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International Journal of Advanced Research in Food Science and Agriculture Technology

Journal homepage:
https://karyailham.com.my/index.php/fsat/index
ISSN: 3030-556X



Performance Analysis of A Light Sensor-Based Dual-Axis Solar Tracking System for Supporting Dragon Fruit Irrigation and Supplemental Lighting

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ARTICLE INFO

Article history:
Received 28 July 2026
Received in revised form 31 August 2026
Accepted 3 September 2026
Available online 29 October 2026

Keywords:
Dual-axis solar tracking; Dragon fruit cultivation; Solar energy management; Supplemental night lighting; Smart irrigation

ABSTRACT

Dragon fruit needs extra light at night to flower out of season but using normal grid electricity is very expensive for remote farmers. Solar panels offer a clean solution but fixed panels often lose a lot of sunlight. This research aims to design and test a 2 kW solar panel system with a dual axis sun tracker and a 10 kWh battery to supply farm loads without grid power. The study uses a white box simulation model in MATLAB Simulink. The system is tested under extreme heavy rain weather using NASA POWER data for January 2026. The power loads include a 300 W water pump working for two hours a day and a 1200 W plant lamp working for four hours at night. The simulation results show the system produces a total of 290.45 kWh of energy and the farm uses 167.50 kWh. The dual axis tracker helps catch 25 to 30 percent more energy than fixed panels. The battery also performs very well with the lowest remaining power level at 41.92 percent. Because the battery never reaches its lowest safe limit the chance of a power blackout is exactly zero percent. In conclusion this off grid agrivoltaic prototype is highly reliable to keep dragon fruit farms productive in bad weather even though the initial cost needs further economic study.

1. Introduction

Dragon fruit (*Hylocereus* spp.) is a plant with high economic value that is widely cultivated in tropical regions. However, this plant naturally bears fruit only when the day is longer than the night [1], [2]. Therefore, to induce flowering during the off-season, from September to March, additional artificial lighting is required at night to convert phytochrome P660 into P730 [3]. Field tests have demonstrated that providing 100 W lighting for 6 hours, from 18:00 to 24:00, successfully induces off-season flowering, with yields reaching 19.85 tons per hectare, while plants without artificial lighting do not flower [2]. However, this conventional method requires substantial electricity consumption, resulting in high electricity costs for small-scale farmers [3], [4]. Furthermore, electricity grids in remote agricultural areas are often unavailable or unstable, highlighting the need for alternative clean energy sources [5], [6].

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Renewable energy technologies, particularly solar photovoltaic (PV) panels, offer a promising approach to reducing pollution in agriculture and achieving zero-emission targets [7], [8], [9], [10]. However, conventional fixed solar panels often experience energy losses because they cannot capture maximum sunlight throughout the day [10], [11], [12]. To address this limitation, a dual-axis solar tracking system can be employed using light sensors or astronomical calculations to automatically adjust the panel position so that it continuously faces the sun [11], [12], [13]. The use of dual-axis solar tracking has been reported to increase electrical power generation by up to 52% compared with fixed solar panels [11]. Another study reported a 40% increase in energy generation for rural applications [12]. This additional energy can be stored in a battery system to simultaneously power automatic water pumps and plant lighting systems [14], [15].

In addition to nighttime lighting, proper irrigation is essential for maintaining crop yields and conserving water [15]. Internet-connected automatic solar-powered water pumps can regulate irrigation according to plant requirements, potentially reducing water consumption by up to 30% and increasing crop yields by 20% compared with manual irrigation methods [1], [4]. To evaluate the performance of this integrated system under actual operating conditions, computer simulations can be conducted using MATLAB Simulink. A simulation model can be developed comprising a solar tracking algorithm, a 2 kW solar PV system, a 10 kWh battery, a 300 W water pump operating from 06:00 to 07:00 and 16:00 to 17:00 WIB, and a 1200 W dragon fruit lighting system operating from 18:00 to 22:00 WIB. This model can be used to evaluate system reliability and battery performance during the rainy season using weather data obtained from NASA POWER for January 2026 [16].

