J. Res. Technol. Eng. 7 (2) , 2026, 22-35

Journal of Research Technology and Engineering
www.jrte.org

# Optimisation of a Lightweight Solar PV and Wind Energy Hybrid System for Off-Grid Rural Area in Neduntheevu, Sri Lanka with Battery Energy Storage System (BESS)

*M.D.R. Weerasuriya, Udara S.P.R. Arachchige

Faculty of Engineering, NSBM Green University, Sri Lanka
mdrweerasuriya@students.nsbm.ac.lk

Received:20 January 2026; Revised: 08 February 2026; Accepted: 15 March 2026; Available online: 10 April 2026

**Abstract**: The need for clean energy in areas without grid connection has become a significant focus. Hence, hybrid solar, wind microgrids combined with Battery Energy Storage Systems (BESS) and intelligent Energy Management Systems (EMS) are considered potential solutions. This research is about the design of an optimized, lightweight solar, and reliable hybrid system for Neduntheevu, Sri Lanka, which also includes techno, economic optimization based on HOMER, MATLAB/Simulink dynamic simulations, and PSCAD transient analysis. The proposed system are making use of the sister nature of solar and wind resources, also BESS and EMS have been used to power a population of approximately 5, 000 continuously, stably, and cost, effectively. Reliability assessments (LOLP, EENS), sensitivity studies, economic and environmental evaluations result in a very low dependence on fossil fuels, carbon emissions, and operational costs, and keeping the system strong even if the weather changes and the load condition vary. This study offers a practical framework for implementing sustainable, resilient, and economically viable hybrid microgrids in remote off, grid communities.

**Index Terms**: Hybrid microgrid, Renewable energy integration, Battery energy storage systems, Techno-economic optimization, Rural electrification.

## 1 Introduction

The rapid depletion of fossil fuel resources and increased evidence of global warming have created a need for a transition to sustainable alternatives for electricity generation. [1]. Solar photovoltaic (PV) and wind energy systems are seen as the most promising ones due to their availability, scalability, cost, effectiveness especially if local power generation of remote and off, grid areas is concerned [1],[2]. Investing in a hybrid solar, wind system can enhance energy reliability thus the supply can be balanced during the time when either source is unavailable. Besides that, the hybrid system results in fewer downsizing requirements compared to the use of a single, source system [1],[3].

Hybrid PV, wind systems are especially good for rural areas in developing countries where there is no or very limited plan for extending the centralised grid. Take Ethiopia as an example, a country relying heavily on biomass as an energy source, where solar, wind standalone systems have been explored as viable options to expensive and polluting diesel generators [2]. The same kind of solutions have been implemented worldwide, showing that decentralised hybrid systems are capable of ensuring cheap and reliable electricity supply in places where centralised infrastructure is either too costly or impossible from a technical point of view [3].

Battery Energy Storage Systems (BESS) have a vital role in solving the problem of solar and wind generation intermittency through maintaining a stable supply and alleviating the mismatch between generation and load demand. The technological improvements in energy storage, mainly hybrid battery combinations, have facilitated the reliable operation of systems with less degradation and longer service life [4],[5]. Efficient BESS connection stabilizes frequency and voltage fluctuations and makes the system more resilient to renewable variability [4],[5].

Since the complication of creating such systems, optimisation tools have become indispensable to get the best compromise between the cost and the reliability. Such simulation platforms as HOMER, PSCAD, and MATLAB/Simulink have been broadly used to dimension hybrid microgrids, check their techno, economic viability, and make sensitivity analysis under changing climatic and load conditions [1],[2],[3]. The use of optimization methods, comprising approximation and evolutionary techniques, has also been extended to improving both the system design and the running strategies [3].

Generally, the combination of solar PV, wind energy, and BESS into hybrid microgrids presents a green and resilient solution for rural electrification. Yet, there are still difficulties in determining the best system size, extending the storage life, and finding the right balance between cost and reliability. Closing these holes is crucial to unlocking the potential of solar, powered hybrid systems for off-grid villages.

### 1.1 Hybrid microgrids for off-grid rural electrification

Access to reliable electricity is essential for social and economic development, however, a significant number of rural and remote communities worldwide still suffer from energy poverty. There are over 1.3 billion people mainly in developing countries who do not have access to electricity, and about 17.5% of the world's population remains without a reliable power supply [6]. In these regions, it is often not economically viable to extend centralized grid infrastructure because of difficult terrain, high capital costs, and sparsely populated areas [7].

Hybrid microgrids (HMGs) can be a great solution if they combine generation sources, storage, and control systems that are localised, to form energy ecosystems that are resilient and self, sufficient [8]. Simple microgrids that might depend on a single source are different from HMGs in that the latter incorporate two or more different energy sources, such as a combination of solar PV, wind, and a diesel or gas turbine backup that is dispatchable, along with energy storage systems [8]. By doing this, the renewable energy's intermittency is solved, and it is still possible to power local loads without interruption. The main elements of HMGs are renewable and conventional generation, BESS (battery energy storage systems), advanced control and optimisation platforms, and the distribution network that caters to residential, commercial, or industrial consumers [8].

