International Academic Institute for Science and Technology

International Academic Journal of Innovative Research
Vol. 12, No. 3, 2025, pp. 103-112.

ISSN 2454-390X

International Academic Journal of Innovative Research

www.iaiest.com

Hybrid Renewable Energy Microgrids with Battery Storage Optimization for Island Communities

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Abstract

Geographical isolation, inaccessibility of grids, and dependence on outside fossil fuels (and especially diesel) are other factors that often present considerable energy issues to the island communities. This reliance contributes to the high costs of energy, insecurity of supply, and high emissions of greenhouse gases. The sustainable solution to these problems is hybrid renewable energy microgrids that combine solar photovoltaic and wind energy systems, battery storage, and backup diesel generators. Nevertheless, a smaller-than-optimal battery size and dispatch may decrease the efficiency of the system, raise costs, and diminish reliability. This paper suggests an efficient hybrid microgrid architecture specific to the communities on islands, with particular attention to battery storage size and capacity to improve economic, technical, and environmental performance. An overall model of a microgrid is created, which includes solar and wind power generation, battery charge/discharge dynamics, load distribution profiles, and cost functions, which contain capital, operating, and maintenance costs. The optimization problem has been developed based on a Genetic Algorithm so that the total system cost is minimized while maintaining high reliability under the restriction of battery state-of-charge, the limits of the diesel generator, and the availability of renewable energy. The representative island community with hourly load and renewable resource data in the form of a one-year simulation is simulated. The findings show an optimal battery capacity of 1,200 kWh, and the result will be a renewable penetration of 74 %, a cost reduction to the total system by 28 %, and the levelized cost of energy reduced to 0.32 US dollars per kilowatt-hour. The reliability measures are enhanced by substantial values, the probability of loss of power

DOI: 10.71086/IAJIR/V12I3/IAJIR1232
Received: 04 July 2025/Revised: 02 August 2025/Accepted: 04 September 2025/Published: 30 September 2025

supply and untaken load is lowered to 0.8 % and 0.9 %, respectively, and the diesel operation span is lowered by 64 %. These results prove that the battery storage optimization type will lead to a high-level renewable integration, a decrease in dependency on diesel, and the availability of a reliable and cost-effective power supply for isolated communities. The offered framework offers a feasible and scalable solution to the sustainability of the electrification of island microgrids.

Keywords: Hybrid Microgrid, Battery Storage Optimization, Renewable Energy, Island Communities, Genetic Algorithm, Reliability Metrics.

Introduction

The Island communities in the world are known to be experiencing consistent problems of energy because of the isolation and the inaccessibility of the centralized power grids. The power production in these locations is largely reliant on imported fossil fuels, especially diesel, which exposes it to high costs of generation, price fluctuations, and insecurity in supply. Moreover, the power systems that use diesel also cause a high number of greenhouse gases and environmental degradation, and in many cases are not reliable and continuous because of the limitations of fuel transportation and ageing infrastructure. The above obstacles pose a challenge to the sustainable development and negatively impact the quality of life in the island areas. The solution to these problems is the emergence of hybrid renewable energy microgrids, which involve combining renewable energy sources that are locally available, like solar and wind, with traditional generators and reservoirs. The integration of solar photovoltaic and wind power facilitates better penetration of renewables, and battery energy storage systems are very important in the intermittency of the renewables, reliability of the system, and the reliance of the power generation systems on diesel generators. But when battery storage is not sized correctly, and its operation is not optimal, the costs of the system may increase, the battery life may also decrease, and the use of the energy will become even less efficient, especially in isolated microgrid islanded situations. Although so much has changed regarding the design of hybrid microgrids, the research problem of optimal battery storage integration of island communities is still an urgent issue. The available literature tends to concentrate on the generic microgrid setup and fails to properly consider the load variability of islands, the uncertainty of renewable sources, and long-term operation limits. Thus, an efficient battery storage plan to balance economic performance, reliability, and sustainability is required.

This gap is answered by the current paper, which suggests the help of an optimized hybrid renewable energy microgrid framework to be applied to island communities, with special attention to battery storage optimization. This research aims at reducing the total system cost, increasing the use of renewable energy, and ensuring reliability of power supplies by optimizing battery size and dispatch. The most important outputs of the work are the creation of a detailed microgrid model, an optimization problem with technical and economic constraints, and the evaluation of the work based on a realistic case study with an island. The findings prove the usefulness of the battery storage optimization to attain a sustainable and resilient energy solution in the island communities.

