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Techno-Economic Optimization of a Solar-Battery Agricultural Energy Hub for Irrigation in Banyumas Village, Sampang: A HOMER Pro Simulation Study

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ABSTRACT

Agricultural productivity in Banyumas Village, Sampang Regency, Madura, faces significant constraints due to fluctuating water availability and high dependence on diesel-powered irrigation pumps, which impose economic burdens and generate substantial greenhouse gas emissions. This study designs and optimizes a Solar-Battery Agricultural Energy Hub integrating photovoltaic generation and battery storage to supply irrigation and auxiliary agricultural loads. The proposed system comprises a 750 W irrigation pump operating eight hours daily, two 10 W LED lamps operating six hours daily, and a 45 W electric fan operating six hours daily, resulting in a total installed load of 815 W and a daily energy demand of 6.39 kWh. The methodology employs HOMER Pro simulation to evaluate multiple PV and battery configurations based on technical indicators, including annual energy production, renewable fraction, unmet electrical load, excess electricity, and capacity shortage, as well as economic indicators comprising Net Present Cost, Cost of Energy, and payback period. The optimization identified an optimal off-grid configuration consisting of a 3 kW photovoltaic array, a 20 kWh lead-acid battery bank, and a 2 kW converter, achieving a renewable fraction of 100% with annual PV production of 4,658 kWh against an annual electrical load of 3,123 kWh. The system records minimal unmet electrical load of 1.04 kWh/year and capacity shortage of 1.88 kWh/year, demonstrating reliable supply capability. Economically, the configuration yields a Net Present Cost of USD 21,861.93 and a Cost of Energy of USD 0.8915/kWh, with the battery bank representing the largest lifecycle cost. These findings indicate that while the proposed energy hub is technically feasible and environmentally sustainable, its economic competitiveness relative to conventional diesel-based irrigation remains challenging. The study contributes primary load profile data and context-specific optimization results for the Madura region.

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1. Introduction

Agricultural productivity in Banyumas Village, Sampang Regency, Madura, faces a fundamental challenge arising from fluctuations in water availability, particularly for farmland irrigation during the dry season. This challenge is exacerbated by the heavy reliance on diesel-powered pumps, which impose an economic burden on farmers due to fluctuating fuel prices and contribute to greenhouse gas emissions. Ibrahim et al. [1] demonstrated that diesel-based irrigation systems for smallholder farms in arid regions can generate up to 993 kg of CO₂ emissions annually while exposing farmers to increasing uncertainty in fuel costs. Paradoxically, this dependence is particularly pronounced in regions with abundant solar energy potential but limited energy infrastructure, a condition described by several researchers as "agricultural energy poverty" [2].

Solar energy utilization for agricultural irrigation has been demonstrated to be technically and economically feasible in various contexts. Salwagan [3] reported that implementing Solar-Powered Irrigation Systems (SPIS) in the Philippines significantly improved crop yields, crop quality, and farmers' income while reducing irrigation and energy costs compared with conventional diesel-powered pumps [3]. Similar findings were reported by Ani et al. [4], who employed HOMER software to assess the feasibility of a solar-powered water pumping system in the Karshi community, Nigeria. Their findings indicated that solar-powered pumping technology provides a reliable and economically viable alternative to diesel-powered irrigation [4]. However, the long-term effectiveness of such systems depends not only on their water-pumping capabilities but also on their ability to supply auxiliary electricity to agricultural facilities and the appropriate sizing of photovoltaic (PV) components and battery storage [5].

Beyond the technical feasibility of solar-powered irrigation, recent studies have emphasized the importance of integrating battery energy storage systems to improve operational reliability and ensure energy availability during periods of low solar irradiance. Wangsupphaphol et al. [6] demonstrated that integrating photovoltaic generation with lithium-ion battery storage in agricultural applications can significantly improve energy self-sufficiency and reduce long-term operating costs. Similarly, Maulana [7] reported that hybrid PV-battery systems in rural areas can provide a more resilient electricity supply while reducing dependence on conventional fossil-fuel generators. In Indonesia, Hartopo and Rosyadi [8] further demonstrated that integrating HOMER Pro and PVSyst can support the optimal sizing of renewable energy systems under site-specific environmental conditions, thereby minimizing energy shortages and avoiding excessive component oversizing.

An important consideration that is often overlooked in solar irrigation system design is that modern agricultural operations require electricity not only for water pumping but also for auxiliary loads, including lighting and ventilation in agricultural facilities. A case study conducted in Gunungkidul, Yogyakarta, documented that a 4 kWp off-grid solar irrigation system installed in late 2022 ceased operating by mid-2024 due to inadequate operation and maintenance practices, resulting in permanent damage to the inverter and battery bank [9]. This failure highlights the importance of considering not only capital and operating costs in techno-economic optimization but also the long-term reliability and sustainability of the system. Inaccurate sizing of PV arrays and battery storage can lead to two undesirable outcomes: insufficient energy generation to meet operational requirements or excessive energy production resulting from oversized components [10].

The Solar-Battery Agricultural Energy Hub proposed in this study addresses these requirements by integrating photovoltaic generation and battery storage to supply electricity to irrigation pumps and auxiliary loads in agricultural facilities. The proposed system consists of a 750 W irrigation pump operating for eight hours per day, two 10 W LED lamps operating for six hours per day, and a 45 W

electric fan operating for six hours per day. The total installed load is 815 W, with a daily energy consumption of 6.39 kWh. This load configuration reflects the practical electricity requirements of small-scale agricultural facilities, where energy is needed not only for irrigation but also for supporting daily operations [11]. Bekak et al. [12] demonstrated in Oebau Village, Rote Ndao, that off-grid solar-powered water pumping systems can provide an effective solution for areas without access to the national electricity grid by utilizing battery-stored energy and DC-to-AC conversion through an inverter to operate water pumps [12].

