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Techno-Economic Optimization of a Solar PV-Battery System for Light-Trap-Based Shallot Pest Management in Nganjuk, Indonesia

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ABSTRACT

Shallot farming in Nganjuk Regency, Indonesia, faces pest problems such as beetles, sucking ladybugs/bees, ants, and grasshoppers that can interfere with growth and reduce crop productivity. One approach that can be developed is the use of light trap devices powered by renewable energy. This study aims to design and analyze a solar power plant (PLTS) system as an energy source to support the pest repellent system on onion farmland. The system analysis was conducted using HOMER Pro software, incorporating solar radiation data. The simulation was used to determine the system configuration capable of meeting the energy requirements of the pest control devices by considering technical and economic factors, including generation capacity, energy storage, energy production, system reliability, Net Present Cost (NPC), and Levelized Cost of Energy (LCOE). The simulation results showed that the optimal system configuration consisted of a photovoltaic module with a capacity of 0.700 kW, two SAGM 12 205 batteries, and a converter with a capacity of 0.398 kW. The system is capable of producing 1,382 kWh/year of renewable energy to meet an annual load demand of 942 kWh/year, achieving a 100% renewable energy share. The system's Net Present Cost (NPC) is IDR 65,412,740, and the Levelized Cost of Energy (LCOE) is IDR 753.52/kWh. The study's results indicate that an energy system based on renewable energy sources can serve as an independent electricity source to support the application of pest control technology in shallot farming. The optimization results also suggest that the contribution of wind turbines to an optimal configuration requires further study based on the characteristics of wind potential and the technical parameters of the turbines used.

1. Introduction

Red onions are an agricultural commodity that faces problems with plant pests, including insects that can disrupt plant growth and productivity. One method that can be used for pest control is the light trap. Research on the application of light traps in red onion farming shows that this method can

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be used as an alternative for pest control, including as an alternative to conventional control techniques [7], [8].

Energy requirements are a key consideration in operating light traps in agricultural settings. Solar energy can serve as an alternative energy source to power pest control devices autonomously. Previous research has developed a solar-powered pest repellent system for red onion fields utilizing ESP32-based hardware [1]. In addition, a solar-powered pest trap system has been developed for rice crops by integrating a solar energy source with a control system [2].

In solar power systems used to supply energy to light traps, batteries are required to store the energy generated by solar panels so it can be used when solar energy production is insufficient. Therefore, the capacity of the photovoltaic (PV) panels, batteries, and converters must be determined based on the device's energy requirements as well as the system's energy generation and storage capabilities. Modeling using HOMER Pro can be used to evaluate renewable energy system configurations based on technical and economic aspects. A techno-economic approach to renewable energy systems has been applied to various agricultural applications to analyze energy production, load requirements, system configurations, and economic parameters [5], [6].

Previous studies have examined the use of light traps for shallots and the utilization of solar energy for pest control systems. However, studies that specifically optimize solar PV-battery systems to meet the energy needs of light traps in shallot farming in Nganjuk using HOMER Pro remain limited. Determining the appropriate capacity of the PV panels, batteries, and converters is necessary to ensure the devices' energy needs are met while taking technical and economic aspects into account. Therefore, this study aims to perform a techno-economic optimization of a solar PV-battery system as an energy source for light-trap-based shallot pest management in Nganjuk using HOMER Pro. The analysis was conducted based on generation and storage capacity, energy production, load fulfillment, renewable fraction, Net Present Cost (NPC), and Levelized Cost of Energy (LCOE).