Although considerable research has focused on solar PV systems and artificial lighting for agricultural applications, previous studies have generally examined these components separately [2], [3], [4], [11], [12]. Limited research has investigated the integration and performance of dual-axis solar tracking systems designed to simultaneously power irrigation pumps and artificial plant lighting under rainy-season conditions. Such research is important for developing energy-independent agricultural systems that reduce reliance on electricity grids and maintain a reliable power supply for agricultural equipment [17], [18]. Therefore, the main objective of this study is to design, model, and evaluate the performance of a 2 kW solar PV system integrated with a 10 kWh battery using MATLAB Simulink. The system will be evaluated for its ability to supply electricity to a 1200 W lighting system and a 300 W water pump over 31 days during the rainy season, with target values of 290 kWh for total electricity generation, 165 kWh for electricity consumption, and a minimum remaining battery state of charge of 45%.

2. Methodology

This research employs a white-box modeling approach using MATLAB Simulink to evaluate a dual-axis solar tracking system equipped with light sensors. The system supplies electricity to scheduled agricultural loads. Instead of using black-box software or prebuilt Simscape physical libraries, the model is developed using native Simulink blocks, basic mathematical operations, and dynamic integrators. This approach allows the mathematical calculations for power flow, battery state of charge (SOC), and loss of load probability (LOLP) under extreme weather conditions to be clearly examined [5], [13], [18].

The modeling procedures are presented sequentially in the flowchart shown in Figure 1. The simulation begins by calculating the sun's position. The system then determines whether the solar panel angle is optimal. If the angle is not optimal, the system reads the sensor data to adjust the actuator position before recalculating the sun's position. Once the optimal angle is achieved, the system proceeds to convert solar energy into electrical energy. The generated electricity is

subsequently stored in the battery system, which supplies the power required by the water pump and plant lighting system. Finally, the overall system performance is analyzed, and the simulation results are presented before the process is completed.

