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Performance Assessment of a Solar Water Pumping System Under High-Head Conditions in Sumba, Indonesia

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Abstract:

A 2.4 kWp Solar Water Pumping System (SWPS) was installed in Kadaghu Tana, South West Sumba, to provide clean water from a total head of 115 m. The site receives 4.8-6.0 kWh/m2/day of solar irradiation. The system uses Photovoltaic (PV) modules connected to a Lorentz DC pump through an MPPT controller. Performance was evaluated through simulation and field monitoring. Key parameters assessed were flowrate, hydraulic energy, wire-to-water efficiency, motor efficiency, and daily pump operating hours. The pump operated 07.00–16.00 WITA, slightly earlier than the simulated 08.00 start time. The average monitored flowrate (1.07 m^3/h) closely matched the simulated value (1.08 m^3/h). Monthly average output was 10.75 m^3 (monitoring) versus 10.83 m^3 (simulation). The PV system produced 7.34 kWh/day, yielding a yield factor of 3.06 kWh/kWp/day. Hydraulic energy output was 3.31 kWh/day, resulting in overall system efficiency of 26–30%, consistent with typical Lorentz DC pump performance. System performance aligns well with simulation predictions. Operation is strongly influenced by irradiance, ambient temperature, total dynamic head, and well characteristics. The SWPS demonstrates reliable performance for remote clean-water supply in Sumba.

1. Introduction

Indonesia possesses significant solar energy potential, estimated at approximately 207.8 GWp. Despite this, the installed photovoltaic capacity remains low relative to the potential. As of June 2024, Indonesia's installed solar power capacity reached only 664.5 MW. The majority of this capacity is attributed to on-grid installations (PLN), totaling 285 MW, including the recently commissioned 145 MW Cirata floating solar power plant, which nearly doubled the on-grid solar power capacity by 2023 (Halim et al., 2024).

Solar water pumping systems (SWPS) are a key application of photovoltaic energy. A SWPS is found to be more economical, eco-friendly, reliable, and low-maintenance, with a long lifespan, compared to diesel-powered water pumps. A 4–6-year payback period is found for some of the systems. The recent Indian subsidy provided and the latest scheme available for installation purposes are also discussed in the work (Verma et al., 2021). A study by Meah et al. (Meah et al., 2008) discussed the benefits and applications of SWPS in rural areas, particularly in the western US, where prolonged drought is occurring. With the high cost of extending electricity distribution lines and the availability of groundwater and sunlight, solar water pumps are a more economical option for small applications. Solar-powered water pumping systems have advantages over diesel engines or electric generators because they are more environmentally friendly, have low fuel costs, and require little maintenance.

Another study analyzing the performance of solar-powered AC water pumps, conducted by Mustafa Elrefai et al., reported monitoring results from SWPS in El Wahat, Egypt, with a solar panel capacity of 45 kWp. The data showed that the daily water volume that can be pumped is 788 m3 over 1 year, and the maximum output in the summer is 887 m3, with an energy production of 5 kWh/kWp/day (Mustafa et al., 2016). Solar power generation based on solar PV systems is cost-effective in developing countries such as India. A study by Pachaivannan et al. compared remote solar water pumping systems across several climate-sensitive regions of India, accounting for factors such as location, system size, and performance. PVsyst simulation software was used to design a standalone solar water pumping system. Input data was obtained from four climatically diverse locations in southern India. A comparative analysis was performed for the four regions based on solar yield, performance ratio (PR), energy losses, and pump efficiency. The PVsyst simulation analysis showed that the overall pump efficiency ranged from 57% to 66%, and the performance ratio ranged from 51% to 69%. These results are helpful for making policy decisions on the best locations for solar power plants (Pachaivannan et al., 2024).

The implementation of SWPS in Indonesia was dominated by government projects to help the water crisis in remote areas with limited electricity. However, the installations were often experiencing system failure. Research by Susanto, D.A. found that the problem of installing SWPS can be addressed by conducting descriptive qualitative research through a case study on 25 SWPS installations. The performance of SWPS was sub-optimal due to improper use, installation, and component maintenance (Susanto et al., 2020). Sinaga et.al. designed and constructed a SWPS with a water flow rate of 3000 liters per hour to support farmers in Kupang, Nusa Tenggara Timur. The result shows that the estimation to get a flow rate of water by 3000 Lph, the pump head was at 1.5 m. The pump head affects the flow rate of water. If the pump head (H) increases by 1 m, the flow rate of water (A) will decrease by 389.66 Lph. (Sinaga et al., 2023). The research by Nizar Amir proposed the utilization of SWPS for paddy field irrigation at Bangkalan, Madura. HOMER software has been used to generate an optimal configuration of the system. It showed that SWPS is more cost-effective than a diesel generator (Amir, 2021).