Table 1
State of the Art of Previous Research

References	Method	Research Materials/Subjects	Key Findings
[7] Factors Influencing Shallot Farmers' Decision to Adopt Light Traps in Demak, Central Java	Analysis of factors influencing the adoption of light traps	Shallot farmers in Demak, Central Java	Identifying the factors influencing farmers' decisions to adopt light trap technology.
[8] Efficiency Study and Comparison of Shallot Farmers' Income Based on Pest Control Techniques Using the Light Trap Method and Conventional Techniques	Efficiency study and comparison of plant pest control methods	Farmers and shallot crops; light trap and conventional methods	Comparing the efficiency of plant pest control and farmers' income using the light trap method and conventional methods.
[1] Design and Implementation of a Solar-Powered Pest Repellent System for Shallot Farms Using Ultrasonic and Light Emitters Based on ESP32	Design and implementation of a solar-powered pest control system based on ESP32	Shallot fields	Developing a pest control system that utilizes solar energy, ultrasonic waves, and light emitters based on ESP32.
[2] Development of a Solar-Powered Automatic Pest Trap for Rice Cultivation in Indonesia	Design and development of a solar-powered automatic pest trap	Rice	Developing an automatic pest trap system that utilizes solar energy as its power source.
[5] Modeling Solar Photovoltaic Systems on Dairy Farms for Cost	Modeling and techno-economic analysis of PV systems	Energy systems on dairy farms	Analyzing PV systems based on energy production, cost

Savings and GHG Emission Reduction			savings, and emission reductions.
[6] Feasibility study and performance analysis of a microgrid with 100% hybrid renewables for a real-world agricultural irrigation application	Feasibility study and performance analysis of renewable energy systems	Agricultural irrigation systems	Evaluating the feasibility and performance of a renewable energy microgrid system to meet irrigation energy needs.

2. Methodology

2.1 Research Flow Chart

The research was conducted in several stages, beginning with the identification of light trap energy needs, the collection and processing of load and solar radiation data, and ending with the determination of system component capacities. Next, the system—comprising photovoltaic (PV) panels, batteries, and converters—was modeled and simulated using HOMER Pro. The simulation results were then analyzed based on technical and economic parameters, including energy production, load fulfillment, renewable fraction, Net Present Cost (NPC), and Levelized Cost of Energy (LCOE). The final stage of the study was to determine the optimal system configuration based on the results of the technical and economic analysis. Overall, these research stages are illustrated in Figure 1.

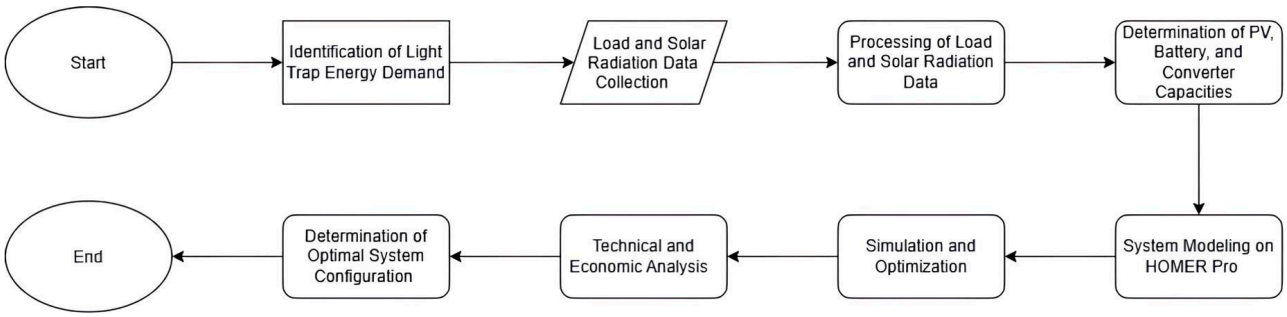


Fig. 1. Research Methodology Flowchart

2.2 Research Location and Load Profile

This study was conducted on a pest control application for shallots in Nganjuk Regency, East Java, with light traps as the primary research subject. The selection of light traps was based on their use as a method for controlling plant pests in shallot cultivation. Previous studies have shown that light traps have been used as an alternative method for pest control in red onion cultivation [7], [8]. The research location and the area where the system was implemented are shown in Figure 2.

The system's electrical energy requirements are determined based on the operational characteristics of the light trap, including device power and operating duration. These parameters are used to develop a load profile that represents energy consumption patterns during the operating period. The load profile is then used as input in HOMER Pro modeling to determine the required capacity of photovoltaic (PV) systems, batteries, and converters. The energy demand modeling approach in agricultural applications has also been used to evaluate the feasibility and performance of renewable energy systems [6].