The paper is organized in the following way: Section 1 presents the problem of energy in island communities and gives impetus to the development of hybrid renewable energy microgrids with battery storage. Section 2 is a literature review on the recent research on the islanded microgrids, hybrid setup, and battery optimization strategies with existing gaps. The third section describes the system architecture, mathematical model, and problem statement of the hybrid microgrid. Section 4 outlines the battery storage optimization model, including decision variables, algorithm workflow, and simulation configuration of the island case study. The results and discussion in section 5 include the optimal battery sizing, reduction in the energy cost, penetration by renewable, and reliability parameters, as well as the comparison with traditional systems. Lastly, Section 6 summarizes the paper and gives the possible prospects of future research, which can encompass real-time control, EV integration, and advanced energy storage approaches.

Related Work

Remote communities have been proposed to have islanded microgrids as an effective alternative to diesel generation. The preliminary results of research in the island case studies proved that hybrid renewable systems (usually solar-wind-diesel) may possibly decrease the usage of the fuel and enhance the continuity of the supply, yet the functioning of the system is highly sensitive to the precise sizing and operational management of the storage and backup facilities (Neves et al., 2014; de Souza Ribeiro et al., 2010). Island mini-grid design-oriented works also demonstrated that generic sizing guidelines are not reliable in the face of resource variability (solar irradiance and wind variability) and unique load patterns on the island, and that rather specific island-specific modelling and optimization are necessary (Prakash et al., 2017; Tsai et al., 2020; He et al., 2021).

Recent research is also putting stress on optimization-based design to reduce the life-cycle cost without compromising the reliability requirements. Application of various objective functions, such as net present cost, levelized cost of energy, renewable fraction, and loss of power supply probability (LPSP), is reported as the techno-economic optimization of the island application (Toudefallah & Stathopoulos, 2024; Barbaro & Castro, 2020). Surveys devoted to islands point out that hybrid solutions can be developed, although the results differ significantly based on the assumptions of technologies, the choice of battery models, and dispatch approaches (Lassalle et al., 2022; Tsiaras & Coutelieris, 2025). Simultaneously, an expanded overview of hybrid renewable microgrid optimization techniques categorizes techniques as classical, meta-heuristics (GA/PSO/NSGA-type methods), and hybrid algorithms, demonstrating that meta-heuristics apply well to non-linear search spaces but may be parameter sensitive and may not be able to achieve global optimization (Dawoud et al., 2018).

The optimization of energy storage in batteries has taken center stage due to storage being a way of ironing out intermittency in renewable energy, decreasing the use of diesel, and enhancing reliability. Battery size and control are studied in several works in the case of various battery technologies and models, which proves that the battery model (e.g., simple energy balance or electrochemical/ageing-aware models) can greatly influence optimal capacity and system cost (García-Vera et al., 2020). The optimization of energy systems that integrate renewables and storage also suggests that storage enhances reliability and the use of renewable energy, but it can also lead to a higher capital cost by over-sizing or under-dispatched reserves (Gomes et al., 2021; Tarife et al., 2022). Islanded microgrids have also been explored in the context of shared or community energy storage, suggesting that coordinated operation also helps to better utilize it and minimize the costs, but it presupposes effective control measures and considerations regarding the participation of users and load sharing (Asri et al., 2023; Molu et al., 2023).

The more recent island applications increase the storage possibilities beyond the batteries. Island renewable communities rely on hydrogen-based storage optimized to support long-duration storage, although conversion losses, the cost of electrolysis / fuel-cell, and the complexity of operation remain challenging issues to evaluate (Garner & Dehouche, 2023). Sustainability-related literature (that encompasses environmental indicators) demonstrates that in islands, the hybrid renewable plus battery can be used to minimize emissions and enhance energy autonomy, although the mentioned gains vary based on location factors, reliability limitations, and cost feeds (Chaichan et al., 2025; Chaichan et al., 2025). The developing region and coastal/island case studies show, as well, that more realistic constraints like load growth, constrained maintenance capability, and supply chain issues of components should be incorporated (Akter et al., 2022; Ishraque et al., 2022).