Prior to the SWPS installation, a simulation of the system is vital to ensure good system performance. Husein A. Kazem proposed an optimal solar water-pumping system design for Oman, evaluated using both HOMER software and MATLAB simulations with hourly meteorological data. The selected location experienced temperatures from 12.8°C to 44.5°C and a maximum insolation of 7.45 kWh/m²/day. The system, using a 0.81 kW water pump, achieved an average energy output of 2.9 kWh, an annual yield factor of 2016.66 kWh/kWp, and a capacity factor of 22.97%. The cost analysis showed the energy price to be favorable at about 0.24 USD/kWh, making PV water pumping systems promising for Oman (Kazem et al., 2021).

Previous studies have extensively applied simulation techniques to analyze the performance of solar photovoltaic (PV) water pumping systems under varying environmental and operational conditions. Numerical modeling and MATLAB/Simulink-based simulations have been used to evaluate system behavior, including PV array output, motor–pump dynamics, and control strategies such as maximum power point tracking (MPPT) and DC–DC converters (Shabbir & Iqbal, 2025). However, the performance evaluation of SWPS from the experimental field-based data is very important compared to the simulation result to ensure that the system are able to meet the requirement especially for high head application.

SWPS was installed by Renewable Energy Development Institute of Universitas Kristen Immanuel in Kadaghu Tana Village, North Kodi District, Southwest Sumba County, in July 2022. Before the installation, a simulation was conducted to determine pump specifications that match the community's water needs and the surrounding field conditions using Lorentz Compass software. The modeling, simulation, and analysis of the PV system for water pumping is a vital step before assembling it at any location, enabling a better understanding of its behavior under real weather conditions at that location (Dlimi et al., 2024).

In January 2024, monitoring data from the solar pump system were retrieved using the integrated pump scanner software. These data were subsequently recorded in Microsoft Excel for analysis to assess the operational workload of the installed solar water pumping system. The monitoring dataset spans from July 2022, when the system was installed, to 2024, when the data were collected. This study aims to analyze the simulation results of the SWPS technical specifications in Kadaghu Tana Village, to assess the system's performance, compare actual performance with simulation outcomes, and to evaluate key performance indicators such as flow rate, hydraulic energy, motor efficiency, wire-to-water efficiency, and pump ignition time. Solar water pumping systems have been implemented globally to address water supply needs, particularly in remote areas.

This study focuses on the performance assessment of a 2.4 kWp solar water pumping system operating under high-head conditions in Sumba, Indonesia. While previous research has extensively examined the performance of solar pumping systems in low-head or moderate-head environments, limited empirical data exist for high-head installations in equatorial island regions. Understanding the real-world performance of such systems is critical for optimizing design, improving energy efficiency, informing policy decisions, and enhancing water resource management in similar rural settings.

By evaluating system efficiency, energy yield, water output, and the influence of environmental factors such as solar insolation and temperature, this research aims to generate data-driven insights that support the broader implementation of solar water pumps in challenging terrain. The findings are expected to contribute to the scientific literature on renewable energy applications in developing regions and support Indonesia’s national goals for rural electrification and sustainable agriculture.

2. Theoretical Framework

2.1 SWPS Simulation

Prior to the SWPS installation, a simulation was conducted. Shabbir & Iqbal utilized Lorentz Compass that specialized in SWPS technical model and HOMER for the economics assessment. It conducted through three steps i.e. site characterization, proposed design architecture and simulation result and analysis. Site characterization covers the estimated daily water consumption, total dynamic head and solar irradiance. The second step is load calculation that shows the energy demand of SWPS. The proposed design architecture is defined by Lorentz Compass design. The last step is analyzing the simulation result. From the simulation it can be determined the system size to meet the daily water consumption considering local climate condition, water temperature and system losses. The simulation result predicts daily water output in m^3/hr, include water output, photovoltaic energy generation, solar irradiation, rainfall distribution and ambient temperatures (Shabbir & Iqbal, 2025).

2.2 SWPS Performance Parameters

In designing SWPS, it is necessary to pay attention to the total dynamic head (TDH) (m) and discharge Q (m3/hour). TDH consists of static head H_{st}, drawdown head H_d, total loss head H_1 (m), and pressure head H_p (m). TDH components for deep water are shown in Figure 1 (Mustafa et al., 2016). Draw-down head represents the depth level of the pumped water.

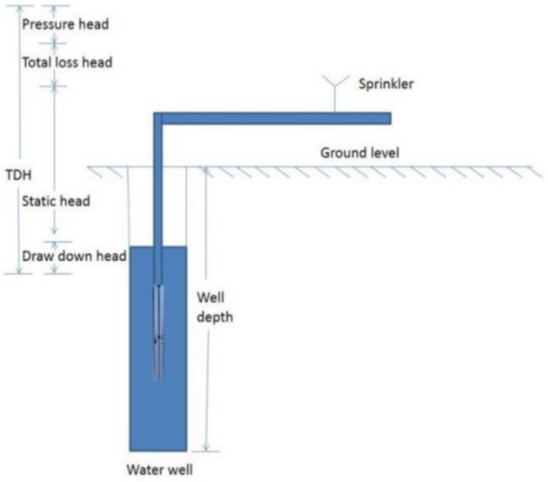

Figure 1. *Total Dynamic Head (THD) components of deep water (Mustafa et al., 2016)*

