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Low-Carbon Electrification of Remote Communities in Neduntheevu, Sri Lanka Using Solar-Wind-Battery Hybrid Microgrid: A Techno-Environmental Review and Design Synthesis

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Abstract**—***Remote islands like Neduntheevu face persistent reliance on diesel power due to grid extension infeasibility, creating economic, logistical, and environmental vulnerabilities. Assessing hybrid microgrids, we focus on small islands aiming for low-carbon power. With Neduntheevu as a benchmark - peaking at 250 kW at night, drawing 93,907 kWh yearly, the study looks at solar-wind-battery mixes, how they work together, and how energy is dispatched. It probably reduces battery size without raising loss risks much. The system relies on solid AC, DC, or hybrid power paths tested against real conditions like rust, rough transport, and weak structures. Power management decisions shape how long units run and stay stable. Simulations handle reliability checks instead of live testing. Long-term environmental damage is reviewed regularly. Battery size matches usage peaks tightly. EMS strategies, spanning rule-based, optimization, and AI-assisted frameworks, are evaluated for dynamic stability, predictive dispatch, and battery life extension. Techno-economic analysis, emphasizing Net Present Cost (NPC) and Levelized Cost of Energy (LCOE), is combined with a cradle-to-grave Life Cycle Assessment (LCA) that accounts for transport, installation, operation, and end-of-life battery impacts. Results indicate that solar-wind hybrid microgrids with robust EMS can substantially reduce diesel dependence, lower emissions, enhance supply reliability, and maintain cost-effectiveness in remote island contexts. This synthesis provides a design framework and research agenda for practical low-carbon electrification of isolated communities.*

Keywords**—** *Energy Management System: Energy security: Hybrid microgrid: PV wind complementarity: Remote island electrification*

I. INTRODUCTION

Off-grid islands need clean power. Small size and distance mean they rely on foreign fuel. That raises bills and climate risks. Thing is, local grids stay weak Costs go up fast. Energy security shrinks. Community growth stalls [1]. Diesel power systems in islands not only cause fuel dependence, which is one of the main economic and logistic vulnerabilities, but also produce public health and environmental problems. Diesel producers release air pollution that becomes dangerous to people's health and the environment when generating particulate matter and CO_2; this is one of the negative effects of continuous diesel use that makes the situation even more difficult for small communities [2]. Island has been investing in hybrid micro-grids, which are capable of combining complementary resources, mixing renewable with backup use of dispatch, that can be reliable and emit less pollutants. For instance, a microgrid comprising wind, tidal, and diesel energy sources is being analysed as a means of not only reducing diesel usage and emissions but also increasing renewable energy share as compared to the diesel-only supply [2]. Off-grid rural islands have the experience that electrification under the limited hours of operation of diesel-powered systems puts a cap on the electricity use and the resulting developmental outcomes of the communities whereas hybrid systems with renewable generation and storage can result in offering the whole day (including 24-hour service) and hence, increased number of households with appliances, and greater use of electricity for productive purposes yet affordability which is the capital intensity of such systems, remains the key constraint [3].

Neduntheevu (Delft Island), a geographically isolated island in the Palk Strait, provides a realistic case for assessing low-carbon off-grid electrification and the challenges of grid extension and fuel logistics. Recently, the island was described as the largest inhabited island in the region, with a considerable resident population (~4,800) and limited natural freshwater resources. Besides, it illustrates other key features that make centralized grid extension and supply through logistics-heavy fuel particularly difficult in remote islands [4],[5]. Moreover, the island's electricity demand pattern corroborates its suitability as an anchor for the study. It shows a night peak of approximately 250 kW and monthly electricity consumption ranging from 72,305 to 112,530 kWh [6]. The size of the demand is such that it requires microgrid planning focused on reliability, generation complementarity, and storage, dispatch, yet it is still typical for remote community systems rather than mainland grids.

This review distinguishes itself by combining typically disparate threads in a single integrated island ready synthesis. A multi-platform approach is implemented to ensure the seamless linkage of high level technoeconomic sizing (System Advisor Model) with EMS and dynamic validation (MATLAB/Simulink) then to transient/stability analysis where the result isn't only sizing. LOLP/EENS along with sensitivity analysis form the basis of design in a reliability first approach linking uncertainty from weather/load to supply adequacy while simultaneously identifying viable PV systems and aligning economic and environmental factors with low carbon criteria.

This project aims at investigating various aspects of the hybrid microgrid for the Neduntheevu system including design, location of different components, energy management and its role, reliability, environmental as well as financial parameters and modelling tools.

II. REVIEW METHODOLOGY

This review methodology ensures a transparent and reproducible evidence synthesis. It addresses five research questions: (i) optimal PV-wind-battery architectures for renewable fraction and island stability, (ii) EMS strategies to minimize battery degradation while maintaining reliability, (iii) application and limits of LOLP/EENS and unmet load metrics, (iv) sensitivity of LCOE/NPC to battery aging, payback, and backup assumptions, and (v) LCA boundary practices, including gaps in island logistics and cradle-to-grave considerations.

