Journal of Solar Energy Research (JSER)

Journal homepage: www.jser.ut.ac.ir

Enhancing Stand-Alone PV Pumping Efficiency: An Experimental Study of Low-Tilt Angle Optimization in Southern Hemisphere Season

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ARTICLE INFO

Article Type:

Research Article

Received:2026.02.12
Accepted in revised form:2026.08.07

Keywords:
Solar water pumping;
Tilt angle optimization;
Seasonal adjustment;
Stand-alone PV;
Tropical climate;
Energy efficiency

A B S T R A C T

This experiment investigates the performance optimization of a stand-alone photovoltaic water pumping system (PVWPS) in the tropical region of Yogyakarta, Indonesia (7°S latitude), specifically during the December Solstice. While conventional designs often utilize fixed latitude-based tilt angles, this research proposes a seasonal micro-adjustment strategy to address the sun's extreme Southern position during the rainy season. An experimental comparison was conducted between two low-tilt configurations (5° vs. 10°) on a 1.65 kWp off-grid system powering a 290 W surface pump. Data were collected under real operating conditions (10:00–14:00) and filtered to exclude cloud-edge anomalies. The results reveal that the 5° tilt angle outperforms the 10° configuration, achieving an average electrical efficiency of 17.5% compared to 16.6%. The near-flat orientation minimizes cosine losses and maximizes direct irradiance capture when the sun is at the Tropic of Capricorn. This study recommends a seasonal manual adjustment to 5° during the December planting season to enhance water discharge reliability in remote agricultural areas.

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Cite this article: Setiawan,A Agus, Nugroho,A Tri, Annajmi,D Al Humam, Jati,R Rizkiyanto, Irfandi,M , Budiyono,B and Maulana,W . (2026). Enhancing Stand-Alone PV Pumping Efficiency: An Experimental Study of Low-Tilt Angle Optimization in Southern Hemisphere Season. Journal of Solar Energy Research, 11(3), 3211-3220. doi: 10.22059/jser.2026.410950.1719

DOI: 10.22059/jser.2026.410950.1719

1. Introduction

Solar photovoltaic (PV) technology has a significant role in the global energy transition, particularly for agricultural applications in remote areas. In developing countries, water pumping for irrigation and domestic use heavily relies on diesel generators, which are costly and environmentally detrimental [1]. The transition from diesel to solar photovoltaic water pumping systems (PVWPS) has been identified as a sustainable solution to ensure water security and reduce carbon emissions, as comprehensively reviewed in recent literature [2], [3], [4], [5], [6]. In the context of Indonesia, specifically in karst regions like Gunungkidul, the implementation of sustainable water supply systems is crucial for disaster resilience and community reconstruction, as highlighted in early studies by Setiawan et al. [7], [8]. The immense solar energy potential in tropical regions offers a viable opportunity to address these water scarcity challenges through efficient stand-alone PV systems [9]. Recent advancements in this field have emphasized the integration of smart water management technologies, utilizing microcontrollers and real-time sensor data to enhance the self-sufficiency of rural populations [10].

The efficiency of a PV system is highly influenced by the amount of solar irradiation incident on the module's surface. One of the critical parameters affecting this is the tilt angle. Conventional installations often employ a fixed-tilt configuration based on the site's latitude to minimize installation complexity and costs [11]. However, recent studies indicate that relying solely on latitude-based fixed angles does not yield maximum energy output throughout the year due to the seasonal variation of the sun's position [12]. Tamoor et al. [13] demonstrated that optimizing the tilt angle, rather than using a static position, can significantly enhance system efficiency and reduce the Levelized Cost of Energy (LCOE). To move beyond traditional empirical rules, hybrid frameworks integrating machine learning and localized climatic data are now being utilized to predict monthly optimal tilt angles across diverse climate zones [14]. Furthermore, simplified calculation models have been developed to reveal annual variation patterns, indicating that in low-latitude cities, the monthly optimal tilt angle can even decrease to negative values [15]. While these computational advancements provide valuable theoretical insights, there remains a need for empirical field validation in specific tropical microclimates. Experimental investigations by Arslan and Çunkaş [16] emphasized that the optimal tilt angle varies for each site and requires precise determination based on local climatic conditions, rather than general rules of thumb [17], [18], [19],