Hybrid configurations play a major role in rural electrification by greatly enhancing both the reliability and affordability of the power supply compared to the old diesel, only systems. A comparative study made in Gracias a Dios, Honduras, showed that a solar, diesel, battery hybrid microgrid was able to provide the cheapest Levelized Cost of Electricity (LCOE) at $0.43/kWh [7]. This was even better than diesel, only generation which was priced at $0.78/kWh and standalone solar PV with batteries at $0.46/kWh[7]. Besides that, the hybrid system reduced the number of energy cuts and thus increased supply efficiency[7]. Interestingly, in Pakistan, a hybrid solar, wind microgrid system modeled using MATLAB was able to give a stable, sinusoidal voltage output while also effectively mitigating transient disturbances, thus being efficient extreme solutions for the deprived rural areas [7].

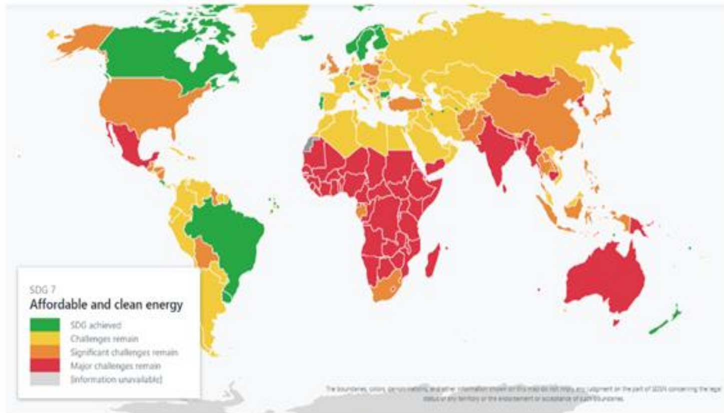


**Fig. 1**. Map of the progress of SDG 7 "affordable and clean energy" across the world [9]

Furthermore, HMGs make communities more resilient and sustainable besides the economic aspect, as illustrated in Fig 1. Their ability to operate on a local energy source keeps the power running without interruption even during a grid failure, which is of great value to hospitals, schools, and areas frequently affected by natural disasters [8]. Hybrid systems lessen the reliance on fossil fuels by using renewable energy sources, thus releasing fewer greenhouse gases and helping to ease global warming [6], [8]. In addition, hybrid microgrids facilitate the provision of energy in isolated islands and rural areas, which leads to the social and economic development of the local community and helps achieve the national electrification targets [6], [7].

On the whole, hybrid microgrids are a game changer for rural electrification in that they can balance cost, reliability, and sustainability. Their capability to integrate with local resources and adapt to the load conditions makes them very suitable for off, grid communities, for example, in South Asia, Central America, and small island nations.

### 1.2 Importance of solar and wind combination

Combining solar and wind power has been seen as a very effective way to overcome the issues of single renewable energy systems. Worldwide, increasing electricity demand along with the obstacles such as very costly grid extension, deteriorated infrastructure, and environmental issues have strengthened the necessity of green energy solutions [10]. Solar and wind are the two most generous sources of renewable energy. Besides that, when they are united in a hybrid system, it leads to considerable benefits regarding the certainty of supply, production efficiency, and ecological sustainability [10].

One of the main benefits of hybrid solar, wind systems is that they have a generation profile that is complementary to each other. Solar energy is mainly generated during the day in a clear sky, whereas wind energy is generally more available at night or when it is cloudy and stormy [10]. Such complementary behavior guarantees a more steady and uninterrupted supply of electricity than single, source systems [10]. Hence, hybrid systems not only enhance power reliability but also lessen the need for large energy storage facilities and at the same time satisfy a higher level of load by mitigating the intermittency that is characteristic of standalone solar or wind generation [10].

Moreover, Hybridisation can bring about economic advantages to both communities and utilities. After the initial capital costs have been paid, the running costs of solar and wind systems are almost none, existent since both sources are based on free and natural resources. Communities that install such devices have an opportunity to enjoy the benefits of a lower energy bill and even, in some cases, the advantage of selling excess electricity back to the grid [10]. Besides that, the local implementation of hybrid systems stimulates economic growth and the creation of jobs through the installation, operation, and maintenance of these systems [10]. Also, ownership models at the community level, for instance, cooperatives, can be used as a mechanism for economic empowerment and to keep the financial benefits circulating within the local economies [10].

From an environmental perspective, solar-wind hybrid systems reduce dependence on fossil fuels, thereby cutting greenhouse gas emissions and improving local air quality [10] mentioned in Table 1 below [11].

