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Optimization of a Brownfield Microgrid Comprising a Diesel Power Plant, Solar Power Plant, and Energy Storage System to Support the Diesel Power Bunaken Island: Integration of HOMER Pro and PLS-SEM

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Abstract
Bunaken Island operates a diesel–PV–BESS hybrid microgrid; however, diesel dependence remains substantial because of degraded PV capacity, limited energy storage, and a temporal mismatch between solar generation and evening peak demand. This study evaluated a brownfield-based dedieselization strategy using a sequential explanatory mixed-methods approach. Four scenarios were simulated using HOMER Pro: baseline, dispatch optimization, PV revitalization, and 100% renewable dedieselization. The simulation outputs were subsequently integrated with Partial Least Squares Structural Equation Modeling (PLS-SEM) to examine the relationships among economic performance, technical performance, environmental and social factors, and microgrid optimization. Under the baseline assumptions, revitalizing the PV system to 287 kWp while retaining the existing 540 kWh BESS resulted in a net present cost (NPC) of US$8.386 million and a levelized cost of energy (LCOE) of US$0.327/kWh, compared with US$11.261 million and US$0.440/kWh, respectively, under the baseline scenario. Renewable energy penetration increased from 4.66% to 24.30%, accompanied by an annual diesel fuel reduction of approximately 116,000 liters. A 100% renewable configuration was technically feasible with 2,000 kWp of PV capacity and a 6,480 kWh BESS but required approximately US$4.52 million in capital expenditure. The PLS-SEM model yielded an R^2 value of 0.998 for microgrid optimization; economic performance was the strongest determinant (f^2 = 90.428), while technical performance contributed primarily through its effect on economic performance. The findings supported a phased optimize–modernize–decarbonize pathway for energy transitions in small-island and conservation-area microgrids.

INTRODUCTION

Energy transition in small-island electricity systems involves not only technology selection but also constraints related to existing assets, fuel logistics costs, load characteristics, and reliability requirements. In the Indonesian context, the de-dieseling program is particularly important because many isolated diesel power plants (Pembangkit Listrik Tenaga Diesel [PLTD]) are located in archipelagic regions that are difficult to connect to the main grid. In such systems, solar photovoltaic (Pembangkit Listrik Tenaga Surya [PLTS]) systems and Battery Energy Storage Systems (BESS) offer opportunities to reduce fuel consumption; however, their economic benefits depend heavily on how effectively existing assets are operated and revitalized.

Bunaken Island provides a relevant case study because its electricity system has transitioned from a purely diesel-based configuration to a hybrid diesel–solar PV–BESS system. The existing system comprises a solar PV installation with a capacity of 286.7 kWp and a BESS with a nominal capacity of 540 kWh; however, part of the PV capacity is no longer fully operational, while the limitations of the existing battery technology constrain energy shifting from daytime generation to nighttime demand. Peak demand occurs at night, whereas maximum solar generation occurs during the day. Consequently, diesel generators continue to play a dominant role in the island's annual electricity supply (Arévalo et al., 2025; Hamilton et al., 2019; Holdmann et al., 2019; Peerapong & Limmeechokchai, 2017; Wolf et al., 2016).

The research focus therefore shifts from determining which new technologies should be installed to identifying how existing assets can be optimally utilized. A brownfield optimization approach is employed to evaluate potential interventions requiring limited incremental investment before large-scale system expansion is considered. This perspective is important because previous investments are treated as sunk costs, while new decisions focus on incremental expenditures, component replacement, dispatch strategies, and savings realized over the project life cycle (Afriani & Poletti, 2026; Frick et al., 2021; Galli, 2018; Luchkov et al., 2026; Perwez et al., 2015).