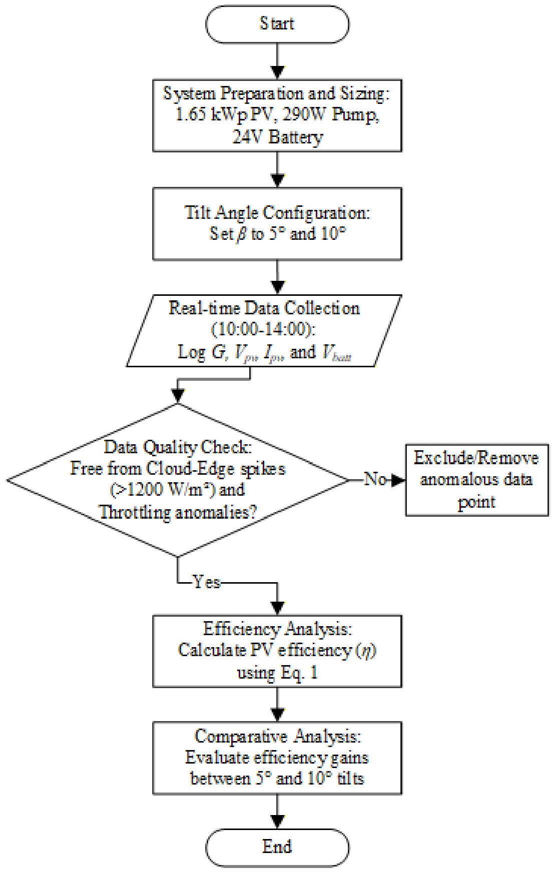

Figure 1. The experimental procedure in this study [20].

In tropical regions near the equator, the strategy for tilt angle optimization differs significantly from high-latitude regions. Previous research by Kristiyana et al. [21] studied the PV modules' performance at various angles (5°–25°), suggesting that a 20° tilt is generally optimal for annual performance. However, there is a lack of specific studies focusing on the "December Solstice" phenomenon in the Southern Hemisphere, where the sun reaches its southernmost point. During this specific rainy season, cloud cover and diffuse radiation become dominant factors. Recent geospatial studies by Télesphore et al. [22] in Benin and Apriani et al. [23] in Indonesia propose that low-tilt angles (near-flat) might offer superior performance in equatorial zones by minimizing self-shading and maximizing diffuse radiation capture, a concept also supported by Vineesh and Bhattacharya [24] and others [25], [26]. While efforts to maximize energy capture often involve complex electronic control strategies, such as combining metaheuristic optimizers with direct torque control for induction motors [27], there remains a critical need for cost-effective physical optimization. Empirical validation of this low-tilt strategy specifically for pump applications during the critical planting season in December remains limited.

This study aims to address this research gap by experimentally investigating the stand-alone PVWPS' performance under two specific low-tilt angle configurations (5° and 10°) during the December Solstice period in Yogyakarta, Indonesia. Unlike previous general optimizations or complex computational frameworks, this study focuses on the "seasonal micro-adjustment" required to maximize water discharge when the sun is in the extreme South. The study builds upon the pioneering work of solar pumping in the region by Setiawan et al. [28], integrating modern data cleaning techniques to filter cloud-edge effects and throttling anomalies, providing a robust efficiency analysis for tropical seasonal optimization.

2. Materials and Methods

The overall experimental procedure, from system sizing to data analysis, is systematically illustrated in the flowchart presented in Figure 1.

2.1. Experimental Site and Setup

The experimental study was conducted in the special region of Yogyakarta, Indonesia (Coordinates: 7° 46'S, 110° 23'E), which represents a typical tropical climate in the Southern Hemisphere. The data collection campaign was carried out during the December Solstice period (December 2025), characterized by the sun's position at the Tropic of Capricorn (23.5°S). Following the experimental validation approach by Arslan and Çunkaş [16], this study utilized a real-time outdoor measurement method. Two inclination configurations were tested sequentially: a near-flat tilt (5°) and a standard low tilt (10°), both oriented towards the North to face the sun's trajectory. The 5° angle was selected as the minimum practical threshold required to ensure self-cleaning from dust and effective rainwater drainage in tropical environments, as recommended by Chiteka et al. [29], while maximizing the capture of direct solar irradiance during the solstice. The 10° angle serves as a baseline for standard low-tilt installations