From a methodological perspective, techno-economic optimization of standalone renewable energy systems has advanced considerably through simulation software such as HOMER Pro (Hybrid Optimization of Multiple Energy Resources). HOMER Pro enables the evaluation of numerous potential system configurations based on specified electrical load profiles, local renewable energy resources, and reliability requirements. It also facilitates multi-parameter sensitivity analyses, making it particularly suitable for rural electrification applications [13]. The software is widely used to assess system performance using indicators such as total energy generation, renewable fraction, unmet electrical load, excess electricity production, Net Present Cost (NPC), Cost of Energy (COE/LCOE), and simple payback period. In Tunisia, Mariem et al. [14] employed HOMER to identify an optimal configuration for a solar-powered groundwater extraction system, concluding that a hybrid PV-diesel configuration offered a favorable economic trade-off for agricultural irrigation [14]. Similarly, Mojumder et al. [15] demonstrated that integrating lithium-ion battery storage into a PV-diesel generator system in Bangladesh resulted in a technically reliable and economically feasible configuration, achieving a competitive LCOE of USD 0.154/kWh [15].

Although HOMER Pro has been widely applied to solar-powered irrigation systems, techno-economic optimization specifically tailored to Banyumas Village, integrating both irrigation and auxiliary agricultural facility loads within a unified energy hub, remains insufficiently investigated. Previous studies in Indonesia have predominantly focused on standalone irrigation pumps without considering supporting agricultural loads, thereby overlooking the complexity of actual operational load profiles [16]. Furthermore, many existing studies have not adequately addressed sensitivity analyses involving fuel price fluctuations and declining battery costs, despite the importance of these parameters for long-term investment sustainability. Recent techno-economic assessments indicate that although off-grid PV-BESS configurations can eliminate carbon dioxide emissions during operation, they may result in a Cost of Energy (COE) of USD 0.365/kWh, approximately 60% higher than that of hybrid generator-PV-BESS configurations (USD 0.219/kWh) [17]. This trade-off between economic feasibility and environmental performance requires further evaluation in the context of Banyumas Village, consistent with the observations of Rahmani and Murayama [18], who emphasized the importance of post-construction support for rural solar water pumping systems in Indonesia [18].

Recent advances in techno-economic optimization have also emphasized the importance of evaluating renewable energy systems using multiple performance indicators rather than focusing exclusively on energy generation. Prasetyo et al. [19] demonstrated that HOMER Pro can identify economically viable renewable energy configurations by simultaneously considering NPC, COE, renewable fraction, and excess electricity generation. Furthermore, Susanto et al. [20] emphasized that the long-term sustainability of solar water pumping systems depends not only on technical performance but also on operational, economic, and institutional factors. These findings indicate that successful implementation of renewable energy-based irrigation infrastructure requires a comprehensive assessment framework integrating technical reliability, economic feasibility, and sustainability considerations.

To establish the position of the present study within the existing literature, Table 1 summarizes nine relevant studies, highlighting their methodologies, system configurations, research objectives, and limitations. As presented in Table 1, most previous studies focused on standalone irrigation pumps without integrating auxiliary electrical loads from agricultural facilities. Furthermore, relatively few studies incorporated multi-parameter sensitivity analyses within the specific context of eastern Indonesia.

Table 1
State of the Art

Authors (Year)	Fokus Kajian	Keterbatasan
Ibrahim et al. [1]	CO ₂ emissions and fuel cost uncertainties in small-scale diesel irrigation	Does not evaluate renewable energy alternatives
Salwagan [3]	Impact of SPIS on crop yields, farmers' income, and irrigation costs in the Philippines	Does not analyze PV/battery capacity optimization
Ani et al. [4]	Techno-economic feasibility of solar water pumping in Karshi, Nigeria	Excludes auxiliary agricultural loads
Satria et al. [6]	Operational and maintenance failures of a 4 kWp off-grid SPIS in Yogyakarta	Lacks cost sensitivity analysis
Bekak et al. [9]	Off-grid solar water pumping solution for unelectrified areas in Rote Ndao	Lacks multi-parameter sensitivity optimization
Mariem et al. [11]	Most economical configuration of hybrid PV–diesel systems for irrigation in Tunisia	Relies on diesel generators (non-zero emissions)
Mojumder et al. [11]	Technical and economic feasibility of PV + Li-ion battery + diesel in Bangladesh (LCOE \$0.154/kWh)	Still incorporates a diesel generator
Soleimani et al. [13]	Economic and environmental trade-offs of off-grid PV–BESS vs. hybrid generator–PV–BESS (CoE \$0.365 vs. \$0.219/kWh)	Not tailored to the Indonesian agricultural context
Rahmani & Murayama [14]	<i>Post-construction support for community solar water pumping in Indonesia</i>	Does not address techno-economic optimization

Based on the comparative analysis presented in Table 1, three major research gaps can be identified: (i) the lack of studies integrating primary irrigation pumping and auxiliary agricultural facility loads within a unified energy hub framework for Banyumas Village; (ii) limited multi-parameter sensitivity analyses addressing fluctuations in fuel prices and projected reductions in battery costs; and (iii) the limited availability of primary electrical load profile data specific to agricultural operations in the Madura region.

The primary objective of this study is to design and optimize a Solar-Battery Agricultural Energy Hub capable of reliably meeting irrigation and supporting electrical load requirements in Banyumas Village while considering both technical and economic performance. Specifically, the study aims to: (i) determine the optimal PV capacity and battery storage configuration for a total installed load of 815 W and daily energy consumption of 6.39 kWh; (ii) evaluate the techno-economic performance of the proposed system using NPC, COE, and simple payback period; and (iii) investigate system sensitivity to variations in key parameters, including fuel prices, battery capital costs, and solar irradiance.

The significance of this study lies in three principal contributions. First, from a methodological perspective, it demonstrates the application of HOMER Pro to optimize community-scale agricultural energy hubs in eastern Indonesia, providing a framework that can be adapted to similar rural settings. Second, from an empirical perspective, it provides primary load data and location-specific optimization results for Banyumas Village, addressing an identified gap in renewable energy research in Madura. Third, from a practical perspective, the findings are expected to improve agricultural

energy self-reliance, reduce dependence on fossil fuel-based irrigation systems, and support sustainable agricultural productivity in Banyumas Village.