Numerous studies have examined microgrid optimization and energy transition in small-island systems, providing theoretical and methodological foundations for this research. Sinha and Chandel (2014) identified HOMER as one of the most widely used tools for optimizing hybrid renewable energy systems. Ali et al. (2021) emphasized the importance of dispatch strategies, particularly load following and cycle charging, in optimizing system operation, while Ishraque et al. (2021) found that cycle charging was more economical for systems with low renewable penetration, whereas load following was more suitable for systems with substantial storage capacity. Gomes et al. (2021) showed that battery sizing and charging strategies significantly affected life-cycle costs, and Amer et al. (2024) highlighted battery degradation as a critical factor that is often overlooked in optimization studies. Ajiboye et al. (2023) reviewed various optimization approaches, including linear programming, genetic algorithms, and software-based simulations, while Gholami et al. (2023) developed reliability metrics that accounted for renewable energy intermittency.

In the Indonesian context, Sulaeman et al. (2021) and Simatupang et al. (2021) examined challenges associated with remote microgrids and identified policy support, technical capacity, and community acceptance as key success factors. Riayatsyah et al. (2022) analyzed a grid-connected hybrid system using HOMER Grid and found that renewable energy integration reduced costs and emissions, although the optimal configuration depended on fuel prices. Prawitasari et al. (2024) developed a systematic decision-making approach for rural microgrid optimization at Baron Technopark, emphasizing the simultaneous consideration of operational and economic factors. Internationally, Odetoye et al. (2023) found that 100% renewable configurations in Nigeria were technically feasible but required high initial investment, supporting a phased transition approach. Miao et al. (2023) applied multi-criteria decision analysis to island microgrid planning on Yongxing Island by integrating technical, economic, and environmental considerations. Baniya and Giurco (2024) emphasized that brownfield optimization, which accounts for existing assets, can result in more rational investment decisions than direct system replacement.

Although previous research has made substantial contributions, several gaps motivate this study. Most studies have focused on greenfield optimization, in which new systems are designed from scratch, whereas research on brownfield optimization that treats existing assets as sunk costs remains limited, despite the fact that many small islands in Indonesia already have electricity infrastructure that should be optimized before major replacement or expansion. Furthermore, previous studies have tended to emphasize techno-economic aspects, while environmental and social considerations have received less attention, even though community acceptance and environmental impacts are particularly important in conservation areas such as Bunaken. In addition, few studies have integrated HOMER Pro simulation with Partial Least Squares Structural Equation Modeling (PLS-SEM) to examine the relationships among factors influencing microgrid optimization. Such integration provides a more comprehensive understanding of the determinants of successful energy transitions. Research on Indonesian microgrids has also largely emphasized technical aspects, while studies combining techno-economic optimization with stakeholder perception analysis remain limited (Ma et al., 2025; Prasetyo, 2026; Reber et al., 2016).

Microgrid studies typically prioritize indicators such as Net Present Cost (NPC), Levelized Cost of Energy (LCOE), renewable fraction, and emissions. However, implementation decisions in conservation areas are also influenced by community acceptance and socio-environmental considerations. Therefore, this study integrates techno-economic optimization using HOMER Pro with Partial Least Squares Structural Equation Modeling (PLS-SEM). This integration addresses two complementary objectives: determining a technically and economically efficient microgrid configuration and identifying the factors that most strongly influence optimization outcomes. Based on the identified research gaps, this study aims to evaluate the existing condition of the Bunaken microgrid, compare four scenarios for reducing and ultimately eliminating diesel dependence, identify the optimal configuration based on Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) while considering renewable energy penetration, reliability, and emissions, and examine the relationships among economic performance, technical performance, socio-environmental factors, and microgrid optimization using PLS-SEM. The primary contribution of this study lies in integrating brownfield techno-economic optimization with path modeling to formulate a phased transition strategy for the electricity system of a tourism island located within a conservation area.

METHOD

Research Design and Data

The research employed a sequential explanatory mixed-methods design. The first phase involved quantitative techno-economic simulation using HOMER Pro, while the second phase applied Partial Least Squares Structural Equation Modeling (PLS-SEM) to examine relationships among latent variables by integrating simulation outputs with perception data. Secondary data included power plant configurations, load profiles, fuel consumption, operating costs, economic parameters, and solar resource data. Primary data were collected using a five-point Likert-scale questionnaire covering environmental, social acceptance, and socioeconomic dimensions.