**Table 1**. Comparison of greenhouse gas emissions for different energy generation systems [11]

| Energy System | g $CO_2$/kWh |
|---|---|
| Coal | 975 |
| Gas | 608 |
| Oil | 742 |
| Nuclear | 66 |
| CSP Parabolic trough | 26 |
| CSP Power tower | 38 |
| PV monocrystalline | 45 |
| PV thin film | 14 - 48 |
| Wind | 9.7 - 16.5 |
| Hydro | 10-13 |
| Geothermal | 38 |
| PV polycrystalline silicon | 9-72.4 |

According to Table 2, this system requires the lowest level of water consumption [11], [12]. Their deployment supports climate change mitigation while contributing to a cleaner and healthier environment for communities [12]. Importantly, such systems also enhance resilience by reducing reliance on centralised grids that may be vulnerable to disruptions caused by natural disasters or infrastructure failures [10].

**Table 2**. Water consumption for different energy systems [11]

| Energy System | (L/MWh) |
|---|---|
| PV and CPV | 0-20 (For Cleaning) |
| CSP with wet cooling | 2900-3800 |
| CSP with dry cooling | 250-300 |
| Wind | 0-4 |
| Coal | 1800-4200 |
| Nuclear | 1500-3200 |
| Geothermal | 5300 |

Besides that, global market projections for hybrid solar, wind systems are very positive. The hybrid systems market is expected to expand substantially in the Asia, Pacific, North America, and Africa regions as a result of rapid industrialization, supportive government policies, and the rising awareness of climate change [10]. Moreover, the combination of smart grid technology integration, IoT, enabled monitoring, and developments in energy storage are some of the emerging trends that further strengthen the performance, efficiency, and acceptance of the hybrid systems..

The combination of solar and wind energy overall constitutes a very strong approach to securing an electricity supply that is reliable, affordable, and sustainable. Hybrid systems, by taking advantage of the complementary features of these two types of energy, do not only solve the problem of intermittency but also lead to various benefits such as energy independence, economic resilience, and environmental conservation at both the community and national levels.

### 1.3 Role of BESS and EMS

There are studies on various BESS and EMS configurations, but many only focus on the conventional battery types and standard control algorithms and do not consider advanced hybrid storage and intelligent EMS integration in a single framework. The study at hand combines state of the art battery technologies with a smart EMS model to result in better energy balance and reliability, which are key to the sustainability of microgrids that supply isolated communities such as Neduntheevu.

The integration of Battery Energy Storage Systems (BESS) and Energy Management Systems (EMS) forms the basis of the dependable and efficient operation of hybrid renewable energy microgrids. Their joint function is to maintain energy balance, increase system stability, and promote the cost, effectiveness of using renewable energy.

### 1.4 Battery Energy Storage Systems (BESS)

BESS is a feasible option that can address the problem of intermittency and variability of renewable energy sources (RESs), especially solar PV and wind. Mechanical, thermal, or chemical storage systems are limited by their geographic, cost, or operational factors, whereas BESS has higher efficiency, flexibility, and faster response [13]. That is why BESS can be very helpful in stabilizing grids with low strength, controlling power fluctuations, and allowing the installation of renewable energy sources. For example, pumped hydro and compressed air storage, which are really efficient, depend on the availability of the suitable site, and flywheels have problems with capacity and component wear. On the other hand, thermal and chemical storage systems have either high operational costs or are quite complicated, whereas supercapacitors or superconducting magnetic storage are limited by scalability and subzero requirements [13].

However, BESS is a programmable, scalable, and cost, efficient solution to support the operation of a modern hybrid microgrid. Functionally speaking, BESS is mainly there to store excess energy when there is low demand and to supply energy when the demand peaks. In that way, the load is satisfied, and the usage of backup fossils and fuel generators is minimized [14]. BESS is used not only for renewable integration but also in the residential, commercial, and industrial sectors to reduce energy costs through peak shaving and load shifting, provide backup power for critical loads, support off, grid systems, and supports fast EV charging without overloading the grid [14]. Moreover, declining installation costs and improvements in battery efficiency have enhanced the economic feasibility of BESS, further supporting its adoption in distributed and off-grid systems.

BESS contributes to the environment in a number of ways. One such way is that it enables higher use of renewables which in turn lessens the reliance on Peaker plants and fossil fuel generation. The result is a decrease in greenhouse gas emissions, better air quality, and the achievement of carbon neutrality objectives [15]. BESS is especially vital for remote or islanded areas like Neduntheevu in Sri Lanka, where it cuts down on diesel backup requirements which in turn reduces both the cost and the environmental impact of running the backup.

**1.5 Energy Management Systems (EMS)**

BESS provides the capabilities of storage and dispatch but to a large extent, its effectiveness depends on the EMS. The EMS is the intelligence layer of the hybrid microgrid that adjusts the energy flow between the generation, storage, and load. Advanced EMS strategies to guarantee the highest performance of hybrid renewable energy systems (HRES) have recently been highlighted in the literature. For example, Dsouza et al. have constructed an EMS model driven by the Starling Murmuration Optimization Algorithm (SMOA) coupled with a Kronecker Neural Network (KNN), thereby attaining 95% efficiency and lowering the cost to $17, 000, while the other methods, e.g. SSA, PSO, and WHO, resulted in higher costs [16]. Thus, the efficiency and economic advantages of a solution can be greatly enhanced through an EMS that is well optimized.

