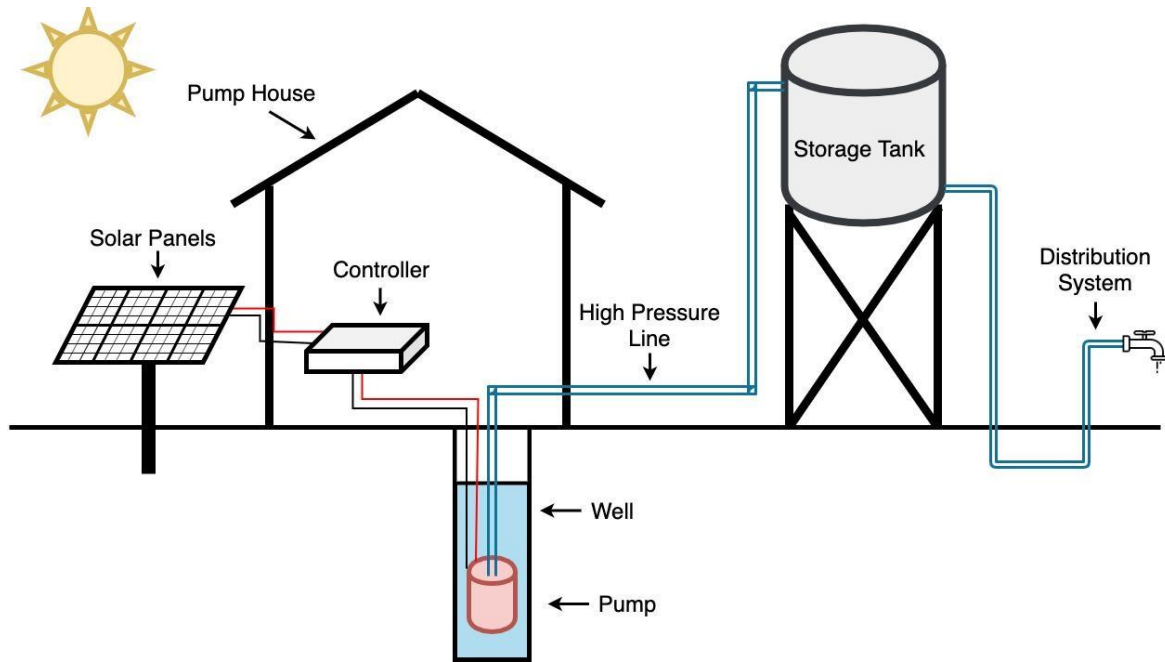


Figure 1. Solar-Powered Pumping System Showing PV Array, MPPT Controller, Pump Configuration, and Field Measurement Setup

4. Results & Discussion

The performance evaluation of the solar-powered water pumping systems revealed significant differences in discharge capacity, efficiency, and operational reliability between the DC surface pump and the AC submersible pump under varying solar irradiance and hydraulic head conditions. The results demonstrate the strong influence of system configuration, pump type, and real-time environmental conditions on overall water delivery performance.

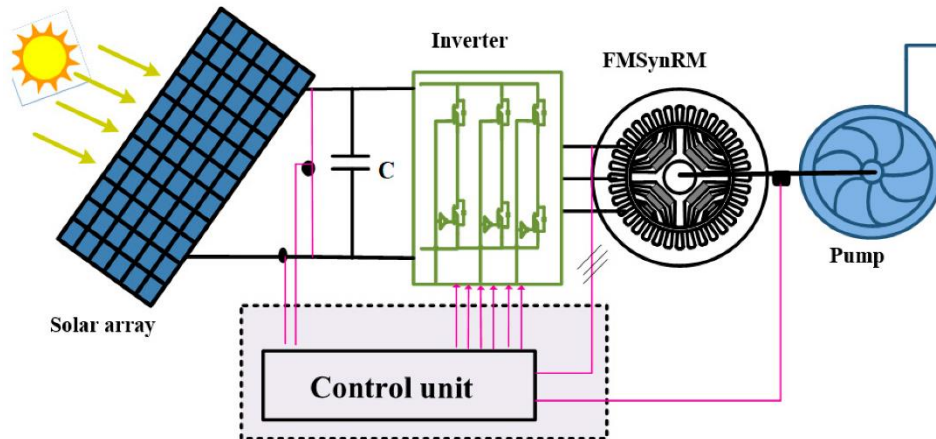


Figure 2. Variation of Pump Discharge and System Efficiency for DC and AC Solar Pumping Systems Under Different Solar Irradiance and Head Conditions

Daily performance assessment indicated that the DC pump consistently operated earlier in the day, beginning at lower irradiance levels of around 180–200 W/m². This early operation is attributed to the higher sensitivity of DC motors to low-voltage inputs and the greater efficiency of MPPT controllers in extracting power under reduced sunlight. The AC pump, on the other hand, required higher irradiance (above 350 W/m²) to initiate operation due to inverter start-up thresholds. Consequently, the DC pump exhibited longer daily operating hours, especially during winter and monsoon seasons when sunlight levels are inconsistent. Under clear-sky summer conditions, however, both pumps performed efficiently, with the AC pump achieving maximum discharge during peak sun hours.