The PLS-SEM dataset comprised 108 observations generated from four scenarios and 27 sensitivity conditions for each scenario. Socio-environmental data were obtained from 47 respondents and aggregated according to the corresponding scenarios before being matched with the simulation observations. The measurement model used formative constructs and was evaluated using the Variance Inflation Factor (VIF) and the significance of outer weights. The structural model was assessed using R^2, f^2, path coefficients, t-statistics, and p-values, with bootstrapping based on 5,000 subsamples.

Table 1. Definitions of Bunaken microgrid simulation scenarios

Scenario	Focus	PLTS	BESS	PLTD	Dispatch
Sken-0	Baseline existing system	55 kWp effective / damaged	540 kWh lead-acid	460 kW	Load Following
Sken-1	Operational optimization without capacity addition	55 kWp effective / damaged	540 kWh lead-acid	460 kW	Cycle Charging
Sken-2	Solar PV asset revitalization	287 kWp	540 kWh eksisting	460 kW	Load Following
Sken-3	Dedieselization to 100% RE (Renewable Energy)	2.000 kWp	6.480 kWh	Deactivated	Cycle Charging

Source: Authors' compilation based on HOMER Pro simulation design, 2024

Economic Analysis and Optimization

The economic analysis follows the life-cycle cost principle over the 25-year project lifespan. In the brownfield scenario, the investment cost of existing assets is not recalculated. CAPEX is only applied to new capacity and relevant replacement costs. The HOMER Pro optimization objective is to minimize Net Present Cost (NPC), while the LCOE is used as an indicator of energy costs between scenarios.

$$LCOE = [\Sigma_t (I_t + O_t + F_t)/(1+r)^t] / [\Sigma_t E_t/(1+r)^t] \quad (1)$$

where I_t is the investment/replacement cost in year t, O_t is the operation and maintenance cost, F_t is the fuel cost, E_t is the electrical energy served, r is the real discount rate, and t is the analysis period.

$$NPV = \Sigma_t CF_t/(1+r)^t - I_0 \quad (2)$$

NPV is used to calculate the financial benefits relative to the initial investment, particularly fuel and operating cost savings compared to the baseline. A sensitivity analysis is performed on fuel prices, discount rates, and load growth. Changes in fuel prices are an important variable because subsidies can alter the economic competitiveness of diesel systems compared to renewable energy-based systems.

PLS-SEM Model

Four latent constructs are employed: System Economics (X1), Microgrid Technical Performance (X2), Environmental and Social Aspects (X3), and Microgrid Model Optimization (Y1). Five paths were tested: X1→Y1, X2→Y1, X3→Y1, X2→X1, and X3→X2. Hypotheses are accepted at a $p\text{-value} < 0.05$. Effect interpretation utilizes f^2 to determine the relative contribution of exogenous constructs to endogenous constructs.

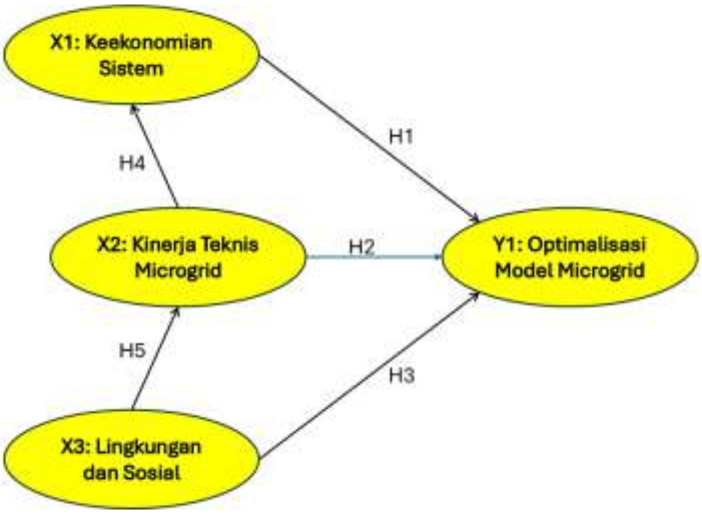

Figure 1. PLS-SEM path diagram of the study (adapted from the thesis)
Source: Authors' adaptation based on research model, 2024

