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Analysis of the Impact of Solar Radiation on the Battery Charging Duration and Operation of a DC Solar-Powered Water Pump

Bakti Indra Kurniawan[1]*, Mohammad Noor Hidayat[1], Priya Surya Harijanto[1], Ananda Setyo Abimanyu[1], Naufaliawan Abraham[1]

[1] Department of Electrical Engineering, Politeknik Negeri Malang, 65141, **Indonesia.**

*bakti@polinema.ac.id

Abstract

This research examines the effect of solar irradiance on the performance of a solar-powered water pump (SWP). The primary objective is to determine how solar irradiance affects battery charging time and pump operational duration. Using a system consisting of a solar panel, a battery, and a pump in the Malang region, we collected data on both sunny and cloudy days. The results indicate that solar irradiance is a crucial determinant of the system's efficiency. On sunny days, battery charging is faster, and the pump can operate for a longer period. Conversely, on cloudy days, battery charging slows down, and the pump's duration becomes shorter. This study concludes that solar irradiance is a key factor in optimizing SWP systems, and the use of a battery is essential to ensure stable operation.

Keywords: Battery Charging, Efficiency, Solar Water Pump, Solar Irradiance

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1. Introduction

Solar energy is one of the most promising renewable energy sources, especially for countries located along the equator, such as Indonesia. The country benefits from consistent and abundant solar radiation throughout the year, which provides a significant opportunity for harnessing solar energy. Specifically, in Malang City, located in East Java Province, solar energy potential is maximized due to its stable solar radiation intensity [1]. This region's favorable climatic conditions—characterized by year-round sunshine—provide an ideal environment for the development of renewable energy technologies, including solar-powered water pumps (SWPs) [2].

Over the past few decades, solar energy has gained significant attention as an alternative to conventional energy sources, particularly in regions with limited access to electricity or in rural areas. In Indonesia, many rural areas and islands still face challenges related to energy accessibility and reliability, which makes solar power a viable and environmentally friendly solution [3]. Previous studies, such as those conducted by Timotius, 2023 and Fathaddin, 2023, have demonstrated the feasibility of using solar energy for water pumping in tropical climates, including Indonesia [4]. These studies emphasize how solar radiation levels directly influence the performance of photovoltaic systems, which in turn affect the efficiency of solar-powered water pumps.

The operation of solar-powered water pumps is highly dependent on solar irradiance. The amount of solar radiation received by the photovoltaic (PV) panels determines the energy output, which powers both the battery charging process and the pump's operation [5-8]. Variations in solar radiation throughout the day, as well as seasonal fluctuations, can significantly affect the duration of battery charging and the operational time of the pump [9-11]. On days with higher irradiance, solar panels are able to charge the battery more quickly and allow the pump to operate for longer periods. In contrast, on cloudy or rainy days, the reduced solar radiation results in slower battery charging and shorter pump operation times.

In the context of Malang City, which experiences both sunny and cloudy days throughout the year, understanding the impact of solar radiation on battery charging duration and pump operation is essential for optimizing solar-powered water pump systems. The goal of this study is to investigate how variations in solar irradiance affect the performance of SWP systems, focusing on the relationship between solar radiation, battery charging times, and pump operation durations [12].

By examining this relationship, this research aims to contribute to the optimization of energy storage systems, such as batteries, to ensure more stable and efficient operation of solar-powered water pumps, particularly in regions where sunlight intensity is inconsistent [13]. Furthermore, the findings of this study have the potential to support Indonesia’s national energy policy, which targets increasing the share of renewable energy to 23% by 2025 and 31% by 2050.

The results of this study are expected to provide valuable insights for the development of sustainable and efficient solar energy technologies in rural and remote areas of Indonesia. These technologies could not only help address local water needs but also contribute to reducing the environmental impact of conventional energy sources [14]. As such, this research is not only relevant to the field of renewable energy but also plays a crucial role in the broader context of sustainable development and energy security in Indonesia [15].

2. Methods

The research process begins with the collection of solar radiation duration data and irradiance conditions in Malang City for a day. The next step is to analyze the solar radiation conditions, including the highest, lowest, and average radiation values. Following that, a State of Charge (SoC) test is performed on a 12V 21Ah $LiFePO_4$ battery using two 60 Wp solar panels, starting from 10:00 AM to 2:00 PM with an initial SoC of 20%. The next step involves conducting a Depth of Discharge (DoD) test on the same 12V 21Ah $LiFePO_4$ battery with a DC 180W water pump load at 80% DoD. The final stage involves analyzing data on the effect of solar radiation on battery charging time and the operational duration of the DC 180W pump.