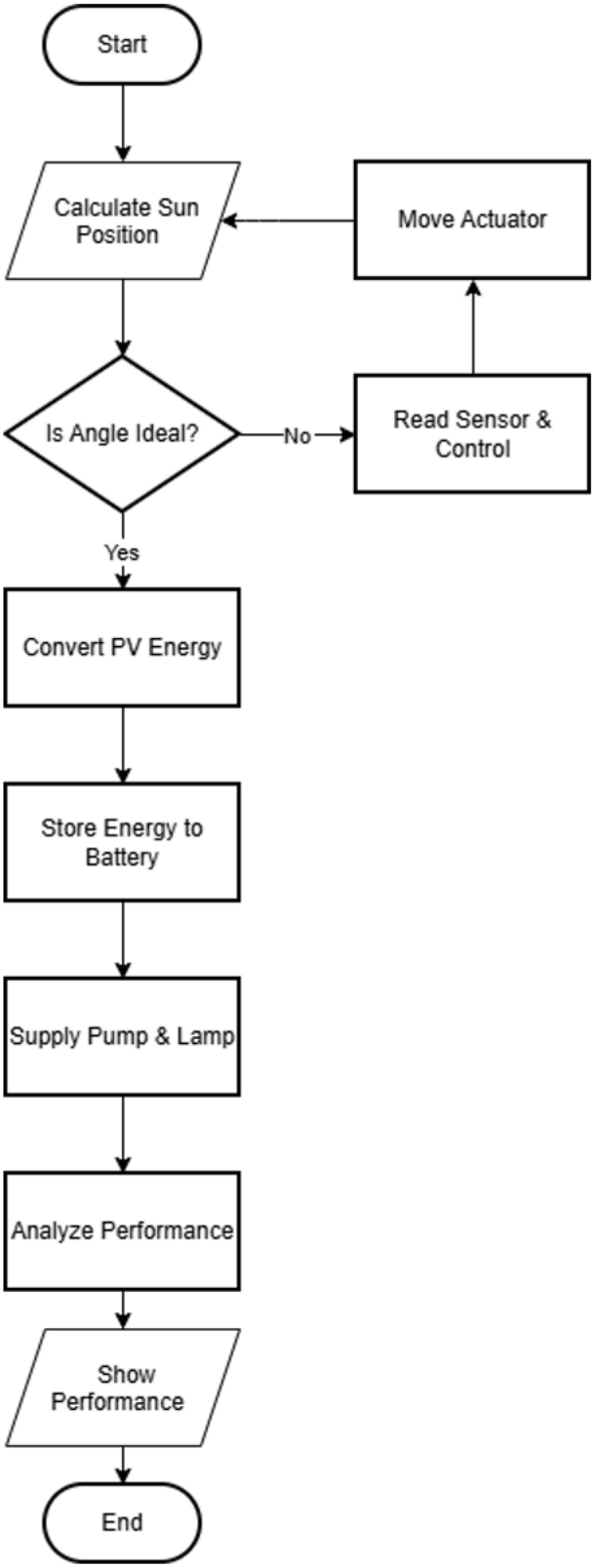


Fig. 1. Flowchart of the white-box modeling simulation process

2.1 System Architecture and White-Box Modeling Framework

The proposed system consists of a 2 kW standalone solar PV array, a zenith–azimuth dual-axis solar tracker, a 10 kWh DC-coupled battery, and an automatic load management system. The load manager controls the dragon fruit lighting system and precision irrigation, as illustrated in Figure 2. The entire system employs a DC-coupled bus configuration to reduce energy losses associated with AC conversion and facilitate direct power transfer from the solar PV array to the battery [17].

The solar panel temperature is maintained at 25 °C under Standard Test Conditions (STC). This temperature is intentionally fixed at 25 °C to ensure that the simulation focuses specifically on evaluating the solar tracker's effectiveness in capturing sunlight without the influence of performance reductions caused by variations in environmental temperature [16].

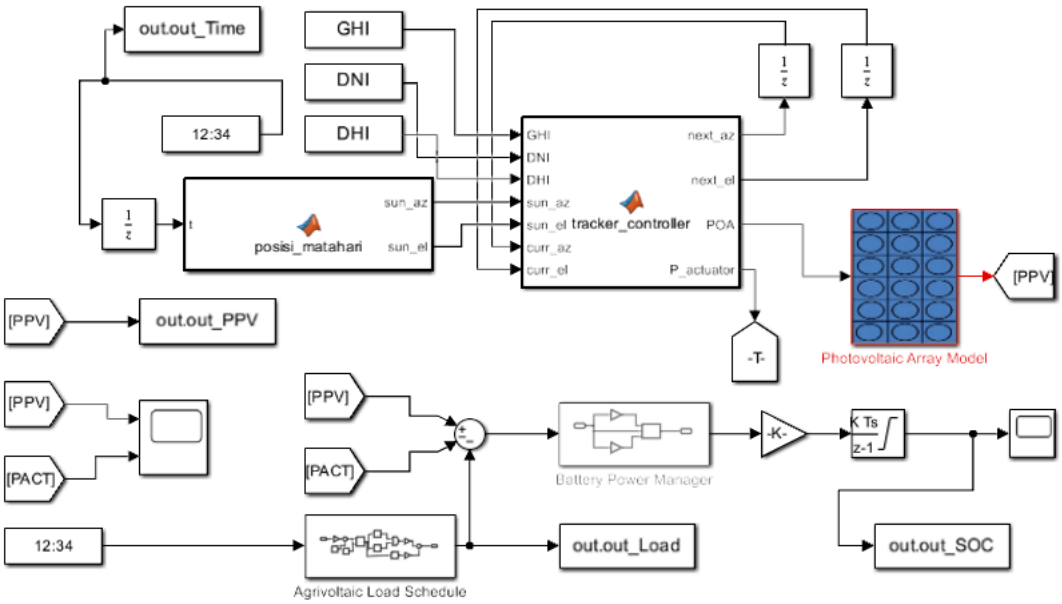


Fig. 2. System architecture and power flow block diagram

2.2 Meteorological Data Processing and Time Compensation

The meteorological data used in this simulation were obtained from the NASA Prediction of Worldwide Energy Resources (POWER) database. Hourly meteorological data for January 2026 were specifically selected because this month represents the peak of the extreme rainy season, characterized by extensive cloud cover and limited sunlight [16]. These conditions are important for evaluating the performance and reliability of the solar PV and battery systems under unfavorable weather conditions.

However, the raw data obtained from NASA are recorded in Coordinated Universal Time (UTC). Since the simulation location is in Indonesia, this time standard must be adjusted to match the local agricultural operating schedule. To address this time difference, a dedicated Timer Subsystem was developed within the MATLAB Simulink model. This subsystem uses a simple mathematical operation to add a constant offset of seven hours to the original time signal. This adjustment synchronizes the meteorological data with Western Indonesian Time (WIB), allowing the scheduled water pump and plant lighting system to operate at the specified local times without delays.