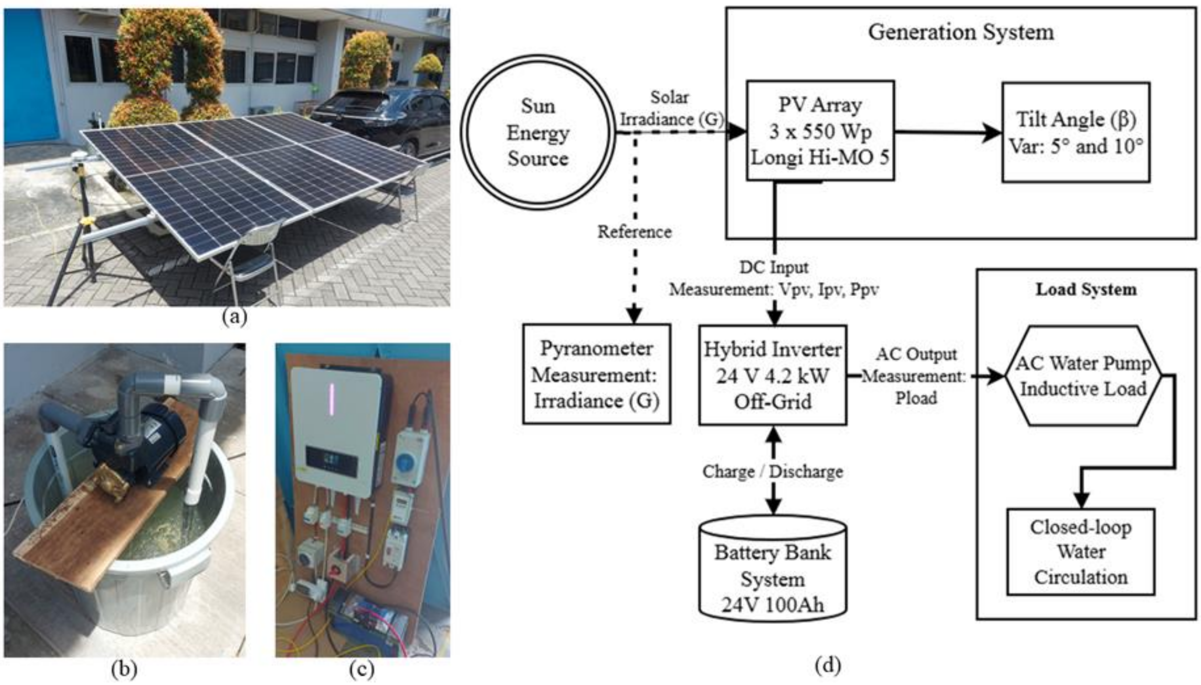

Figure 2. (a) PV Array 3×550Wp; (b) 290 Watt AC Water Pump Testing; (c) Inverter and Measurement Tools Set up; (d) The schematic diagram of the experiment

in the region. The physical installation of the test bed, illustrating the adjustable mounting structure and the placement of the PV array, as well as the schematic diagram, are shown in Figure 2.

2.2 PV Pumping System Specifications

Table 1. System Components and Specifications

Component	Parameter	Value
PV Module	Model	Longi Hi-MO 5_m (LR5-72HPH-550M)
	Cell Type	Mono-crystalline
	STC P_{max}	550 Wp
	STC V_{oc}	49.80 V
	STC I_{sc}	13.98 A
	Module Efficiency	21.3 %
	Configuration	3 Modules in Series (Total 1.65 kWp)
Inverter	Type	Hybrid Off-Grid Inverter
	Rated Power	4.2 kW
	System Battery Voltage	24 VDC
	Waveform	Pure Sine Wave
Battery Bank	Nominal Voltage	24 V
	Capacity	100 Ah
Pump	Type	Surface Centrifugal Pump
	Rated Output Power	125 W
	Rated Input Power	0.29 kW (290 W)
	Max. Suction Head	9 m
	Max. Total Head	33 m
	Max. Capacity	33 L/min
	Pipe Size	1 inch (Suction & Discharge)

The stand-alone PVWPS consists of a set of photovoltaic generators, a hybrid inverter, a battery bank, and a surface centrifugal pump. The specifications of the system components are detailed in Table 1. The PV array comprises three mono-crystalline silicon modules (Longi Hi-MO 5), each with a peak power of 550 Wp, connected in series to achieve a total capacity of 1.65 kWp. The system utilizes a 4.2 kW off-grid hybrid inverter integrated with a 24V battery bank to stabilize the voltage supply to the pump, ensuring continuous operation during intermittent cloud cover [30]. The coupling of the battery bank ensures stable motor operation, mitigating the intermittency issues common in direct-coupled systems [31], [32].

The centrifugal pump was selected with a rated total head of 33 m to represent the technical requirements for small-scale irrigation in the karst areas of Southern Java, where water sources are often located at significant depths [28]. However, to ensure a stable and controlled load for the electrical efficiency analysis, the experimental setup in this study utilized a closed-loop configuration with a static head of approximately 0.5 m. In this setup, the actual electrical input power (P_{in}) required by the pump is approximately 290 W, while the rated hydraulic output power is 125 W. This configuration allows the research to focus on the PV array's conversion efficiency and the system's response to tilt angle optimization under a consistent mechanical load.

2.3 Data Acquisition and Processing

Table 2. Specifications of Measurement Instruments

Instrument	Model	Parameter	Range	Accuracy
Pyranometer	Kipp and Zonen CMP3	Solar Irradiance (G)	0 to 2000 W/m^2	ISO 9060 Class C (Non-linearity < ±3%)
DC Clamp Meter	Fluke 376	DC Voltage (V_{pv})	0 to 1000 V	1% ± 5 digits
		DC Current (I_{pv})	0 to 999.9 A	2% ± 5 digits

Data acquisition was carried out using a set of calibrated instruments as detailed in Table 2. Solar irradiance (G) was measured on the plane of the array (POA) using a Kipp & Zonen CMP3 pyranometer, which complies with ISO 9060 Spectrally Flat Class C standards and features a non-linearity of less than ±3%. Electrical parameters, including PV voltage (V_{pv}), current (I_{pv}), and power (P_{pv}), were recorded using the inverter's built-in monitoring system. While P_{pv} was recorded directly, the values correspond to the product of real-time voltage and current ($P = V \times I$). This data was then cross-validated using a Fluke 376 True-RMS clamp meter to ensure measurement consistency. This instrument provides a DC voltage accuracy of 1% ± 5 digits and a DC current accuracy of 2% ± 5 digits.

Data were logged at 5-minute intervals from 10:00 to 14:00 local time. This specific time window was selected to capture the peak solar window and ensure the experimental site was free from external shading. The research site is located within a university environment characterized by dense vegetation and trees exceeding 3 meters in height, which cast significant shadows outside of this four-hour period.