To measure the impact of temperature on panel efficiency, the temperature of the panels was measured using a K-type thermocouple sensor placed near the surface of the panel. This measurement helps to identify the relationship between panel temperature and the output power generated.

Tabel 1. Additional Data on Solar Panel Temperature and Output

Time	Solar Radiation (W/m^2)	Panel Temperature (°C)	Panel Output (W)
10:00 AM	950	32	54
10:30 AM	1120	35	65
11:00 AM	1300	38	78
11:30 AM	1180	37	70
12:00 PM	900	36	55
12:30 PM	750	34	45

This data reflects the relationship between solar radiation, panel temperature, and output power. As observed, higher solar radiation caused the panel temperature to increase, which in turn increased the panel output until a certain threshold. After reaching this point, a decrease in efficiency was observed due to the high operational temperature of the panels, indicating the importance of temperature management for maximizing the system's efficiency.

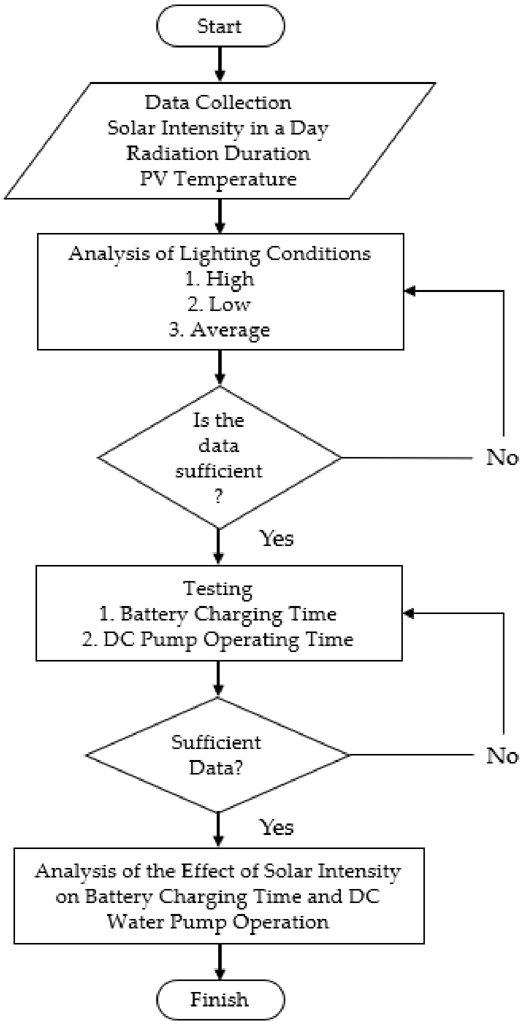

Figure 1. Research Flowchart

The State of Charge (SoC) test was conducted over two days to compare the battery charging times on each day. The test started at 10:00 AM and continued until the battery SoC reached 100%. The Depth of Discharge (DoD) test was conducted with two load variations: one for a water tank height of 1 meter and one for 4 meters. In the experiment on the effect of solar panel temperature on power output, two methods were used: direct experimentation and the use of the Pvsyst software to obtain more accurate data and visualization.

In the system setup, the solar panels were oriented to the north due to the research location's latitude of -7.997 and longitude of 112.634. The optimal tilt angle was used since Malang District is located south of the equator [8].

2.1 Equipment Specifications

Foldable PV (Photovoltaic Panel) is a type of portable photovoltaic panel designed for mobile applications and flexible outdoor use. This panel functions to absorb sunlight and convert it into electrical energy. It can be folded into a compact size, making it easy to transport and store, making it ideal for portable energy systems like DC water pumps [9].

Figure 2. Foldable PV Panel

Specifications of the Foldable PV used:

- Rated Power: 60 W (±5W)
- Open Circuit Voltage (Voc): 25.6 V
- Short Circuit Current (Isc): 3.06 A
- Max Power Voltage (Vmp): 22 V
- Max Power Current (Imp): 2.94 A
- Efficiency: 25%
- IP (Ingress Protection): 68

A battery is an essential device for storing electrical energy, which can be used as needed and can be easily carried or moved to other locations. A small-scale example is the use of batteries in hybrid electric drive (HEV) systems or renewable energy applications [10].