Friction head (m) represents the pressure loss in the pump due to friction. The friction head can be calculated with the equation

$$H_f = 4k_f \frac{8lQ^2}{D^5\pi^2 g} \tag{1}$$

where kf is an empirical factor that describes friction loss that depends on the Reynolds number, l is the pipe length (m), g is the acceleration of gravity (m/s2) and Q is the discharge (m3/s). Additional head is needed to consider head loss due to pipe and valve adjustments. Additional head can be calculated using the equation

$$H_f = 4k_{fi} \frac{8lQ^2}{D^4\pi^2 g} \tag{2}$$

with kfi is the fitting loss factor. Total head loss H_1 is the sum of friction head H_f and fitting loss head H_{fi} (m) which is written in the equation

$$H_1 = H_f + H_{fi}. \tag{3}$$

Total dynamic head T_{DH} equation can be written as

$$T_{DH} = H_{st} + H_d + H_1 + H_p. \tag{4}$$

The required hydraulic power P_h (W) can be written as

$$P_h = \frac{\rho g\, T_{DH} Q}{3600}. \tag{5}$$

where P_h denotes hydraulic power (W), ρ is water density (kg/m³), g is gravitational acceleration (m/s²), and Q is volumetric flow rate (m³/s). Pump efficiency (η_{pump}) measures how effectively the pump converts input energy (usually mechanical or electrical) into hydraulic energy to move fluid. The equation for estimating pump efficiency is presented in Equation 6.

$$\eta_{pump} = \frac{P_h}{P_s} \tag{6}$$

where P_h represents the hydraulic power (kW) and P_s denotes the shaft power (kW). Increasing the pump capacity generally leads to higher discharge rates and longer operating durations due to improved hydraulic performance. However, a larger pump also increases the overall system cost, including capital investment and associated components. Therefore, an optimal pump design is needed based on environmental and economic factors (Verma et al., 2021).

Pump capacity can be determined by dividing the hydraulic power by the selected pump efficiency, namely (Budi et al., 2020)

$$P_2 = \frac{P_h}{\eta_{pompa}}. \tag{7}$$

SWPS uses solar irradiation as its energy source, which hits the solar panel. Solar irradiance (W/m2) and the surface temperature of the solar panel affect the DC power output of the PV array, Pmp (W). The pump controller works by converting Pmp (W) into 3-phase AC power PAC (W). The controller has a maximum power point tracking technique to extract maximum power from the PV array. The motor converter then converts the AC power into mechanical power through the motor shaft Psh (W). The pump works by transferring mechanical energy to extract water from the well. In order for the solar pump design to be accurate, the water output volume needs to be calculated to match the design with the water needs. The SWPS performance parameters that will be evaluated in this study include flow rate, hydraulic energy, yield factor, wire-to-water efficiency, pump efficiency, and pump start time (Maity et al., 2024; Mustafa et al., 2016). Yield Factor (Y_F) in kWh/kWp/day is the ratio of daily, monthly, or annual AC energy output (E) in kWh/day to the installed P_V array ($P_V\ W_p$) in kWp.

$$Y_F = \frac{E}{P_v W_p}. \tag{8}$$

Wire to water energy efficiency (W_e) represents the overall system efficiency and is given by the equation

$$W_e = \frac{H_e}{P_{v_e}}. \tag{9}$$

where H_e represents the daily hydraulic energy delivered by the system (Wh/day), calculated as the product of hydraulic power (P_h) and the pump operating duration (h/day). The photovoltaic energy supplied to the system (P_{v_e}) is expressed in Wh/day.

The Lorentz pump uses a pump scanner application to download pump monitoring data. This monitoring data is stored on a smartphone to be recorded in Microsoft Excel, and its performance is analyzed. Several parameters that will be evaluated in this study include motor efficiency, flow rate, output energy, and pump operating time.

3. Method

3.1 Location

Sumba is an island located in the province of East Nusa Tenggara (NTT), Indonesia. The area of the island is about 11,000 km². The neighboring islands of Sumba are Sumbawa to the northwest, Flores to the northeast, Timor to the east, and Australia to the south and southeast. The Sumba Strait is in the north of the island. To the east extend the Sawu Sea and the Indian Ocean to the south and west, the population is estimated at 830,187 in 2024 (Hivos, 2011). The season in Sumba is divided into the rainy and dry seasons. The drought season is longer than the rainy season. The rainy season usually occurs from December to April, and the remaining eight months are dry. In Sumba, rainfall ranges from 0 mm to 294 mm. In contrast, the maximum number of rainy days is less than 25 days. The national average number of rainy days is 226 days. The temperature range is about 15-36 degrees Celsius (BPS Indonesia, 2021; Budi et al., 2020; Halim et al., 2024). In addition, Sumba has excellent potential for daily global horizontal sunshine of 4.8-6.0 kWh/m2, which is equivalent to the Indonesian average (Energy Sector Management Assistance Program, 2020).

