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Design and Construction of an IoT-Based Water Pump Cart with a Sliding Solar Panel System for Agricultural Applications

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ABSTRACT

Limited access to energy and irrigation in agricultural areas has encouraged the development of autonomous renewable energy-based water pumping systems. This study presents the design and implementation of a mobile solar-powered water pumping system integrated with an Internet of Things (IoT)-based irrigation platform and a sliding photovoltaic (PV) mechanism to optimize solar energy harvesting. The proposed system consists of an 800 Wp PV array, a 12 V 200 Ah battery, soil moisture sensors, and a real-time IoT monitoring platform. System performance was evaluated through experimental testing under field conditions. Results demonstrate that the system can produce a water discharge of approximately 1200 liters/hour and fulfill irrigation demands of 1500 liters within 1.25 hours. The available energy capacity of 1200 Wh was sufficient to support pump operation requiring around 1000 Wh per cycle, ensuring stable and autonomous performance. Field implementation also showed improvements in agricultural productivity, with crop yield increasing by 36% and harvesting time reduced by 17%. These findings indicate that the proposed system is technically feasible, energy-efficient, and suitable as a sustainable irrigation solution for small-scale farming applications in remote areas.

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I. Introduction

Agriculture remains a fundamental pillar of the global economy, particularly in developing countries such as Indonesia, where it plays a crucial role in food security and rural livelihoods. However, the agricultural sector is increasingly challenged by climate change, resource degradation, and rising food demand, all of which necessitate more efficient water and energy management strategies [1]. In this context, the energy–water nexus has emerged as an important framework for developing sustainable agricultural systems by emphasizing the interdependence between water availability and energy consumption.

In many rural agricultural areas, irrigation systems still depend on grid electricity or fossil fuel-powered pumps, which are often associated with unstable energy access, high operational costs, and increased greenhouse gas emissions [2], [3]. These limitations are particularly critical in remote regions where electrical infrastructure remains limited or unreliable. Consequently, Solar Water Pumping Systems (SWPS) have gained significant attention as a renewable-energy-based alternative due to their capability to utilize abundant solar resources while reducing long-term operational costs and environmental impacts [4].

Despite these advantages, the performance of conventional SWPS is still constrained by the use of fixed photovoltaic (PV) configurations that cannot continuously maintain optimal solar irradiation angles throughout the day. Although active solar tracking systems can improve energy harvesting efficiency, they generally require additional actuators, control circuits, and parasitic power consumption, which increase system complexity, maintenance requirements, and implementation costs. Therefore, there is a growing need for simpler and more energy-efficient alternatives capable of enhancing solar energy utilization without relying on complex tracking mechanisms. One promising approach involves mechanically adaptive PV structures, such as sliding photovoltaic mechanisms, which can improve effective solar exposure while maintaining structural simplicity and lower energy consumption [5], [6].

Simultaneously, the rapid advancement of Internet of Things (IoT) technology has transformed conventional irrigation practices into intelligent and data-driven systems. IoT-based irrigation systems commonly integrate environmental sensors, including soil moisture and water level sensors, with electrical monitoring parameters such as PV voltage, current, battery condition, and water flow rate to enable real-time monitoring and automated irrigation control. Previous studies have demonstrated that IoT-enabled irrigation systems can improve water-use efficiency by approximately 30–50% compared with conventional irrigation methods [7], [8]. However, most existing studies primarily focus on stationary irrigation systems using fixed PV installations or complex active solar trackers. Furthermore, the integration between adaptive solar energy harvesting mechanisms and intelligent irrigation control remains relatively limited, as these two aspects are generally investigated separately.

Based on the literature review, three major research gaps can be identified. First, existing SWPS designs predominantly utilize either static PV modules or actively tracked systems, while low-complexity mechanical approaches for improving solar energy harvesting remain insufficiently explored. Second, most IoT-based irrigation systems emphasize monitoring and automation functions without integrating adaptive renewable-energy optimization mechanisms. Third, mobility and portability aspects are rarely considered, despite their importance for small-scale agricultural environments requiring flexible irrigation deployment across multiple cultivation areas.