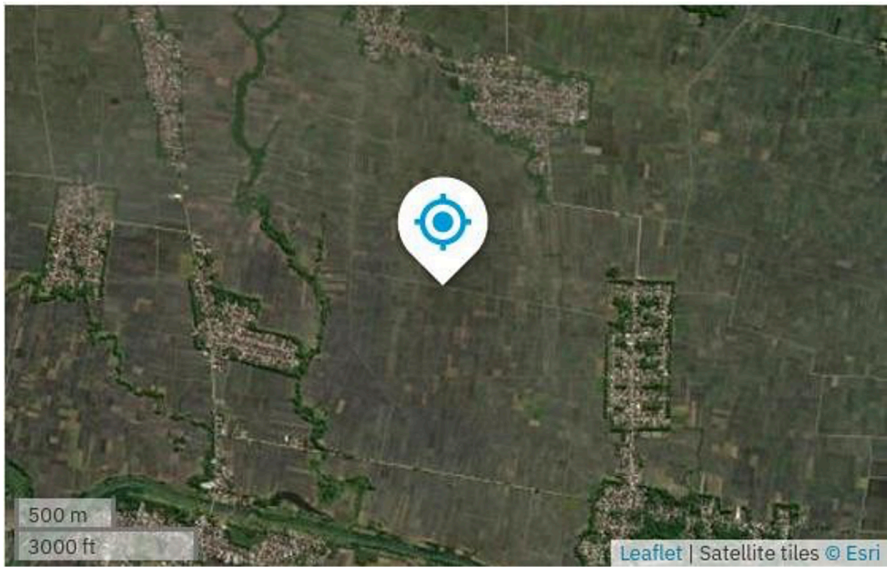


Fig. 2. Research Location

2.3 System Design and HOMER Pro Simulation

The designed system is a solar photovoltaic (PV)-battery system used to meet the energy needs of the light trap. The system consists of photovoltaic (PV) panels as the energy generation source, a battery as the energy storage medium, and a converter as the power conditioning component to regulate the flow of energy between the generation source, the battery, and the load. The system configuration is designed to support the autonomous operation of the light trap by utilizing solar energy. The use of solar energy in agricultural pest control systems has been applied in previous studies [1], [2].

The key system parameters used in the HOMER Pro modeling include PV capacity, battery type and quantity, converter capacity, and load energy requirements. Based on the system configuration in the simulation results, the PV module used is the LONGi Solar LR6-72 with a capacity of 0.700 kW, two Trojan SAGM 12 205 batteries, and a Studer AJ 1000-12 converter with a capacity of 0.398 kW. The load consists of an AC Primary Load with an energy requirement of 942 kWh/year. These parameters are summarized in Table 2.

Table 2
State of the Art of Previous Research

Component	Specifications	Capacity/Quantity	Function
Photovoltaic (PV)	LONGi Solar LR6-72	0.700 kW	Generates electrical energy from solar radiation
Battery	Trojan SAGM 12 205	2 units	Stores electrical energy from the PV system
Converter	Studer AJ 1000-12	0.398 kW	Conditioning and converting the power flow
Load	AC Primary Load	942 kWh/year	Meeting the light trap's energy needs

Modeling and simulation were performed using HOMER Pro by inputting the light trap load profile, solar power source, and the technical and economic parameters of the system components. The capacities of the PV system, battery, and converter were used in the simulation process to evaluate various system configurations. The modeled system consists of a PV system as the energy source, a battery as the energy storage, a converter as the power conditioner, and the light trap as the load.

2.4 Technical and Economic Analysis

A technical analysis was conducted to evaluate the system's ability to meet the light trap's energy needs. The parameters analyzed included PV generation capacity, battery storage capacity, electricity production, load energy consumption, and the renewable fraction. These parameters were used to determine the system's ability to supply energy from renewable sources and meet the load's needs during the simulation period.

An economic analysis was conducted to determine the total cost of the system over the analysis period. The economic parameters used include Net Present Cost (NPC) and Levelized Cost of Energy (LCOE). NPC is used to indicate the total cost of the system over the analysis period, while LCOE is used to indicate the average cost of energy generated by the system. This approach to technical and economic analysis of renewable energy systems for agricultural applications has also been used in previous studies [5], [6].

The HOMER Pro simulation results were used to compare the technical and economic performance of the obtained system configurations. These results then served as the basis for determining the system configuration capable of meeting the light trap's energy needs while considering aspects of energy generation, storage, load fulfillment, and system costs.