The condition of the villages in Sumba is such that they have difficulty accessing clean water. The village community in Sumba typically has to walk up to 5 km to access water due to challenging road conditions. However, it is not uncommon for a village to have no nearby water source, so people have to buy water from the city for Rp 120,000–200,000 per water truck, with a water buffer capacity of 5,000–8,000 liters. Usually, a family has to buy water 2-3 times a month, indicating that the water-filling standards for family members are not met. The location is at Kadaghu Tana Village, Southwest Sumba, as shown in Figure 2.

Figure 2. *SWPS Location in Kadaghu Tana Southwest Sumba (Google map)*

3.2 SWPS Spesification

The SWPS used is the LORENTZ PS2-1800 C-SJ1-25 Submersible Pump. The SWPS system is shown in Figure 3. The solar water pump system consists of a solar panel array, a pump, and a controller. This pump is designed to be more efficient. The storage system is a water tank, not electricity stored in batteries. The energy source for the solar water pump is solar panels connected in series or parallel. The SWPS workflow is explained as follows: First, the solar panels absorb solar radiation and convert it into electrical energy. Second, the electrical energy powers the entire pump system. The motor converts electrical energy produced by the PV system into mechanical rotation torque to drive the pump's impeller/rotor. The pump controller controls and regulates the system's operation, acting like an automatic transmission to help the pump start and prevent it from stopping in low sunlight. Submersible impellers/submersible water pumps function to pump water from the ground to the surface. The water is stored in the water storage, which acts as a reservoir. Finally, the water is distributed to the residents and the farm.

The SWPS has a maximum power rating of 1.8 kW, which defines the upper limit of electrical power that can be delivered to the motor during operation. The maximum input voltage of 200 V and an optimum voltage at maximum power (Vmp) greater than 102 V indicate the required operating voltage range for efficient energy conversion from the photovoltaic array. The motor current is limited to 14 A to ensure safe operation and prevent overheating. The system is designed to achieve a maximum efficiency of 98%, indicating minimal power losses during energy conversion. Additionally, the wide ambient operating temperature range of −40 to 50 °C demonstrates the system's suitability for outdoor installation and reliable operation under varying environmental conditions, including the hot, harsh climates typical of eastern Indonesia.

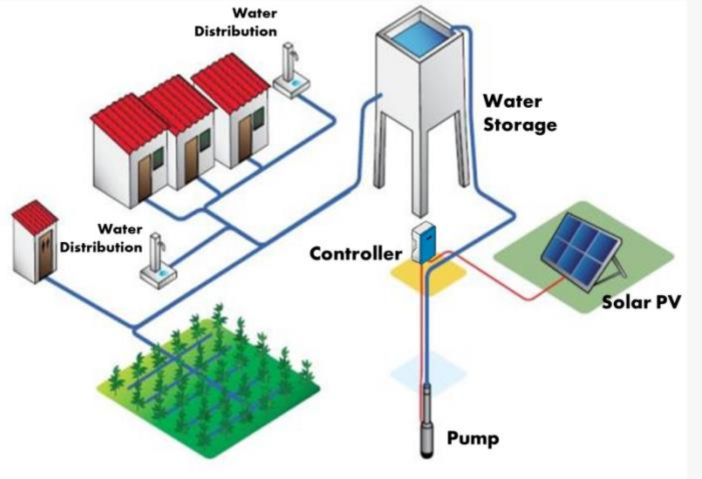

Figure 3. *SWPS components (APJ Energy Lda, 2018)*

The total number of solar modules used is 24. Each module has a rated maximum power output of 100 Wp under standard test conditions, which determines the nominal energy contribution of the PV array. The voltage and current at maximum power, 18.7 V and 5.35 A, respectively, indicate the optimal operating point at which the module delivers maximum electrical power. The open-circuit voltage (23 V) represents the maximum voltage available from the module when no load is connected. At the same time, the short-circuit current (5.72 A) indicates the maximum current generated under short-circuit conditions. These parameters are essential for proper PV array configuration, ensuring compatibility with the pump controller's voltage requirements and enabling efficient, safe operation of the solar water pumping system.

Solar pump controller plays an important role in SWPS. It controls and monitors the pump, tracks the Maximum Power Point Tracking (MPPT), protects the pump, controls inputs and outputs, and acts as a data logger. It is equipped with pump scanner apps to monitor the real-time and historical data from the system, such as running time, output, irradiation, controller temperature, input current, and input voltage. The monitoring data was then downloaded using the same apps installed in the smartphones using Bluetooth connection.

3.3 Data Collection

The data used is simulation data to determine the specifications of the solar water pump to be installed using the Lorentz Compass software. In addition, solar water pump monitoring data in Kadaghu Tana Village has been downloaded using pump scanner software. This data is then recorded in Microsoft Excel. The data is then analyzed and compared to simulation predictions. The steps of the research were site characterization (high head SWPS in Kadaghu Tana), proposed design architecture (PV capacity, pump specification, static and total head), simulation result and analysis, SWPS installation, performance monitoring from field data, data analysis, and conclusions. In this study, Key Performance Indicators (KPIs) were used to evaluate SWPS performance, including motor efficiency, flow rate, energy output, and pump operating time.