Figure 3. Lifepo4 Battery

Specifications of the Lifepo4 Battery used:

- Nominal Voltage: 12.8 V
- Charging Voltage: 13.7 Max / 14.2 V
- Capacity (Ah/Wh): 21 Ah/268 Wh
- Discharge (W): Max. 200 W
- Minimum Voltage: 12 V
- Production Date: 20-06-2025

A Maximum Power Point Tracker (MPPT) is an electronic circuit that optimizes the operation of solar panels to achieve maximum power output. One method to achieve this is by adjusting the voltage, either increasing or decreasing it, until the maximum power point of the panel is reached [11].

Figure 4. Lifepo4 Battery

Specifications of the Solar Charge Controller used:

- System Minimum Voltage: 12/24 V DC
- Rated Charge Current: 30 A
- Rated Discharge Current: 30 A
- Battery Input Voltage Range: 8-32 VDC
- Max. PV Open Circuit Voltage: 100 VDC
- Max. PV Input Power: 390 W(12V) / 780W(24V)
- Self-Consumption: 30mA (12V) / 16mA (24V)
- Battery Support: Sealed/Flooded/Gel
- IP Rate: IP33
- RS485 Interface: 5VDC/200mA (RJ45)
- LCD Backlight Time: 60 sec (default)
- Dimensions: 230x165x63 mm

- Weight: 31 KG

A pump is a mechanical device used to raise fluids from a lower place to a higher one or to move fluids from a low-pressure area to a high-pressure area. Pumps are also used to increase the flow rate in piping systems. The pump works by applying pressure and drawing fluid. The suction side of the pump reduces the pressure in the pump chamber, creating a pressure difference between the surface of the fluid being drawn and the pump chamber itself [4].

Figure 5. DC Water Pump

Specifications of the DC Water Pump used:

- Model: HNWQB 12 V
- Max. Flow: 1.5 m^3/h
- Max. Head: 15 m
- Power: 180 W
- Outlet: 1 INCH
- Voltage: 12 Volt
- Single Line Diagram (SLD) of Equipment

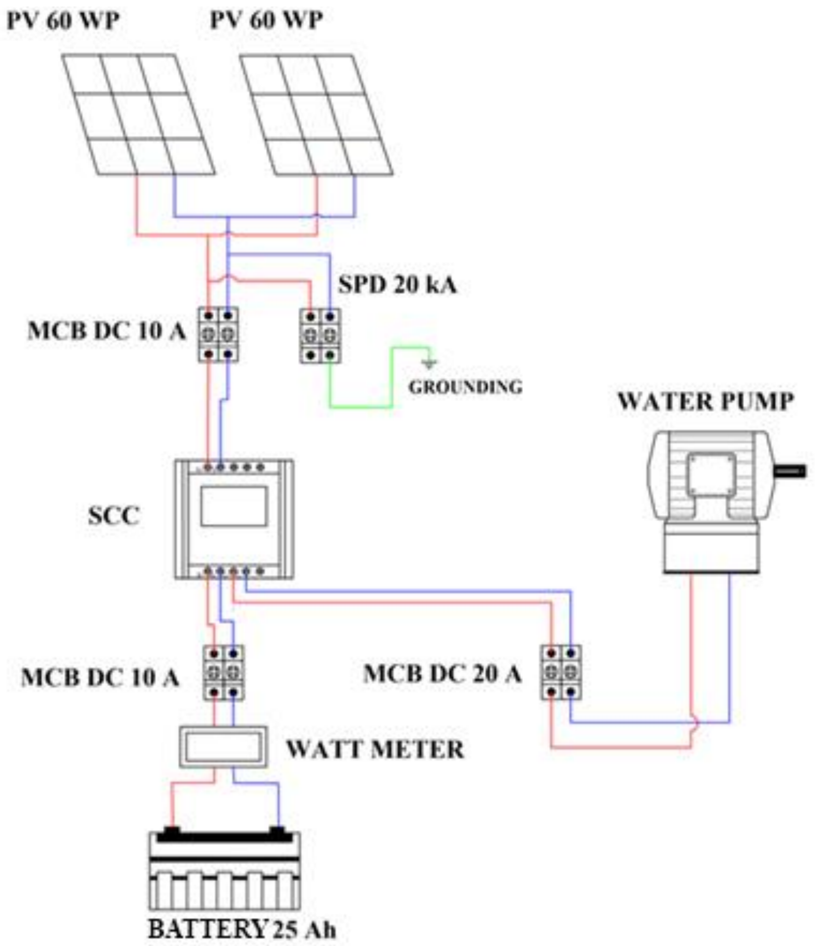

Figure 6. Single Line Diagram of Equipment

This diagram illustrates the portable Solar Power Generation System (PLTS) used to drive the water pump. The following is an explanation of each component and its function:

PV (Photovoltaic) 60 WP: These are two solar panels with a capacity of 60 Watt Peak (WP) each. They serve as the primary energy source, converting sunlight into direct current (DC) electricity. In this diagram, the two panels are connected in parallel to combine their output power.

SPD (Surge Protection Device) 20 kA: This component protects the system from voltage surges (such as lightning or other electrical disturbances). When a voltage surge occurs, the SPD directs the surge to the ground to prevent damage to other electronic components.

MCB (Miniature Circuit Breaker) DC 10 A: This circuit breaker acts as protection against overcurrent. It disconnects the circuit in the event of an overload or short circuit, thus protecting the SCC and other components.

SCC (Solar Charge Controller): This is the brain of the system. The SCC regulates the charging process from the solar panels to the battery. It is crucial in preventing overcharging (which can damage the battery) and over-discharging (which can reduce battery lifespan).

25 Ah Battery: This component stores the electrical energy generated by the solar panels. The 25 Ah battery stores energy for use when the solar panels are not generating electricity, such as at night or on cloudy days.

Watt Meter: This device measures the electrical power usage from the battery. The watt meter displays the amount of power being consumed by the load.

MCB DC 20 A: This is another circuit breaker installed after the battery and before the load. Its function is similar to the previous MCB, protecting the water pump from excess current.Water Pump: This is the load device driven by the PLTS system. The water pump uses DC electricity from the battery to pump water.

2.1 Solar Irradiance Conditions in Malang City

Indonesia has two distinct seasons, namely the dry season and the rainy season. Therefore, solar irradiance conditions vary throughout the year, especially in Malang City, East Java. According to the Central Statistics Agency, the solar irradiance conditions throughout the year in 2023 are as follows [12]:

Tabel 2. Duration of Solar Irradiation

Month	Solar Irradiation Duration (Hours/Day)
January	7,6
February	7,0
March	5,0
April	2,8
May	5,8
June	4,7
July	6,8
August	6,8
September	6,8
October	8,4
November	8,3
December	9,1

The data in Tabel 2. shows the average number of sunlight hours per day in each month. Malang City tends to receive the highest solar radiation in October to December, exceeding 7 hours per day. The lowest radiation occurs in March to June, below 4.5 hours per day.

Solar radiation is electromagnetic radiation generated by nuclear fusion reactions at the Sun's core. Under clear sky conditions, the energy that reaches Earth's outer atmosphere is typically 1367 W/m² in the form of short waves (± 4.0 μm). However, only a portion of this energy reaches Earth's surface and oceans. As radiation enters the Earth's atmosphere, several processes occur – some of it is scattered by atmospheric particles, some is absorbed by these particles, and some is absorbed by the Earth's surface [13].

As a tropical country, Indonesia has a high potential for solar energy, with an average daily irradiation of 4.5 to 4.8 KWh/m²/day. However, the electricity generated by solar cells is highly dependent on sunlight intensity, causing the power output of solar panels to be fluctuating [14].

3.Results and Discussion

3.1 Solar Irradiance Conditions in Malang City in One Day

To assess the actual solar irradiance, experiments were conducted with two 60-Watt solar panels from 10:00 AM to 12:50 PM in Singosari District, Malang Regency, with measurement intervals of 5 minutes. To gather the required data, experiments were conducted as follows:

Figure 7. Irradiation and Output Power Graph of the Panel

From the data in **Figure 7**, the experiment shows a significant variation in solar intensity. The highest solar intensity was recorded at 11:55 AM at 1324.9 W/m², while the lowest intensity occurred at 12:15 PM at 283.2 W/m². The average solar intensity recorded was around 942.0 W/m². It should be noted that measurements were not taken simultaneously, which may result in data variations due to changing weather conditions. The intensity of sunlight significantly affects the output of solar panels. As solar intensity increases, the voltage and current output of the photovoltaic (PV) system also rise, increasing the overall power output.