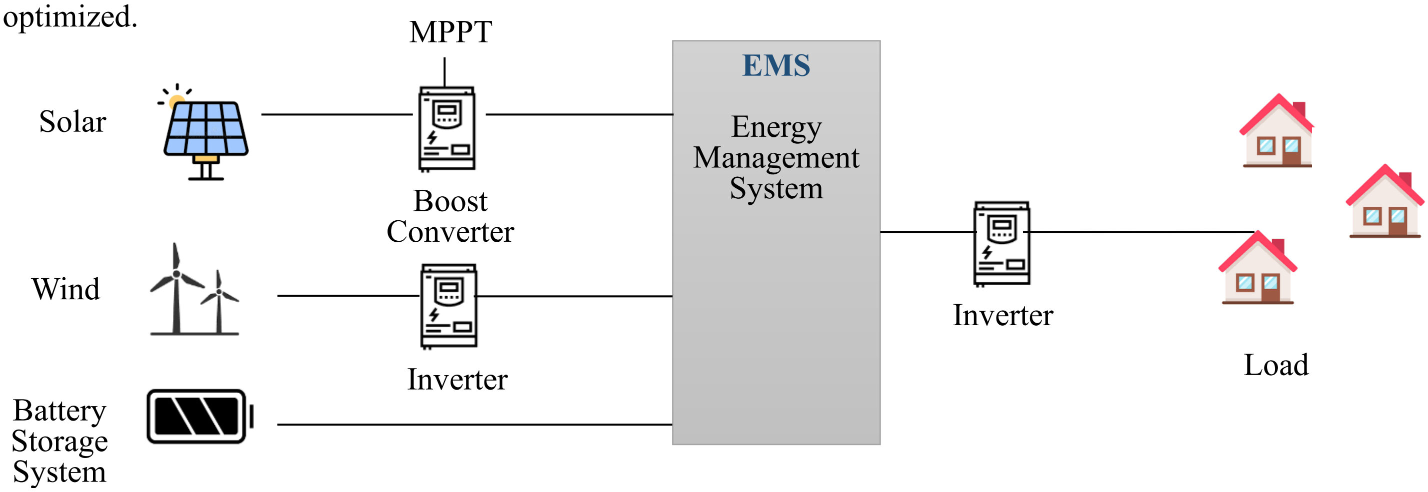


**Fig 2**. EMS layout

Basically, most EMS structures also in Fig 2 focus on the use of renewable energies, regulation of battery state of charge (SoC), and maintenance of a reliable supply by load balancing between critical and non, critical loads. Besides that, progressive EMS methods even include demand response programs (DRP) to gain better control over the consumer, side loads and thus bring about greater cost savings and higher operational stability [16]. Furthermore, EMS points out suitable decisions when there is uncertainty by planning energy flows in the most efficient way while taking into account the variability of renewable generation, demand, and market prices [16].

**1.6 Combined Role of BESS and EMS**

Working in unison, BESS and EMS substantially change the face of hybrid renewable energy systems. Instead of being just "intermittent" and "unstable" setups, with these two combined, such systems become "reliable, resilient, and economically viable energy solutions". BESS guarantees storage, stability, and flexibility. On the other hand, EMS gives optimization, control, and intelligent scheduling[14]. The combination of these two technologies offers several advantages such as increasing grid reliability and the share of renewables, lowering the cost of energy and reducing environmental impact, thereby facilitating the achievement of broader clean energy and electrification goals [13], [15].

**1.7 Why Neduntheevu is relevant**

Neduntheevu which is also called Delft Island is one of the major islands in the Palk Strait lying to the north of Sri Lanka. It is the largest of the seven inhabited islands of the Jaffna region, covering an area of around 50 to 62 km$^2$ in an oval shape, the length varies from 8 to 11 km and the width is about 6 km [17],

[18]. The island presently has a Tamil community of about 4000, 5000 people but according to the records of the past, the population was more than 20 000 before the war [19]. The people mainly depend on their small compounds and are mostly located in the northern half of the island [17], [18].

Neduntheevu being an off-grid island has renewable energy potential and the socio-economic factors there will be a good example of a battery hybrid microgrid optimization. This study takes advantage of those special conditions, and it provides a fixed framework which is a solution to the problems that islands face (for example: different load profiles, resource variability, logistical constraints) in sustainable electrification.

#### 1.7.1 Energy and Grid Status

Neduntheevu is still off the grid with daily power consumption of 2920kWh, depending on three diesel generators (250kVA, 250kVA, 330kVA) and with mini grids for its power supply. That dependence on fossil fuels means there is a high cost of generation, pollution emissions, and a limited reliability level of the power supply since fuel for generators needs to be transported by ocean from boats and during the bad weather times it will be challenging. Being a remote island, it is not economically viable to extend the national power grid to Neduntheevu, which is why decentralised hybrid renewable energy solutions become a strong alternative here.

