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Integrated HOMER Pro–AHP Optimization of Standalone PV–BESS for Sustainable Household Electrification on Remote Islands

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Abstract

Background: Remote islands in Indonesia continue to experience limited access to reliable electricity due to geographical isolation and the lack of grid infrastructure. Batun Island in East Belitung Regency currently depends on diesel generators, resulting in high operational costs, fuel transportation challenges, and environmental concerns.
Objective: This study aims to evaluate the feasibility and determine the optimal configuration of a standalone Solar Photovoltaic (PV) system integrated with a Battery Energy Storage System (BESS) to meet household electricity demand.
Methods: A quantitative approach was employed by integrating HOMER Pro techno-ecoomic simulation with the Analytical Hierarchy Process (AHP) for multi-criteria decision-making. Four alternative PV–BESS configurations were evaluated based on technical, economic, environmental, regulatory, socio-cultural, and risk criteria.
Results: The simulation results showed that all configurations were technically capable of supplying the estimated daily electricity demand of 89.99 kWh with a 100% renewable energy contribution. Among the evaluated alternatives, the 50 kWp PV and 200 kWh BESS configuration achieved the highest preference score of 0.889, with an AHP consistency ratio of 0.070, indicating reliable decision-making. This configuration also achieved the lowest NPC (USD 158,577) and LCOE (USD 0.37/kWh).
Conclusion: The findings demonstrate that integrating HOMER Pro and AHP provides a comprehensive framework for optimizing standalone renewable energy systems and supports sustainable rural electrification planning for isolated islands in Indonesia.

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INTRODUCTION

Electricity plays an essential role in supporting economic activity, education, healthcare, and overall quality of life. Nevertheless, unequal electricity access remains a major issue in many developing countries, including Indonesia (Bergsteinsson et al., 2021; Djenouri et al., 2022). By the end of 2024, Indonesia's national electrification ratio had exceeded 99%; however, hundreds of small outer islands still depend on limited or diesel-based electricity services, while the National Energy Policy targets a renewable energy share of at least 23% of the primary energy mix (Maulidia, 2019; Pangestu, 2026). While urban regions continue to experience rapid infrastructure development, several remote islands still face limitations in accessing reliable electricity services. Geographic isolation, dispersed populations, and high infrastructure investment requirements often make grid expansion economically difficult (Ali et al., 2021; Zhang et al., 2023). In many remote regions, diesel generators remain the dominant electricity source because they are relatively simple to install and operate. However, long-term dependence on diesel generation creates additional challenges, especially for isolated islands where fuel transportation relies heavily on weather conditions and logistics availability. Fuel price fluctuations, high operational costs, and greenhouse gas emissions also reduce the sustainability of diesel-based electrification systems (Jia et al., 2023; Samatar et al., 2025).

Batun Island, located in East Belitung Regency, Bangka Belitung Province, is among the islands that have not yet been connected to the national electricity network. The island consists of approximately 41 households along with several public facilities such as a school, a mushalla, and a village hall. Electricity demand in the area continues to increase as communities require more stable energy access to support domestic and social activities. Considering the geographical characteristics of Indonesia, renewable energy has become one of the most promising alternatives for rural electrification (Abdullah et al., 2026; Bergsteinsson et al., 2021; Ruiz et al., 2020). Solar energy is particularly interesting because Indonesia receives relatively high solar irradiation throughout the year. The availability of solar resources creates opportunities for implementing standalone photovoltaic systems in remote islands where extending transmission networks is technically difficult (Ahmed et al, 2024; Wang et al., 2023).