4. Result

The installed solar water pump system has a capacity of 2.4 kWp, consisting of a PV module connected to a Lorentz DC pump through an MPPT controller. The test location is in Kadaghu Tana, Southwest Sumba, with an average daily irradiation of 4.8–6.0 kWh/m². The system is used for a clean water supply with a total head of 115 m, which includes static head and friction loss head in the pipe. Testing was conducted to evaluate the hydraulic performance and efficiency of the system based on several main parameters, namely flow rate, hydraulic energy, motor efficiency, wire-to-water efficiency, and pump start time.

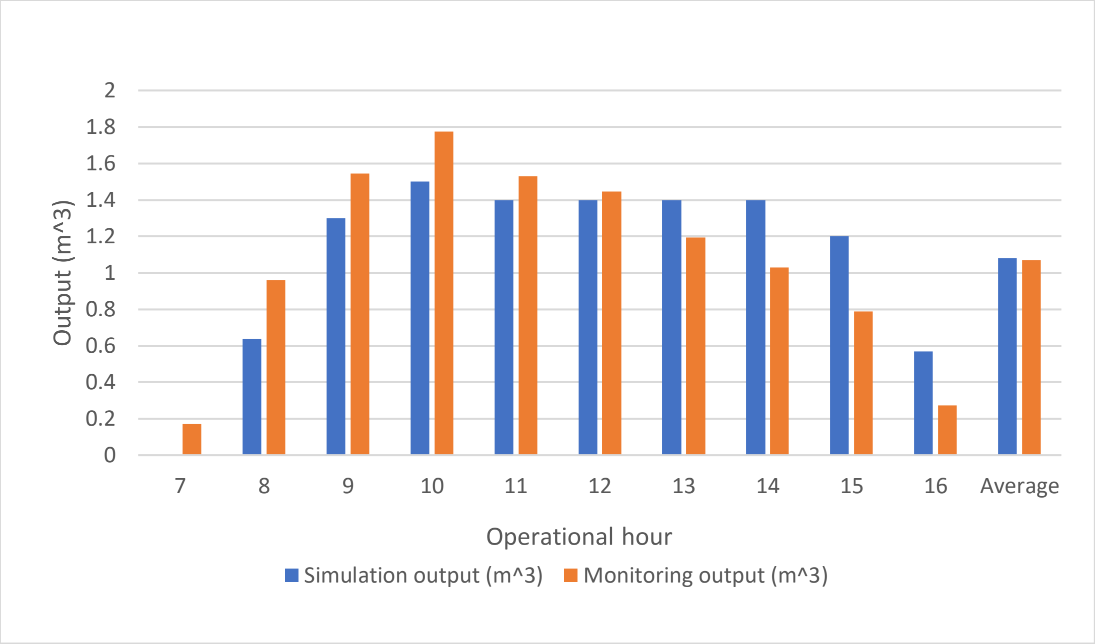

Figure 4. *SWPS Output Results at each Operational Hour*

From Figure 4, it can be seen that SWPS is predicted to pump water from 08.00-16.00, and the highest output is at 10.00 because at this time the system produces the most optimal electricity energy. The energy produced by the PV system depends on solar irradiance and the PV surface temperature. At 10.00, the solar irradiation is high, but the photovoltaic surface temperature is considered lower compared to 11.00-13.00. Therefore, at 10.00, the water output was the highest. The monitoring results show that the pump works from 07.00-16.00. SWPS will start pumping water when the intensity of solar energy hitting the solar panel is sufficient. However, because solar radiation intensity data in Kadaghu Tana village were unavailable at the time of data collection, it was not possible to determine the minimum light intensity required for the SWPS to start pumping water.

Simulation results predicted an average water discharge of 1.08 m^3/hour, and monitoring results indicated an average water discharge of 1.07 m^3/hour, as shown in Figure 4. In terms of water discharge, the SWPS performance was in line with simulation predictions. During daily operation, discharge increased during the day when solar radiation intensity peaked (9:00–1:00 PM WITA) and decreased in the morning and evening. This daily discharge meets the Lorentz pump performance standards for heads above 100 m, which typically ranges from 9–12 m^3/day for a PV capacity of 2.4 kWp. This demonstrates optimal integration between the panel, controller, and pump capacities. Furthermore, if the minimum water required by one person per day is 60 liter (Nathanael et al., 2025), based on the simulation, this system provided water for 168 persons. The total amount of water pumped by SWPS was 10,7 m^3 per day, so this amount of water was sufficient for 168 persons. However, due to limited water source in the area, 500 persons nearby the SWPS site depend on the water from this system. For further recommendation, more SWPS need to be built in the future in the area.