RESULTS AND DISCUSSIONS

Load Characteristics and Solar Energy Potential

The load profile of Bunaken presents characteristics that pose challenges for the integration of solar PV systems. The daytime base load ranges from 80 to 120 kW, while the evening peak reaches approximately 250–300 kW. This temporal variation necessitates appropriate operational strategies for diesel power plants and energy storage systems. Meanwhile, an average daily solar radiation of 5.0–5.5 kWh/m²/day indicates that solar energy is the most promising renewable energy source for development. Wind, ocean current, and biomass resources are not the focus of the optimal configuration due to technical limitations, supply constraints, or environmental risks.

Figure 2. Typical daily load curve for Bunaken Island
Source: PT PLN (Persero) load data, processed by the authors, 2024

Economic Comparison of Four Scenarios

Simulation results indicate that revitalizing existing assets yields greater economic impact than merely changing the dispatch strategy. Scenarios 0 and 1 result in identical NPC and LCOE values under baseline conditions. Conversely, restoring the solar PV capacity to 287 kWp in Scenario 2 reduces the NPC to US$8.386 million and the LCOE to US$0.327/kWh. Compared to the baseline, NPC savings amount to approximately US$2.875 million over 25 years, while renewable energy penetration rises to 24.30%.

Table 2. Comparison of simulation results for the four scenarios under baseline conditions

Parameter	Sken-0	Sken-1	Sken-2	Sken-3
NPC (US$)	11.261.250	11.261.250	8.386.054	8.647.062
LCOE (US$/kWh)	0,440	0,440	0,327	0,348
CAPEX (US$)	0	0	486.680	4.519.760
OPEX (US$/year)	881.332*	881.332*	618.215*	323.000*
RE Penetration (%)	4,66	4,66	24,30	100,00
Fuel Consumption (L/year)	636.466	636.466	~520.000	0
CO_2 Emissions (kg/year)	1.664.728	1.664.728	~1.360.000	0

Source: HOMER Pro simulation output processed by the authors, 2024

Scenario 3 eliminates fuel consumption and operational emissions from diesel power plants (PLTD) but requires a CAPEX of approximately US$4.52 million. The LCOE for this scenario is US$0.348/kWh, which remains higher than that of Scenario 2 under the base case. These findings indicate that a 100% renewable energy target is technically achievable but does not yet represent the most efficient short-term investment decision, given that diesel prices remain subsidized and existing PLTD assets remain available as a source of flexibility.