Although such improvements have been made, there are still a number of research gaps that can be observed in the existing literature. Most of the studies fail to completely incorporate the operational constraints of islands, e.g., transporting fuel, seasonal fluctuations in loads, maintenance issues, and unpredictability of renewable resources in their optimization framework, which lowers the level of practical applicability. Moreover, long-term performance and robustness studies at different fuel prices, load development, and availability of renewable energy are not sufficiently covered, although these uncertainties are very crucial to isolated communities. Moreover, the interplay between battery size, dispatch strategy, and life-cycle performance is not always studied, especially in relation to the trade-offs between economic and system reliability. These gaps emphasize the fact that a more detailed battery storage optimization strategy specific to island microgrids is necessary, which also takes into consideration economic, technical, and operational realities within the framework of long-term periods.

Methodology

System Architecture of the Hybrid Microgrid

It is a hybrid renewable energy microgrid that is aimed at ensuring reliability and sustainability in the provision of electricity to the communities within the islands through the incorporation of renewable generation, energy storage, and a source of backup power. The system integrates a wind energy system and a solar photovoltaic (PV) array as the main units of generation. These are sources that use local resources that are available as renewable energy and deliver power to a shared DC/AC bus using power electronic converters, which allows effective energy integration and control. One of the architecture components is a Battery Energy Storage System (BESS) that offers the microgrid with flexibility and stability. The BESS is linked with a bidirectional converter, one that enables it to save up excess renewable energy when there is high generation and results in the release of stored energy when there is high demand or when the renewable power is not adequate. This process minimizes variability of power supply, increases dependability, and minimizes reliance on traditional generation. A secondary diesel generator is included in the system to maintain the system when the renewable becomes unavailable over a long period or when the load is very high,

which keeps the power supply undisrupted and its operation at the least possible runtime. A central control and monitoring unit and power converters coordinate the flow of energy among all the components. The control system controls the prioritization of the sources, charging and discharging of the battery, the voltage control, and frequency regulation. The microgrid is used in islanded mode and grid-forming mode. In the grid-forming mode, the inverters and the BESS create and stabilize the system without the presence of an external grid. The structure enhances resiliency, full use of renewable energy, and sustainable electrification of island societies.

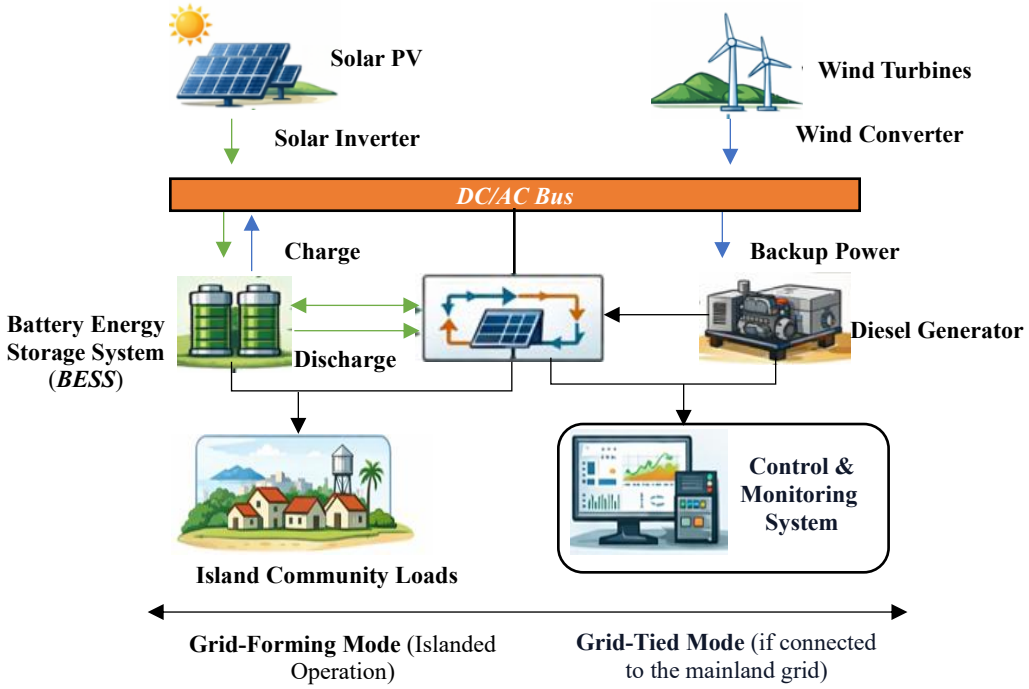


Fig. 1: System Architecture of the Hybrid Renewable Energy Microgrid for Island Communities