#### 1.7.2 Renewable Energy Potential

Renewable energy sources, especially solar and wind, can be very efficiently utilized on the island. The flat and open landscape of Neduntheevu, along with the constant coastal winds, makes it an ideal place for wind energy generation [18]. Latest climate statistics support the islands green energy potential. Daytime temperatures on the island average between 84 and 89$^0$F. Moreover, the high solar irradiation level shown by the UV index of 10/11, combined with the wind speeds above 11 mph that allow for continuous hybrid generation, confirms the suitability of the island.

#### 1.7.3 Social-Economic and Geographical Relevance

Compared to neighboring islands like Analaitivu, Neduntheevu has a relatively large population which makes it a more significant case for hybrid microgrid optimization. The island with an estimated population of 5, 000 has a higher demand profile and thus serves as an ideal site for solar, wind, battery system simulation. Moreover, the inhabitants' dependency on shallow brackish wells and the collection of rainwater for their water supply, instead of natural freshwater streams, indicates the island's susceptibility to the scarcity of basic resources [17], [18]. This is yet another reason why sustainable and resilient energy solutions are vital in improving the quality of life.

The island is quite a significant place in the Jaffna region due to its environmental and cultural characteristics such as coral, based beaches, semi-arid vegetation, palmyra palms, and historical artifacts places like the Dutch fort [17]. Nevertheless, these very factors necessitate energy development to be eco, friendly and energy projects must find a balance between environmental conservation and cultural heritage.

### 1.8 Strategic Relevance for Research

Neduntheevu is a perfect one example is to map out, and then test, a solar PV, wind, BESS hybrid microgrid that is made best. Different conditions such as the remoteness of the place, presence of renewable energy sources, a sizable community, and the island's development being pointed out have been the main ones in national energy planning reports, collectively, provide excellent reasons for its choice. The results of this study can serve as a source of inspiration for setting up solar, powered microgrids on other rural islands and isolated villages in Sri Lanka and elsewhere in the world.

## 2 System Optimisation and Simulation Approaches

Although HOMER, MATLAB/Simulink, and PSCAD have all been used individually in the hybrid microgrid design, their combined application within a multi-platform optimization and simulation framework has not yet been fully investigated. This paper further develops the method by using capabilities of each tool for economic sizing, dynamic EMS simulation, and transient stability analysis thus, the hybrid system is optimized both technically and financially for Neduntheevu's off, grid environment.

Designing and assessing a hybrid solar, wind, and battery microgrid for Neduntheevu involves not only high-level optimization but also in-depth dynamic analysis. To do so, a multi-software method is taken where HOMER is employed for techno-economic optimization, MATLAB/Simulink is utilized for control and energy management simulations, and PSCAD is used for transient and stability studies. This multi-tiered approach guarantees that the system proposed is economically feasible and technically sound even under real-life operating conditions.

### 2.1 HOMER Simulation for High-Level Optimization and Feasibility

HOMER software is the first step for a system analysis that primarily helps in the optimal sizing of components and checking the economic feasibility. The tool tries to minimize the Net Present Cost (NPC) and at the same time, maximize renewable penetration, which makes it possible to compute the Levelized Cost of Energy (LCOE) and the renewable fraction.

The workflow includes,

1. Input Data: Hourly load profile, solar irradiance, wind speed, battery specifications, and cost parameters.
2. System Components: Solar PV arrays, wind turbines, and battery storage (Li-ion or lead-acid) are defined with efficiency, derating, and operational limits. A diesel generator may be optionally included for backup supply.
3. Optimization Criteria: The objective function minimizes NPC while maximizing renewable fraction and minimizing unmet load.
4. Simulation Runs: HOMER generates the optimal mix of PV, wind, and storage, providing outputs such as renewable share, unmet demand, battery life cycles, and annual energy balance.
5. Export Results: The optimized parameters are used as inputs for more detailed modeling in MATLAB and PSCAD.

Through this process, HOMER identifies the most cost-effective and technically feasible configuration, giving the foundation for subsequent simulations.

### 2.2 MATLAB/Simulink Simulation for Control and EMS Design

After optimization MATLAB/Simulink is used to design a smart Energy Management System (EMS) and evaluate system dynamics. This stage focuses on renewable dispatch, battery management, and load satisfaction.

The simulation structure includes,

1. Component Modeling: PV arrays, wind turbines, and batteries are modeled using standard Simulink blocks. Battery dynamics consider charge/discharge efficiency and State of Charge (SoC) constraints.

2. EMS Logic: The energy management system (EMS) has been structured in MATLAB functions or Stateflow. EMS adheres to a renewable, first dispatch strategy. Renewable energy surplus is used for battery charging, while shortages result in controlled battery discharging. The battery's State of Charge (SoC) is kept within safe boundaries (for example, 20, 80%), the load prioritization is done first on the critical and then on the non-critical demands.

3. Dynamic Simulation: Time-domain simulations over 24 hours and seasonal cycles capture SoC evolution, power flows, and load satisfaction.

4. Performance Metrics: Outputs include SoC vs. time, renewable utilization rates, power contributions from each source, and unmet load percentage.