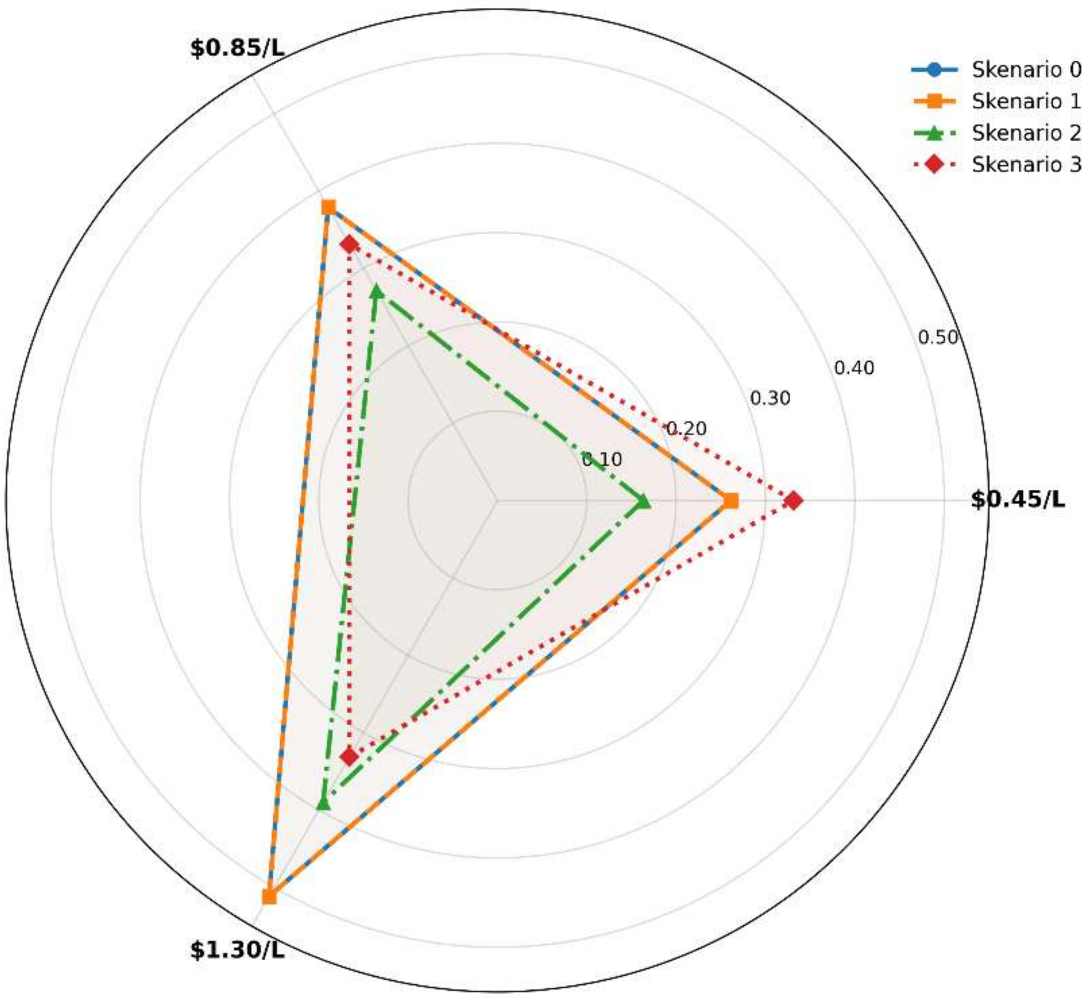

Figure 3. LCOE sensitivity to fuel prices

Source: HOMER Pro sensitivity analysis output, processed by the authors, 2024

Sensitivity analysis reinforces the role of fuel pricing policy. The higher the fuel price, the more rapidly the economic advantage of renewable energy-based configurations grows. This is crucial for the assessment of diesel-to-renewable transitions, as subsidized fuel prices can mask the true economic costs of diesel systems and delay investments in energy storage. Therefore, project evaluations should not rely solely on the fuel prices paid by operating units but should also consider economic costs and the logistical risks associated with island supply.

Optimal Configuration and the Significance of Brownfield Optimization

Table 3. Optimal configuration resulting from HOMER Pro optimization

Parameter	Sken-0	Sken-1	Sken-2	Sken-3
PLTS (kWp)	55 (damaged)	55 (damaged)	287	2.000
BESS (kWh)	540 lead-acid	540 lead-acid	540 (unchanged)	6.480
PLTD (kW)	460	460	460	Deactivated
Inverter (kW)	160	160	400	400
Dispatch	Load Following	Cycle Charging	Load Following	Cycle Charging

Source: HOMER Pro simulation output processed by the authors, 2024

HOMER Pro's decision to retain the 540 kWh BESS in Scenario 2 is a significant finding. In a brownfield model, existing batteries are treated as assets with sunk initial capital costs. Adding new batteries is only viable if fuel savings and operational benefits can offset the additional investment. As long as the diesel power plant remains active as a flexible backup, revitalizing the solar PV system yields a more attractive benefit-cost ratio than direct BESS expansion.