The integration of Battery Energy Storage Systems (BESS) further improves the feasibility of standalone solar systems. Battery storage enables electricity generated during daytime to be utilized during nighttime or low irradiation periods, thereby improving system reliability and energy continuity (Mohamed et al., 2022; Serrano-Gomez et al., 2024). Recent developments in battery technology and renewable energy economics have also contributed to the increasing attractiveness of PV–BESS systems for isolated microgrids (Aksbi et al., 2025; Jufri et al., 2021). Several previous studies have evaluated renewable energy systems for rural electrification and demonstrated that battery energy storage systems can significantly improve operational reliability in isolated renewable energy systems (Altayf et al., 2024). Techno economic optimization using HOMER Pro has also been widely applied to evaluate standalone renewable systems (Tang et al., 2022). In addition, Multi-Criteria Decision Analysis approaches such as Analytic Hierarchy Process have proven effective in integrating technical, economic, environmental, and risk considerations into renewable energy planning (Zaheb et al., 2024; Gupta & Bhargava, 2024). Despite the growing number of studies related to hybrid renewable systems, research focusing specifically on standalone PV–BESS optimization for Indonesian remote islands remains relatively limited (Ahmed et al, 2024; Rufinaldo & Brent, 2025).

To address the electricity challenges faced by remote islands, this study investigates the optimization of standalone PV–BESS configurations for Batun Island using HOMER Pro simulation and Analytic Hierarchy Process analysis. The objectives of this research are to assess the solar energy potential and electricity demand in Batun Island, to design and simulate several standalone PV–BESS configurations, to conduct techno economic evaluation using HOMER Pro, and to determine the optimal configuration using AHP-based multi-criteria analysis. The results of this study are expected to support sustainable electrification strategies for isolated islands in Indonesia while contributing to renewable energy policy development (Gupta & Bhargava, 2024).

This study offers a novel decision-support framework for rural electrification by integrating HOMER Pro techno-economic optimization with the Analytical Hierarchy Process (AHP) to identify the most suitable standalone PV–BESS configuration for a remote Indonesian island. Unlike previous studies that mainly emphasize technical or economic optimization, this research simultaneously incorporates six decision dimensions (technical, economic, environmental, regulatory, socio-cultural, and risk criteria) into the configuration selection process. Furthermore, the study extends conventional optimization by performing sensitivity analyses under 5% and 10% future electricity load growth scenarios, enabling the assessment of system adaptability and long-term resilience. This integrated multi-criteria approach provides a more comprehensive and practical framework for renewable energy planning in isolated island communities and contributes to sustainable off-grid electrification strategies in Indonesia. Compared with earlier HOMER Pro-based optimization studies that focused primarily on grid-connected or hybrid diesel systems (Riayatsyah, 2022) and AHP applications that were limited to renewable energy site selection (Al Garni & Awasthi, 2017; Khan et al., 2023), the present study uniquely combines both tools for configuration-level decision-making in an Indonesian remote island context.

This study aims to determine the optimal standalone solar photovoltaic–battery energy storage system (PV–BESS) configuration for household electrification on Batun Island, Indonesia, by integrating HOMER Pro techno-economic simulation with the Analytical Hierarchy Process (AHP). Specifically, the research evaluates the island's electricity demand and solar energy potential, compares alternative PV–BESS configurations based on technical, economic, environmental, regulatory, socio-cultural, and risk criteria, and assesses system robustness under future electricity demand growth scenarios to support sustainable and reliable rural electrification planning. In practical terms, the findings provide direct guidance for local governments in prioritizing island electrification programs, for PLN in planning off-grid renewable energy investments, and for national energy policymakers in formulating incentive schemes for PV–BESS deployment on remote islands.

METHOD

This research employed a quantitative methodology integrating simulation-based techno economic analysis and Multi-Criteria Decision Analysis (MCDA). The research framework consisted of the following stages: Data collection, Electricity load estimation, Solar resource assessment, PV–BESS configuration design, HOMER Pro simulation, AHP evaluation and Selection of optimal configuration. The overall methodology was designed to evaluate both technical and economic feasibility while incorporating qualitative considerations through AHP. The data collection process focused on obtaining information related to electricity demand, solar energy potential, and technical specifications of the energy system components.