After the time adjustment, the hourly solar irradiance data serve as the primary input to the solar tracking model. The system uses this meteorological profile to calculate the direct and diffuse solar irradiance incident on the moving solar panel surface at each time interval. By incorporating continuous and synchronized meteorological data, the simulation can evaluate the electrical energy generated by the dual-axis solar tracking system throughout the day, from sunrise to sunset.

2.3 Mathematical Formulations and Subsystem Equations
2.3.1 Photovoltaic Generation and Solar Tracking Model

The electrical power generated by the 2 kW solar PV array at time *t* depends on the incident solar irradiance and the overall system efficiency. This calculation follows standard solar engineering principles commonly described in photovoltaic textbooks [10]. The mathematical expression used to calculate the generated electrical power is presented in Equation (1).

$$P_{PV}(t) = P_{\text{rated}} \times \left(\frac{G_{POA}(t)}{G_{STC}} \right) \times \eta_{\text{sys}}$$

where the rated photovoltaic power is 2000 W, and the reference solar irradiance is 1000 W/m². To maximize solar exposure, the solar zenith and azimuth angles are continuously calculated using an approach similar to that developed by the National Renewable Energy Laboratory (NREL). The solar tracker adjusts the panel orientation to maintain an incidence angle of approximately 0°, allowing maximum exposure to incoming solar radiation.

2.3.2 Battery Storage and State of Charge Dynamics

The 10 kWh (10,000 Wh) DC battery stores the generated solar energy to supply agricultural loads during both daytime and nighttime operation [17], [18]. The initial battery state of charge (SOC) is set to 100%, while the minimum allowable SOC is maintained at 20% to prevent excessive battery discharge. The SOC at time *t* is calculated by integrating the net battery power relative to the battery's rated energy capacity, as expressed in Equation (2).

$$SOC(t) = SOC(t_0) + \int_{t_0}^{t} \left(\frac{P_{\text{batt_in}}(\tau) \times 100}{E_{\text{capacity}} \times 3600} \right) d\tau$$

In Equation (2), *SOC(t)* represents the battery state of charge (%) at time *t*, while $SOC(t_0)$ represents the initial battery state of charge. P_{batt_in} denotes the power flowing into or out of the battery, and $E_{capacity}$ represents the rated battery energy capacity of 10,000 Wh. The factor of 100 converts the calculated value into a percentage, while the factor of 3600 accounts for the conversion from hours to seconds.

2.3.3 Agrivoltaic Scheduled Load and Power Balance

The total electrical load consists of two scheduled agricultural operations. The first is a 300 W precision irrigation pump operating during the daytime from 06:00 to 07:00 WIB and from 16:00 to 17:00 WIB. The second is a 1200 W dragon fruit lighting system operating at night from 18:00 to

22:00 WIB to induce off-season flowering [1], [2], [3]. The mathematical expressions for the power balance are presented in Equations (3) and (4).

$$P_{\text{load}}(t) = P_{\text{pump}}(t) + P_{\text{light}}(t)$$

$$P_{\text{net}}(t) = P_{\text{PV}}(t) - P_{\text{load}}(t)$$

In Equation (3), P_{load} represents the total electrical power required by the agricultural system, while P_{pump} and P_{light} represent the power consumed by the water pump and dragon fruit lighting system, respectively. In Equation (4), P_{net} represents the remaining power after subtracting the total agricultural load, P_{load}, from the photovoltaic power generation, P_{PV}. System reliability is evaluated using the Loss of Load Probability (LOLP), which is calculated as the ratio of the total unmet power demand to the total required power over the 31-day simulation period [18]. This metric is expressed mathematically in Equation (5).

$$\text{LOLP} = \frac{\int_0^T \max\left(0,\ P_{\text{load}}(t) - P_{\text{PV}}(t) - P_{\text{batt,max}}(t)\right)\ dt}{\int_0^T P_{\text{load}}(t)\, dt}$$

In Equation (5), LOLP represents the proportion of the total electrical energy demand that the system cannot supply. (T) represents the total simulation period of 31 days. The numerator calculates the total unmet energy demand when the electrical load exceeds the combined photovoltaic power generation and maximum available battery discharge power, $P_{batt,max}$. The denominator represents the total electrical energy required by the agricultural system throughout the simulation period.

2.4 Boundary Conditions and Simulation Configuration

The simulation is conducted using MATLAB Simulink with a fixed-step solver and a time step of 1 hour over a 31-day period, corresponding to a total of 744 hours in January 2026. Each parameter is selected based on the specifications of real-world hardware components. All operational boundary conditions governing the white-box simulation model are summarized in Table 1.