To ensure the accuracy of the efficiency analysis, a rigorous data cleaning procedure was applied. Raw data were filtered to exclude anomalies caused by the "Cloud Edge Effect" (irradiance spikes >1200 W/m²) and "Throttling Mode" (where the inverter limits power because the battery is full). Only data points where the system operated under Maximum Power Point Tracking (MPPT) mode with a consistent load were retained.

Furthermore, an uncertainty analysis was performed using the Root Sum Square (RSS) method based on standard experimental procedures [33]. The total uncertainty of the efficiency calculation u_η is expressed in Equation (1):

$$u_\eta = \sqrt{(u_G)^2 + (u_V)^2 + (u_I)^2} \quad (1)$$

Where u_G, u_V, and u_I represent the percentage uncertainties of the pyranometer (3%), voltage measurement (1%), and current measurement (2%), respectively. By substituting these values, the maximum expected uncertainty is calculated as ±3.74%, which is well within the acceptable threshold for field experiments, indicating a high level of reliability for the acquired data.

2.4 Performance Calculation

The instantaneous power output (P_{pv}) of the PV array is calculated as the product of voltage and current. The electrical conversion efficiency (η) of the PV system is calculated using Equation (2), based on the standard definition provided by Duffie and Beckman [34] and utilized in similar pumping studies by Kristiyana et al. [21] and others [35]:

$$\eta = \frac{P_{pv}}{G \times A_{pv}} \times 100\% \quad (2)$$

Where P_{pv} is the output power (W), G is the solar irradiance on the tilted PV surface (W/m²), and A_{pv} is the total area of the modules (m²). The results are then analyzed to determine the correlation between tilt angle (β), irradiance intensity (G), and power generation efficiency (η).

3. Results and Discussion

3.1. Environmental Conditions and System Response

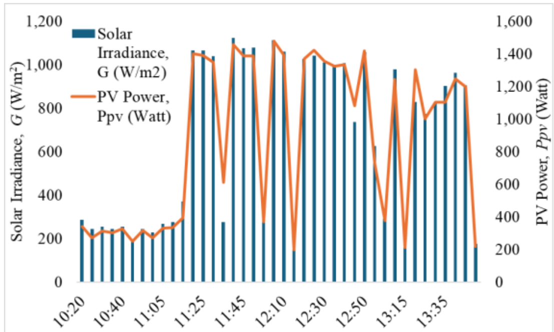

Figure 3. Solar Irradiance, G (W/m^2) and PV Power, P_{pv} (Watt) vs Time

The experimental data were acquired during the rainy season (December), characterized by high variability in solar irradiance due to rapid cloud movement. Figure 3 illustrates the daily profile of solar irradiance (G) and the corresponding PV power output (P_{pv}).

As depicted in Figure 3, the irradiance profile exhibits severe fluctuations, repeatedly dropping from peak values above 1000 W/m² to below 200 W/m² within minutes. This high variability is characteristic of the December monsoon season, driven by thick, fast-moving cumulus clouds. The system is highly responsive to these fluctuations, with the corresponding PV power curve (P_{pv}) closely tracking the irradiance drops.

Despite these extreme drops in input energy and the intermittent conditions typical of the tropical wet season, the hybrid PV system successfully powered the pump (rated input: 290 W) continuously during the effective sun hours (10:00 – 14:00). The integration of the battery bank successfully buffered these generation gaps, preventing the pump from stalling and proving the reliability of the hybrid configuration under adverse tropical weather.

3.2. Effect of Tilt Angle on Power Generation

To understand the direct impact of tilt angle (β) on energy generation, the generated PV power (P_{pv}) is plotted against solar irradiance (G) for both 5° and 10° configurations, as shown in Figure 4:

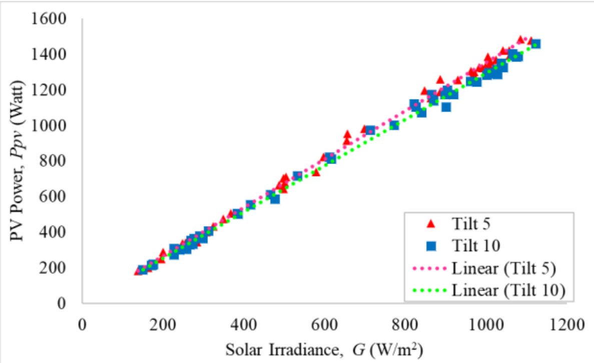

Figure 4. Solar Irradiance, G (W/m^2) effect on the generated PV Power, P_{pv} (Watt)

The linear regression analysis indicates a strong positive correlation for both angles. However, a divergence is observed at higher irradiance levels (>800 W/m²). The 5° tilt (represented by red triangles) consistently produces higher power output compared to the 10° tilt (blue squares). For instance, at peak irradiance (approx 1100 W/m²), the 5° setting configuration achieved a peak power of approximately 1480 W, slightly outperforming the 10° setting configuration. This validates that the near-flat orientation captures the solar angle more effectively during the solstice period.