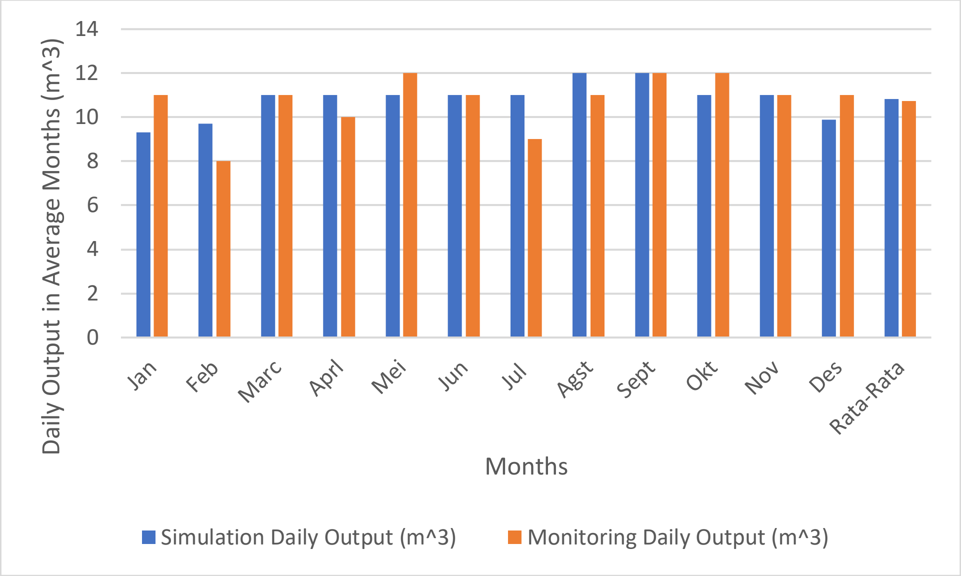

Figure 5. *Yearly Output in 2022 and 2023*

Figure 5 shows the yearly output in 2022 and 2023. The highest output was in May, September and October. This was happened because in May, September and October the solar irradiation was higher than other months and the energy produce by PV system were higher i.e. 13 kWh in May and October and 14 kWh in September compared the others months. The lowest output was 8 m^3 in February. The ideal condition for this output was only sufficient for 168 persons, but due to lack of water sources 500 person depend on the water pumped by this system. In the future, more SWPS system will be needed to fulfill the water needs.

The highest average daily output from the simulation results is predicted in August and September, while the monitoring results occur in May, September, and October. The average SWPS output for each month from the simulation and monitoring results is 10.83 m^3 and 10.75 m^3, respectively. The yield factor value is the ratio of daily, monthly, or annual AC energy output to the installed PV array. The simulation results show that the total AC energy output from July 5, 2022, to January 21, 2024, in Kadaghu Tana is 4146 kWh; thus, the daily energy value is 7.34 kWh/day for an installed PV capacity of 2.4 kWp. The yield factor value is 3.06 kWh/kWp/day. Yield factor is a solar panel performance indicator that shows how efficiently solar panels convert sunlight into electrical energy. A higher yield factor value means the solar panel's ability to convert solar energy into electricity is greater. Hydraulic energy is calculated using the formula: $E_{hyd} = \rho g H Q$. By substituting the known values of $\rho = 1000$ kg/m^3, $g = 9.81$ m/s^2, $H = 115$ m, and $Q = 10.57$ m^3/day, the hydraulic energy value is $E_{hyd} = 3.31$ kWh/day. This value indicates the system output energy actually used to lift water. Compared to the daily energy produced by PV (around 10.8–12.5 kWh/day), the overall system energy efficiency is in the range of 26–30%.

Wire-to-water efficiency indicates the percentage of electrical power successfully converted into hydraulic power. If the average input power to the pump is 1.5–1.7 kW (typical for a 2.4 kWp Lorentz pump), then the efficiency value ranges from 26%–29%. This value is in accordance with the international standard for DC BLDC pumps (20–35%). The pump operating duration per day ranges from 8–9 hours, with the active period following the solar radiation curve. The pump starts working around 7:00 AM and stops at 4:00 PM. This startup time is consistent with a battery-free system that relies solely on PV input. The runtime of 8–9 hours is considered good, considering the excellent irradiation conditions in Sumba. The volume of water successfully pumped from the SWPS describes the system's performance.

Environmental conditions at the SWPS location, especially solar radiation and ambient temperature, significantly influence the water flow rate from the SWPS. Table 3 shows the comparison of SWPS performance values between simulation and monitoring results.

Table 3. *Comparison of Operational time, Flow rate, Output from Simulation and Monitoring Result*

Description	Simulation	Monitoring
Operational hour	08.00-16.00 WITA	07.00-16.00 WITA
Daily output in average months	10.83 m^3	10,75 m^3
Flow rate	1,08 m^3/jam	1,07 m^3/jam
Months of Maximum flow-rate	Agustus, September	Mei, September, Oktober

5. Discussion

5.1 Discussion Of Findings

The operational output of the solar water pumping system (SWPS) follows the diurnal solar irradiance pattern. As irradiance increases from early morning toward midday, the available electrical power generated by the PV array rises accordingly, resulting in higher pump input power and increased water discharge. Consequently, peak pumping performance typically occurs during late morning to midday, when solar energy availability is at its highest.