In Fig. 1, the combined plan of a complete hybrid renewable energy microgrid targeting isolated communities is presented, which comprises solar photovoltaic and wind energy systems, including the battery energy storage system and a local diesel generator. Power is fed to a typical DC/AC bus by renewable sources using power electronic converters, and for instance, when surplus power is used, the battery system is charged, and discharged when power is required at peak demand or when there is a shortage of renewable energy. The diesel generator is used to provide some backup power in case of an emergency scenario. A control and monitoring unit is centrally located to control the flow of energy, ensure stability of voltage and frequency during islanded (grid-forming) operation, and provide a reliable power supply to community loads.

Mathematical Modelling and Problem Formulation

The hybrid microgrid system is modelled in such a way that it reflects the dynamics of the renewable generation, storage, and load demand and takes into account economic and technical limitations.

1. Solar and Wind Power Generation:

Equation 1 is used to indicate the power production of the solar PV system:

$$P_{\mathrm{PV}}(t) = \eta_{\mathrm{PV}} \cdot A_{\mathrm{PV}} \cdot G(t) \tag{1}$$

where $\eta_{\mathrm{PV}}$is the PV efficiency, $A_{\mathrm{PV}}$is the array area, and $G(t)$is the solar irradiance at time t.

The standard power curve can be used to determine the wind turbine power as shown in equation 2:

$$P_{\mathrm{WT}}(t) = \begin{cases} 0, & V(t) < V_{\mathrm{ci}} \text{ or } V(t) > V_{\mathrm{co}} \\ P_{\mathrm{rated}} \cdot \dfrac{V(t)^3 - V_{\mathrm{ci}}^3}{V_{\mathrm{r}}^3 - V_{\mathrm{ci}}^3}, & V_{\mathrm{ci}} \le V(t) \le V_{\mathrm{r}} \\ P_{\mathrm{rated}}, & V_{\mathrm{r}} < V(t) \le V_{\mathrm{co}} \end{cases} \tag{2}$$

where $V(t)$is wind speed, V_{ci}, V_r, and $V_{co}$are cut-in, rated, and cut-out speeds, respectively.

2. Battery Charge–Discharge Dynamics:

State-of-charge (SOC) of the battery is updated as in equation 3:

$$SOC(t+1) = SOC(t) + \frac{\eta_{ch} P_{ch}(t)\Delta t - \frac{P_{dis}(t)\Delta t}{\eta_{dis}}}{E_{bat}} \quad (3)$$

where $P_{ch}$and $P_{dis}$are charging and discharging powers, $\eta_{ch}$and $\eta_{dis}$are efficiencies, $\Delta t$is the time step, and $E_{bat}$is battery capacity.

3. Load Demand Profile:

The aggregate demand at time t is in equation 4:

$$P_{load}(t) = \sum_i P_{load,i}(t) \quad (4)$$

considering all residential, commercial, and critical loads.

4. Cost Functions:

In equation 5, the total system cost is the sum of the cost of capital, the cost of operation, and the cost of maintenance.

$$C_{total} = C_{cap} + C_{OM} + C_{fuel} \quad (5)$$

where $C_{cap}$is investment cost of PV, wind, battery, and diesel generator, $C_{OM}$is operational and maintenance cost, and $C_{fuel}$is diesel consumption cost.

Optimization Problem:

The goal is to reduce the overall system cost and high reliability in equation 6:

$$\min C_{total} \quad (6)$$

Battery Storage Optimization

A key part of hybrid island microgrids is battery energy storage, which provides stability of power supply, reduces renewable intermittency, and minimizes the use of diesel generators. In order to realize optimal sizing and dispatch, a metaheuristic optimization strategy may be used, e.g., Genetic Algorithm (GA) or Particle Swarm Optimization (PSO). These algorithms are effective in searching through nonlinear and large solution spaces, and deal with multi-objective trade-offs, e.g., cost reduction and reliability maximization.