2. Methodology

This study employed a simulation-based approach to design and evaluate a solar-battery energy system for agricultural irrigation in Banyumas Village, Sampang Regency, East Java, Indonesia. The proposed system was designed to supply electricity to the primary irrigation load while supporting essential electrical equipment in an agricultural shelter. HOMER Pro was selected as the primary simulation and optimization tool because it enables the interactions among photovoltaic generation, battery storage, power conversion, and electrical demand to be evaluated throughout the project lifetime.

The methodology began with identifying the agricultural electricity requirements and developing a daily electrical load profile. Solar resource data were subsequently used to estimate the photovoltaic energy generation potential at the study location. The proposed PV-battery system was modeled in HOMER Pro by varying the capacities of the PV array and battery storage. The resulting configurations were evaluated and compared using technical performance and economic indicators. This approach ensured that the system configuration was determined not solely by installed capacity but also by its ability to meet agricultural electricity demands while maintaining efficient energy utilization and acceptable economic performance.

2.1 Research Approach

This study adopted a simulation-based techno-economic approach to design and optimize a Solar-Battery Agricultural Energy Hub for agricultural irrigation and supporting electrical loads in Banyumas Village, Sampang Regency, East Java, Indonesia. The proposed system was configured as an off-grid renewable energy system consisting of photovoltaic (PV) generation, battery storage, a power converter, and agricultural electrical loads.

The research began by identifying and calculating the electricity requirements of the agricultural facility. The electrical load profile consisted of an irrigation water pump, two LED lamps, and an electric fan. Each component was characterized according to its rated power and daily operating duration to determine the total electricity demand.

The subsequent stage involved assessing the solar energy resources available at the study location and incorporating the resulting data into the PV system model. The PV array, battery storage, and converter were then modeled using HOMER Pro. Different PV and battery capacities were evaluated to determine their effects on technical performance and economic feasibility.

The simulation results were assessed using technical indicators, including annual electricity generation, renewable fraction, unmet electrical load, excess electricity, and battery operating characteristics. Economic performance was evaluated using Net Present Cost (NPC), Cost of Energy (COE), and payback period. The overall research procedure is illustrated in Figure 1.

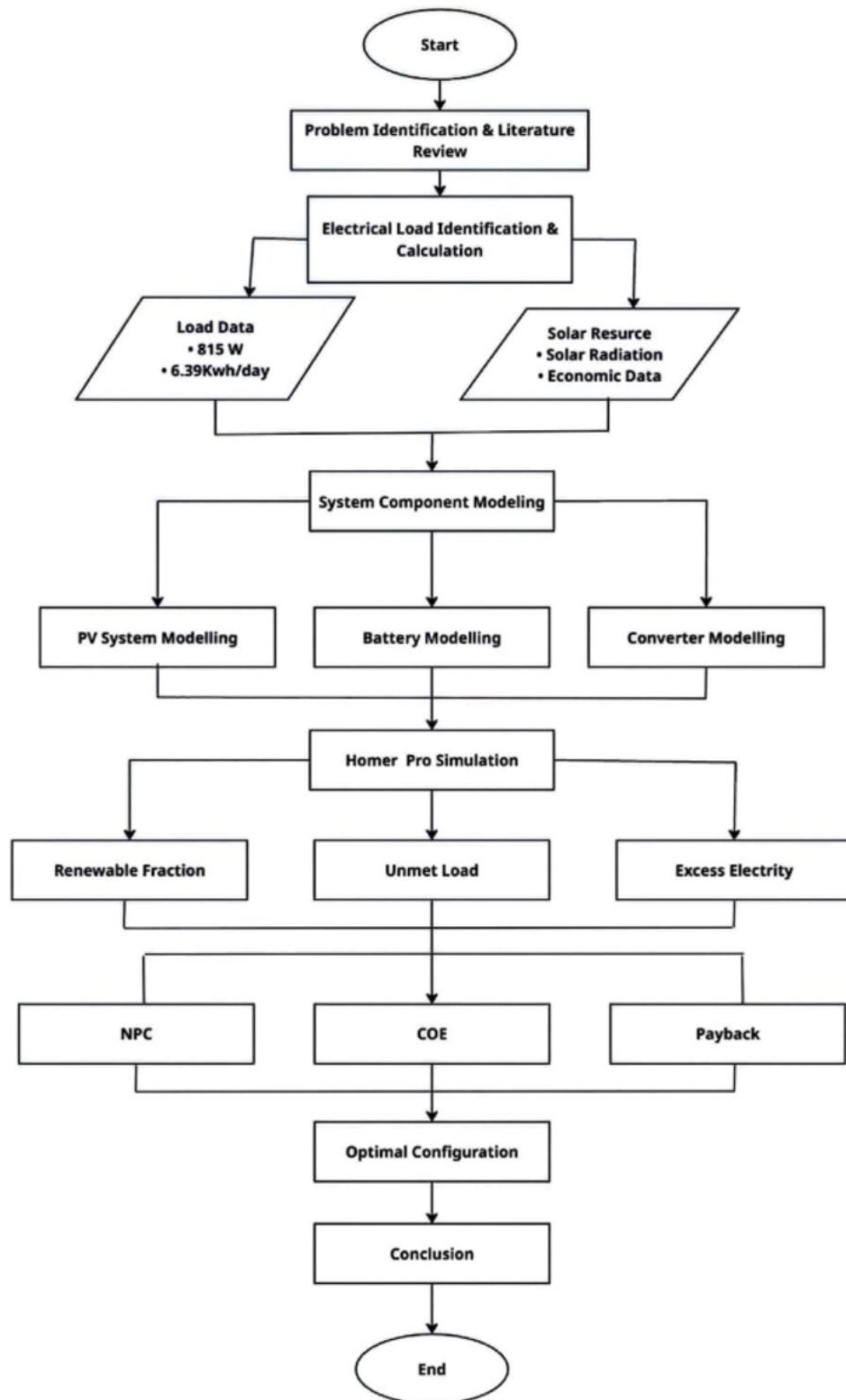


Fig. 1. Research flow of the proposed solar-battery agricultural energy system

2.2 Research Location and Object

The study was conducted in Banyumas Village, Sampang Regency, Madura, East Java, Indonesia. The research site is located at latitude $7^{\circ}07'56.81''$ S and longitude $113^{\circ}14'53.14''$ E. Banyumas Village was selected because agricultural activities in the area are affected by fluctuations in water availability, particularly during the dry season. Previous implementation of solar-powered water pumping systems in the area has demonstrated the potential of solar energy as an alternative electricity source for agricultural irrigation.