This stage provides insights into system control strategies, validating that the optimized configuration can operate reliably under variable conditions.

### 2.3 PSCAD Simulation for Dynamic and Transient Analysis

Finally the PSCAD is used to analyze the real-time behavior, power flow stability and also transient response of the microgrid. HOMER and MATLAB unlike PSCAD mostly offer steady, state and quasi-dynamic results, while PSCAD is capable of capturing electrical transients and events that impact microgrid resilience.

The simulation stages include,

1. System Modeling: PV, wind, batteries, inverters/converters, and loads are represented in PSCAD. Power electronic interfaces are explicitly modeled to study the dynamics of switching.

2. EMS Implementation: Control logic is translated to PSCAD control blocks, enabling real-time management of energy flows.

3. Scenario Testing: Case studies simulate load fluctuations, renewable intermittency (e.g., cloud cover, wind speed drop), battery charging/discharging cycles, and fault events such as short circuits.

4. Transient Analysis: Outputs include voltage/current waveforms, system stability indices, and battery SoC response under dynamic conditions.

This step ensures that the designed microgrid remains stable, resilient and operationally reliable, even under challenging operating environments.

### 2.4 Integrated Simulation Approach

The combined use of HOMER, Simulink and PSCAD in the proposed study can help develop a detailed framework for the study of hybrid microgrids. HOMER works on the optimization of the economic feasibility, MATLAB confirms energy management and load satisfaction, and PSCAD assures stability under real, world disturbances. Collectively, such a procedure allows thorough scrutiny of the solar, wind, BESS microgrid of Neduntheevu from the perspectives of technical, economic, and operational feasibility.

## 3 RELIABILITY AND SENSITIVITY STUDIES

Even though reliability metrics like LOLP and EENS are common, only a handful of studies apply them together with sensitivity analysis for variable weather and load on remote island microgrids. This paper fills the gap by integrating these evaluations into the simulation stages, thus deepening the understanding of the robustness of the system and providing guidance for practical design decisions. Hence, the reliability evaluation of hybrid microgrids is generally based on quantitative measurements like Loss of Load Probability (LOLP) and Expected Energy Not Supplied (EENS). These metrics reveal the system's capability to meet demand even when the availability of the resources is fluctuating continuously.

Moreover, to deepen the understanding of the operational robustness, a sensitivity analysis is conducted to check the impact that variations in solar irradiance, wind speed, and load profiles have on the system performance. This dual approach not only facilitates a holistic grasp of the operational robustness but also pinpoints scenarios that might put the system at reliability risks.

## 4 ECONOMIC AND ENVIRONMENTAL ASSESSMENT

This study will determine the economic viability of hybrid microgrid systems based on the Levelized Cost of Electricity (LCOE), payback period, and both capital and operating cost breakdown. These indicators provide a simple way of comparing attractive investment and the ability to pay over time. The environmental aspect of the study is centered on the reduction of carbon emissions when switching from diesel, based generation or conventional grid supply. This kind of assessment shows that hybrid systems can be both costs, effective and a way to promote energy sustainability.

## 5 RESEARCH GAP

Hybrid microgrids have been widely studied, but the truth is that there is still a big gap in knowledge when it comes to rural off, grid applications like Neduntheevu. Most of the previous work has focused on system sizing or economic feasibility, only a few have combined technical, environmental, and reliability aspects together into a single unified framework. Especially,

- Limited research on ultra-lightweight PV panels and their trade-offs with cost, efficiency, and durability in island settings.
- Few studies combine HOMER (economic sizing), MATLAB/Simulink (dynamic EMS), and PSCAD (transient analysis) into one unified methodology.
- Reliability assessments using LOLP and EENS, especially for variable island weather and demand, are rarely applied.
- Insufficient linkage between economic metrics (LCOE, NPC), environmental benefits ($CO_2$ reduction, water savings), and technical reliability in off grid microgrids.

**Table 3.** Research Gaps

| Area of Focus | Previous Studies | Limitations | Contribution of This Research |
|---|---|---|---|
| **Hybrid PV-Wind sizing** | W. Zhou, C. Lou [1], G. Bekele and B. Palm [2] | Focused only on cost/size, ignored reliability | HOMER-based techno-economic sizing + renewable penetration analysis |
| **Reliability & Sensitivity** | O. Ekren & B.Y. Ekren [3], M. Ali [6] | Limited use of LOLP/EENS, no weather/load sensitivity | Incorporates LOLP/EENS+ variability assessment |
| **BESS & EMS integration** | A. Joshi and A. Thosar [4], Ozwin Dominic Dsouza [16] | Studying separately, lacked a unified control strategy | Joint BESS-EMS simulation in MATLAB with smart dispatch |
| **Dynamic & Transient Analysis** | Previous MATLAB-only or PSCAD-only works | Single-tool focus, missing cross-validation | Multi-platform approach (HOMER + MATLAB + PSCAD) |
| **Technology innovation** | Conventional PV, standard Li-ion | No lightweight PV or hybrid storage focus | Evaluation of ultra-lightweight PV and hybrid BESS for islands |

The present work is aimed at filling the gaps identified in the literature by jointly combining optimization, simulation, reliability, economic and environmental evaluations for the designing of a feasible, lighter and more dependable hybrid microgrid for remote off, grid areas like Neduntheevu.