3.3 Efficiency Analysis

The performance advantage of the lower tilt angle (β) is further clarified through the efficiency analysis presented in Figure 5.

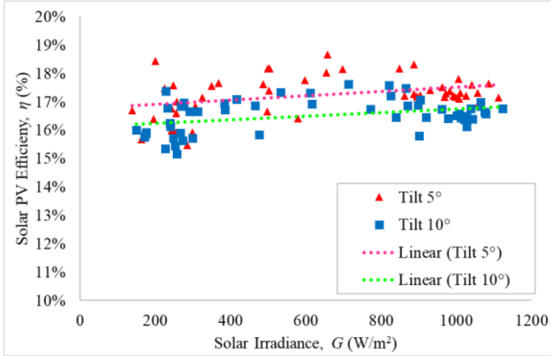

Figure 5. Scatter Plot of Solar PV Efficiency, η (%) vs Solar Irradiance, G (W/m^2)

The scatter plot reveals a distinct performance gap. The 5° tilt setting configuration demonstrates a superior conversion efficiency trend (pink dotted line) compared to the 10° setting configuration (green dotted line). The average efficiency for the 5° tilt was recorded at ~17.5%, whereas the 10° tilt averaged at ~16.6%. The gain of approximately 0.9% in efficiency is significant for a standalone system, as it translates directly into increased water discharge volume over the course of a day.

3.4. Discussion: Why 5° is Better in December?

The superior performance of the lower tilt angle of 5° during December can be attributed to the specific solar geometry of the experimental location. The research site is located at 7°S latitude. During the December Solstice, the sun is placed at the Tropic of Capricorn 23.5°S. Hence, the sun's path is significantly south of the zenith. For a North-facing panel, a steep tilt (e.g., 10° or 15°) would result in a larger incidence angle relative to the sun's rays coming from the South. Conversely, a flatter surface (5°) effectively presents a better projection area to the sun overhead, minimizing cosine losses.

This finding aligns with the geospatial optimization study by Télesphore et al. [22], who found that in equatorial regions (similar to Benin), optimal tilt angles (β) are often significantly lower than the site latitude to maximize annual yield. Furthermore, our results empirically validate the simulation by Apriani et al. [23] in the Indonesian tropical context, which emphasizes the benefits of optimizing orientation to capture maximum irradiation. While some studies suggest sophisticated tracking systems for maximum yield [36], [37], or complex optimization algorithms [38], [39], [40], our results indicate that simple seasonal adjustments on fixed structures [13], [41], [42] offer a more cost-effective solution for small-scale farmers in developing regions.

One might argue that a 0° (flat) tilt could be theoretically optimal. However, a minimum tilt is necessary for maintenance. The choice of 5° in this study is supported by Chiteka et al. [29], who suggest that a slight inclination is required to facilitate self-cleaning of dust and water drainage, preventing soiling losses that are prevalent in tropical climates. Additionally, as noted by Vineesh and Bhattacharya [24] and other array studies [43], [44], lower tilt angles (β) in array configurations reduce inter-row shading, which is crucial for maintaining consistent voltage in string-inverter systems like the one used in this study. Therefore, this study confirms that for the specific period of the Southern Hemisphere summer (December), a seasonal micro-adjustment to a near-flat angle (5°) is more advantageous than the standard latitude-based tilt (10°-15°) typically recommended in general literature [45], [46].

4. Conclusions

This experimental study successfully investigated the impact of low-tilt angle (β) optimization on a stand-alone PVWPS during the December Solstice in the Southern Hemisphere tropical region. Based on the field measurements and data analysis, the following conclusions are drawn:

1. Seasonal Solar Geometry: The hypothesis that a near-flat angle (5°) captures solar irradiance more effectively than the standard low angle (10°) during the December rainy season is confirmed. This is due to the sun's position at the Tropic of Capricorn (23.5°S), which favors a flatter orientation for North-facing panels in Yogyakarta (7°).
2. Performance Enhancement: The 5° tilt configuration demonstrated a superior electrical efficiency of 17.5%, compared to 16.6% for the 10° tilt. An absolute efficiency gain of 0.9% was achieved, particularly under high irradiance conditions (>800 W/m²).
3. Practical Implication: For agricultural applications in tropical Indonesia, a fixed-tilt system is not optimal year-round. It is recommended to implement a seasonal manual adjustment strategy: employing a standard tilt (15°-20°) during the dry season (sun in the North) and reducing it to a near-flat angle (5°) during the planting season in December (sun in the South).
4. Design Recommendation: Although a 0° tilt is theoretically viable, the 5° tilt is maintained as the minimum threshold to ensure self-cleaning against dust and effective water drainage, crucial for maintaining long-term reliability in off-grid remote areas.
5. Limitations and Future Works: This study is primarily limited by its focus on a specific solstice period and the use of a controlled shallow-head setup (0.5 m) with a stable flow rate. This configuration was intentionally chosen to isolate and accurately measure the electrical conversion efficiency of the PV array without the compounding variables of hydraulic fluctuations. Future work should extend the measurement campaign across multiple seasons (dry and wet) and incorporate dynamic deep-well pumping loads to comprehensively evaluate the actual hydraulic efficiency and long-term water yield of the micro-adjusted PVWPS.