Electricity Demand

Electricity demand was estimated based on household consumption patterns and public facility requirements in Batun Island. The demand profile consisted of 41 households and three public facilities including a school, a *mushalla*, and a village hall. The total estimated electricity demand reached approximately 89.99 kWh/day. The daily load was calculated using a bottom-up approach by multiplying the rated power of each appliance by its estimated daily operating hours, resulting in an average household consumption of approximately 2.00 kWh/day for 41 households (82.00 kWh/day) plus 7.99 kWh/day for the school, *mushalla*, and village hall, with an estimated evening peak demand of approximately 9.5 kW, as detailed in Table 2a. For simulation purposes, the load profile was assumed to be evenly distributed over 24 hours to represent stable daily electricity consumption. This simplifying assumption is justified because household consumption on Batun Island is dominated by continuous base loads such as lighting, fans, and refrigeration, while detailed hourly metering data are not yet available for the island. The uniform profile therefore provides a conservative baseline for system sizing, and its potential influence on the simulation results was further examined through the 5% and 10% load growth sensitivity scenarios.

Table 1
Estimated Appliance Load Profile and Daily Demand Calculation

Load Component	Power (W)	Hours/day	Energy (kWh/day)
LED Lighting (4 units)	4 × 10	6.0	0.24
Television	60	5.0	0.30
Electric Fan (2 units)	2 × 45	6.0	0.54
Small Refrigerator	50 (avg.)	24.0	0.60
Rice Cooker	350	0.75	0.26
Phone Charging & Others	12	5.0	0.06
Subtotal per Household	–	–	2.00
41 Households	–	–	82.00
School	–	–	3.99
Mushalla	–	–	2.00
Village Hall	–	–	2.00
Total Daily Load	–	–	89.99

Solar Resource Data

Solar irradiation data were obtained from the Global Solar Atlas database. The average solar irradiation in Batun Island was recorded at 3.94 kWh/m^2/day or approximately 1,430 kWh/m^2/year. This solar potential indicates that photovoltaic systems can be effectively implemented to support standalone electrification systems in the region. Although satellite-derived datasets such as the Global Solar Atlas may contain uncertainties in coastal tropical regions, previous validation studies have shown that satellite-based irradiance estimates agree well with ground measurements at monthly and annual scales (Urraca, 2018). The adopted value is also consistent with earlier solar resource assessments for the Bangka Belitung region, and future work is encouraged to compare the satellite data with local meteorological measurements once ground stations become available.

Technical and Economic Parameters

Technical specifications and economic parameters of PV modules, batteries, converters, and balance-of-system components were collected from HOMER Pro databases, manufacturer datasheets, and previous literature. The parameters included: PV module efficiency, Battery capacity, Battery depth of discharge, Converter efficiency, Component lifetime, Capital cost, Replacement cost and Operation and maintenance cost.

System Configuration Design

Four standalone PV–BESS configurations were developed for comparative analysis:

Table 2
Alternative

Alternative	PV Capacity	Battery Capacity
A1	32 kWp	282 kWh
A2	35 kWp	270 kWh
A3	40 kWp	280 kWh
A4	50 kWp	200 kWh

All configurations were designed with one day of battery autonomy and without diesel generator backup. This design approach reflects the objective of achieving a fully renewable off-grid energy system. The system design also considered: Battery round-trip efficiency, Battery state of charge constraints, Converter efficiency, Renewable energy fraction and System reliability

Homer Pro Simulation

The techno economic simulations were conducted using HOMER Pro software. HOMER Pro was selected because it is widely used for renewable energy system optimization and techno economic analysis. The simulation aimed to evaluate: Net Present Cost (NPC), Levelized Cost of Energy (LCOE), Renewable fraction, Annual energy production, Excess electricity, Battery autonomy and Operational feasibility. The simulation process compared all alternative configurations under identical load and solar resource conditions.