This behavior is consistent with previous field and modeling studies. Imjai et al. (2020) reported that water pumping performance closely tracks solar resource availability, with maximum discharge occurring during periods of high irradiance. Similarly, Habib et al. (2023) and (Eker, 2005) demonstrated that pump discharge and delivered water volume increase proportionally with solar irradiance, reaching their maximum values around peak solar hours.

The yearly output of a SWPS is strongly influenced by seasonal variability in solar irradiance and sunshine duration, especially in tropical climates. In many equatorial regions, including Indonesia, the dry season typically runs approximately from May to October, featuring longer sunshine duration, clearer skies, and reduced cloud cover, which increases the available solar resource. Consequently, solar energy systems (including SWPS) tend to produce higher monthly output during these months, especially around the mid-year dry season and transitional periods such as May, September, and October. This consistent pattern of increased sunshine and irradiance during dry periods has been documented in tropical solar resource studies, which note clear seasonal cycles with higher sunshine hours and irradiance in the dry months compared to the wet season when cloud cover and rainfall reduce solar availability

For example, sunshine duration across several locations in Bali exhibited peak values during May to October, corresponding with higher solar energy availability, while irradiance analyses in Indonesia showed increased irradiance around the equinox periods (March–April and September–October), which are typical months for maximal radiation levels (Nugroho et al., 2025).

Sumba Island, located just south of the equator in East Nusa Tenggara Province of Indonesia, experiences a tropical monsoonal climate with only two distinct seasons, a dry season from approximately May to November and a wet season from December to April. During the dry season, there is clearer sky, reduced cloud cover, and longer periods of sunshine due to reduced rainfall and lower atmospheric moisture, which enhances solar irradiance reaching the surface. In contrast, the wet season has more frequent clouds and higher rainfall, which tends to reduce solar resource availability.

Because of this seasonal pattern, solar insolation and consequently solar water pumping output, tends to increase during the dry season months, particularly around the mid-season periods such as May, September, and October when the dry conditions are well established and cloud cover is minimal. This results in higher monthly SWPS output during these months compared to other periods of the year.

This climatic behavior is typical for equatorial tropical regions: while the length of daylight is nearly constant year-round, seasonal changes in cloudiness and rainfall, governed by monsoon winds, significantly affect solar resource quality. In equatorial zones like Sumba, the solar zenith angle does not vary much over the year, but cloud cover does, with clearer skies during the dry season leading to increased solar irradiation and thus higher energy production potential for solar systems.

The performance of SWPS is influenced by multiple interrelated technical, environmental, and hydraulic factors. Key technical parameters include pump head, TDH, pump efficiency, PV array capacity, module efficiency, orientation, mounting configuration, degradation rate, and the amount of unused or curtailed solar energy. Environmental conditions, particularly solar irradiance and ambient temperature, directly affect PV output and consequently the hydraulic energy delivered by the system. In addition, hydraulic and demand-related parameters, such as water flow rate, daily water demand, well characteristics, and maximum draw-down rate, contribute substantially in determining system stability and operating time. Variations in irradiance may also induce fluctuations in pump pressure, requiring appropriate pressure compensation mechanisms to maintain operational reliability (Ahmed et al., 2023; Chandel et al., 2015; Maity et al., 2024; Mustafa et al., 2016).

5.2 Implications

This study provides field-based validation of a 2.4 kW SWPS operating under high-head conditions in Sumba Island, Indonesia, where access to reliable electricity and water infrastructure remains limited. By directly comparing monitored performance data with simulation outputs, the research bridges an important gap between theoretical modeling and actual system behavior. While simulation tools are widely used for system sizing and feasibility assessment, discrepancies often arise due to real operating losses, fluctuating irradiance, temperature effects, and hydraulic inefficiencies. The present findings therefore contribute valuable empirical evidence that strengthens confidence in performance prediction models while highlighting the necessity of incorporating site-specific parameters, particularly under high TDH conditions.

From a technical perspective, the results demonstrate that photovoltaic-driven pumping systems remain viable even when subjected to elevated hydraulic loads. High-head applications demand greater hydraulic power making system efficiency more sensitive to electrical and mechanical losses. Field observations of motor efficiency, flow rate variation, energy yield, and operating time under real irradiance and ambient temperature conditions provide practical design insights. These findings complement previous reviews of solar water pumping technologies, which emphasize the importance of accurate system sizing and local climate considerations in off-grid applications (Aliyu et al., 2018; Gevorkov et al., 2023). The empirical data generated in this study therefore extend the literature by specifically addressing high-head performance in a tropical rural context.