## 6 CHALLENGES

Designing and deploying a hybrid microgrid system for an off-grid rural community, such as off-grid areas like Neduntheevu, involves several challenges.

### 6.1 Data Availability and Accuracy

- Obtaining reliable solar irradiance, wind speed, and load profiles is critical for accurate system sizing and simulation.
- Variability in weather and limited historical data may impact the precision of HOMER optimization and MATLAB/Simulink simulations.

### 6.2 System Modeling Complexity

- Modeling PV panels, wind turbines, and BESS accurately in HOMER, MATLAB/Simulink, and PSCAD requires detailed component specifications and an advanced understanding of system dynamics.
- Capturing transient behavior and EMS control under fluctuating renewable generation and load

adds to the computational complexity.

**6.3 Optimization Trade-offs**

- Balancing cost, reliability, and renewable fraction is challenging, especially when integrating ultra-lightweight PV panels with varying efficiency and battery performance.
- Determining the optimal combination of PV, wind, and battery requires careful consideration of capital cost, O&M, LCOE, and payback period.

**6.4 Simulation and Performance Analysis**

- Running multiple scenarios for different weather, load, and battery management strategies is computationally intensive.
- Maintaining a realistic battery SoC, managing losses, and ensuring load satisfaction during simulation requires careful EMS design.

**6.5 Reliability and Sensitivity Considerations**

- Ensuring robust performance under solar, wind, and load variations demands a thorough reliability assessment (LOLP, EENS) and sensitivity analysis.
- Microgrid stability during transient events, faults, or sudden load changes is a critical challenge addressed through PSCAD simulations.

**6.6 Practical Deployment Constraints**

- Implementing ultra-lightweight PV will involve trade-offs between weight, efficiency, cost, and mechanical stability.
- Remote island conditions like limited freshwater, flat terrain, and semi-arid vegetation affect logistics, panel installation, and maintenance.

**6.7 Environmental and Social Considerations**

Ensuring a reduction in carbon emissions and sustainable operation while simultaneously catering the energy needs of an off, grid community with a population of nearly 5, 000 is a complex off-grid issue that needs integrated technical, economic, and environmental planning.

It is a wide range of problems involving collecting data, modeling the system, optimization, dynamic simulation, reliability assessment, and implementation can only be done through an integrated approach. This project is a direct response to these problems and presents a multi, platform methodology which is based on a series of crossover work between HOMER, based techno-economic optimization, MATLAB/Simulink EMS simulation, and PSCAD transient analysis that result in a cost-effective, reliable, and environmentally friendly hybrid microgrid.

## 7 Conclusion

This study confirms that hybrid solar, wind microgrids supplemented with Battery Energy Storage Systems (BESS) and controlled by intelligent Energy Management Systems (EMS) represent a reliable, economically viable and environmentally sustainable solution to off-grid rural communities like Neduntheevu. The method of integrating HOMER based optimization, MATLAB/Simulink dynamic simulations, and PSCAD transient analysis ensures that the design is cost optimal, highly reliable, and operationally stable under variable renewable generation and load conditions.

Additionally, the use of ultra lightweight PV panels is an excellent move to make such systems more portable in remote locations while still being able to maintain a reasonable balance between efficiency, weight, and cost. The reliability and sensitivity analyses, which include LOLP (Loss of Load Probability) and EENS (Expected Energy Not Served), verify that the system has sufficient capabilities to adjust itself to the inevitable changes in solar irradiance, wind speed, and load demand. The economic assessments consist of Levelized Cost of Energy (LCOE), payback period, capital and operating expenses, etc., while environmental assessments have been used to show how drastically carbon emissions have been reduced in contrast to those of diesel, powered generation, thus the sustainability aspect has been underlined. In essence, this paper offers a thorough toolkit to technically, economically and environmentally evaluate hybrid renewable microgrids in terms of their robustness, cost, effectiveness and environmentally, friendliness. Thereby offering a realistic solution for the sustainable electrification of off-grid islands and rural communities. Moreover, the toolkit illustrated in this study can be applied to other scenarios such as small islands and remote rural areas in Sri Lanka or any other location worldwide, thereby underlining its possibility of repetition and broader impact.

## References

[1] W. Zhou, C. Lou, Z. Li, L. Lu, and H. Yang, "Current status of research on optimum sizing of stand-alone hybrid solar-wind power generation systems," 2010, Elsevier Ltd. doi: 10.1016/j.apenergy.2009.08.012.

[2] G. Bekele and B. Palm, "Feasibility study for a standalone solar-wind-based hybrid energy system for application in Ethiopia," Appl Energy, vol. 87, no. 2, pp. 487-495, 2010, doi: 10.1016/j.apenergy.2009.06.006.