The implication is that the investment sequence is just as important as the final capacity target. Replacing the entire system at once might result in a clean system, but it does not necessarily yield the lowest transition costs. In the case of Bunaken, panel repairs, inverter restoration, strengthened operations and maintenance, and dispatch optimization are steps that should be taken prior to large-scale storage expansion.

PLS-SEM Results

The structural model demonstrates very high explanatory power. The R^2 for Microgrid Model Optimization reached 0.998, while the R^2 values for Technical Performance and Economics were 0.925 and 0.847, respectively. These values indicate that the tested relationship structure effectively explains the majority of the variation in the endogenous constructs within the research dataset.

Table 4. R^2 values of endogenous constructs

Endogenous Construct	R^2	Interpretation
Y1: Microgrid Model Optimization	0,998	Strong
X2: Technical Performance of Microgrid	0,925	Strong
X1: System Economics	0,847	Strong

Source: PLS-SEM analysis output (SmartPLS), processed by the authors, 2024

Table 5. Effect size (f^2) for each hypothesis path

Path	f^2	Effect Size
X1 → Y1 (Economics → Optimization)	90,428	Very large
X3 → X2 (Environment → Technical Performance)	12,323	Large
X2 → X1 (echnical Performance→ Economics)	5,537	Large
X3 → Y1 (Environment → Optimization)	0,299	Medium
X2 → Y1 (Technical Performance→ Optimization)	0,013	Small

Source: PLS-SEM analysis output (SmartPLS), processed by the authors, 2024

The X1→Y1 path has an f^2 value of 90.428, representing the most dominant influence. Meanwhile, the direct influence of X2→Y1 is relatively small, yet X2 exerts a significant influence on X1. This pattern demonstrates that improvements in technical performance become decisionally significant primarily when translated into economic gains. Substantively, these results align with HOMER Pro simulations: the rehabilitation of the solar PV plant increases renewable energy generation, reduces diesel consumption, and ultimately lowers both NPC and LCOE.

Table 6. Summary of PLS-SEM hypothesis testing (N=108)

H	Path	β	t	p	Decision
H1	X1 → Y1	-1,099	98,086	0,000	Accepted
H2	X2 → Y1	-0,017	1,745	0,041	Accepted
H3	X3 → Y1	-0,090	5,486	0,000	Accepted
H4	X2 → X1	-0,920	153,997	0,000	Accepted

H	Path	β	t	p	Decision
H5	X3 → X2	0,962	416,431	0,000	Accepted

Source: PLS-SEM analysis output (SmartPLS), processed by the authors, 2024

The negative signs on certain coefficients must be interpreted in conjunction with the coding direction of the cost indicator and the transformed indicators. Therefore, substantive interpretation relies not only on the coefficient signs but also on indicator definitions, scale direction, effect size values, and consistency with simulation results. All five hypotheses met the significance criteria at the 5% level within the study dataset.

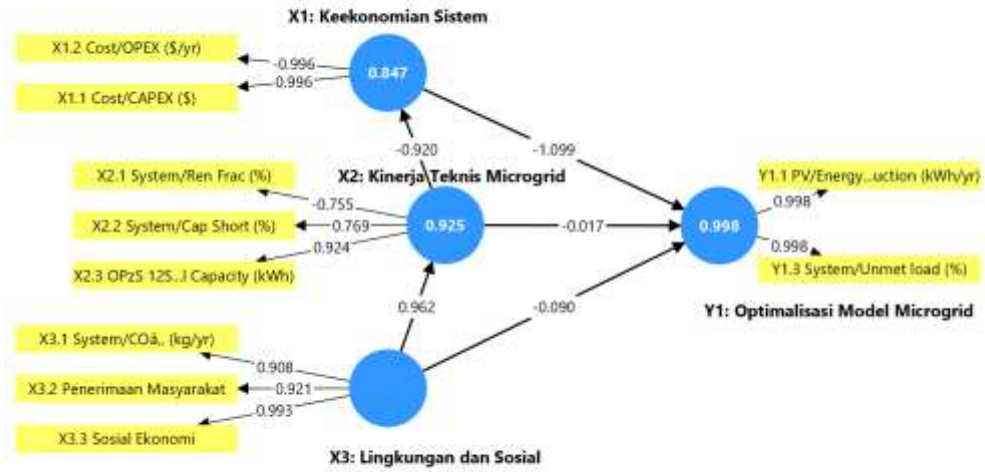

Figure 4. PLS-SEM model estimation results (Source: thesis)