To address these limitations, this study proposes an IoT-based mobile solar water pumping system incorporating a sliding photovoltaic (PV) mechanism for smart agricultural applications. The proposed system integrates a mechanically adaptive sliding PV structure, real-time IoT monitoring, automated irrigation control, and a mobile cart platform into a unified architecture. Unlike conventional systems that rely on fixed PV installations or active tracking methods, the proposed sliding mechanism is designed to increase solar energy harvesting capability while maintaining low mechanical complexity and reduced auxiliary power consumption.

The objectives of this study are threefold: (1) to design and implement a mobile IoT-based solar water pumping system with a sliding PV mechanism, (2) to evaluate the effectiveness of the sliding PV configuration in improving solar energy harvesting performance compared with conventional fixed PV systems, and (3) to analyze the system capability in achieving stable irrigation operation through real-time monitoring and automatic soil-moisture-based control. System performance is quantitatively evaluated based on electrical efficiency, irrigation stability, solar energy utilization, and IoT monitoring reliability. The proposed system is expected to achieve higher solar energy absorption efficiency and improved irrigation effectiveness while maintaining low operational complexity suitable for small- and medium-scale agricultural applications.

Table 1. Systematic comparison between the proposed system and previous studies

Study	IoT Monitoring	Solar Tracking	Sliding PV	Mobile System	Auto Irrigation	Contribution
Author A	✓	Fixed PV	✗	✗	✓	Smart irrigation only
Author B	✓	Active Tracking	✗	✗	✓	Higher energy efficiency
Author C	✗	Fixed PV	✗	✓	✗	Portable irrigation cart
Proposed Study	✓	Sliding PV	✓	✓	✓	Integrated low-complexity adaptive irrigation system

In addition, the novelty of this work lies in the integration of four key aspects within a single low-cost architecture: (1) a mechanically adaptive sliding PV mechanism, (2) mobile irrigation deployment, (3) IoT-based real-time monitoring, and (4) automated irrigation control based on environmental parameters. A systematic comparison between the proposed system and previous studies is presented in Table 1 to highlight the distinct contributions and advantages of the proposed approach. Therefore, this study contributes to the development of practical, energy-efficient, and intelligent irrigation technologies that support sustainable and smart agriculture implementation.

A. Theoretical Framework

1. Solar Water Pumping System (SWPS)

A Solar Water Pumping System (SWPS) is a renewable-energy-based irrigation system that utilizes photovoltaic (PV) modules to convert solar radiation into electrical energy for operating water pumps. The performance of SWPS is highly dependent on solar irradiance intensity, environmental temperature, and PV panel orientation. In agricultural applications, SWPS offers several advantages, including reduced operational costs, low greenhouse gas emissions, and independence from conventional electrical grids. However, conventional SWPS commonly employ fixed PV configurations, which are unable to maintain optimal solar exposure throughout the day, resulting in suboptimal energy conversion efficiency and unstable irrigation performance under varying environmental conditions.

2. Sliding Photovoltaic Mechanism

The sliding photovoltaic (PV) mechanism is a mechanically adaptive approach designed to improve solar energy harvesting without employing complex active solar tracking systems. Unlike active trackers that require continuous rotational movement using motors and control algorithms, the sliding mechanism utilizes linear mechanical displacement to increase the effective solar exposure area while maintaining lower auxiliary energy consumption and reduced system complexity. In this study, the sliding PV structure is implemented to enhance electrical power generation efficiency while preserving system simplicity, portability, and suitability for small-scale agricultural applications. The effectiveness of the sliding mechanism is evaluated by comparing its electrical performance with that of conventional fixed PV systems under similar environmental conditions.