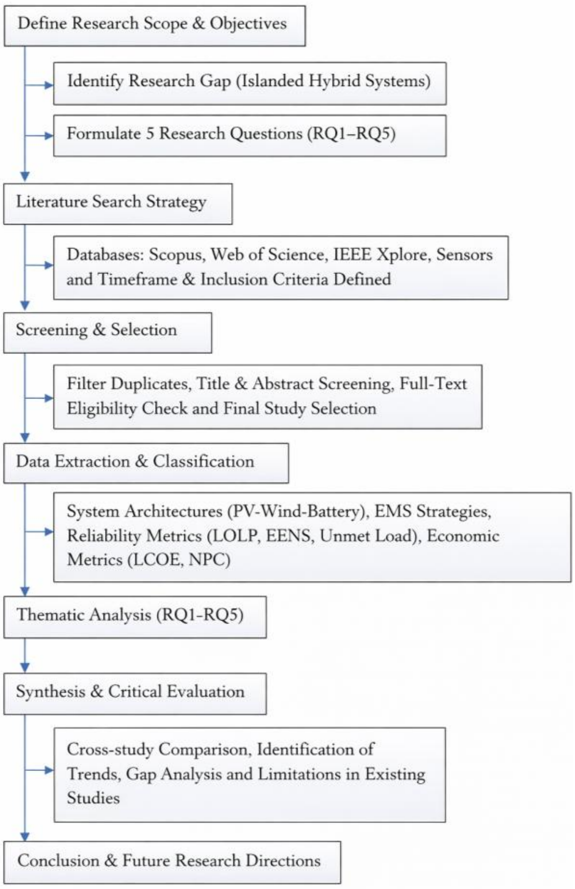

Fig. 1. Methodology of Review

III. ISLAND CONTEXT: DEMAND-RESOURCE-CONSTRAINTS

A. Island Electricity Consumption

According to the received data from the Ceylon Electricity Board (CEB) Jaffna area office, the consumption on Neduntheevu island, Sri Lanka, the night-time peak demand, is approximately 250 kW.

TABLE I. Island Electricity Consumption in 2025

Month No.	Electricity Consumption (kWh)	
	Month	**Value**
1	January	72305
2	February	73305
3	March	89509
4	April	99046
5	May	104525
6	June	90750
7	July	94380
8	August	94730
9	September	108930
10	October	112530
11	November	91560
12	December	95310

Referring above to Table I, one important assumption is that the island has an average annual energy demand of 93,906.67 kWh for the year 2025.

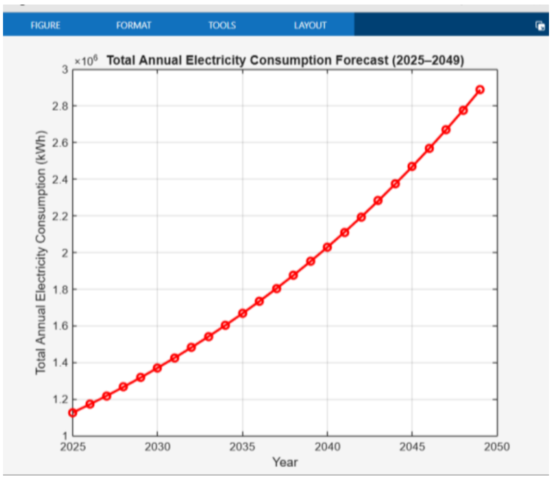

Fig. 2. Annual Electricity Consumption Forecast

As shown in Fig. 2, the annual electricity consumption forecast is calculated based on Sri Lanka's typical annual growth rate of approximately 4% [7].

B. Impact of Resource Complementarity on Microgrid Reliability

The diurnal opposition in natural resources, i.e., solar radiation during the daytime and wind at night, is one of the biggest advantages of hybrid microgrids in terms of reliability. For instance, in Neduntheevu, as shown in Fig. 3 below, the PV heat-map created with SAM using NASA Power data shows that there is strong solar power generation from 08:00 to 17:00, whereas the wind speed profile mentioned in Fig. 4 below, extracted from the SAM simulation using data from Climate.OneBuilding, shows higher and more stable wind values during the evening and night hours. Such natural offsetting of resource availability substantially lowers the risk of simultaneous low-generation periods, which is the main reason behind complementarity-driven reliability gains.

Large-scale work establishes that solar-wind pairings are seasonally and diurnally anticorrelated, with typically negative or close to zero levels of correlation at hourly time frames, implying that shortages in one resource are most of the time made up by the other [8]. Jurasz et al. reveal that combining the two sorts of resources drastically lessens the occurrence of resource droughts, as the chances of a one-day drought drop from 11.5% (solar) and 21.3% (wind) to 6.2% only when both are mixed [8]. This impact of smoothing is also pointed out in extensive reviews where wind solar complementariness is indicated to decrease ramping stress, increase the adequacy of supply, and facilitate the stability of the islanded system [9].