2.5 Optimal System Selection

The optimal system configuration was determined based on the results of the HOMER Pro optimization, taking into account technical and economic parameters. The selection process involved comparing the system configurations generated from the simulations based on the systems' ability to meet the light trap's energy needs and the use of renewable energy sources. Key parameters used in the selection process include photovoltaic (PV) capacity, number of batteries, converter capacity, electricity production, load energy consumption, renewable fraction, Net Present Cost (NPC), and Levelized Cost of Energy (LCOE).

The selected configuration must be capable of supplying the energy required by the light trap during the simulation period, taking into account the PV generation capacity and energy storage in the batteries. The converter is also factored in to ensure that the power conditioning capacity aligns with the system's needs. In addition to technical aspects, economic parameters are used to assess the cost implications of the generated configurations, ensuring that system selection is based not only on component capacity but also on the system's economic performance.

The results of the HOMER Pro optimization are then used to determine a configuration that meets energy needs with an appropriate combination of components based on the simulation results. The selected configuration is subsequently used as the basis for analyzing system performance in the results and discussion section. Values for component capacity, energy production, load consumption, renewable fraction, NPC, and LCOE are obtained directly from the HOMER Pro simulation results and used to evaluate the performance of the selected system configuration.

3. Results

3.1 HOMER Pro Simulation Results and Optimal System Configuration

Techno-economic optimization of an off-grid solar photovoltaic-battery power generation system for onion pest management in Nganjuk Regency, East Java, was successfully conducted using HOMER Pro software. Based on local solar radiation data shown in Figure 3.

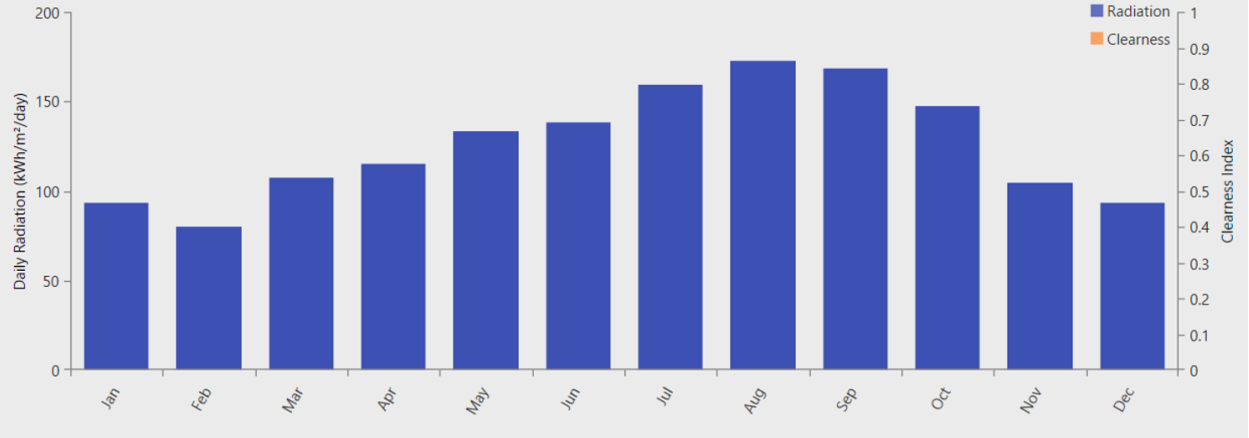


Fig. 3. Daily Radiation

It can be seen that the daily radiation intensity at the study site is relatively high and stable throughout the year, with peak values occurring in August and September—which coincide with the peak of the dry season—and the lowest values in February, which marks the peak of the rainy season with higher cloud cover. This seasonal pattern is consistent with the characteristics of Indonesia's tropical climate and serves as the primary input for HOMER Pro in calculating the energy potential that can be generated by PV modules throughout the year.