Acknowledgements

This research was funded by the Faculty of Engineering, Universitas Gadjah Mada, through the Collaborative Community Service Grant 2025 (Hibah Pengabdian Kepada Masyarakat Kolaborasi). Authors appreciate colleagues of the Department of Nuclear Engineering and Engineering Physics, the Renewable Energy Laboratory team, and the Renewable Energy Systems and Planning (RESP) Research Group, who provided insight and expertise that assisted the research.

Nomenclature

A_{pv}	Total PV modules active area (m^2)
G	Solar irradiance (W/m^2)
I_{pv}	Output current of PV array (A)
I_{sc}	Short-circuit current/SCC (A)
MPPT	Maximum Power Point Tracking
P_{max}	Maximum power at STC (W)
P_{pv}	PV Power output (W)
PV	Photovoltaic
STC	Standard Test Condition
u_η	Standard uncertainty of efficiency calculation (%)
u_G	Standard uncertainty of solar irradiance measurement (%)

u_I	Standard uncertainty of current measurement (%)
u_V	Standard uncertainty of voltage measurement (%)
V_{oc}	Open-circuit voltage/OCV (V)
V_{pv}	Output voltage of PV array (V)
β	Tilt angle (°)
η	Electrical conversion efficiency (%)

References

[1] Jamil, M. K., Smolenaars, W. J., Ahmad, B., Dhaubanjar, S., Immerzeel, W. W., Lutz, A., Akbar, G., Ludwig, F., & Biemans, H. (2025). The effect of transitioning from diesel to solar photovoltaic energy for irrigation tube wells on annual groundwater extraction in the lower Indus Basin, Pakistan. Journal of Agriculture and Food Research, 20, 101799. https://doi.org/10.1016/j.jafr.2025.101799

[2] Kumar, M., Arora, P., Srivastava, N., Padma, J., Singh, R., & Bhosale, A. C. (2025). Optimal sizing of solar photovoltaic water pumping systems by synergizing irrigation patterns and static heads: A comprehensive study in the Indian context. Sustainable Energy Technologies and Assessments, 77, 104341. https://doi.org/10.1016/J.SETA.2025.104341

[3] Rawat, R., Kaushik, S. C., & Lamba, R. (2016). A review on modeling, design methodology and size optimization of photovoltaic based water pumping, standalone and grid connected system. Renewable and Sustainable Energy Reviews, 57, 1506–1519. https://doi.org/10.1016/j.rser.2015.12.228

[4] Sontake, V. C., & Kalamkar, V. R. (2016). Solar photovoltaic water pumping system - A comprehensive review. Renewable and Sustainable Energy Reviews, 59, 1038–1067. https://doi.org/10.1016/j.rser.2016.01.021

[5] Allouhi, A., Buker, M. S., El-houari, H., Boharb, A., Benzakour Amine, M., Kousksou, T., & Jamil, A. (2019). PV water pumping systems for domestic uses in remote areas: Sizing process, simulation and economic evaluation. Renewable Energy, 132, 798–812. https://doi.org/10.1016/j.renene.2018.08.019

[6] Campana, P. E., Li, H., Zhang, J., Zhang, R., Liu, J., & Yan, J. (2015). Economic optimization of photovoltaic water pumping systems for irrigation. Energy Conversion and Management, 95, 32–41. https://doi.org/10.1016/j.enconman.2015.01.066

[7] Setiawan, A. A., Sugiarto, S., Zhao, Y., Nayar, C. V., Wijaya, M. E., Melfiana, E., Negara, T. A., Utomo, B., & Assidiq, A. F. (2007). Development of sustainable power and water supply for remote areas and disaster response and reconstruction in Indonesia. 2007 Australasian Universities Power Engineering Conference, 1–6. https://doi.org/10.1109/AUPEC.2007.4548051

[8] Setiawan, A. A., Zhao, Y., & Nayar, Chem. V. (2009). Design, economic analysis and environmental considerations of mini-grid hybrid power system with reverse osmosis desalination plant for remote areas. Renewable Energy, 34(2), 374–383. https://doi.org/10.1016/j.renene.2008.05.014

[9] Tri Nugroho, A., Pramono Hadi, S., Sutanta, H., & Adikara Ajrin, H. (2024). Optimising Agrivoltaic Systems: Identifying Suitable Solar Development Sites for Integrated Food and Energy Production. Journal of Power, Energy, and Control, 1(1), 1–11. https://doi.org/10.62777/pec.v1i1.3

[10] Rumbayan, M., Pundoko, I., Sompie, S. R., & Ruindungan, D. G. (2025). Integration of smart water management and photovoltaic pumping system to supply domestic water for rural communities. Results in Engineering, 25, 103966. https://doi.org/10.1016/j.rineng.2025.103966

[11] Hafez, A. Z., Soliman, A., El-Metwally, K. A., & Ismail, I. M. (2017). Tilt and azimuth angles in solar energy applications – A review. Renewable and Sustainable Energy Reviews, 77, 147–168. https://doi.org/10.1016/j.rser.2017.03.131