This study focused on developing a proposed Solar-Battery Agricultural Energy Hub to supply electricity for agricultural irrigation and supporting activities. The system was modeled as an autonomous off-grid configuration in which electricity demand is supplied by an integrated PV-battery system without connection to the utility grid.

The primary electrical load was a 750 W irrigation water pump, representing the main productive component of the system. Two 10 W LED lamps and one 45 W electric fan were included as auxiliary electrical loads for the agricultural facility. Based on the proposed operating schedule, the total installed load was 815 W, with an estimated daily electricity demand of 6.39 kWh/day.

The geographical location of the study area is presented in Figure 2.

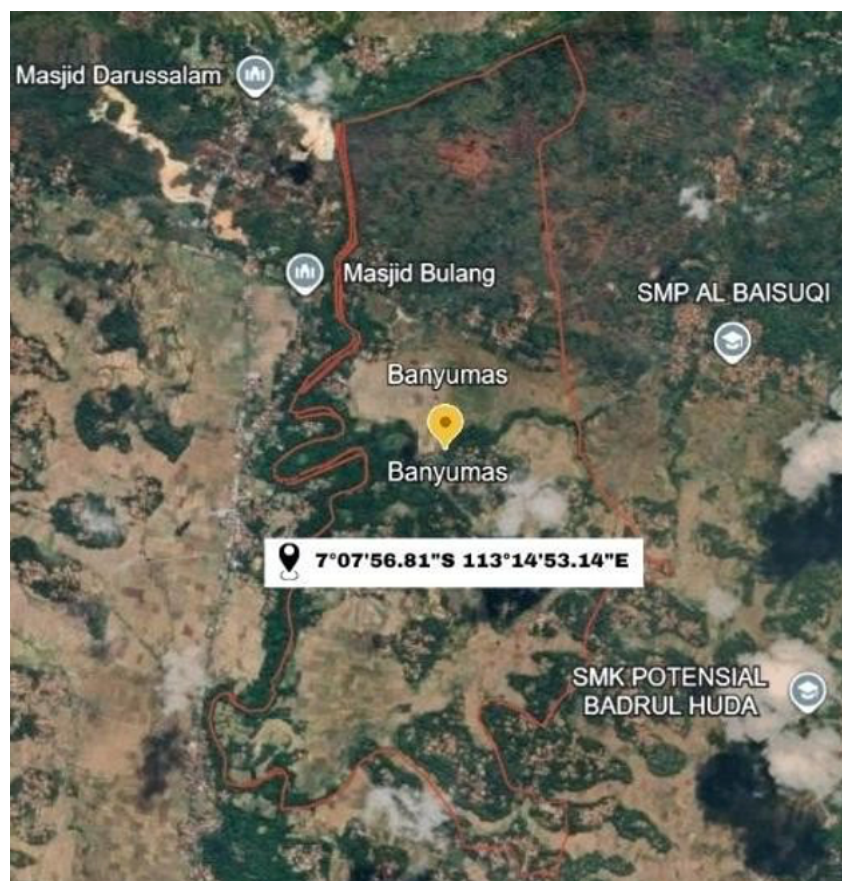


Fig. 2. Study area location in Banyumas Village, Sampang Regency

The main characteristics of the study area and proposed system are summarized in Table 2.

Table 2

Characteristics of the Study Object

Parameter	value	unit
location	Banyumas Village, Sampang	—
Latitude	7°07'56.81"S	—
Longitude	113°14'53.14"E	—
System configuration	Off-grid	—
Main energy source	Solar PV	—
Energy storage	Battery	—
Main load	Irrigation pump	—
Supporting loads	LED lamp and electric fan	—
Total installed load	815	W
Daily energy demand	6.39	kWh/day

The information presented in Table 2 establishes the baseline conditions used for subsequent system modeling and simulation.

2.3 Solar-Battery Agricultural Energy Hub System Design

The proposed Solar-Battery Agricultural Energy Hub integrates a photovoltaic array, battery storage, a power converter, and agricultural electrical loads into a unified energy system. The system was designed to utilize solar energy as the primary electricity source, while battery storage compensates for variations between PV generation and electrical load demand.

The proposed system configuration modeled in HOMER Pro is illustrated in Figure 3.

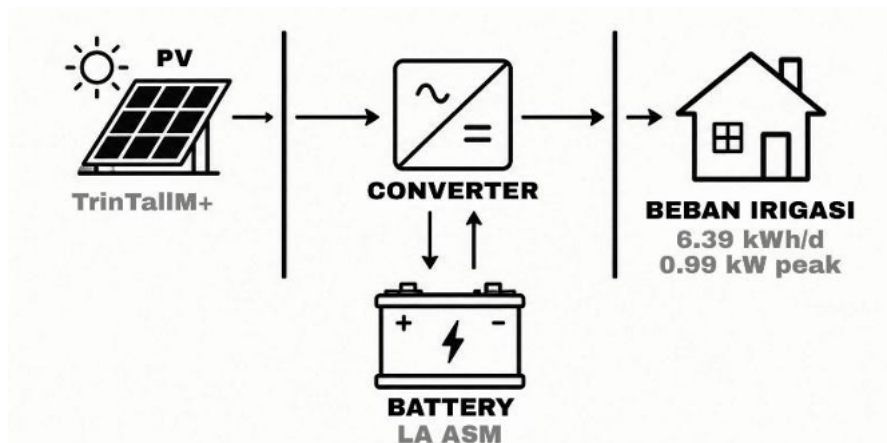


Fig. 3. Proposed Solar-Battery Agricultural Energy Hub configuration modeled in HOMER Pro

The system operates through several energy pathways. During periods of sufficient solar irradiance, the PV array supplies electricity directly to the agricultural loads. When PV generation exceeds instantaneous electricity demand, the surplus energy is directed to the battery for storage. Conversely, when PV generation is insufficient, particularly during periods of low solar irradiance or at night, the battery supplies the required electricity through the converter.