Table 1
Operational Simulation Parameters

Component	Parameter
Solar panel	2000 W
Solar tracker	Dual axis
Battery	10 kWh
Battery limits	20% to 100%
Water pump	300 W
Plant lamp	1200 W
Weather data	NASA POWER
Time step	1 hour

3. Results

3.1 Photovoltaic Power Generation Profile and Sun Tracker Effect

The agricultural solar power system was simulated using hourly satellite data obtained from NASA POWER for the Malang region, located at latitude 7.9589° South and longitude 112.6196° East, during January 2026. This period was selected to evaluate system reliability under rainy-season conditions characterized by substantial variations in solar irradiance. Based on the simulation results, the native Simulink model successfully responded to variations in weather conditions without computational delays. The power generation profile over three consecutive days, from Day 10 to Day 13, shows a bell-shaped curve that corresponds to the plane-of-array (POA) irradiance profile.

The integration of a mechanical solar tracking controller based on solar zenith and azimuth angle algorithms significantly increases the area under the power generation curve. Compared with conventional fixed solar PV systems, the dual-axis tracking system captures more direct normal irradiance (DNI) during the early morning and late afternoon. Quantitatively, the integration of the dual-axis solar tracking system is projected to increase total daily energy generation by approximately 25–30% compared with fixed solar panel installations. This improvement occurs because the actuator continuously adjusts the solar panel orientation to maintain a near-perpendicular angle of incidence, particularly during the morning and afternoon. The additional energy generation is important for maximizing battery charging before the nighttime lighting load begins operating. This improvement is reflected in the steeper slope of the power generation curve and the extended daily energy production period, with peak power approaching the rated panel capacity of 2000 W under favorable solar irradiance conditions, as shown in Figure 3.

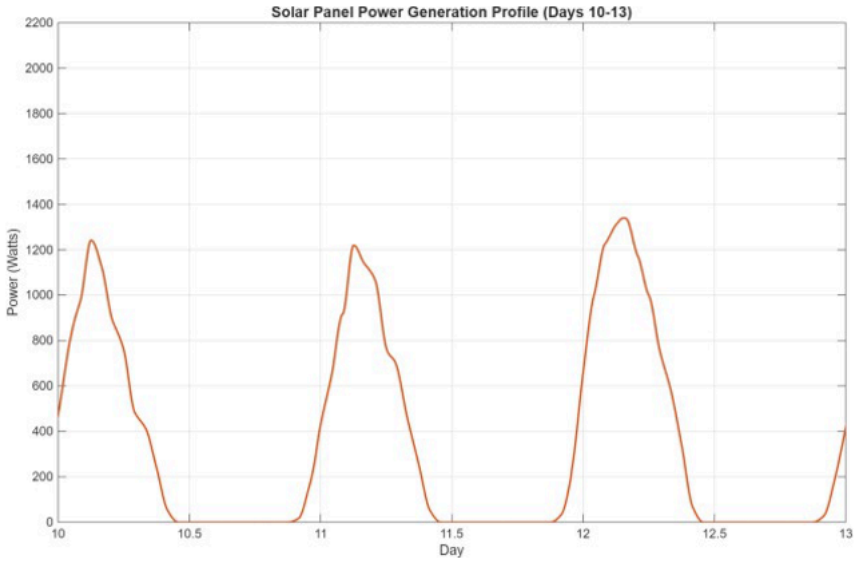


Fig. 3. Solar panel power generation profile from Day 10 to Day 13

3.2 Agrivoltaic Load Schedule Characteristics and Synchronization

One of the main challenges in modeling systems using Coordinated Universal Time (UTC) data is synchronizing the operating load schedule with local time. Adjusting the scheduling algorithm by adding a constant offset of seven hours successfully synchronizes the time data with Western Indonesian Time (WIB).

The power consumption profile exhibits a rectangular waveform corresponding to the scheduled operating periods, as shown in Figure 4. The 300 W water pump operates consistently from 06:00 to 07:00 WIB and from 16:00 to 17:00 WIB. Meanwhile, the highest electrical load is associated with the 1200 W plant lighting system, which operates from 18:00 to 22:00 WIB to stimulate dragon fruit flowering. The power consumption of the solar tracking motor was found to be relatively low and did not significantly affect the stability of the DC voltage supply to the main electrical loads.