[12] Lu, N., & Qin, J. (2024). Optimization of tilt angle for PV in China with long-term hourly surface solar radiation. Renewable Energy, 229, 120741. https://doi.org/10.1016/j.renene.2024.120741

[13] Tamoor, M., Bhatti, A. R., & Farhan, M. (2025). An improved approach for enhancing the PV system efficiency through optimization of tilt angle. Solar Energy, 297, 113607. https://doi.org/10.1016/J.SOLENER.2025.113607

[14] Lin, O. Z., Štěpanec, L., Koutroulis, E., Juchelkova, D., & Aye, H. Y. (2026). Optimizing monthly solar PV tilt angles and energy yield across global climate zones: A hybrid machine learning and PVLib approach. Renewable Energy, 260, 125163. https://doi.org/10.1016/j.renene.2025.125163

[15] Zhang, X.-X., Chen, J.-L., Dou, H.-Q., Liu, C.-Y., & Hou, X.-Y. (2025). Calculation model for the monthly optimal tilt angle of fixed photovoltaic panels. Thermal Science, 29(2 Part B), 1403–1409. https://doi.org/10.2298/TSCI2502403Z

[16] Arslan, M., & Çunkaş, M. (2025). An experimental study on determination of optimal tilt and orientation angles in photovoltaic systems.

Journal of Engineering Research, 13(3), 2689–2701. https://doi.org/10.1016/J.JER.2024.07.015

[17] Benghanem, M. (2011). Optimization of tilt angle for solar panel: Case study for Madinah, Saudi Arabia. Applied Energy, 88(4), 1427–1433. https://doi.org/10.1016/j.apenergy.2010.10.001

[18] Kaldellis, J., & Zafirakis, D. (2012). Experimental investigation of the optimum photovoltaic panels' tilt angle during the summer period. Energy, 38(1), 305–314. https://doi.org/10.1016/J.ENERGY.2011.11.058

[19] Zang, H., Guo, M., Wei, Z., & Sun, G. (2016). Determination of the Optimal Tilt Angle of Solar Collectors for Different Climates of China. Sustainability 2016, Vol. 8, Page 654, 8(7), 654. https://doi.org/10.3390/SU8070654

[20] Danandeh, M. A., & Mousavi G., S. M. (2018). Solar irradiance estimation models and optimum tilt angle approaches: A comparative study. Renewable and Sustainable Energy Reviews, 92, 319–330. https://doi.org/10.1016/J.RSER.2018.05.004

[21] Kristiyana, S., Susastriawan, A. A. P., Sudarsono, & Purwanto, Y. (2025). Investigation an Effect of Tilt Angle and Water Cooling on Performance of a Photovoltaic Module of a Solar-Powered Vehicle Charging Station. Journal of Solar Energy Research, 10(1), 2195–2202. https://doi.org/10.22059/jser.2025.396549.1578

[22] Télesphore, N. C., Richy, A. G. M., Fiacre, Z., Melhyas, K., Audace, D. K. B., Pierre, A. D., Isaac, A., Clarence, S. G., & François-Xavier, F. (2025). GIS-based optimization of photovoltaic panel orientation in Benin using genetic algorithms and K-means clustering. Solar Compass, 16, 100142. https://doi.org/10.1016/J.SOLCOM.2025.100142

[23] Apriani, S., Mangkuto, R. A., Saputro, A. G., & Chow, E. C. (2024). Performance prediction and optimisation of even-lighting agrivoltaic systems with semi-transparent PV module in the tropical region. Solar Energy, 283, 113013. https://doi.org/10.1016/j.solener.2024.113013

[24] Vineesh, V., & Bhattacharya, J. (2022). Comparing hut-shaped-east-west array for fixed photovoltaic panels against conventional equator facing parallel rows for power output per unit field area. Energy for Sustainable Development, 70, 225–238. https://doi.org/10.1016/j.esd.2022.07.019

[25] Irandoostshahrestani, M., & Rousse, D. R. (2025). Optimizing off-grid PV/wind systems with battery and water storage for rural energy and water access. Journal of Energy Storage, 140, 119155. https://doi.org/10.1016/j.est.2025.119155

[26] Sarr, A., Soro, Y. M., Tossa, A. K., & Diop, L. (2024). A new approach for modelling photovoltaic panel configuration maximizing crop yield and photovoltaic array outputs in agrivoltaics systems. Energy Conversion and Management, 309. https://doi.org/10.1016/j.enconman.2024.118436

[27] Hilali, A., El marghichi, M., Makhad, M., Loulijat, A., el Ouanjli, N., Mossa, M. A., Almalki, M. M., & Alghamdi, T. A. H. (2024). Optimization of solar water pumping systems through a combined approach based on MPPT-Bat and DTC. PLOS ONE, 19(12), e0309330. https://doi.org/10.1371/journal.pone.0309330

[28] Setiawan, A. A., Purwanto, D. H., Pamuji, D. S., & Huda, N. (2014). Development of a Solar Water Pumping System in Karsts Rural Area Tepus, Gunungkidul through Student Community Services. Energy Procedia, 47, 7–14. https://doi.org/10.1016/j.egypro.2014.01.190