The primary energy pathways are represented as follows:

- Solar Radiation → PV Array → Converter → Agricultural Loads

- PV Array → Battery → Converter → Agricultural Loads

The agricultural loads comprise an irrigation pump, two LED lamps, and an electric fan. Unlike conventional solar-powered irrigation systems that primarily consider pumping requirements, the proposed configuration integrates irrigation and auxiliary facility loads within a single energy system. This configuration represents a small-scale agricultural energy hub in which solar generation and battery storage are jointly utilized to support both productive agricultural activities and daily facility operations.

2.4 Electrical Load Profile

The electrical load profile was developed based on the electricity requirements of the agricultural irrigation facility. The irrigation pump was considered the primary electrical load because its operation directly supports water distribution for agricultural activities. Two LED lamps and an electric fan were included as auxiliary loads to support lighting and ventilation requirements within the agricultural shelter and surrounding working area.

The proposed system consists of one 750 W irrigation water pump operating for eight hours per day, two 10 W LED lamps operating for six hours per day, and one 45 W electric fan operating for six hours per day. The daily electricity consumption of each load was calculated using Equation (1):

$$E_i = P_i \times t_i$$

where E_i represents the daily electricity consumption of load i (Wh/day), P_i is the rated power (W), and t_i is the daily operating duration (h/day).

For the irrigation pump:

$$E_{\text{pump}} = 750 \times 8 = 6,000 \text{ Wh/day}$$

For the two LED lamps:

$$E_{\text{lamp}} = 2 \times 10 \times 6 = 120 \text{ Wh/day}$$

For the electric fan:

$$E_{\text{fan}} = 45 \times 6 = 270 \text{ Wh/day}$$

Therefore, the estimated total daily electricity requirement is:

$$E_{\text{daily}} = 6,000 + 120 + 270 = 6,390 \text{ Wh/day} = 6.39 \text{ kWh/day}$$

The total connected electrical load is calculated as:

$$P_{\text{total}} = 750 + (2 \times 10) + 45 = 815 \text{ W}$$

The calculated electrical load characteristics are presented in Table 3.

Table 3
Electrical Load Profile of the Agricultural Energy Hub

Load	Quantity	Power/Unit	Total Power	Operating Time	Energy/day
Irrigation water pump	1	750 W	750 W	8 h/day	6,000 Wh
LED lighting	2	10 W	20 W	6 h/day	120 Wh
Electric fan	1	45 W	45 W	6 h/day	270 Wh
Total	4	-	815 W	-	6,390 Wh/day

The calculated load profile provides the initial basis for the HOMER Pro simulation model. However, the annual electricity consumption used in the simulation was determined from the complete hourly load profile entered into HOMER Pro. Therefore, the annual electricity consumption reported in the Results section was obtained directly from the simulation output rather than by multiplying the nominal daily consumption by 365.

2.5 Solar Resource and PV Modeling

Solar radiation was the primary renewable energy resource considered in this study. Solar resource data for the study location were entered into HOMER Pro to estimate the electricity generation potential of the PV array throughout the year. The PV array was modeled as the primary electricity generation component. During periods of sufficient solar irradiance, PV generation supplies electricity to the agricultural loads and charges the battery when surplus energy is available. When PV generation falls below electricity demand, the battery provides the required energy through the converter.

PV capacity was treated as an optimization variable in HOMER Pro. Several capacity options were evaluated to determine the effects of PV sizing on annual electricity generation, battery operation, excess electricity production, and load fulfillment. The primary PV parameters considered in the simulation included rated capacity, capital cost, replacement cost, operation and maintenance costs, component lifetime, and derating factor. The application of HOMER Pro to evaluate PV system sizing and economic performance followed the general modeling approaches adopted in previous HOMER-based solar energy studies.

2.6 Battery Storage Modeling

Battery storage was incorporated into the proposed system to address the temporal mismatch between solar electricity generation and agricultural electricity demand. This consideration is particularly important because PV generation occurs primarily during daylight hours, whereas some auxiliary electrical loads may operate outside periods of peak solar energy production.

The battery stores surplus electricity generated by the PV array and supplies electricity to the loads when PV output is insufficient. The basic energy balance during periods of sufficient PV generation can be expressed as:

$$E_{PV} = E_{load} + E_{battery} + E_{excess}$$

During periods of insufficient PV generation, the energy balance is expressed as:

$$E_{load} = E_{PV} + E_{battery}$$

These relationships are subject to the allowable battery state of charge and energy conversion losses.

Battery capacity was varied during the HOMER Pro optimization process to determine whether increasing storage capacity significantly improved electricity supply reliability or resulted in unnecessary additional investment. The final optimized configuration obtained from the simulation incorporated a 20 kWh lead-acid battery bank. The battery therefore served as the primary energy storage component of the proposed agricultural energy hub.

The incorporation of battery storage is also consistent with the solar irrigation configuration reported in the previous Banyumas study, in which stored PV electricity was utilized when solar generation decreased due to cloudy conditions or the absence of sunlight.

2.7 Converter (Inverter) Modeling

The converter connects the DC-side PV array and battery storage components to the AC agricultural loads. This component is necessary because the irrigation pump, LED lamps, and electric fan were modeled as AC electrical loads.

Converter capacity was selected based on the maximum electrical demand and operating characteristics of the agricultural equipment. The converter was also modeled according to its efficiency, capital cost, replacement cost, and expected service life.

The optimized HOMER Pro configuration incorporated a 2 kW converter. This capacity provides sufficient power conversion capability for the modeled agricultural loads, which have a calculated total connected load of 815 W.

The converter was treated as an independent component in the economic model because its service life and replacement requirements differ from those of the PV array and battery storage system. A similar component-based modeling approach was adopted in the HOMER Pro study of the Ranu Grati PV system.

2.8 System Configuration in HOMER Pro

The proposed system was modeled in HOMER Pro as an off-grid solar-battery energy system consisting of PV generation, battery storage, a converter, and agricultural electrical loads.