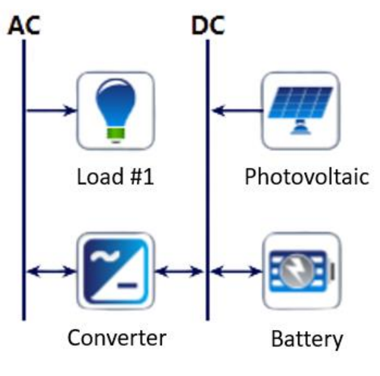

Figure 1. *Schematic of Microgrid System*

Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) was employed to determine the optimal configuration based on multiple criteria. Six evaluation criteria were considered: Technical, Economic, Environmental, Social-cultural, Regulatory and Risk. A total of eight experts participated in the AHP pairwise comparison process. The experts were selected purposively based on explicit competency criteria, namely a minimum of five years of professional or academic experience in renewable energy or power systems, direct involvement in rural electrification planning, operation, or utilization, and balanced representation of academic, industrial, governmental, and consumer stakeholder groups. Pairwise comparison matrices were developed using Saaty's scale. The weighting process generated the relative importance of each criterion. The individual judgment matrices of the eight experts were aggregated using the geometric mean method to form a single group pairwise comparison matrix, from which the final AHP criteria weights were derived. The consistency ratio (CR) was calculated to ensure consistency in the decision-making process. The final preference score for each alternative was determined using weighted aggregation.

Table 3

Criteria and Sub-Criteria

Criteria	Sub-Criteria	Description
Technical (A)	System Reliability (A1)	Measures the system's ability to supply continuous electricity under varying load and solar conditions.
	PV Capacity Performance (A2)	Evaluates PV output effectiveness relative to solar irradiation and system sizing.
	Battery Autonomy (A3)	Assesses battery capability to provide backup energy during low-solar or nighttime periods.
Economic (B)	Net Present Cost (NPC) (B1)	Represents total lifetime cost of the system discounted to present value.
	Levelized Cost of Energy (LCOE) (B2)	Indicates cost per kWh of electricity produced over the system's lifetime.
	Operation & Maintenance Cost (B3)	Covers routine maintenance, replacement components, and operational expenses.
Environmental (C)	CO_2 Emission Reduction (C1)	Quantifies emission savings compared to diesel-based power generation.
	Land Use Impact (C2)	Evaluates environmental footprint associated with PV array installation.
Socio-Cultural (D)	Community Acceptance (D1)	Reflects how well the system aligns with local community needs and preferences.
	Affordability for Users (D2)	Considers the financial ability of users to support ongoing operational or tariff costs.
Regulatory (E)	Compliance with National Standards (E1)	Assesses alignment with Indonesian renewable energy regulations and technical standards.
	Support for Electrification Policies (E2)	Evaluates consistency with government rural electrification and energy transition goals.
Risk (F)	Technical Risk (F1)	Addresses potential risks such as equipment failure or supply chain disruptions.
	Financial Risk (F2)	Considers uncertainties related to cost fluctuations, financing, or long-term economic viability.

Table 4

Evaluation Criteria Used in AHP Analysis

Criteria	Description	Type	Indicator
Technical	Ability of the system to reliably supply electricity demand	Benefit	Reliability, autonomy
Economic	Total financial feasibility of the system	Cost	NPC, LCOE, O&M
Environmental	Environmental impact reduction	Benefit	CO_2 reduction
Social-cultural	Community acceptance and social benefit	Benefit	Accessibility, social impact

Criteria	Description	Type	Indicator
Regulatory	Compliance with energy policies and regulations	Benefit	Alignment with RUEN
Risk	Operational and investment uncertainty	Cost	Battery degradation, logistics

The expert respondents involved in this study consisted of eight experts from academic, industrial, governmental, and consumer backgrounds to ensure a comprehensive evaluation of the proposed PV–BESS configurations.