3. IoT-Based Smart Irrigation System

Internet of Things (IoT)-based irrigation systems enable real-time monitoring and automated irrigation control through the integration of sensors, microcontrollers, and wireless communication technologies. In agricultural irrigation applications, soil moisture sensors are commonly used to measure soil water content and determine irrigation requirements automatically. In this study, soil moisture is used as the primary control parameter for pump operation. When the soil moisture value falls below a predefined threshold, the irrigation pump is automatically activated, whereas the pump is deactivated when the soil moisture exceeds the specified threshold value. In addition, the IoT system enables real-time monitoring of electrical parameters, including PV voltage, current, battery condition, and water flow rate, thereby improving system monitoring efficiency and irrigation reliability.

4. Energy Harvesting Efficiency

Energy harvesting efficiency refers to the ability of the photovoltaic system to convert available solar energy into usable electrical energy. The efficiency of PV energy harvesting is influenced by solar irradiance, panel orientation, environmental conditions, and system design. In this study, the energy harvesting performance of the proposed sliding PV mechanism is evaluated by comparing the electrical output generated by the sliding PV configuration with that produced by a conventional fixed PV system. The efficiency of the photovoltaic system can be expressed as:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% \tag{1}$$

where η represents the energy harvesting efficiency (%), P_{out} is the electrical output power generated by the PV system, and P_{in} is the total solar energy input received by the photovoltaic module. This parameter is used to evaluate the effectiveness of the proposed sliding PV mechanism in enhancing solar energy utilization for irrigation applications.

II. Methods

Flow diagram

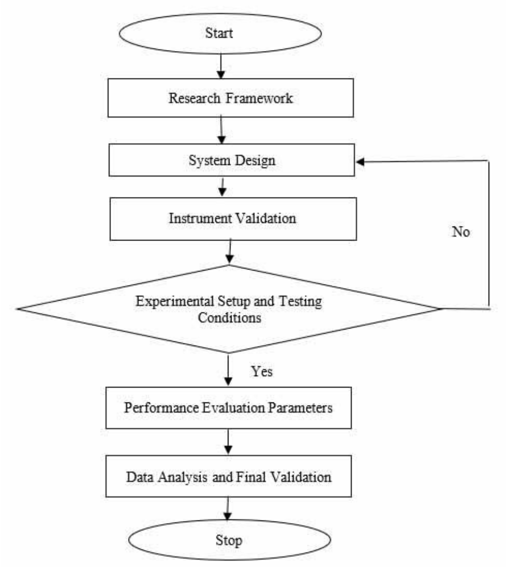


Figure 1. Research flow diagram

A. Research Framework

This research was conducted systematically through several stages, including problem identification, integrated system design, hardware implementation, experimental testing, performance evaluation, and final validation. The study focused on the development of an IoT-based mobile solar water pumping system incorporating a sliding photovoltaic (PV) mechanism for smart irrigation applications in agricultural environments with limited access to conventional energy sources.

The initial stage involved identifying irrigation constraints and energy requirements through field observations conducted in Sidopekso Village, Indonesia. In addition, local solar irradiation data and irrigation water demand were analyzed to determine the appropriate photovoltaic capacity and irrigation system specifications. The research framework was designed to evaluate the effectiveness of the proposed system in improving solar energy harvesting performance and irrigation efficiency compared with conventional fixed PV systems.

B. System Design

The proposed system was developed using a multidisciplinary approach consisting of mechanical, electrical, and IoT subsystems.

1) Mechanical Design

The mechanical subsystem focused on the development of a portable irrigation cart integrated with a sliding photovoltaic mechanism. The sliding system utilized linear rail components to enable adaptive displacement of the PV panel, thereby increasing effective solar exposure while maintaining low mechanical complexity and portability. The mobile cart structure was designed to facilitate flexible deployment across agricultural fields.

2) Electrical Design

The electrical subsystem consisted of photovoltaic panels, a Solar Charge Controller (SCC), battery storage, inverter, and AC water pump integration. The photovoltaic capacity was determined based on irrigation energy requirements and local solar irradiation conditions. The SCC was utilized to regulate battery charging and stabilize electrical energy distribution throughout the irrigation system.