3.2 Effect of Solar Irradiance on Battery Charging Time

In this study, two foldable PV units, each rated at 60 WP, were used, providing a total of 120 WP. The energy produced was used to charge a $LiFePO_4$ 12V 21Ah battery, with the assistance of a 30A MPPT charge controller. Measurements were taken every 5 minutes to capture fluctuations in solar intensity and the characteristics of battery charging in detail. Parameters recorded include solar irradiance (W/m²), voltage, charging current, and charging time. The following graph illustrates the results of the field measurements, which served as the basis for analyzing the relationship between solar irradiance and battery charging time.

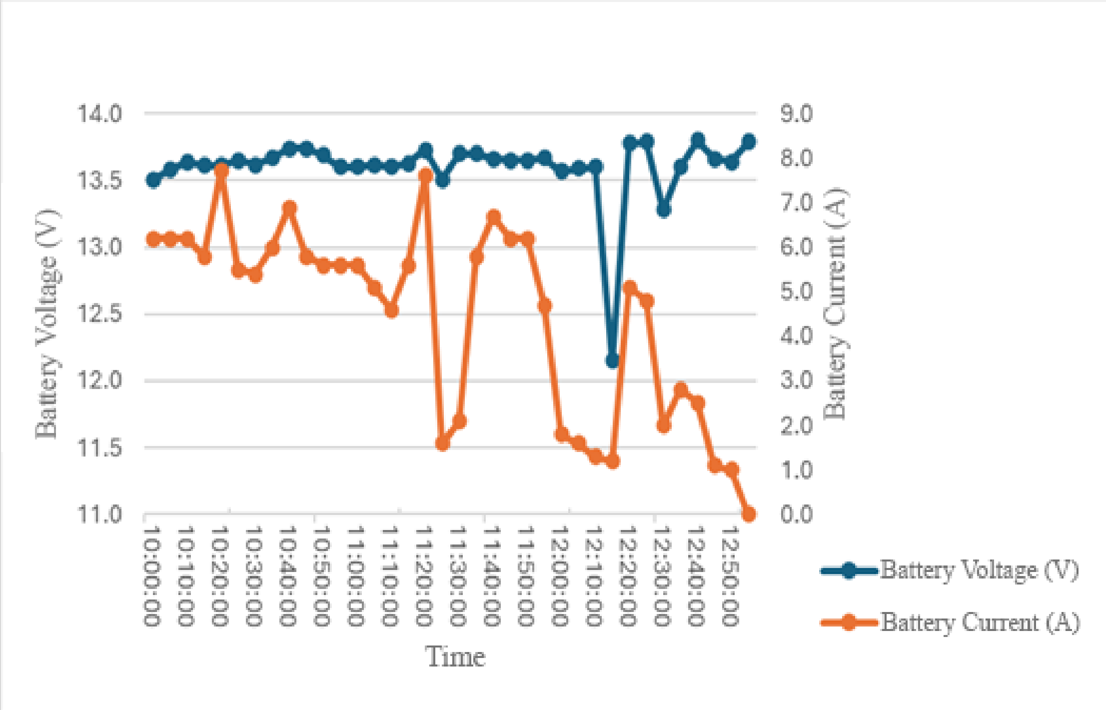

Figure 8. Voltage and Charging Current Graph

Based on the data in **Figure 8**, battery charging started at 10:00 AM with an initial battery voltage of 13.50 V and a State of Charge (SoC) of 20%. The data was recorded every 5 minutes until 12:55 PM, when the SoC reached 100%. The total effective charging time required to increase the battery capacity from 20% to 100% was approximately 175 minutes (3 hours). This process used two 60-WP solar panels, yielding a maximum power output of about 120 WP, with solar irradiance ranging from 800 to 1100 W/m².

The time required to charge the battery using solar panels is influenced by several factors, including changing weather conditions that cause fluctuations in the power converted by the panels. During periods of high irradiance, such as at 10:15 AM (1122.30 W/m²) and 10:40 AM (1070.10 W/m²), the current entering the battery was relatively high, 5.50 A and 5.30 A respectively, which accelerated the charging process. However, at 12:15 PM, the irradiance dropped drastically to 283.20 W/m², reducing the charging current to only 1.00 A, and slowing the charging rate. This shows that solar irradiance is directly proportional to the battery charging speed, as long as the temperature is not extreme and the voltage remains within the optimal range.