The operational energy requirements of the light trap system on shallot farmland are determined based on the number of units, the power capacity of each unit, and the daily operating duration, in line with the importance of matching battery capacity to the operational duration of solar-powered light traps, as emphasized in previous research [18]. In the design of this system, the total operational load consists of 36 light trap units, each consuming 8 watts of power, with an average operating duration of 9 hours per day. Based on these parameters, the total electrical power required by all devices is calculated using Equation (1):

$$P_{total} = N \times P_{unit} \quad (1)$$

where N is the number of light trap units (36 units) and P_{unit} is the power per unit (8 Watts). Based on this calculation, the total load power connected to the system is 288 Watts, or equivalent to 0.288 kW, as shown in Table 3.

Table 3
Load Data

Load	Power (Watts)	Duration (Hours)	Quantity (Units)	Total Power (Watts)
LED Lights	8	9	36	288

Next, the total daily energy consumption is calculated using Equation (2) as the product of the total load power and the daily usage duration. To calculate the projected annual energy demand, the daily energy consumption is multiplied by the total number of operating days in a year (365 days) using Equation (3)

$$E_{day} = P_{total} \times t \quad (2)$$
$$E_{year} = E_{day} \times 365\ day \quad (3)$$

The calculated annual energy consumption of 946.08 kWh/year shows a very high level of agreement with the previously designed HOMER Pro modelling parameters, in which the AC primary load was set at 942 kWh/year. This very minimal difference confirms that the load profile planning for the 36 light trap units is highly accurate and can be optimally supplied by a 0.700 kW solar power plant configuration supported by a battery storage bank, thereby ensuring the system's reliability in an off-grid configuration without experiencing power shortages.

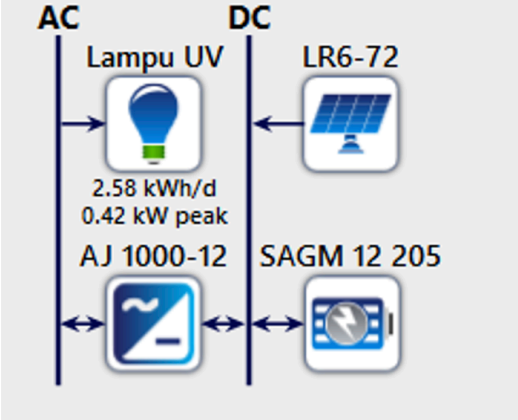
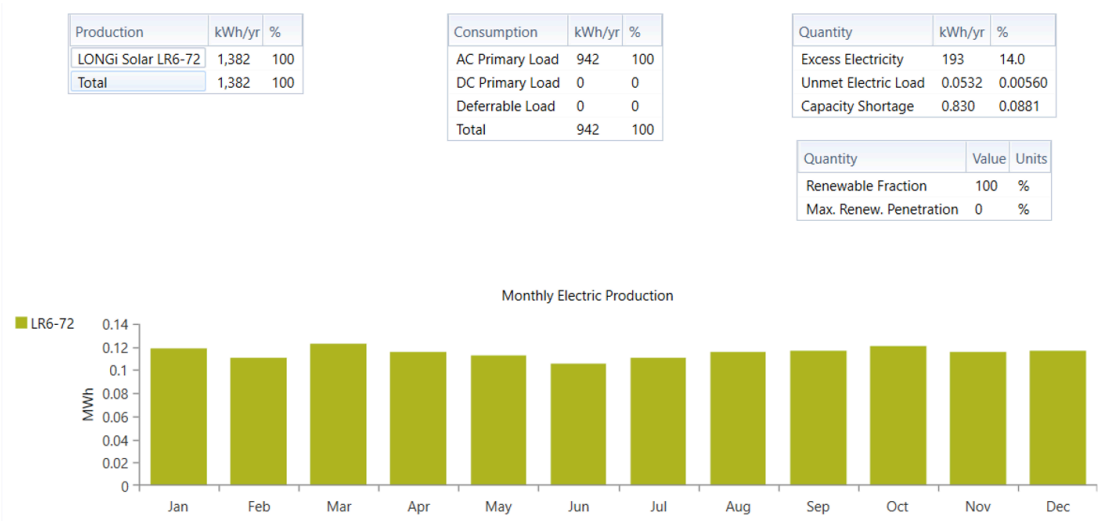