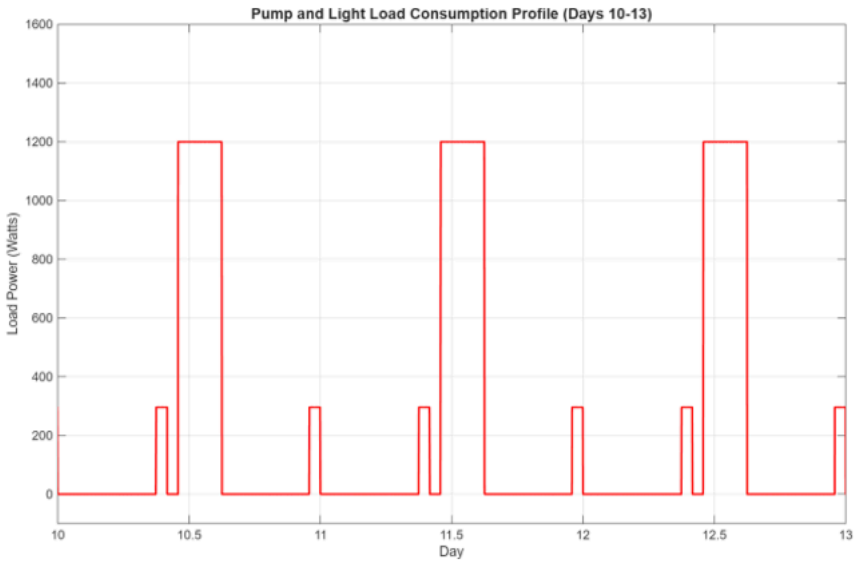


Fig. 4. Pump and lamp load consumption profile from Day 10 to Day 13

3.3 Energy Balance Analysis and Battery System Performance

The technical performance of the proposed hybrid electrical system is evaluated based on the Loss of Load Probability (LOLP) and the reliability of the battery energy storage system during charging and discharging cycles. Table 2 summarizes the overall energy balance parameters over the 31-day simulation period.

Table 2
System Energy Balance Summary for January 2026

System Performance Indicator	Measured Value	Unit
PV Design Capacity STC	2000	W
Storage Battery Capacity	10000	Wh
Total Generated PV Energy	290.45	kWh
Total Agrivoltaic Load Use	167.50	kWh
Energy Balance Surplus	123.00	kWh
Lowest State of Charge SOC	41.92	%

The system generated a total of 290.45 kWh of electrical energy, exceeding the total load demand of 167.50 kWh. The resulting energy surplus of 123.00 kWh indicates that the 2000 W solar PV system has sufficient generation capacity to accommodate potential reductions in power output during cloudy conditions.

The performance of the energy storage system is further demonstrated by the state of charge (SOC) profile, as shown in Figure 5. System reliability was evaluated under extreme weather conditions from Day 10 to Day 13, during which the simulation recorded continuous heavy cloud cover. During this period, solar irradiance decreased significantly from an optimal peak of 900 W/m² to approximately 150 W/m². Although the system experienced temporary power deficits due to unfavorable weather conditions, the 10,000 Wh battery was able to compensate for the reduced photovoltaic power supply and maintain continuous load operation without power interruptions.

Throughout the 31-day simulation period, the minimum battery SOC was recorded at 41.92%. Since the SOC remained above the minimum allowable limit of 20%, the simulated system achieved a Loss of Load Probability (LOLP) of 0%, indicating that the electrical load demand was fully satisfied throughout the simulation period. These operating conditions also contributed to maintaining a stable DC bus voltage and may support a longer battery service life when the system is implemented using actual hardware.