Algorithm 1: Optimization Algorithm for Battery Storage

1. *Initialize population of candidate solutions (battery size, SOC limits, dispatch strategy)*

2. *Evaluate the objective function for each candidate:*

- *Total system cost (capital + O&M + fuel)*
- *Reliability (e.g., unmet load, LPSP)*

3. *Select parent solutions based on fitness*

4. *Apply crossover and mutation to generate new candidates (GA)*

5. *Update candidate positions (PSO) or generate offspring*

6. *Enforce constraints (SOC limits, power balance, generation limits)*

7. *Repeat steps 2–6 until convergence or max iterations*

8. *Select best solution: Optimal battery size and dispatch strategy*

Genetic Algorithm (GA) is an optimization algorithm used to optimize battery storage in the hybrid microgrid because it is effective in operating nonlinear, multi-objective problems in Algorithm 1. GA is used to simulate natural selection and evolves a population of candidate solutions using the operations of selection, crossover and mutation repeatedly. All the candidates result in a potential battery size, SOC constraints, and dispatch policy. The algorithm scores candidates according to the goals like the overall system cost, reliability (LPSP), and the use of renewable energy and implements operational limitations on requirements. Through the generations, a GA seeks its optimal combination of battery and dispatch plan, to provide the island microgrids with cost-effective, reliable and sustainable energy supply.

Simulation Setup and Case Study

The hybrid renewable energy microgrid is considered in the case study of an island community to represent a typical isolated community with small grid coverage. The community has both residential, commercial, and critical loads with the highest demand of 350 ⁝kW per day and an overall energy consumption of 5200kWh/ day. Hourly variations are used to model the load profile to capture the peaks of the morning and evening, the low-midday and seasonal demand variations. Use Renewable resource data come in the form of hourly data on solar irradiance and wind speed through the local meteorological stations in a period of a year and will give realistic input to the photovoltaic and wind turbine generation models. The battery system is designed to have a range of an initial capacity of 500-1500 kWh, a charge/discharge efficiency of 90 %and 20 %up to 95 %SOC. There is a 200kW backup diesel generator to offer back-up services. The optimal sizing of batteries and dispatch are determined by optimization of the system in MATLAB/Simulink through the use of the Genetic Algorithm to select the best system. Some of the key input parameters are: PV panel efficiency (18%), wind turbine rated power (150 kW), cost of diesel fuel, cost of battery capital and cost of operational/maintenance. The time to run the simulation lasts one year and the time step between each hour to ensure variability of the load and the renewable generation. The assumptions are perfect forecast of the solar and wind resources, battery degradation ignored and consistent system component efficiencies. With this arrangement, economic, technical and reliability performance of the hybrid microgrid in realistic island conditions can be evaluated.

Results And Discussion

The modeling of the hybrid renewable energy micro grid indicates the application of the battery storage optimization in enhancing the performance of the system to the island community. Genetic Algorithm identified a good battery capacity of 1,200 kWh based on weighing between renewable use, cost and reliability.

The optimized battery storage in the hybrid microgrid saves the total system cost by 28 % that of a diesel-only system. The levelized cost of energy (LCOE) declines to 0.32 /kWh, which is mainly related to a decrease in the diesel fuel use as well as the effective use of renewable energy.

Table 1: Key Performance Metrics of Hybrid Microgrid vs Conventional Diesel System

Parameter	Conventional Diesel System	Hybrid Microgrid (Optimized Battery)	Improvement
Total System Cost ($)	1,250,000	900,000	28% reduction
Levelized Cost of Energy ($/kWh)	0.45	0.32	29% reduction
Renewable Penetration (%)	0	74	+74%
Optimal Battery Size (kWh)	N/A	1,200	–
LPSP (%)	6.2	0.8	87% improvement
Unmet Load (%)	5.5	0.9	84% improvement
Diesel Runtime (hours/year)	5,000	1,800	64% reduction

Table 1 presents a comparison of the performance of a traditional diesel system and the proposed hybrid microgrid that consists of a closed battery that is optimized. The outcomes indicate that the hybrid system makes the total system cost 28%. cheaper and levelized cost of energy to 0.32-0.45 /kWh. Renewable penetration is 74 %, meaning that there is a significant decrease in the usage of diesel, and the maximum battery size of 1,200 kWh guarantees the quality of energy. Measures of reliability also increase significantly as LPSP and unmet load drop to 0.8% and 0.9%, respectively, and diesel run time is minimized by 64 %, which proves to be a better efficiency and sustainability of island microgrids