Fig. 4. Schematic Diagram

With a primary AC load requirement of 942 kWh/year, the simulation evaluated various component architectures to determine the most reliable and economically viable configuration. The optimization results show that the optimal system configuration consists of LONGI Solar LR6-72 photovoltaic modules with a capacity of 0.700 kW, 2 units of Trojan SAGM 12 batteries with a capacity of 205 kWh at a bus voltage of 120 V, and a Studer AJ 1000-12 converter with a capacity of 0.389 kW [16][17]. This configuration is schematically illustrated in the system diagram in Figure 4, which shows an AC-DC hybrid architecture with a UV lamp (light trap) load of 2.58 kWh/day and a peak load of 0.42 kW on the AC side, consistent with the use of solar-powered UV lamps for sustainable agricultural pest control, as also reported in other studies [22]. Additionally, the LR6-72 PV module and the SAGM 12 205 battery on the DC side are connected via the AJ 1000-12 converter.



Production	kWh/yr	%
LONGi Solar LR6-72	1,382	100
Total	1,382	100

Consumption	kWh/yr	%
AC Primary Load	942	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	942	100

Quantity	kWh/yr	%
Excess Electricity	193	14.0
Unmet Electric Load	0.0532	0.00560
Capacity Shortage	0.830	0.0881

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	0	%

Fig. 5. Production Data Diagram

The monthly energy production pattern shown in the "Monthly Electric Production" graph in Figure 5 reinforces these findings, with the highest production occurring in March and during the August–December period, while the lowest production occurs in June, following the pattern of solar radiation. The consistency of energy production throughout the year without any drastic drops indicates that the PV system is capable of generating energy stably despite seasonal variations, thereby supporting the reliability of the energy supply for the light trap year-round, as also demonstrated in the performance evaluation of solar-powered light traps for controlling the rice black bug, which reported similar performance stability [21].

Quantity	Value	Units
Rated Capacity	0.700	kW
Mean Output	0.158	kW
Mean Output	3.79	kWh/d
Capacity Factor	22.5	%
Total Production	1,382	kWh/yr

Quantity	Value	Units
Minimum Output	0	kW
Maximum Output	0.505	kW
PV Penetration	147	%
Hours of Operation	4,281	hrs/yr
Levelized Cost	343	Rp/kWh

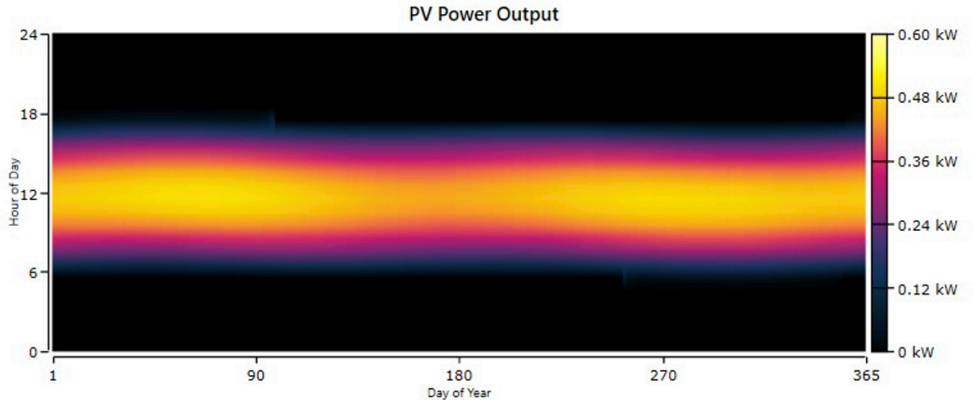


Fig. 6. Monthly Electricity Production

The technical performance of the PV modules is presented in more detail in Figure 6, which shows a rated capacity of 0.700 kW with an actual mean output of only 0.158 kW (3.79 kWh/day) due to variations in daily radiation intensity, as well as a capacity factor of 22.5%, which is considered reasonable for PV systems in tropical Indonesia, consistent with reported rooftop PV capacity factors in Indonesia ranging from 11–15% in other studies [19][20]. The PV penetration rate of 147% indicates that PV generation capacity exceeds average load demand, resulting in an energy reserve margin, while the 4,281 hours/year of operation (approximately 11.7 hours/day) is consistent with the duration of effective sunlight in tropical regions. The annual PV power output pattern is also visualized in the form of a PV Power Output heatmap, which shows a consistent power production band occurring from 8:00 AM to 4:00 PM each day with higher intensity during the dry season, with no power production at night—a natural characteristic of PV systems.