[29] Chiteka, K., Arora, R., Sridhara, S. N., & Enweremadu, C. C. (2021). Influence of irradiance incidence angle and installation configuration on the deposition of dust and dust-shading of a photovoltaic array. Energy, 216, 119289. https://doi.org/10.1016/j.energy.2020.119289

[30] Zhou, K., Ma, X., Gao, F., Yao, J., & Kan, X. (2024). Frequency optimisation and performance analysis of photovoltaic-battery water pumping system. Renewable Energy, 230, 120844. https://doi.org/10.1016/J.RENENE.2024.120844

[31] Hamidat, A., & Benyoucef, B. (2008). Mathematic models of photovoltaic motor-pump systems. Renewable Energy, 33(5), 933–942. https://doi.org/10.1016/j.renene.2007.06.023

[32] Muhsen, D. H., Khatib, T., & Haider, H. T. (2017). A feasibility and load sensitivity analysis of photovoltaic water pumping system with battery and diesel generator. Energy Conversion and Management, 148, 287–304. https://doi.org/10.1016/j.enconman.2017.06.007

[33] Moffat, R. J. (1988). Describing the uncertainties in experimental results. Experimental Thermal and Fluid Science, 1(1), 3–17. https://doi.org/10.1016/0894-1777(88)90043-X

[34] Duffie, J. A., & Beckman, W. A. (2013). Solar Engineering of Thermal Processes (4th ed.). John Wiley & Sons, Inc. https://doi.org/10.1002/9781118671603

[35] Liu, B. Y. H., & Jordan, R. C. (1963). The long-term average performance of flat-plate solar-energy collectors. Solar Energy, 7(2), 53–74. https://doi.org/10.1016/0038-092X(63)90006-9

[36] Dekkiche, M., Tahri, T., & Denai, M. (2023). Techno-economic comparative study of grid-

connected PV/reformer/FC hybrid systems with distinct solar tracking systems. Energy Conversion and Management: X, 18, 100360. https://doi.org/10.1016/j.ecmx.2023.100360

[37] Sharaby, M. R., Sharshir, S. W., ElBahloul, A. A., Kandeal, A. W., & Rashad, M. (2025). Performance evaluation of fixed and sun-tracking photovoltaic systems integrated with spray cooling. Solar Energy, 288, 113310. https://doi.org/10.1016/j.solener.2025.113310

[38] Gürfidan, R., Yiğit, F., & Kabul, A. (2025). Exergy focused optimum solar panel tilt angle determination with improved hybrid model: The case of Turkey. Engineering Applications of Artificial Intelligence, 145, 110220. https://doi.org/10.1016/j.engappai.2025.110220

[39] Qadeer, A., Parvez, M., Khan, O., Jafri, H. Z., & Lal, S. (2024). Optimization of solar radiation on tilted surface in isotropic and anisotropic atmospheric conditions. Next Research, 1(2), 100075. https://doi.org/10.1016/j.nexres.2024.100075

[40] Salilih, E. M., Leon-Salas, W. D., Ruiz Gonzalez, L. G., Larico, P. F., Cornejo, M. V., Postigo-Málaga, M., Pichu, M. O., & Jara Gonzales, J. M. (2025). Energy output assessment and tilt angle optimization of north/south configured bifacial PV module using single diode model in mountainous region. Energy Conversion and Management: X, 28, 101302. https://doi.org/10.1016/j.ecmx.2025.101302

[41] Prunier, Y., Chuet, D., Nicolay, S., Hamon, G., & Darnon, M. (2023). Optimization of photovoltaic panel tilt angle for short periods of time or multiple reorientations. Energy Conversion and Management: X, 20, 100417. https://doi.org/10.1016/j.ecmx.2023.100417

[42] Chen, X. M., Li, Y., Zhao, Z. G., Ma, T., & Wang, R. Z. (2018). General method to obtain recommended tilt and azimuth angles for photovoltaic systems worldwide. Solar Energy, 172, 46–57. https://doi.org/10.1016/j.solener.2018.06.045

[43] Barbón, A., Bayón-Cueli, C., Bayón, L., & Rodríguez-Suanzes, C. (2022). Analysis of the tilt and azimuth angles of photovoltaic systems in non-ideal positions for urban applications. Applied Energy, 305, 117802. https://doi.org/10.1016/j.apenergy.2021.117802

[44] Vishnupriyan, J., Partheeban, P., Dhanasekaran, A., & Shiva, M. (2022). Analysis of tilt angle variation in solar photovoltaic water pumping system. Materials Today: Proceedings, 58, 416–421. https://doi.org/10.1016/j.matpr.2022.02.353

[45] Allen, R. G. ., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration : guidelines for computing crop water requirements (C. Redfern & J. Plummer, Eds.). FAO - Food and Agriculture Organization of the United Nations. https://www.fao.org/4/x0490e/x0490e00.htm

[46] Yadav, A. K., & Chandel, S. S. (2013). Tilt angle optimization to maximize incident solar radiation: A review. Renewable and Sustainable Energy Reviews, 23, 503–513. https://doi.org/10.1016/j.rser.2013.02.027