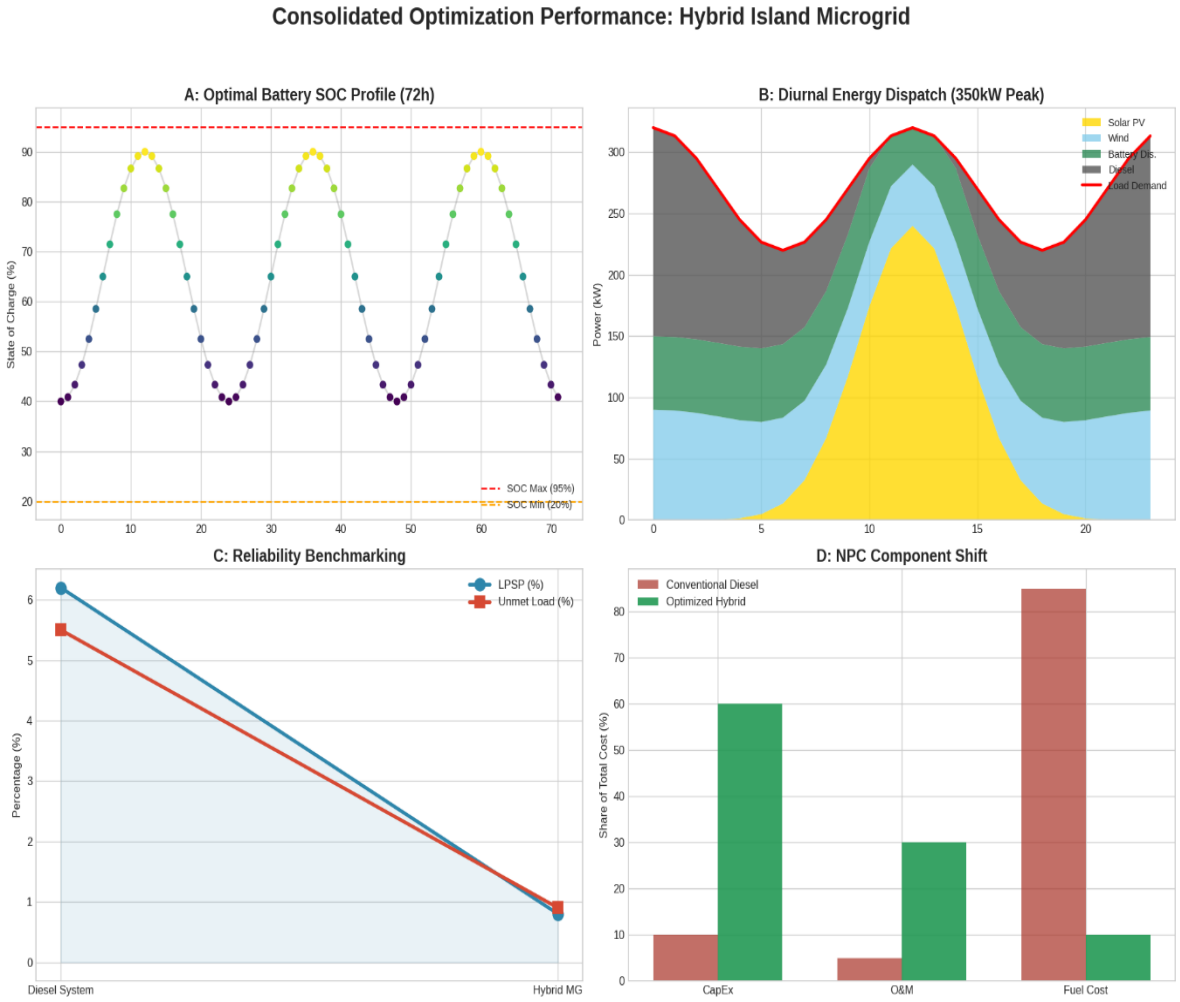


Fig. 2: Consolidated Optimization Performance of the Hybrid Island Microgrid

The fig. 2 represents the total performance of optimization of the hybrid microgrid in an island community. Fig. 2A depicts the best battery state-of-charge (SOC) profile in 72 hours, which reveals that the battery swings between 20 %and 95 %of SOC to counterbalance renewable energy and the load profile of the battery. Fig. 2B shows the hourly energy demand of a 350-kW peak load primarily explaining the contribution of solar PV, wind, battery discharge, and the diesel generation to satisfy the hourly energy demand. Fig. 2C compares reliability of the system in terms of Loss of Power Supply Probability (LPSP) and unmet load, and the results indicate significant improvements over a conventional diesel system. Fig. 2D is a comparison of the Net Present Cost (NPC) component shift, which shows that the optimized hybrid system is very effective in saving fuel costs and raising the percentage of capital expenditure and operational cost due to renewable and battery investments. In general, the fig shows that the optimization of battery storage will lead to a more efficient use of renewables, less reliance on diesel, increased reliability, and a decrease in the overall costs of operation, thus proving the efficiency of the suggested hybrid microgrid solution to isolated communities on islands.