The direct electricity supply pathway is represented as:

Solar Radiation → PV Array → Converter → Agricultural Loads

Meanwhile, the battery storage pathway is represented as:

PV Array → Battery → Converter → Agricultural Loads

During periods of high solar energy availability, PV-generated electricity is prioritized for supplying the agricultural loads. Surplus electricity is directed to the battery for storage. When PV generation decreases, the stored energy is discharged to maintain the electricity supply.

The final configuration obtained from the HOMER Pro optimization consisted of a 3 kW PV array, a 20 kWh lead-acid battery bank, and a 2 kW converter operating as an off-grid system.

2.9 Technical Performance Indicators

The technical performance of the proposed system was evaluated using several indicators generated by HOMER Pro.

2.9.1 Annual PV Production

Annual PV production represents the total electrical energy generated by the photovoltaic array over one year. It is calculated as:

$$E_{PV, \text{annual}} = \sum_{t=1}^{8760} E_{PV, t}$$

where $E_{PV, t}$ represents the PV electricity generated during hour t .

2.9.2 Renewable Fraction

The renewable fraction indicates the proportion of electricity demand supplied by renewable energy sources. In this study, photovoltaic generation was the only renewable energy source. A simplified expression for the renewable fraction is:

$$RF = \frac{E_{\text{renewable}}}{E_{\text{served}}} \times 100\%$$

where $E_{\text{renewable}}$ represents the renewable energy contribution and E_{served} represents the total electrical energy supplied to the loads.

2.9.3 Unmet Electrical Load

Unmet electrical load represents the portion of electricity demand that cannot be supplied by the system. The annual unmet electrical load can be expressed as:

$$E_{\text{unmet}} = \sum_{t=1}^{8760} (E_{\text{load},t} - E_{\text{served},t})$$

This expression applies to periods when electricity demand exceeds the available energy supply.

2.9.4 Excess Electricity

Excess electricity represents renewable electricity that cannot be directly consumed by the loads or stored in the battery because of insufficient storage capacity or limitations in battery charging conditions. The general energy balance is expressed as:

$$E_{\text{excess}} = E_{PV} - E_{\text{load}} - E_{\text{battery,charge}}$$

This relationship applies when PV generation exceeds instantaneous electricity demand and battery charging requirements.

2.9.5 Capacity Shortage

Capacity shortage represents the difference between the required electrical load and the available system capacity during periods of insufficient energy availability. This indicator is useful for evaluating whether the selected PV-battery configuration can maintain an adequate electricity supply under varying solar conditions.

2.10 Economic Analysis

The economic analysis evaluated the lifecycle costs of the proposed Solar-Battery Agricultural Energy Hub. The assessment considered capital expenditure, component replacement costs, operation and maintenance costs, and other economic parameters incorporated into HOMER Pro.

The primary economic performance indicators were Net Present Cost (NPC), Cost of Energy (COE), and payback period.

2.10.1 Net Present Cost

Net Present Cost (NPC) represents the present value of all costs incurred throughout the project lifetime. It is expressed as:

$$NPC = \frac{C_{ann,tot}}{CRF}$$

where $C_{ann,tot}$ is the total annualized cost and CRF is the capital recovery factor. The capital recovery factor is calculated as:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1}$$

2.10.2 Cost of Energy

The Cost of Energy (COE) represents the average cost of supplying electrical energy from the proposed system. It is calculated as:

$$COE = \frac{C_{ann,tot}}{E_{served}}$$

where E_{served} represents the annual electrical energy supplied to the loads.

The HOMER Pro simulation yielded a COE of USD 0.8915/kWh for the selected system configuration.

2.10.3 Payback Period

The payback period estimates the time required to recover the initial investment through the economic savings generated by the system. A simplified expression is:

$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Annual Net Cash Flow}}$$

The actual payback period was obtained from the economic simulation and should not be calculated independently unless the annual cash-flow components are clearly defined.

3. Results

3.1 Optimal System Configuration

The HOMER Pro simulation identified an optimized off-grid system consisting of a 3 kW photovoltaic array, a 20 kWh lead-acid battery bank, and a 2 kW converter. This configuration was selected as the basis for subsequent technical and economic analyses.

Table 4
Optimal System Configuration

Component	Configuration
PV array	3 kW
Battery	20 kWh Lead-Acid
Converter	2 kW
System type	Off-grid
Renewable Fraction	100%

The optimization results indicate that the selected configuration integrates a 3 kW PV array, a 20 kWh lead-acid battery bank, and a 2 kW converter. The system operates independently of the electricity grid and conventional generators, supplying electricity to agricultural loads exclusively through the integrated PV-battery system. Battery storage accommodates variations between PV generation and the hourly electrical load profile, thereby supporting electricity availability during periods of insufficient solar energy generation.

Optimization Results															Categorized		Overall
Left Double Click on a particular system to see its detailed Simulation Results.																	
Architecture				Cost				System		TrinTailM+		LA ASM					
  TrinTailM+ (kW)	 LA ASM	 Converter (kW)	 Dispatch	 NPC (Rp)	 COE (Rp)	 Operating cost (Rp/yr)	 Initial capital (Rp)	 Ren. Frac (%)	 Total Fuel (L/yr)	 Capital Cost (Rp)	 Production (kWh/yr)	 Autonomy (hr)	 Annual Throughput (kWh/yr)	 Nominal Capacity (kWh)	 Usable Nominal C (kWh)		
  3.50	 20	 1.20	 CC	 Rp127M	 Rp4.213	 Rp2.38M	 Rp96.2M	 100	 0	 42,000,000	 4,689	 61.6	 326	 20.5	 12.3		

Fig. 4. Optimal configuration of the Solar-Battery Agricultural Energy Hub obtained from HOMER Pro

3.2 Annual Electrical Energy Balance

The annual electrical performance of the optimized configuration was evaluated using the electrical simulation results generated by HOMER Pro.

Table 5

Annual Electrical Performance of the Optimized System

Parameter	value	unit
Annual Electrical Load	3,123	kWh/year
PV production	4,658	kWh/year
Excess electricity	825	kWh/year
Unmet electrical load	1.04	kWh/year
Capacity shortage	1.88	kWh/year
Renewable fraction	100	%

The optimized system generates 4,658 kWh of electricity annually from the PV array, while the modeled electrical load reaches 3,123 kWh/year. Part of the generated electricity is used to charge the battery, while 825 kWh/year is recorded as excess electricity. The system exhibits an unmet electrical load of only 1.04 kWh/year and a capacity shortage of 1.88 kWh/year. The renewable fraction reaches 100%, indicating that all electricity supplied to the modeled loads originates from the renewable energy system without contributions from the utility grid or fossil fuel-based generators.