Fig. 7. Battery Storage Data Graph

The results of the HOMER Pro simulation indicate the selection of two Trojan SAGM 12 205 batteries configured in parallel at a 12 V bus voltage, with an autonomy of 39.1 hours, indicating the battery's ability to supply the load independently for nearly 1.6 days without PV input, thereby providing adequate reserve capacity to account for days with low solar radiation—a sizing approach for lead-acid batteries in standalone PV-battery systems also employed in other studies [17]. Of the nominal capacity of 5.25 kWh, only about 4.20 kWh can be effectively utilized within the depth-of-discharge limits set to preserve battery lifespan, with a lifetime throughput of 4,570 kWh resulting in an estimated service life of 4.16 years. The battery's round-trip efficiency is also reflected in the comparison of energy in (1,189 kWh/year) and energy out (1,013 kWh/year), resulting in an efficiency of approximately 85%—a reasonable value for sealed AGM lead-acid batteries— and is consistent with findings that battery discharge patterns directly influence the operational duration and effectiveness of solar-powered light traps under field conditions [18]. The battery state of charge (SoC) behavior patterns, displayed via frequency histograms, daily heatmaps, and monthly boxplots, consistently show that the battery's SoC tends to remain in the medium-to-high range (55–85%) throughout the year, with a clear charging pattern occurring during the day when the PV system is actively generating power and a discharging pattern at night to meet the light trap's energy needs, without any drastic drop in SoC even during months with low solar radiation, such as February. This indicates that the capacity of the two battery units is sufficient to maintain a stable energy supply throughout the year. Compared to the baseline system, this proposed configuration provides an optimal balance between technical reliability and cost efficiency for off-grid agricultural applications.

3.2 Technical Performance Analysis

The technical evaluation confirms that the optimized system consistently meets the operational energy needs of the light trap devices throughout the year. The LONGI Solar LR6-72 PV array generates a total annual energy output of 1,382 kWh/year, with an average daily production of approximately 3.79 kWh/day and a capacity factor of 22.5%. This system achieves a renewable fraction of 100%, indicating that all energy used by the main AC load is derived exclusively from

renewable sources without relying on fossil fuels or the utility grid. A summary of the technical operating parameters from the simulation using HOMER Pro is presented in the table below.

Table 4
Technical Performance Analysis

Technical Parameters	Value	Unit
PV Capacity	0.700	kW
Total PV Energy Production	1,382	kWh/year
Average Daily PV Output	3.79	kWh/day
PV Capacity Factor	22.5	%
AC Primary Load	942	kWh/year
Renewable Share	100	%
Excess Electricity	193 (14.0%)	kWh/year
Nominal Storage Capacity	525	kWh
Annual Battery Throughput	1,098	kWh/year
Battery Lifespan	4.16	years

The capacity factor value of 22.5% in Table 4 indicates the ratio of the actual energy generated to the maximum energy that could theoretically be generated if the PV system operated at its installed capacity (0.700 kW) at all times. This value is considered reasonable for small-scale PV systems in tropical Indonesia, given that PV power output is heavily influenced by daily variations in radiation intensity, as shown in the solar radiation pattern in Figure 3, as well as the effective irradiation duration, which lasts only about 11.7 hours per day; these findings are consistent with the evaluation of rooftop PV capacity factors in Indonesia's tropical climate from a previous study [19][20] The PV generation capacity exceeding the average load demand also explains why an excess electricity of 193 kWh/year (14.0%) is recorded in Table 3 [11]; this excess energy serves as a crucial reserve to anticipate days with low solar radiation due to cloudy weather or the rainy season, thereby ensuring the continuity of energy supply to the load.