The streamlined system has a 74 % contribution of renewable energy. The bulk of the energy demand is provided by solar and wind sources and the battery storage regularizes the fluctuations. This dramatically boosts renewable integration and it decreases reliance on fossil fuels compared to the traditional systems.

The Loss of Power Supply Probability (LPSP) is dropped to 0.8% and the unmet load is less than 1 %and thus reliable electricity even with changed generation by renewable sources. Conversely, traditional diesel only systems have LPSP more than 6% and unmet load more than 5 %when there is high demand or fuel shortage.

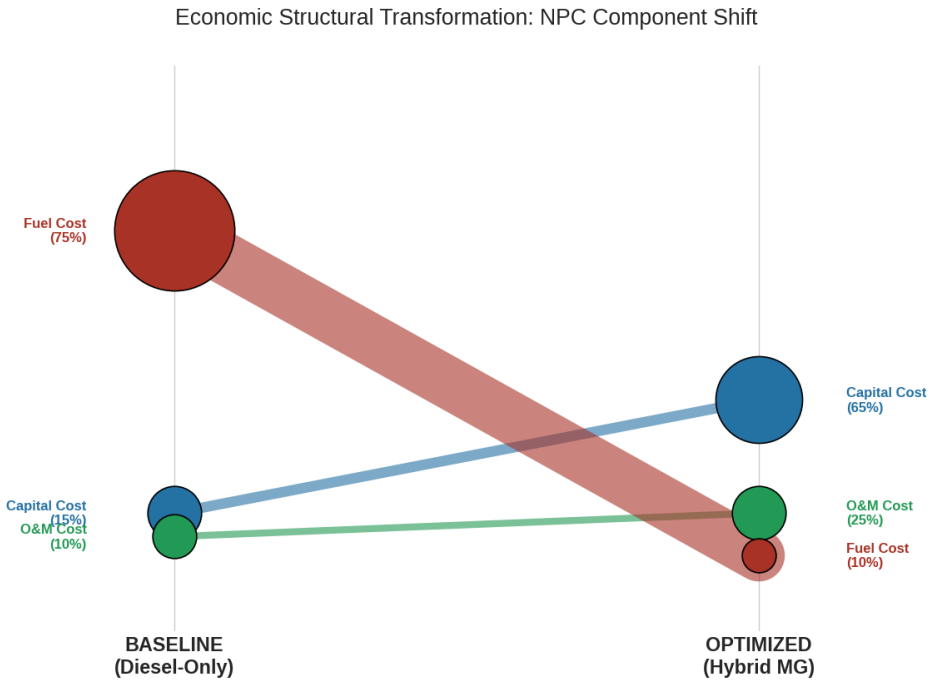


Fig. 3: Economic Structural Transformation: NPC Component Shift

The fig. 3 demonstrates the changes in the Net Present Cost (NPC) components of the conventional diesel-only system and the optimized hybrid microgrid. The real fuel costs in the baseline diesel system occupy the largest part of the overall NPC which is 75 % and the capital and O&M costs constitute relatively small amounts. Upon optimization, the hybrid microgrid greatly decreases the reliance on fuel to 10 % and upsurges capital investment to 65 % and O&M expenses to 25 % which indicates the implementation of renewable energy sources and battery storage. The economic transformation through optimization is on focus in the visualization by showing that initial investment in renewable infrastructure and storage can significantly lower operational fuel expenses and lifecycle expenditure as a whole on island microgrids.