The simulation results indicate that 825 kWh/year of electricity remains unused because it cannot be directly consumed by the loads or stored in the battery under the simulated operating conditions. Nevertheless, the system records an unmet electrical load of only 1.04 kWh/year, demonstrating that the selected configuration can satisfy nearly all the modeled electricity demand. The small remaining energy deficit indicates that insufficient electricity supply occurs only during certain operating periods.

Production	kWh/yr	%
Trina Tallmax M plus	4,689	100
Total	4,689	100

Consumption	kWh/yr	%
AC Primary Load	2,331	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	2,331	100

Quantity	kWh/yr	%
Excess Electricity	2,185	46.6
Unmet Electric Load	1.84	0.0787
Capacity Shortage	2.21	0.0947

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	1,925	%

Fig. 5. Annual electrical performance of the optimized solar-battery system

3.3 Photovoltaic Energy Production

The photovoltaic electricity generation profile was analyzed to examine variations in solar energy production throughout the year.

Monthly PV electricity generation varies according to seasonal changes in solar resource availability. Higher electricity production occurs during months with greater solar irradiance, whereas lower production is observed during periods of reduced solar energy availability. Over the simulation year, the PV array generates a total of 4,658 kWh of electricity. This electricity is used to supply the agricultural loads and charge the battery, while the remaining portion is recorded as excess electricity.

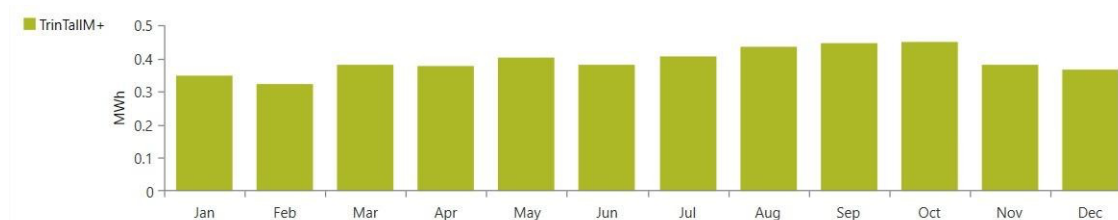


Fig. 6. Monthly photovoltaic energy production

3.4 Battery Performance

Battery performance was evaluated to examine how the 20 kWh energy storage system responds to variations in PV generation and electrical load demand.

The battery state-of-charge profile illustrates the charging and discharging characteristics of the 20 kWh lead-acid battery throughout the simulation period. During periods of high PV electricity generation, the battery is charged using available surplus electricity. Conversely, when PV generation decreases while electricity demand remains active, the battery discharges stored energy to support the loads. This operating mechanism reduces the mismatch between intermittent photovoltaic generation and the agricultural electricity demand profile.

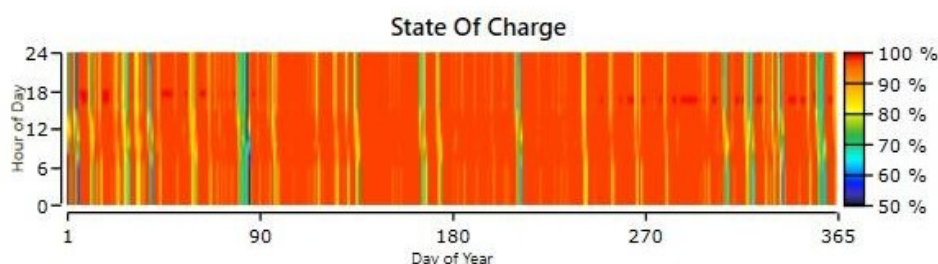


Fig. 7. Battery state-of-charge profile of the optimized system

3.5 Renewable Fraction and Capacity Shortage

The optimized system achieves a renewable fraction of 100%. Because the system is configured as an off-grid PV-battery system without a conventional generator, all electricity supplied to the loads originates from renewable energy generation.

The annual capacity shortage is 1.88 kWh/year, indicating that a small portion of the electricity demand cannot be fully satisfied during certain periods of insufficient energy availability.

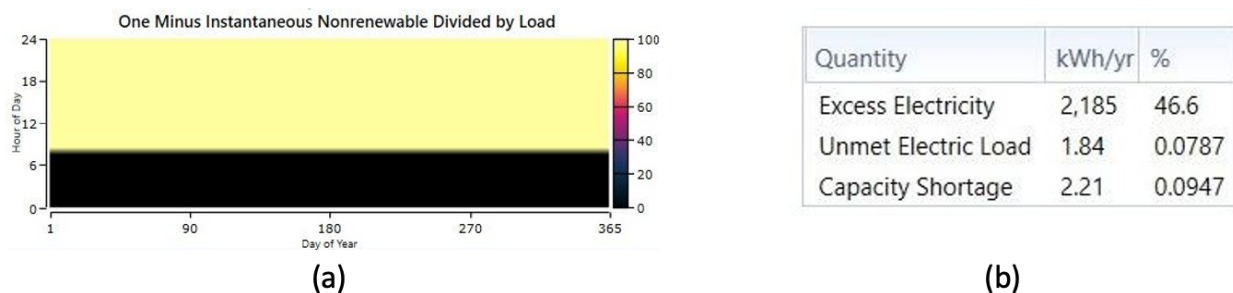


Fig. 8. Renewable penetration and capacity shortage results of the optimized system: (a) Renewable penetration results; (b) Capacity shortage and unmet electrical load

The renewable penetration and electrical reliability results are presented in Figure 8. As illustrated in Figure 8(a), the renewable energy contribution reaches 100%, indicating that all electricity generation originates from the PV system. The renewable production-to-load ratio is reported as 201%, indicating that annual renewable electricity production exceeds annual electricity demand.