In terms of system reliability, the very small unmet electric load value (0.0532 kWh/year or 0.0056%) indicates that the designed system is capable of consistently meeting nearly all of the light trap's operational energy needs throughout the year, with a negligible failure rate in meeting the load [11][14]. This reliability is closely tied to the role of the Trojan SAGM 12 205 battery energy storage subsystem, previously visualized through the State of Charge pattern in Figure 5, which shows a charging cycle during the day in tandem with PV production and a discharging cycle at night to supply the light trap's operational needs, in line with the battery autonomy patterns in previously reported household-scale standalone PV-battery systems [17], and consistent with findings that battery capacity limitations are the primary factor constraining the operational effectiveness of solar-powered light traps in the field [18]. The nominal battery storage capacity of 525 kWh, as listed in Table 4, provides an adequate energy reserve margin, enabling the battery to supply load requirements without experiencing deep discharge conditions that can accelerate degradation, with an estimated service life of 4.16 years before replacement is necessary.

3.3 Economic Evaluation

The economic feasibility of the proposed system is assessed using the Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) parameters. The total net present cost of the optimal configuration was calculated at Rp65,412,740.00, which includes initial capital expenditures—primarily consisting of the battery bank and PV modules—as well as projected replacement and maintenance costs over

the project's lifecycle [12][15][17]. This system yields a competitive average energy cost (Levelized Cost of Energy) of Rp753.52/kWh, demonstrating its economic advantages and feasibility compared to alternatives such as extending the power grid or using diesel generators in remote agricultural areas, as also shown in the LCOE evaluation of PV systems in Indonesia's tropical climate [23] and in feasibility studies of hybrid energy systems in remote rural areas [13][14][24]. Overall, these optimization findings validate that the integration of a 0.700 kW solar PV system and two battery storage units provides a sustainable, cost-effective, and self-sufficient power source for light-trap technology in Nganjuk.

4. Conclusions

This study successfully performed a techno-economic optimization of a solar PV-battery system as an off-grid energy source to support the operation of light traps for pest control in shallot crops in Nganjuk Regency, East Java, using HOMER Pro software. The system load consists of 36 light trap units, each with a power rating of 8 watts and an average operational duration of 9 hours per day, resulting in a total load power of 288 watts and a projected annual energy consumption of 946.08 kWh/year, which closely aligns with the primary AC load specified in the HOMER Pro model of 942 kWh/year. Simulation results show that the optimal system configuration consists of a LONGi Solar LR6-72 photovoltaic module with a capacity of 0.700 kW, two Trojan SAGM 12 205 battery units connected in parallel at a bus voltage of 12 V, and a Studer AJ 1000-12 converter with a capacity of 0.389 kW. This configuration is capable of generating 1,382 kWh/year of renewable energy, with an average daily production of 3.79 kWh/day, a capacity factor of 22.5%, and a renewable fraction of 100%, indicating that the entire energy load is met exclusively from renewable energy sources without the use of fossil fuels or grid connection. The system's reliability is very high, as evidenced by an unmet electric load of 0.0532 kWh/year (0.0056%) and a capacity shortage of 0.830 kWh/year (0.0881%), while excess electricity amounts to 193 kWh/year (14.0%), serving as an energy reserve during periods of low solar radiation. The battery subsystem has an autonomy of 39.1 hours, a nominal capacity of 5.25 kWh with an effective usable capacity of 4.20 kWh, a lifetime throughput of 4,570 kWh, a round-trip efficiency of approximately 85%, and an estimated service life of 4.16 years. From an economic perspective, this system has a Net Present Cost (NPC) of Rp65,412,740.00 and a Levelized Cost of Energy (LCOE) of Rp753.52/kWh, indicating that the system is economically viable for implementation in remote agricultural areas compared to alternatives such as extending the power grid or using diesel generators. These findings address the research objectives by demonstrating that a PV-battery-based energy system can provide a reliable, self-sufficient, and cost-effective electricity supply to support the sustainable implementation of light trap technology in shallot cultivation in Nganjuk Regency.

Acknowledgments
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Conflict of Interest Statement
The authors declare that there is no conflict of interest regarding the publication of this paper. No financial support, grants, or other forms of compensation were received that could have influenced the outcomes of this work. The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest

Data Availability Statement

All data generated or analyzed during this study are included in this published article. Additional datasets are available from the corresponding author upon reasonable request. Where applicable, publicly available datasets used in the study are cited in the references.

Ethics Statement

This study was conducted in accordance with the ethical standards of the institutional and/or national research committee. Ethical approval was obtained where required, and informed consent was obtained from all participants involved in the research

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