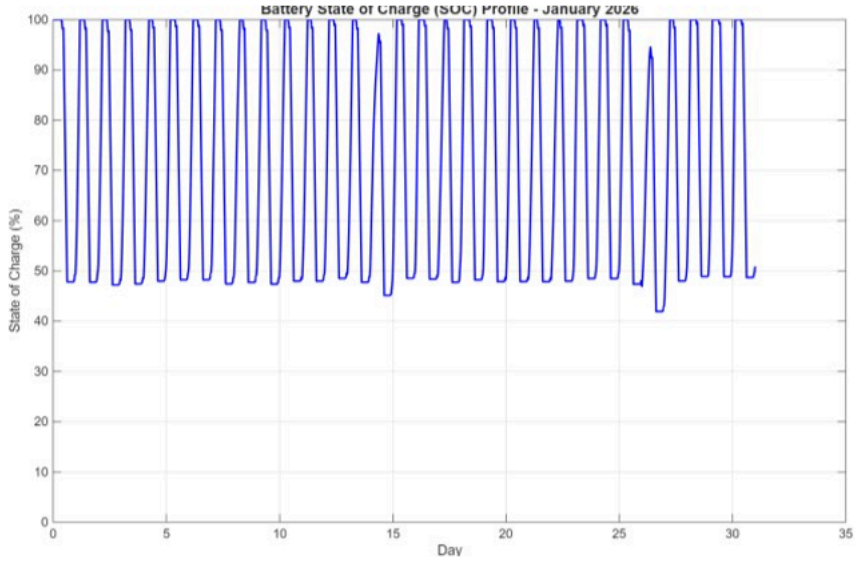


Fig. 5. Battery State of Charge SOC profile for January 2026

3.4 Energy Prototype Design Feasibility for Agriculture

The proposed off-grid agricultural solar power system demonstrates high reliability in integrating clean energy generation with agricultural energy demands. The use of a transparent mathematical modeling approach allows the energy management system to be evaluated without excessive computational simplification. For energy engineering competitions or agricultural capstone projects, this system demonstrates the potential to provide a stable power supply for dragon fruit cultivation. The irrigation system can operate according to the scheduled periods, while nighttime artificial lighting can support off-season flowering without relying on the national electricity grid.

Although the proposed electrical system offers the potential for independent operation and eliminates the need for grid electricity consumption, economic feasibility remains a challenge for practical implementation. The system requires a relatively high initial investment, particularly for the battery energy storage system and mechanical solar tracking components. Therefore, further research is recommended to evaluate the return on investment (ROI) and determine the economic feasibility of implementing the proposed system on a commercial agricultural scale.

4. Conclusions

The native Simulink discrete modeling approach successfully simulated the dynamic behavior of the proposed hybrid power system. The integration of a dual-axis solar tracking system is projected to increase daily energy generation by approximately 25–30% compared with conventional fixed solar panel installations. The proposed system, consisting of a 2000 W solar PV array and a 10,000 Wh battery, demonstrated high reliability under varying weather conditions. Despite a significant reduction in solar irradiance from 900 W/m² to 150 W/m² due to heavy cloud cover, the system generated a total of 290.45 kWh of electrical energy and successfully supplied the agricultural load demand of 167.50 kWh.

The battery management system also demonstrated stable performance, with the minimum state of charge (SOC) reaching 41.92%. The simulated loss of load probability (LOLP) was approximately 0%, indicating that the scheduled irrigation and nighttime dragon fruit lighting operations could be maintained without power interruptions during the simulation period. From a technical perspective, the proposed off-grid electrical system demonstrates the potential for practical application in maintaining agricultural productivity. However, the relatively high initial investment required for mechanical actuators and battery energy storage highlights the need for further research focusing on return on investment analysis to determine the commercial feasibility of the proposed system.

Acknowledgement
This research received no grant funding. However, the authors would like to express their gratitude to the academic advisors from the State University of Malang and the KI-RBSET 2026 committee under the Energy Design Capstone for Agriculture theme for their continuous support and guidance during the development of this agrivoltaic prototype.

Conflict of Interest Statement
The authors declare that there were no internal or external conflicts of interest during the preparation or publication of this manuscript. No financial support, grants, or other forms of compensation were received that could influence the results of this study. This research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

Author Contributions Statement
Muhamad Ferly Farnando conceptualized and designed the study, supervised the project, conducted experiments and data analysis, developed the methodology, and reviewed the manuscript. Muhammad Iqbal Maulana prepared the literature review and identified the necessary requirements. Haudh Al Maa'uun contributed to data interpretation, drafted the initial manuscript, and designed the flowchart. Muhammad Fadil and Mohammad Hisyam Rifai contributed to gathering references and compiling the literature review to support the development of the proposal and manuscript. All authors contributed to revising the manuscript and have read and approved the final version.

Data Availability Statement
All data generated or analyzed during this study are included in the published article. Additional datasets are available from the corresponding author upon reasonable request.

Ethics Statement

This research was conducted exclusively through computer simulations and did not involve human or animal participants. Therefore, formal ethical approval and informed consent were not required. The research was conducted in accordance with the academic and ethical standards of the State University of Malang.

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