3) IoT Monitoring and Control System

The IoT subsystem integrated soil moisture sensors, ultrasonic sensors, voltage sensors, and current sensors with a microcontroller for real-time monitoring and automated irrigation control. The irrigation process was controlled based on soil moisture threshold logic. When the measured soil moisture value fell below the predefined threshold value, the water pump was automatically activated. Conversely, the pump was deactivated when the soil moisture level exceeded the specified threshold. In addition, real-time monitoring of PV voltage, current, battery condition, and water flow rate was transmitted to the IoT platform for system supervision and data logging.

C. Experimental Setup and Testing Conditions

Experimental testing was conducted in an agricultural area located in Sidopekso Village, Indonesia, with an approximate testing area of XX m². The experiments were performed during the dry season under relatively stable weather conditions to minimize environmental disturbances caused by rainfall and excessive cloud cover. Environmental parameters such as solar irradiance, ambient temperature, and weather conditions were monitored throughout the testing period to ensure experimental consistency.

The proposed sliding PV system and the conventional fixed PV system were tested simultaneously under identical environmental conditions. Both systems utilized identical photovoltaic capacities, battery specifications, irrigation loads, water pump configurations, and irrigation durations to ensure fair performance comparison. The primary independent variable in this study was the photovoltaic configuration, namely the sliding PV mechanism and the fixed PV system. Meanwhile, the dependent variables included electrical power generation, energy harvesting efficiency, water flow rate, irrigation stability, and IoT monitoring performance.

Each experimental scenario was repeated three times under similar operating conditions to improve data reliability and reduce random measurement errors. The average values obtained from repeated experiments were used for further analysis and system performance evaluation.

D. Instrument Validation

Several sensors were utilized in this study, including soil moisture sensors, ultrasonic sensors, voltage sensors, and current sensors. Prior to experimental testing, all sensors were calibrated and validated by comparing sensor readings with standard reference measuring instruments.

The soil moisture sensor demonstrated an average measurement accuracy of approximately ±3%, while the ultrasonic sensor exhibited a measurement error of less than ±0.3 cm based on repeated laboratory testing. In addition, voltage and current sensors were validated using a digital multimeter to ensure measurement consistency and reliability. Sensor precision was evaluated through repeated measurements under identical conditions to verify the stability of the IoT monitoring system.

E. Performance Evaluation Parameters

The system performance evaluation focused on electrical performance, irrigation functionality, and IoT monitoring reliability.

1) Electrical Performance Evaluation

The electrical performance parameters included:

- photovoltaic output voltage,
- output current,
- electrical power generation,
- battery charging performance,
- and photovoltaic energy harvesting efficiency.

The photovoltaic energy harvesting efficiency was calculated using:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

where ηrepresents the energy harvesting efficiency (%), $P_{out}$is the electrical output power generated by the photovoltaic system, and $P_{in}$is the total solar energy input received by the PV module.

2) Irrigation and IoT Performance Evaluation

The irrigation and IoT performance evaluation included:

- water flow rate,

- pump pressure stability,
- soil moisture response,
- sensor precision,
- data transmission latency,
- and real-time monitoring reliability.

The performance of the proposed sliding PV system was quantitatively compared with that of the conventional fixed PV configuration to evaluate improvements in solar energy utilization and irrigation effectiveness.

F. Data Analysis and Final Validation

The collected experimental data were analyzed quantitatively using comparative performance analysis between the sliding PV system and the fixed PV system. Average values obtained from repeated experiments were used to evaluate improvements in electrical efficiency, irrigation stability, and IoT monitoring reliability.

The final validation stage was conducted by comparing the experimental results with the initial system design objectives and operational requirements. The overall effectiveness of the proposed system was assessed based on energy harvesting capability, irrigation performance, portability, and real-time monitoring functionality to determine its feasibility for sustainable smart agriculture applications.