Table 5
Evaluation Criteria Used in AHP Analysis

Code	Expert Position	Stakeholder Group
E1	Lecturer in Renewable Energy Engineering	Academician
E2	Project Control Engineer	Business/Industry
E3	Rural Electrification Manager	Government
E4	Household Electricity User Representative	Consumer
E5	Power System Planning Manager	Government
E6	Household Electricity User Representative	Consumer
E7	Lecturer in Electrical Engineering	Academician
E8	Primary Energy and Power Generation Manager	Business/Industry

RESULTS AND DISCUSSION

Results

HOMER Pro Simulation Result

The HOMER Pro simulation was conducted to evaluate the technical and economic feasibility of each PV–BESS configuration under the electricity demand conditions of Batun Island. The simulation considered system operational performance, renewable energy contribution, energy balance, and economic indicators. The simulation results indicate that all configurations were technically capable of supplying the required daily load demand of 89.99 kWh/day. However, each configuration demonstrated different levels of economic performance and energy reliability.

Table 6
Homer Pro Simulation Summary

Alternative	PC (kWp)	BC (kWh)	DLS (kWh/day)	RF	ESR
A1	32	282	89.99	Maximum	Very Good
A2	35	270	89.99	Maximum	Excellent
A3	40	280	89.99	Maximum	Excellent
A4	50	200	89.99	Maximum	Good

PC: PV Capacity
BC: Battery Capacity
DLS: Daily Load Served
RF: Renewable Fraction
ESR: Estimated System Reliability

Table 7
Key Economic Indicators of Each Configuration (HOMER Pro Simulation)

Alternative	NPC (USD)	LCOE (USD/kWh)	O&M Cost (USD/year)
A1	175,942	0.41	5,120
A2	168,435	0.39	4,870
A3	172,880	0.40	4,995
A4	158,577	0.37	4,492

The simulation results show that larger PV capacities increased annual energy production, while higher battery capacities improved battery autonomy and overall system reliability. Among the evaluated configurations, A2 and A3 achieved 100% reliability with battery autonomy reaching 58–60 hours. However, systems with larger capacities also resulted in higher Net Present Cost (NPC) and Levelized Cost of Energy (LCOE). In contrast, A4 offered the lowest NPC, LCOE, and annual O&M cost, although its battery autonomy decreased to 43 hours and reliability slightly dropped to 99.96%. Furthermore, all configurations demonstrated a maximum renewable energy contribution due to the absence of diesel generators, confirming the technical feasibility of implementing fully renewable standalone PV–BESS systems for electrification in isolated island regions such as Pulau Batun.

AHP Criteria Weight Analysis

As shown in Table 8, all experts obtained consistency ratio (CR) values below 0.1, which indicates that their pairwise comparison judgments were sufficiently consistent and reliable for use in the AHP analysis. In addition, the aggregated pairwise comparison matrix calculated using the geometric mean method also resulted in a CR value below 0.1, confirming that the overall evaluation was consistent and suitable for further decision-making analysis.

Table 8

Consistency Ratio of Expert Judgments in the AHP Analysis

Expert	Consistency Ratio (CR)	Status
E1	0.034	Consistent
E2	0.076	Consistent
E3	0.099	Consistent
E4	0.021	Consistent
E5	0.029	Consistent
E6	0.082	Consistent
E7	0.051	Consistent
E8	0.009	Consistent

The AHP analysis produced the criteria weights shown in Table 9.

Table 9

Pairwise Comparison Matrix Between Criteria

Criteria	Weight
Technical	0.243
Economic	0.209
Regulatory	0.164
Risk	0.163
Environmental	0.113
Social-cultural	0.062

The results indicate that technical criteria received the highest priority, followed by economic criteria. This reflects the importance of reliability and affordability in rural electrification systems. The consistency ratio obtained from the pairwise comparison matrix was 0.070, which is below the acceptable threshold of 0.10. Therefore, the AHP judgments were considered consistent.

Alternative Ranking

The final ranking results are presented in Table 10.

Table 10

Final Alternative Ranking

Alternative	Configuration	Final Score	Rank
A1	32 kWp + 282 kWh	0.862	4
A2	35 kWp + 270 kWh	0.876	2
A3	40 kWp + 280 kWh	0.867	3
A4	50 kWp + 200 kWh	0.889	1

The results indicate that Alternative A4 achieved the highest preference score among all evaluated configurations.