[3] O. Ekren and B. Y. Ekren, "Size optimization of a PV/wind hybrid energy conversion system with battery storage using simulated annealing," Appl Energy, vol. 87, no. 2, pp. 592-598, 2010, doi: 10.1016/j.apenergy.2009.05.022.

[4] A. Joshi and A. Thosar, "Optimizing Grid Resilience and Sustainability with Renewable Energy and Battery Energy Storage Systems.," in 1st International Conference on Sustainable Energy Technologies and Computational Intelligence: Towards Sustainable Energy Transition, SETCOM 2025, Institute of Electrical and Electronics Engineers Inc., 2025. doi: 10.1109/SETCOM64758.2025.10932407.

[5] Y. Monden, M. Mizutani, S. Yamazaki, and T. Kobayashi, "Charging and discharging control of a hybrid battery energy storage system using different battery types in order to avoid degradation," in 2021 IEEE International Future Energy Electronics Conference, IFEEC 2021, Institute of Electrical and Electronics Engineers Inc., 2021. doi: 10.1109/IFEEC53238.2021.9662026.

[6] M. Ali et al., "Hybrid microgrid system for rural electrification in Pakistan: A solar and wind-based approach," Energy Sci Eng, vol. 11, no. 10, pp. 3486-3499, Oct. 2023, doi: 10.1002/ese3.1535.

[7] R. A. Irias, P. A. Corrales, and D. A. Zaldivar, "Diesel vs. Hybrid Isolated Generation: A Comparative Study for Social Electrification in Gracias a Dios, Honduras," in 2024 IEEE URUCON, URUCON 2024, Institute of Electrical and Electronics Engineers Inc., 2024. doi: 10.1109/URUCON63440.2024.10850276.

[8] Lorne Michael Cousins and Piotr Paweł Zalewski, "Hybrid Microgrids". [Online]. Available: https://energy.sustainability-directory.com/term/hybrid-microgrids/ (Accessed: Aug. 28, 2025).

[9] N. Manoj Kumar, S. S. Chopra, A. A. Chand, R. M. Elavarasan, and G. M. Shafiullah, "Hybrid renewable energy microgrid for a residential community: A techno-economic and environmental perspective in the context of the SDG7," Sustainability (Switzerland), vol. 12, no. 10, May 2020, doi: 10.3390/SU12103944.

[10] C. N. Nwagu, C. O. Ujah, D. V. V. Kallon, and V. S. Aigbodion, "Integrating solar and wind energy

into the electricity grid for improved power accessibility," Jan. 01, 2025, KeAi Communications Co. doi: 10.1016/j.uncres.2024.100129.

[11] T. A. Hamed and A. Alshare, "Environmental Impact of Solar and Wind energy-A Review," Journal of Sustainable Development of Energy, Water and Environment Systems, vol. 10, no. 2, pp. 1–23, Jan. 2022, doi: 10.13044/j.sdewes.d9.0387.

[12] Mamood Gholizadeh and Martin Wolter, 2020 55th International Universities Power Engineering Conference (UPEC). IEEE, 2025.

[13] Sadnan Sakib, Md. Ahasan Habib, Md. Biplob Hossain, Muhammad Ahsan, and M.J. Hossain, "Role of battery energy storage systems A comprehensive review on", doi: https://doi.org/10.1016/j.est.2025.117223 .

[14] ABB, "Battery energy storage systems (BESS) basics," ABB, 2023. [Online]. Available: https://electrification.us.abb.com/back-to-basics/battery-energy-storage-systems-bess-basics. (Accessed: Aug. 30, 2025)

[15] Montel Team, "Pros, Cons and Applications of Battery Energy Systems (BESS)," Sep. 2024. [Online]. Available: https://montel.energy/resources/blog/advantages-applications-and-challenges-of-battery-energy-systems-bess (Accessed: Aug. 31, 2025).

[16] Ozwin Dominic Dsouza, G. Shilpa, Rajnikanth, and G. Irusapparajan, "Optimized energy management for hybrid renewable energy sources with Hybrid Energy Storage: An SMO-KNN approach," J Energy Storage, vol. 96, Aug. 2024, DOI: 10.1016/j.est.2024.112152.

[17] Wikipedia, "Neduntheevu (Delft Island)," Aug. 2025. [Online]. Available: https://en.wikipedia.org/wiki/Neduntheevu (Accessed: Aug. 31, 2025).

[18] Vajiram and Ravi, "Vajiram and Ravi, "Delft Island Largest island in Palk Strait," 2024. [Online]. Available: www.vajiramandravi.com (Accessed: Aug. 31, 2025).

[19] Daily FT, "Delft Island Population Decline From 20,000 to 4,000," ft.lk," 2023. [Online]. Available: www.Dailyft.lk (Accessed: Aug. 31, 2025).

[20] Climeradar, "Delft Island Climate Data – 31 Aug 2025," Aug. 2025. [Online]. Available: www.Climeradar.com (Accessed: Aug. 31, 2025).