III. Result And Discussion

3.1 System Design and Implementation Results

The IoT-based automatic irrigation system was successfully designed and implemented according to the established specifications. The system consists of a soil moisture sensor, an ambient temperature sensor, and a water level sensor connected to an ESP32 microcontroller. Sensor readings are sent in real time to the ThingsBoard platform via the internet.

The system is powered by four 200 Wp solar panels connected to a 12 V 200 Ah battery via a solar charge controller. The water pump system is automatically controlled based on a predetermined soil moisture threshold.

3.2 Design of a solar power cart with a sliding system

(a) View from the front angle (b) View from the rear angle

Figure 2. Design of a solar power cart with a sliding system

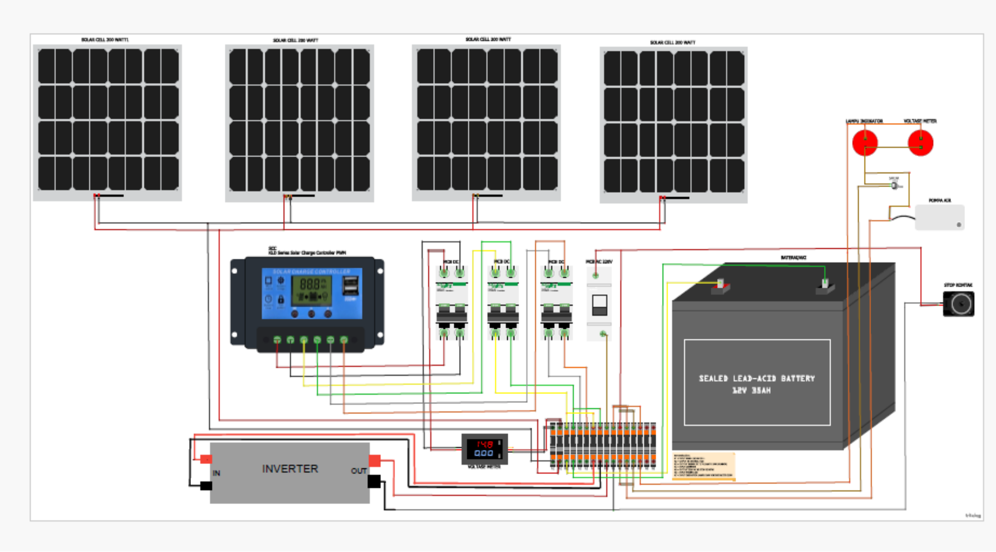


Figure 3. Wiring diagram for PLTS water pump cart

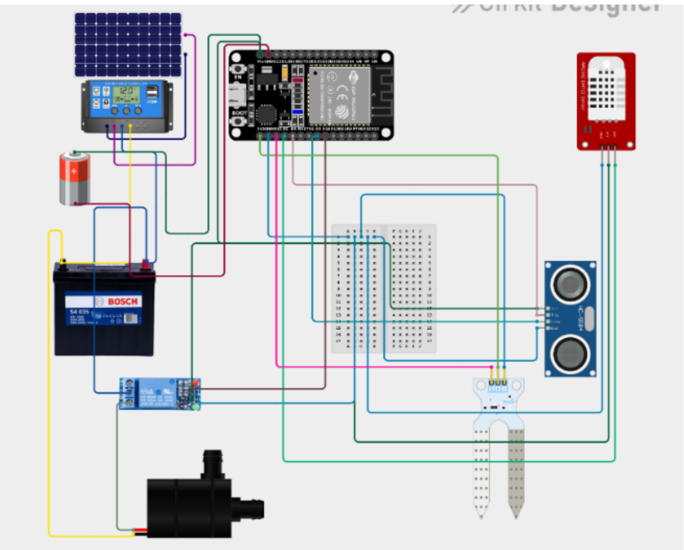


Figure 4. IoT wiring circuit on the solar power plant water pump cart

System Specifications
Total Installed Capacity: 4 x 200 Wp = 800 Wp.
System Voltage: 18 V (Parallel configuration).