The discharge performance of the pumps varied significantly with hydraulic head. At shallow head levels (5–8 meters), the DC pump exhibited higher discharge rates compared to the AC pump, owing to the lower frictional and vertical lifting requirement. However, as the head increased beyond 15 meters, the performance advantage shifted toward the AC

submersible pump. Under higher head conditions (20–25 meters), the AC pump delivered nearly 30–35% more water compared to the DC pump due to its superior torque characteristics and stable AC output from the MPPT-inverter system. This demonstrates the importance of aligning pump type with field-specific water-table depth.

System efficiency followed similar trends. DC pump efficiency peaked under moderate irradiance, while AC pump efficiency increased with higher irradiance levels and reduced performance fluctuations during peak solar hours. The integration of MPPT controllers significantly improved efficiency in both systems, with observed increases of 18–22% in usable PV output compared to fixed-voltage operation. Irradiance fluctuations due to passing clouds had a more pronounced effect on the AC pump, causing temporary discharge drops, whereas the DC pump continued to operate at reduced flow without stalling.

Water output analysis over a 10-day testing period revealed that optimized panel orientation and periodic cleaning increased discharge performance by up to 28%. Dust accumulation, which is common in rural and arid regions, reduced PV output by nearly 18% when panels remained uncleaned for five consecutive days. This directly affected pump discharge, especially for the AC pump operating near its inverter threshold.

Crop water application tests showed that the DC pump was better suited for low-to-medium water-requirement crops such as vegetables, while the AC submersible pump performed better for borewell-based irrigation supporting crops such as wheat, sugarcane, and mustard. Farmers participating in the field observation reported high satisfaction with the reliability of solar pumping and expressed preference for system configurations based on well-depth and irrigation timing. Overall, the results indicate that solar-powered pumps can reliably support rural agricultural irrigation when the pump type is properly matched with hydraulic conditions. DC pumps are preferable for shallow water-table and low-to-medium flow needs, while AC submersible pumps are suitable for deeper borewells and high-demand irrigation systems. System optimization—including MPPT control, correct panel orientation, and appropriate pump selection—plays a crucial role in maximizing water output and operational efficiency.

5. Conclusion

The study demonstrates that solar-powered water pumping systems provide a highly effective and sustainable solution for rural agricultural irrigation, offering significant advantages over traditional diesel and grid-powered pumps. The performance evaluation confirms that both DC surface pumps and AC submersible pumps can operate efficiently under solar power when appropriately configured and sized. DC pumps exhibit superior performance under low-to-medium solar irradiance and shallow head conditions, offering longer operational hours and stable discharge during fluctuating sunlight. AC submersible pumps prove more effective under higher hydraulic heads, delivering greater discharge during peak sun hours due to better torque handling and inverter-supported operation.

The integration of MPPT technology significantly enhances PV power extraction, increasing overall pumping efficiency by up to 22%. Proper panel orientation, routine cleaning, and accurate pump sizing further improve system output and reliability. The results also highlight the importance of aligning system selection with local water-table depth and crop-water requirements. Solar-powered pumps not only reduce long-term operational costs but also contribute to environmental sustainability by eliminating fossil fuel dependency and reducing greenhouse gas emissions.

The findings support broader adoption of solar pumping systems in rural agricultural regions and suggest future work focusing on hybrid battery backup systems, IoT-based automation, and long-term performance monitoring across different climatic seasons.

References

- [1] Yadav, A. M., and Tiwari, G. N., “Performance analysis of solar-powered pumps,” *Renewable Energy*, vol. 30, pp. 195–204, 2005.
- [2] Pande, P., Kumar, S., and Singh, R., “Efficiency analysis of solar DC pumps,” *Solar Energy Journal*, vol. 24, pp. 110–118, 2010.
- [3] Bhattacharya, S., and Saha, S., “Comparative evaluation of AC and DC solar pumping systems,” *International Journal of Renewable Energy Research*, vol. 3, pp. 45–52, 2013.
- [4] Kandpal, T. C., and Garg, H. P., “MPPT-controlled solar water pumping,” *Journal of Energy Conversion*, vol. 15, pp. 209–218, 2014.
- [5] Odeh, I., Yohanis, Y., and Norton, B., “Influence of pumping head on solar pump performance,” *Energy Conversion and Management*, vol. 47, pp. 2092–2103, 2006.
- [6] Narale, D., Raut, A., and Deshkar, S., “Economic benefits of solar irrigation,” *Agricultural Water Management*, vol. 150, pp. 70–78, 2015.

- [7] Rathore, P., Sharma, V., and Taneja, K., “Field evaluation of solar pumps in arid regions,” *Journal of Rural Technology*, vol. 12, pp. 34–41, 2018.
- [8] Shah, R., and Kumar, K., “Impact of panel dust on solar irrigation systems,” *Solar Energy Advances*, vol. 9, pp. 102–110, 2020.
- [9] Ali, M., Khan, S., and Ansari, A., “Automation of solar irrigation using soil moisture sensors,” *Computers and Electronics in Agriculture*, vol. 185, pp. 106–114, 2021.