Figure 8(b) shows that the system records an annual capacity shortage of 1.88 kWh and an unmet electrical load of 1.04 kWh. These relatively small values indicate that the optimized PV-battery configuration can supply nearly all the modeled agricultural electricity demand throughout the year.

3.6 Economic Performance

The economic performance of the optimized configuration was evaluated using the financial results generated by HOMER Pro. The selected configuration has a Net Present Cost (NPC) of USD 21,861.93 and a Cost of Energy (COE) of USD 0.8915/kWh.

Table 6

Economic Results of the Optimized System		
Economic Parameter	value	unit
Net Present Cost (NPC)	21,861.93	USD
Cost of Energy (COE)	0.8915	USD/kWh
PV capacity	3	kW
Battery capacity	20	kWh
Converter capacity	2	kW



Fig. 9. Economic performance of the optimized solar-battery system

The economic performance of the optimized system is presented in Figure 11. The system has a total NPC of Rp126,923,400, a Levelized Cost of Energy (COE) of Rp4,212.84/kWh, and an annual operating cost of Rp2,376,587. The battery accounts for the largest proportion of total lifecycle costs, followed by the PV array and converter. These findings indicate that battery investment and replacement costs contribute substantially to the overall economic performance of the proposed system.

3.7 Comparison of Technical and Economic Results

The principal technical and economic simulation results are summarized in Table 7.

Table 7

Summary of HOMER Pro Simulation Results

Category	Parameter	Result
System	PV capacity	3 kW
System	Battery capacity	20 kWh
System	Converter capacity	2 kW
Technical	PV production	4,658 kWh/year
Technical	Electrical load	3,123 kWh/year
Technical	Excess electricity	825 kWh/year
Technical	Unmet electrical load	1.04 kWh/year
Technical	Capacity shortage	1.88 kWh/year
Technical	Renewable fraction	100%
Technical	NPC	USD 21,861.93
Technical	COE	USD 0.8915/kWh

Overall, the simulation results demonstrate that the selected configuration integrates photovoltaic generation and battery storage to supply agricultural electricity demand without relying on the utility grid or fossil fuel-based generators. Annual PV electricity generation exceeds the modeled annual electricity demand, with part of the generated electricity stored in the battery and the remaining unused portion recorded as excess electricity. The relatively small unmet electrical load and capacity shortage indicate that only a limited amount of electricity demand remains unsupplied during certain operating periods. From an economic perspective, the optimized configuration has an NPC of USD 21,861.93 and a COE of USD 0.8915/kWh.

4. Conclusions

This study designed and optimized a Solar-Battery Agricultural Energy Hub for Banyumas Village, Sampang Regency, Madura, using HOMER Pro simulation to determine the optimal photovoltaic and battery storage configuration for a total installed load of 815 W and a daily electricity demand of 6.39 kWh. The optimization identified an off-grid configuration consisting of a 3 kW photovoltaic array, a 20 kWh lead-acid battery bank, and a 2 kW converter as the most suitable system architecture. The technical simulation results indicate that this configuration generates 4,658 kWh of photovoltaic electricity annually, compared with an annual electrical load of 3,123 kWh. The system achieves a renewable fraction of 100%, with an unmet electrical load of only 1.04 kWh/year and a capacity shortage of 1.88 kWh/year. These results demonstrate that the proposed configuration can reliably satisfy nearly all the modeled agricultural electricity requirements throughout the year.

From an economic perspective, the optimized system has a Net Present Cost of USD 21,861.93 and a Cost of Energy of USD 0.8915/kWh. The battery bank accounts for the largest proportion of lifecycle costs, followed by the PV array and converter. These findings indicate that although the proposed Solar-Battery Agricultural Energy Hub is technically feasible and offers potential environmental benefits, its economic competitiveness remains challenging compared with conventional diesel-powered irrigation systems, particularly because of its relatively high COE. Integrating auxiliary agricultural facility loads with irrigation pumping within a unified energy hub addresses a research gap in previous studies that primarily focused on standalone pumping systems. Furthermore, the study provides primary electrical load profile data and location-specific optimization results for the Madura region.

Several limitations should be acknowledged. The analysis relies on simulated electrical load profiles and solar resource data rather than long-term field measurements. In addition, multi-parameter sensitivity analyses addressing fuel price fluctuations and projected reductions in battery costs were not conducted. Post-construction operation and maintenance considerations, which are important for the long-term sustainability of rural solar irrigation systems in Indonesia, were also excluded. Future research should therefore incorporate field validation of electrical load profiles, comprehensive sensitivity analyses, and evaluations of institutional support mechanisms to improve the practical applicability of the proposed energy hub. Nevertheless, the findings demonstrate that an appropriately sized Solar-Battery Agricultural Energy Hub can provide a technically viable and potentially environmentally sustainable alternative for agricultural irrigation in Banyumas Village, supporting greater energy independence and reducing reliance on fossil fuel-based pumping systems.

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Conflict of Interest Statement

The authors declare that there are no conflicts 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 study. The research was conducted without any commercial or financial relationships that could be construed as potential conflicts of interest.

Author Contributions Statement

Hana Hanifah Raharjo and Nur Hidayatullah Dafana conceptualized and designed the study, conducted the HOMER Pro simulations, and prepared the initial manuscript draft. Rizal Fahmi Kurniawan and Sachan Hirzi contributed to data collection, electrical load profile calculations, and solar resource assessment. Satria Bagas Nur Setyo performed the techno-economic analysis and contributed to the interpretation of the results. Singgih Dwi Prasetyo supervised the project, provided methodological guidance, and reviewed the manuscript. All authors contributed to revising the manuscript, read the final version, and approved it for publication.

Data Availability Statement

All data generated or analyzed during this study are included in this article. Additional datasets, including the hourly electrical load profile and HOMER Pro simulation input files, are available from the corresponding author upon reasonable request. Where applicable, publicly available datasets used in the study, including solar resource data, are cited in the references.

Ethics Statement

This study did not involve human participants or animal subjects. All data used in this simulation-based study were obtained from publicly available sources and field measurements conducted with permission from local authorities. The research was conducted in accordance with the ethical standards of the relevant institutional and/or national research committee.

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