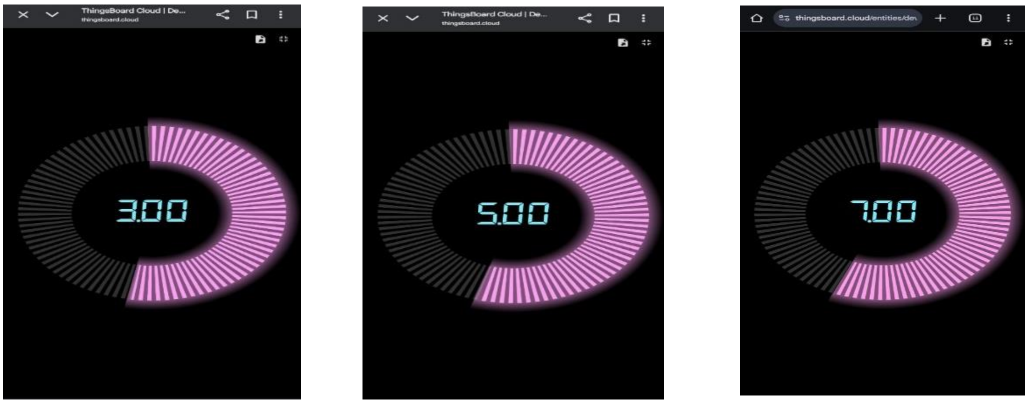
Assumptions: Clear skies in the Probolinggo/East Java area, with an overall system efficiency (cable losses, SCC, temperature) of 75%.

When the panel orientation changes to the west at 12:00, while maintaining a 70° tilt, your power curve will be doubly symmetrical. This is a smart strategy in your cart design to maximize energy harvest at low sun angles (morning and afternoon).
In technical terms, this is known as Manual Discrete Tracking.
Here is the estimated power table after adjusting the position at midday:
Estimated Power Output Table (Watts)
Total Capacity: 800 Wp (4 x 200 Wp)

Hour	Panel Position	Power Estimation (Watt)	Condition Analysis
07:00	Facing East	350 W	Effectively captures the low morning sun.
09:00	Facing East	580 W	Reaching the optimal point for East orientation.
11:00	Facing East	450 W	Power decreases as the sun begins to be perpendicular (above).
12:00	Facing West	300 W	Transition; low power because the sun is at its zenith.
13:00	Facing West	450 W	Power starts to rise again as the sun leans towards the West.
15:00	Facing West	580 W	Second peak; the sun's position is perpendicular to the 70° West panel.
16:00	Facing West	400 W	Still quite strong because the angle of the panel really supports the afternoon sun.
17:00	Facing West	150 W	Remaining radiation before night

3.3 Sensor Test Results

From the results of testing the solenoid sensor under 3 conditions



a. Dry Conditions b. Moist Conditions c. Wet Conditions

Figure 5. Display appears in the open source Thingsboard

Table 1. Soil Moisture Sensor Results

Tgl/Jam	Information
15/03/2026 06:00	Dry
15/03/2026 07:00	Dry
15/03/2026 08:00	Dry
15/03/2026 09:00	Moist
15/03/2026 10:00	Moist
15/03/2026 11:00	Moist
15/03/2026 12:00	Moist
15/03/2026 13:00	wet
15/03/2026 14:00	wet
15/03/2026 15:00	wet
15/03/2026 16:00	wet

Ultrasonic sensor testing
Ultrasonic sensor data collection

Table 2 Ultrasonic Sensor Test Results

Time stamp	Height	Informasi
15/03/2026 06:00	38,5	Pump On
15/03/2026 07:00	37,8	Pump On
15/03/2026 08:00	37,1	Pump On
15/03/2026 09:00	36,9	Pump Off
15/03/2026 10:00	37,1	Pump On
15/03/2026 11:00	36,8	Pump Off
15/03/2026 12:00	37,1	Pump On
15/03/2026 13:00	37	Pump On
15/03/2026 14:00	36,9	Pump Off
15/03/2026 15:00	36,8	Pump Off
15/03/2026 16:00	36,9	Pump Off