Sensitivity Analysis

To evaluate the system sensitivity, load growth scenarios of 5% and 10% were introduced to assess the impact of increasing electricity demand on the technical and economic performance of each PV–BESS configuration.

Table 11

Results of the 5% Load Increase Scenario

Alternative	AHP Score	Rank	Interpretation
A1	0.693	4	The relatively smaller PV capacity reduced system performance under increased load conditions.
A2	0.876	1	Became the most optimal configuration under the 5% load increase scenario.
A3	0.867	2	Demonstrated very strong system resilience against load growth.
A4	0.738	3	Produced high energy output; however, the lower battery capacity reduced energy storage performance.

Based on the AHP evaluation results under the 5% load increase scenario, alternative A2 with a configuration of 35 kWp PV and 270 kWh BESS achieved the highest preference score of 0.876 and ranked first among all evaluated alternatives. This result indicates that the configuration represents the most optimal option under increased energy demand conditions, as it provides the best balance between power generation capacity, energy storage capability, system reliability, and economic performance.

Alternative A3, consisting of 40 kWp PV and 280 kWh BESS, ranked second with a score of 0.867. This configuration demonstrated excellent technical performance and strong system resilience against load growth. However, the higher investment and overall system costs reduced its overall preference compared to A2. Meanwhile, alternative A4 with 50 kWp PV and 200 kWh BESS dropped to third place with a score of 0.738. Although this configuration produced the highest annual energy output, its lower battery capacity reduced the system's ability to effectively accommodate increasing electricity demand.

On the other hand, alternative A1 obtained the lowest score of 0.693 and ranked fourth. The smaller PV capacity limited the system's capability to satisfy higher energy demand despite having relatively large battery storage capacity. These sensitivity analysis results demonstrate that load growth can significantly influence the priority of system configuration selection, indicating that the best configuration under baseline conditions may not necessarily remain the most optimal under future load increase scenarios.

Table 12

Results of the 10% Load Increase Scenario

Alternative	AHP Score	Rank	Interpretation
A1	0.693	4	The PV capacity was no longer sufficient under the 10% load increase scenario.
A2	0.710	3	The configuration still performed reasonably well, although system performance began to decline under higher load conditions.
A3	0.867	1	Became the most optimal and adaptive configuration in responding to increased load demand.
A4	0.738	2	Produced high energy output; however, the lower battery capacity limited the system's storage performance.

Based on the AHP evaluation results under the 10% load increase scenario, alternative A3 with a configuration of 40 kWp PV and 280 kWh BESS achieved the highest preference score of 0.867 and ranked first among all evaluated alternatives. This finding indicates that A3 represents the most optimal configuration and demonstrates the strongest system resilience in accommodating increasing energy demand.

Alternative A4 ranked second with a score of 0.738. Although this configuration provided higher PV capacity and greater annual energy production, its lower battery capacity compared to A3 reduced the overall system performance under higher load conditions. Meanwhile, alternative A2 dropped to third place with a score of 0.710, while alternative A1 remained in the last position due to its relatively smaller PV capacity, which limited the system's capability to cope with increasing electricity demand.

The sensitivity analysis demonstrates that configurations with a more balanced combination of power generation and energy storage capacities tend to provide better system resilience against load growth. Therefore, under a 10% load increase scenario, alternative A3 was identified as the most adaptive and reliable configuration to support the long-term sustainability of rural electrification systems in Pulau Batun.

Discussion

Technical Performance

The technical evaluation demonstrated that all proposed PV–BESS configurations could supply the daily electricity demand of approximately 89.99 kWh/day in Pulau Batun with a renewable energy contribution reaching 100%, as the systems operated without diesel generator support. The simulation results showed that increasing PV capacity significantly improved annual energy production, while larger battery capacities enhanced battery autonomy and overall system reliability.