3.3 Effect of Solar Irradiance on the Operating Duration of the DC Solar-Powered Water Pump

This test was conducted to determine the duration of the operation of a DC solar-powered water pump, using energy from a fully charged $LiFePO_4$ 12V 21Ah battery. The main aim was to analyze how long the battery could maintain the pump's operation from 100% capacity down to the minimum operational limit, which is 20%. During the test, data including battery voltage (V), load current (A), output power (W), battery temperature (°C), remaining capacity (%), and energy (Wh) were recorded.

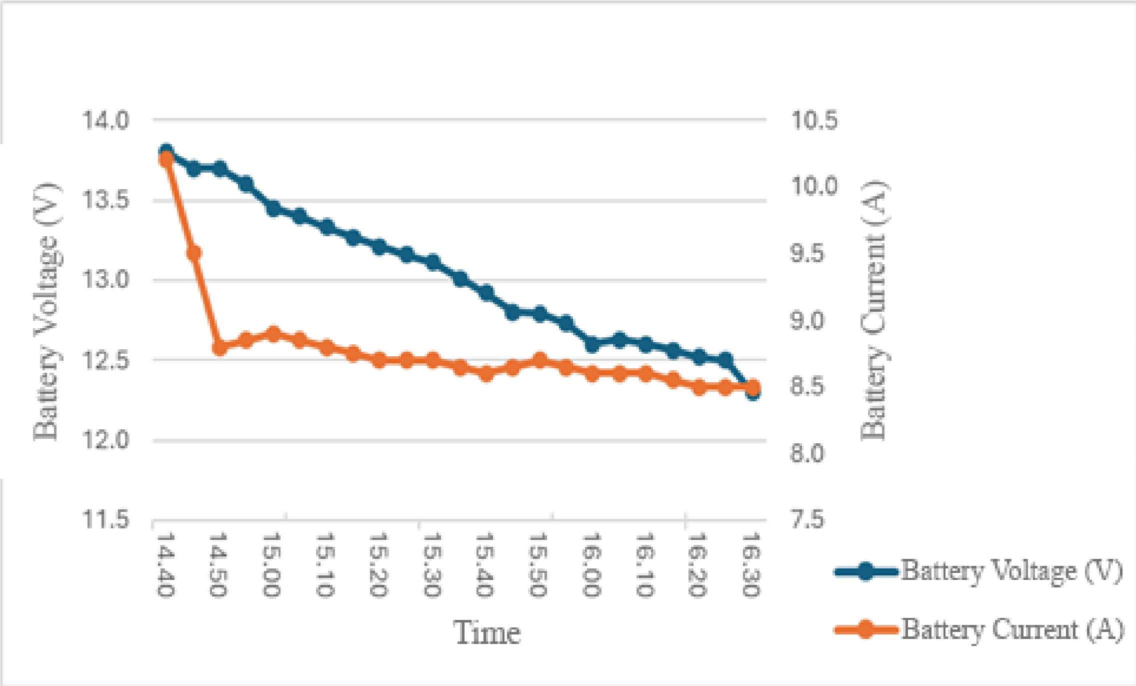

Figure 9. Voltage and Discharge Current Graph

As shown in **Figure 9**, during the operation of the pump, the current initially increased to 10.2 A, while the voltage remained stable at around 13V.

3.4 Effect of Solar Irradiance on the Performance of the DC Solar-Powered Water Pump

On the third day of the experiment, tests were carried out to observe the effect of solar irradiance on the performance of a water pump without using a battery. The test was conducted from 10:30 AM to 2:00 PM under cloudy weather conditions. Using two 60-WP solar panels and a 180-Watt DC water pump, the results of the test were as follows:

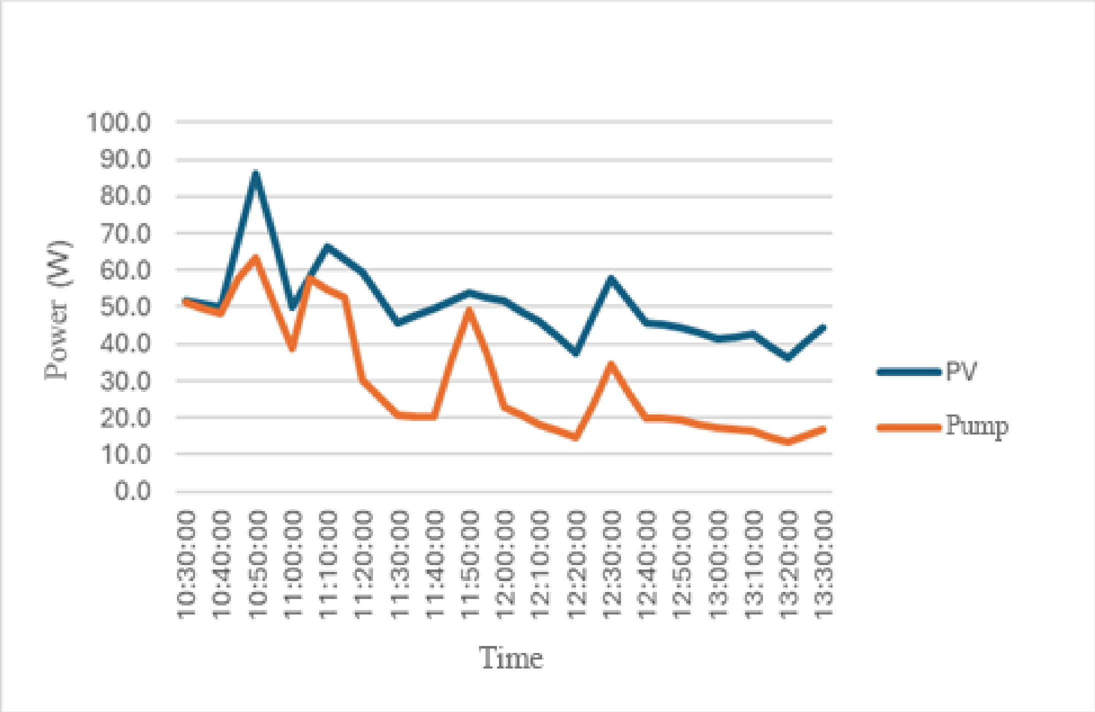

Figure 10. Comparison of Panel Power and Water Pump Power Graph

Based on the data in **Figure 10**, the test was conducted to measure the performance of a 180-Watt DC pump powered directly by two 60-WP solar panels (total 120 WP), without using a battery for energy storage. The observation showed that the power output from the PV panels fluctuated throughout the test as solar irradiance changed. The highest PV power was recorded at 10:50 AM at 86 watts when the irradiance reached 907.3 W/m². Meanwhile, at 12:20 PM, the lowest PV power recorded was only 37.6 watts when irradiance dropped drastically to 123.7 W/m².

The performance of the DC pump greatly depends on the amount of power supplied by the solar panels directly. Since the system did not use a battery, any decrease in solar intensity directly reduced the voltage and current going to the pump, which made the pump unable to perform optimally. In some instances, the pump generated very low power or functioned intermittently (on/off).

Overall, the results of these tests indicate that operating a DC pump without a battery is highly dependent on solar irradiance. When the irradiance is high, the PV power is sufficient to operate the pump at full capacity. However, when the irradiance drops, the performance of the pump decreases as the supply power becomes insufficient. This highlights the need for an energy storage system, such as a battery or capacitor, to ensure stable and efficient pump operation, especially in areas with fluctuating weather conditions.

4. Conclusion

Solar irradiance has a significant impact on the output of solar panels. When the intensity is high (e.g., under clear weather at 1324.9 W/m² at 11:55 AM), the panel generates higher voltage and current, resulting in increased electrical power. On the other hand, when the intensity is low (e.g., under cloudy weather at 283.2 W/m² at 12:15 PM), the output of the panel drastically decreases, particularly the current, which is a key determinant of the system's efficiency.

Battery charging time is highly influenced by solar irradiance. During high irradiance, such as 1129.2 W/m² at 10:20 AM, the battery charges faster due to higher current. However, during low irradiance, such as 283.2 W/m² at 12:15 PM, the lower current results in a slower charging process. In the test, the battery was fully charged (from 20% to 100%) in approximately 3 hours under clear weather conditions.

The operating duration of the pump is also highly dependent on the available energy from the battery and solar irradiance while the system is running. Under high irradiance, the fully charged battery can operate the pump for about 2 hours. In contrast, when irradiance is low, the available energy is limited, and the pump's operational duration becomes shorter. Additionally, in the experiment where the pump operated without a battery, powered directly by the PV panels, it was shown that the pump's power was generally insufficient, making the performance inefficient.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - All data is available from the authors.

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Additional information - No additional information from the authors.

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