3.4 Solar Power System Energy Performance Analysis

The system uses an 800 Wp solar panel connected to a 12 V, 200 Ah battery. The battery's energy capacity is calculated as follows:
$E = V \times Ah$
$E = 12 \times 200 = 2400$ Wh

Considering a 50% Depth of Discharge (DoD) limit to maintain battery life, the effective usable energy is:
$2400 \times 50\% = 1200$ Wh

The average daily energy production of the solar panels, based on field measurements, is approximately 150 Wh per day. Therefore, the system is capable of recharging the energy used daily while remaining within the safe operating limits of the battery.

3.5 Pump Performance Analysis and Water Requirements

The pump used has a 12V 800Wp specification. The average pump flow rate, based on field tests, is approximately 20 liters/minute or approximately 1,200 liters/hour.

Land water requirements are calculated using the volume formula:
Volume = Length × Width × Height
$10 \times 5 \times 0.03 = 1.5 \text{ m}^3 \wedge 3$

Since 1 m^3 = 1,000 liters, the total water requirement is:
$1.5 \times 1{,}000 = 1{,}500$ liters
Time required to meet these water requirements:
$1{,}500 \div 480 = 1.25$ hours
Energy used by the pump in one irrigation cycle:
800 W × 1.25 hours = 1,000 Wh
This value is still below the effective energy of the battery (1200 Wh), so the system is considered capable of operating independently without power shortages.

3.6 Impact on Agricultural Productivity

Based on interviews and field observations, before the system was implemented, the average harvest yield ranged from 1–1.2 tons per planting period. After the solar-powered irrigation system was implemented, the yield increased to approximately 1.5 tons per planting period.
Average yield before the system:
(1+1.2)/2=1.1 tons
Yield increase:
1.5-1.1=0.4 tons
Percentage increase:
(0.4/1.1)×100%≈36%

Furthermore, the harvest period, which previously ranged from 115–120 days, has been reduced to 95–100 days.
Average harvest time acceleration:
20÷117×100%≈17%

These results indicate that a stable irrigation system contributes to increased productivity and accelerated harvest times.

3.7 System Efficiency Summary

Overall, the system demonstrated:
Effective available energy: 1200 Wh
Energy used per cycle: 1000 Wh
Safe energy reserve: ±200 Wh
Yield increase: ±36%
Harvest time acceleration: ±17%
This demonstrates that the solar irrigation system is not only technically feasible but also has a significant impact on agricultural efficiency and productivity.

IV. Conclution

Based on the design and testing of an irrigation system based on four 200 Wp solar panels with a 12 V 200 Ah battery, the system produces an average daily energy of ±1200 Wh. With a DoD of 50%, the effective energy available is ±1200 Wh, while the consumption of an 800 W pump per irrigation cycle is ±93 Wh, indicating that the system works very safely and energy-stable. From a technical perspective, the system is capable of supplying 1,500 liters of water per cycle for ±3.1 hours, with battery capacity allowing operation for up to ±54 full cycles or approximately 167 hours in total, providing abundant energy reserves. The implementation of IoT allows remote monitoring and control, facilitating irrigation management and real-time data collection. Field observations and farmer interviews show an increase in yields from an average of 1.1 tons to 1.5 tons per planting period (±36%) and an acceleration of harvest time from an average of 117.5 days to 97.5 days (±17%). This IoT-based solar irrigation system has proven to be technically and energy-feasible and has a significant impact on time efficiency and agricultural productivity, making it an economical and sustainable irrigation alternative for small-scale farmers, especially in areas with limited access to conventional electricity.

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