Among the evaluated alternatives, A2 (35 kWp PV + 270 kWh BESS) and A3 (40 kWp PV + 280 kWh BESS) achieved the highest reliability level of 100%, with battery autonomy ranging from 58 to 60 hours. These configurations demonstrated strong technical resilience in maintaining stable electricity supply under varying operating conditions. Meanwhile, A4 (50 kWp PV + 200 kWh BESS) produced the highest annual energy generation due to its larger PV capacity. However, the lower battery storage capacity reduced battery autonomy to 43 hours and slightly decreased system reliability to 99.96%.

The sensitivity analysis further indicated that system configuration performance was strongly influenced by load growth conditions. Under the 5% load increase scenario, A2 achieved the highest AHP score due to its balanced combination of generation capacity, storage capability, reliability, and economic performance. However, under the 10% load increase scenario, A3 became the most preferred alternative because its larger PV and battery capacities provided better adaptability and system resilience against increasing electricity demand.

These findings confirm that properly sized standalone PV–BESS systems can effectively support rural electrification in isolated island regions while maintaining high reliability and operational sustainability without relying on fossil fuel-based generation systems.

The findings of this study are consistent with international research employing similar optimization approaches. Das and Zaman (2019) reported that optimally sized PV–battery systems can reliably serve remote communities in Bangladesh at competitive energy costs, while Aziz et al. (2019) demonstrated that combined dispatch strategies improve the techno-economic performance of PV–battery hybrid systems for isolated loads (Arifina et al., 2026). The LCOE range obtained in this study is comparable to those studies, confirming that the proposed framework positions this research within the global body of literature on off-grid renewable energy optimization while extending it to the Indonesian remote island context.

Nevertheless, the methodological approach has inherent limitations. HOMER Pro relies on hourly time-step simulation with simplified battery degradation models and cannot capture sub-hourly transient behavior, while AHP depends on subjective expert judgments and pairwise consistency. Alternative multi-criteria decision-making methods such as TOPSIS, ANP, or PROMETHEE could produce different ranking sensitivities, and comparative application of these methods is recommended for future validation (Jameel et al., 2026; Kumar, 2017).

Economic Analysis

The economic analysis revealed that system capacity significantly influenced the Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and annual operation and maintenance

(O&M) costs of each configuration. Alternative A4 demonstrated the lowest NPC of USD 158,577 and the lowest LCOE of USD 0.37/kWh due to its relatively optimized investment structure and lower battery capacity. In addition, A4 also recorded the lowest annual O&M cost of USD 4,492/year.

Meanwhile, alternatives with larger battery capacities such as A1, A2, and A3 provided higher reliability and battery autonomy but required higher investment costs. Among these alternatives, A2 showed the most balanced techno-economic performance, achieving 100% reliability while maintaining lower NPC and LCOE values compared to A3. Conversely, A3 achieved excellent technical performance but experienced increased economic burden due to higher system sizing and investment requirements.

The results indicate that economic feasibility in standalone PV–BESS systems is highly dependent on achieving an optimal balance between PV capacity, battery storage, reliability targets, and long-term operational costs. Furthermore, the elimination of diesel generators reduces fuel transportation costs, minimizes fuel price uncertainty, and improves long-term energy security for remote island communities.

Environmental and Social Implications

The implementation of standalone PV–BESS systems in Pulau Batun provides significant environmental benefits through the utilization of fully renewable energy sources. Since all evaluated configurations operated without diesel generators, greenhouse gas emissions and fossil fuel consumption can be substantially reduced. This condition supports Indonesia's renewable energy transition targets and contributes to sustainable energy development in remote island regions.

From a social perspective, improved electricity access is expected to enhance community welfare and support various socio-economic activities. Reliable electricity supply can improve educational activities, household productivity, public service quality, communication access, and economic opportunities for local communities. Electrification also has the potential to stimulate small-scale economic activities and improve the quality of life in isolated rural areas. It should be clarified that these anticipated social impacts are conceptual in nature and are derived from previous empirical studies on rural electrification and theoretical assumptions rather than from primary community survey data collected in this study (Kalemis & Upham, 2026; Riva, 2018) field-based social assessments are therefore recommended to verify these benefits on Batun Island.