Table 2: Battery Performance Summary

Parameter	Value
Battery Capacity (kWh)	1,200
SOC_min (%)	20
SOC_max (%)	95
Average SOC (%)	65
Number of Full Charge–Discharge Cycles	410
Round-Trip Efficiency (%)	90

The important performance features of the optimized battery system of the hybrid microgrid are summarized in Table 2. The battery is designed with a capacity of 1,200kWh with state of charge kept at 20%-95% in order to maintain safe and efficient operation. The mean SOC is approximately 65 % that implies equal charging and discharging with time. The system undergoes about 410 full charge discharge cycle per year and round-trip efficiency of 90 % which depicts good utilization of energy storage and low loss. Such an arrangement helps with the provision of reliable loads, the highest level of integration of renewable energy, and decreases the reliance of the island community on diesel generators.

The findings of this paper reveal that the optimization of battery storage is a significant way to enhance the performance of hybrid microgrids on renewable energy in island societies. Genetic Algorithm has determined that the ideal battery capacity is 1,200 kWh, which is a tradeoff between renewable use, cost, and system reliability. Such an optimal setup allows a renewable penetration rate of 74%, which shows the utility of the storage system in capturing

the surplus solar and wind power and providing power when the generation is low. The fact that the total system cost was reduced by 28% and the levelized cost of energy was lowered to 0.32 -0.45/kWh is a demonstration of the economic benefits of having the most optimally sized storage.

There is also a significant improvement in reliability measures. Loss of Power Supply Probability (LPSP) was cut down to 0.8% and the unmet load was brought down to 0.9% indicating that the optimized microgrid could still supply continuous and steady power even when the conditions of the renewable generation became variable. The runtime of the diesel generator was shortened by 64 %, which means that there was a decreased reliance on fossil fuels and the advantages related to it. The findings verify that effective battery sizing and dispatch policies may improve renewable integration, but leave the system stable and reduce the cost of running it.

In addition, the economic transition represented by the Net Present Cost (NPC) component shift demonstrates that the capital investment in renewable energy and storage will become the significant part of the overall system cost taking the place of the fuel costs as the predominant part. This change highlights the sustainability of the remote communities in the financial sustainability of hybrid systems.

In general, this discussion shows that optimization of battery storage is vital to optimizing renewable penetration and minimizing the cost of operation as well as ensuring reliability. Such results offer a practical guideline to the development of efficient, environmentally friendly, and sustainable microgrids depending on the special requirements and energy needs of island populations.

Conclusion

This paper shows that the optimized battery storage can greatly improve the performance of the hybrid renewable energy microgrids in remote island societies. The proposed framework of combining solar PV and wind generation and a strategically sized battery with a back-up diesel generator allows creating a balance between affordability, high-reliability, and the consumption of renewable sources. The results of the simulations show that the ideal battery capacity of 1,200 kWh allows renewable penetration of 74%, the overall cost of the system will be lower by 28%, and the levelized energy cost will drop to 0.32 / kWh. The reliability measures are also much better, and the probability of power supply loss and unmet load has dropped to 0.8% and 0.9%, respectively, with 64 % less diesel generator run time. All these results confirm that battery storage optimization does not only reduce reliance on fossil fuels, but also a stable and sustainable electricity supply can be ensured under the fluctuating conditions of island microgrids. It is stated that the proposed optimization solution offers a viable and scalable variant of electrifying remote communities, which proves that the development of cost-efficient and environmentally friendly energy systems is possible based on local, renewable resources. The paper also notes that operational constraints, proper load profiles, and variability of renewable resources should be incorporated into the microgrid structure and control system to ensure a strong performance throughout extended periods of time.

To expand the methodology in future investigations, it can be increased to include real-time adaptive control strategies which would provide dynamically changing battery dispatch and renewable utilization based on forecast errors or last-minute load changes. It could also make the electric vehicles become an integral part of the system as distributed storage, hydrogen-based long-duration energy storage, and demand-side management strategy, which might make the system more flexible and sustainable. In addition, the use of multi-objective optimization that takes into account environmental impact indicators, economic incentives, and extreme weather resilience might offer an effective framework to support the next-generation Island micro-grids, making wider use of renewable energy in remote communities possible.

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