Source: PLS-SEM analysis output (SmartPLS), processed by the authors, 2024

Implementation Strategy: Optimize–Modernize–Decarbonize

Synthesizing the simulation and PLS-SEM results yields a three-stage strategy. The first stage is "Optimize," involving the restoration of existing asset functionality and dispatch optimization. The second stage is "Modernize," achieved through phased solar PV expansion, retrofitting BESS to lithium-ion technology, and upgrading monitoring systems. The third stage is "Decarbonize," transitioning to 100% renewable energy once storage costs become more competitive and system flexibility needs can be met without routine diesel generator (PLTD) operation.

Table 7. Bunaken Island diesel phase-out roadmap

Phase	Timeline	Primary Action	Primary Action
Optimize	1–2 years	Dispatch optimization; revitalization of 287 kWp Solar PV; inverter restoration	RE penetration ≈24.3%; unmet load 0%; LCOE ≤ US$0.327/kWh
Modernize	3–7 years	Solar PV expansion; lithium-ion BESS retrofit; digital monitoring	RE penetration ≥50%; battery DoD 80–90%; diesel emissions & costs reduced
Decarbonize	8–15 years	Solar PV ±2,000 kWp; BESS ±6,480 kWh; productive dump load; emergency backup Diesel Gen	RE penetration 100%; routine Diesel Gen operation eliminated; very low operational emissions

Source: Authors' synthesis based on HOMER Pro simulation and PLS-SEM analysis results, 2024

This roadmap avoids two extremes: retaining diesel power for too long due to subsidies, or forcing a 100% renewable energy investment before the economics have matured. For conservation areas like Bunaken, this stage also allows system operators to improve maintenance quality and ensure that emission reductions go hand in hand with enhanced reliability.

CONCLUSION

Brownfield optimization offered a more rational pathway for the dedieselization of the Bunaken Island microgrid than direct system replacement. Revitalizing the solar PV system to 287 kWp while retaining the existing 540 kWh BESS provided the most favorable short-term configuration under baseline conditions, with a Net Present Cost (NPC) of US$8.386 million and a Levelized Cost of Energy (LCOE) of US$0.327/kWh. These values were lower than those of the baseline scenario, which recorded an NPC of US$11.261 million and an LCOE of US$0.440/kWh, while renewable energy penetration increased to 24.30%.

Achieving 100% renewable energy operation was technically feasible with approximately 2,000 kWp of solar PV capacity and a 6,480 kWh BESS; however, this configuration required approximately US$4.52 million in capital expenditure (CAPEX), making it more appropriate as a long-term target. The PLS-SEM analysis indicated that economic performance was the dominant determinant of microgrid optimization, whereas technical performance primarily exerted its influence through improved economic outcomes. Consequently, the recommended implementation pathway was optimize–modernize–decarbonize: first restoring and optimizing existing assets, then modernizing the solar PV–BESS system in stages, and finally transitioning toward 100% renewable energy operation once technical and economic conditions became favorable.

Policymakers should consider revising fuel subsidy policies to better reflect the actual economic cost of diesel and providing incentives for phased renewable energy development. System operators should prioritize the restoration of degraded PV capacity and implement data-driven dispatch strategies before undertaking large-scale BESS investments. Future research should expand the analysis to other small islands with different system characteristics, incorporate additional variables such as policy stability and climate variability into the PLS-SEM model, and apply longitudinal approaches or real-time monitoring data to validate the long-term performance of the proposed phased transition strategy.

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