Moreover, the development of renewable energy-based electrification systems can reduce dependency on fuel transportation logistics, which often become a major challenge in remote islands. Therefore, the proposed PV–BESS systems not only improve technical energy access but also contribute to long-term social and economic sustainability for rural communities (Ridha, 2021; Sarkar et al., 2026).

The proposed HOMER Pro–AHP framework is also transferable to other remote islands in Indonesia with comparable characteristics, such as isolated islands in the Riau Islands, Maluku, and East Nusa Tenggara provinces, which experience similar solar irradiation levels of 3.5–5.0 kWh/m^2/day and comparable household load structures. Applying the framework to these regions would primarily require adjusting local load profiles, solar resource inputs, and logistics cost parameters, thereby increasing the generalizability of the research results for national rural electrification planning.

CONCLUSION

This study successfully integrated HOMER Pro simulation and Analytical Hierarchy Process (AHP) analysis to evaluate the technical and economic feasibility of standalone PV–BESS systems for rural electrification in Pulau Batun. The simulation results confirmed that all proposed configurations were technically capable of supplying the daily electricity demand of approximately 89.99 kWh/day with a 100% renewable energy contribution and high system reliability.

The results demonstrated that increasing PV capacity improved annual energy production, while larger battery capacities enhanced battery autonomy and system reliability. Among the evaluated configurations, A2 (35 kWp PV + 270 kWh BESS) demonstrated the most balanced performance under baseline and 5% load increase conditions, achieving high reliability with relatively lower economic costs compared to larger systems. However, under the 10% load increase scenario, A3 (40 kWp PV + 280 kWh BESS) became the most adaptive and resilient configuration due to its stronger capability in accommodating future electricity demand growth.

The AHP analysis indicated that technical and economic criteria were the most influential factors in determining the optimal configuration. The consistency ratio value below 0.1 confirmed that the decision-making process was sufficiently consistent and reliable. In addition, the implementation of standalone PV–BESS systems offers several long-term benefits, including reduced dependence on fossil fuels, lower greenhouse gas emissions, improved energy reliability, and enhanced electricity access for remote communities.

This study contributes to sustainable rural electrification planning in Indonesia and may serve as a reference for future renewable energy development in isolated island regions. Nevertheless, several limitations remain in this research. The load profile was assumed to be relatively stable, while detailed analysis of battery degradation, component price fluctuations, and long-term demand uncertainty was not comprehensively evaluated. Therefore, future studies are recommended to incorporate sensitivity analysis on PV and battery prices, load growth forecasting, real-time energy management optimization, hybrid renewable integration, and detailed lifecycle environmental assessment to improve system planning accuracy and long-term sustainability evaluation. Future research is also encouraged to explore the integration of complementary renewable energy sources such as wind or micro-hydro power, and to apply artificial intelligence-based optimization techniques, including metaheuristic and machine learning approaches, to enhance configuration design and real-time energy management.

Based on these findings, several specific recommendations are proposed. Policymakers are advised to include standalone PV–BESS systems in national rural electrification roadmaps and to provide fiscal incentives or viability-gap funding for remote island projects. PLN and energy planners are recommended to adopt the 50 kWp PV + 200 kWh BESS configuration as the baseline design for Batun Island under current demand, while reserving expansion space toward the 40 kWp + 280 kWh configuration in anticipation of load growth above 10%. Local governments are encouraged to facilitate land permits, establish community-based operation and maintenance units, and integrate productive-use programs so that electricity access translates into local economic development.

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AUTHOR CONTRIBUTION STATEMENT

Syaifa Laila Sany: conceptualization, methodology, simulation, data analysis, manuscript preparation, editing. Christian Harito: supervision, validation, review.

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