Beyond technical validation, this research carries important socio-economic and sustainability implications. In remote areas where diesel fuel is costly and grid infrastructure is limited, solar water pumping systems offer a decentralized and low-operating-cost alternative. Prior studies in rural Indonesia have shown that SWPS deployment can enhance local resilience, reduce operational expenditures, and improve access to essential water services (Rahmani et al., 2022). By documenting real-world system behavior under challenging hydraulic and climatic conditions, this study supports broader efforts to integrate renewable energy technologies into rural development strategies.

Therefore, the findings reinforce the role of solar water pumping systems as a technically feasible and environmentally sustainable solution for addressing water scarcity in off-grid, high-elevation regions. The combination of simulation comparison, field validation, and seasonal performance analysis provides evidence that can inform system designers, policymakers, and development agencies seeking scalable renewable energy–based water supply solutions in eastern Indonesia and similar tropical environments.

5.3 Limitation

This study evaluates the technical performance of a single 2.4 kWp solar water pumping system operating under high-head conditions in Sumba Island. As the analysis is based on one installation, the findings reflect site-specific climatic, hydraulic, and operational characteristics. Therefore, the results cannot be directly generalized to systems installed in different geographical locations, hydraulic configurations, or environmental conditions. Variations in solar resource patterns, groundwater depth, pipe network design, and user demand profiles may lead to different performance outcomes.

The monitoring period covers one year of operation. Although this duration captures seasonal variability, it does not account for long-term system degradation effects such as photovoltaic module aging, pump wear, scaling in pipelines, or gradual efficiency reduction of electrical components. Multi-year performance monitoring would provide a more comprehensive understanding of reliability, durability, and lifecycle behavior under sustained high-head operation.

Furthermore, this study focuses primarily on technical performance indicators, including irradiance response, motor efficiency, flow rate, output energy, and operating time. Economic evaluation, such as life-cycle cost analysis, payback period, levelized cost of water, and comparison with diesel-based alternatives, was beyond the scope of this work. Integrating techno-economic analysis in future studies would strengthen decision-making support for policymakers and rural infrastructure planners.

5.4 Future Works

Future research should extend monitoring over multiple years to assess long-term reliability and component degradation. The installation of on-site irradiance sensors and enhanced electrical monitoring would enable more detailed wire-to-water efficiency analysis and improved performance modeling. Additionally, comparative multi-site studies and integrated techno-economic evaluations would further strengthen the basis for large-scale deployment of SWPS in similar tropical and high-head environments.

6. Conclusion

This study evaluated the performance of a 2.4 kWp solar-powered water pumping system operating under high-head conditions in Kadaghu Tana, Sumba, Indonesia, and assessed its suitability for remote water supply applications. The results demonstrate that the system operates reliably under local solar irradiation levels of 4.8–6.0 kWh/m^2/day, confirming the technical feasibility of photovoltaic-driven pumping in off-grid, high-elevation environments.

Field monitoring shows that pump operation occurs between 07:00 and 16:00 WITA, slightly earlier than predicted by simulation (08:00–16:00 WITA), indicating effective utilization of early-morning irradiance. The highest operational output was consistently observed during 10:00–11:00, corresponding to peak solar irradiance conditions and maximum available PV power. This confirms the strong correlation between diurnal solar radiation patterns and hydraulic performance under high-head loading.

Seasonal analysis further reveals that system output peaks in May, September, and October, which coincide with the dry-season period in Sumba when cloud cover is reduced and solar resource availability is higher. This seasonal alignment enhances the suitability of SWPS for rural water supply, as higher system productivity occurs during periods of increased water demand and limited rainfall.

The monitored average flow rate and monthly water output closely match simulation results, validating the hydraulic and energy modeling approach for high-head applications. Key performance indicators, including yield factor, hydraulic energy output, and overall system efficiency, indicate stable performance and efficient solar energy utilization. These findings confirm that the selected integration of PV capacity, MPPT control, and Lorentz DC pump is technically appropriate for off-grid, high-head conditions in Sumba. Overall, this study provides field-based evidence supporting solar water pumping as a reliable and sustainable solution for remote communities facing water and electricity constraints.

Author's Contribution

Emerita Setyowati: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Supervision. **Anita Yuan:** Methodology, Writing – review & editing. **Shanti Dharmawanti:** Data collection, Data presentation, reviewing. All authors have reviewed and approved the final manuscript and agreed to the order of authorship.

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Ethical statement

This article reports a theoretical/modelling/simulation study and does not involve human participants or animals. The authors confirm that no personal or sensitive data were collected, processed, or analyzed in this study.

Declaration of AI use

AI tools may have been used in the translation or editing of this article. All AI-assisted outputs were carefully reviewed, revised, and approved by the authors.

Conflict of Interest

The authors declare that there is no conflict of interest, either financial or non-financial, that could be perceived as influencing the work reported in this manuscript. All authors have reviewed and approved this statement.

Supplementary Materials and Data Availability

No public repository is currently available for the dataset. However, the instruments and key data summaries used in this study can be obtained from the corresponding author upon reasonable request.

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