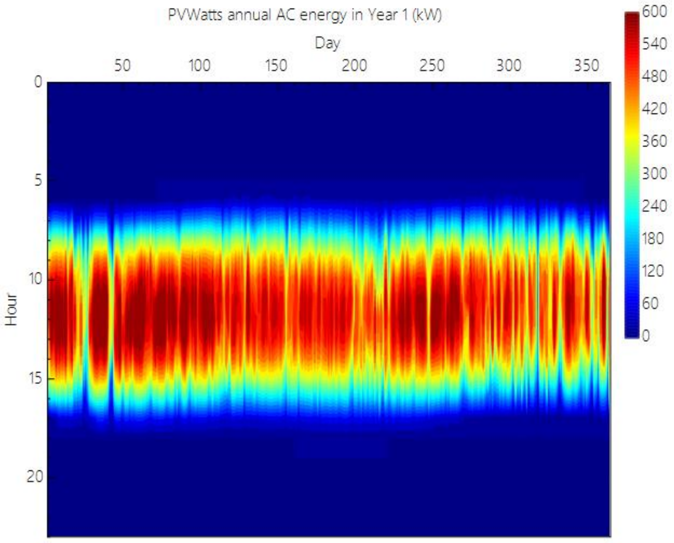

Fig. 3. Annual PV Heat Map of Neduntheevu

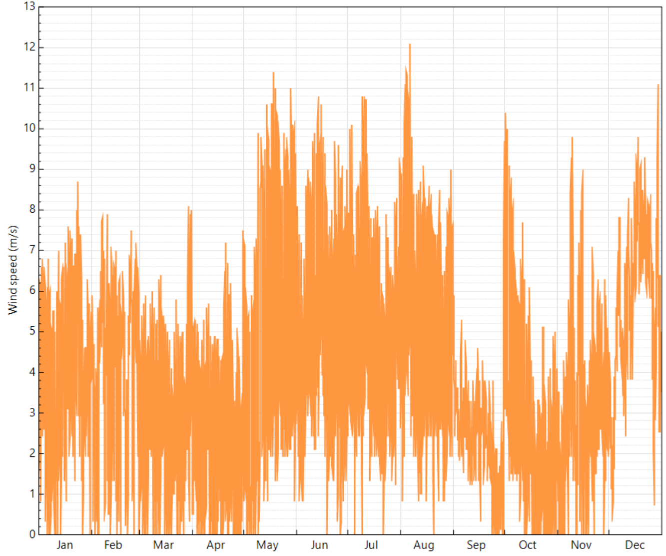

Fig. 4. Annual Wind Speed Plot of Neduntheevu

1) *Reduced Storage Oversizing*

Since solar output goes to zero at night and wind speed is frequently up to that time, the combined profile lowers the number and duration of battery discharge cycles. Research papers always demonstrate that by combining sources of energy, microgrids can reach higher levels of renewable energy with smaller batteries, as there will be fewer hours when power generation is below the minimum level [9]. This is also the case with your Neduntheevu source patterns, where the wind at night caves in about ~250 kW of the island's night peak, thus lessening the load/ stress on the BESS.

2) *Lower Unmet Load Probability (LOLP) and Expected Energy Not Served (EENS)*

Complementarity directly contributes to the reduction of the hours where both resources are failing together. Research shows that hybrid systems have much lower LOLP/EENS figures than corner PV or wind systems, even before storage is incorporated [9]. This is especially the case for remote islands, as they have to keep the reliability intact without a grid backup.

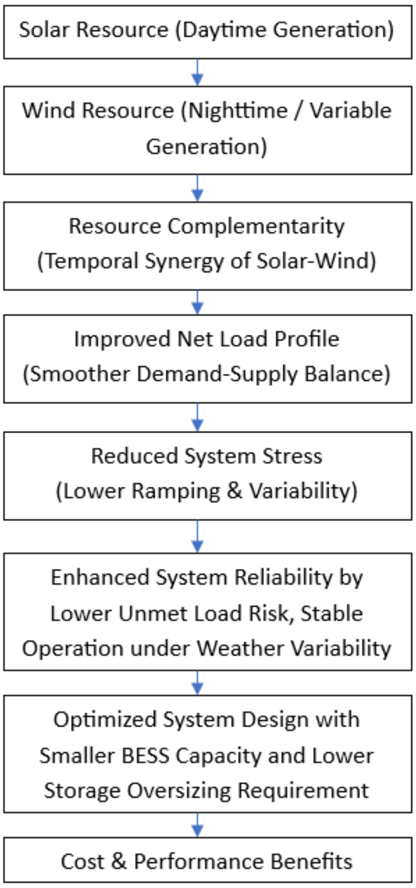

Fig. 5. Flow Diagram: Role of Solar-Wind Complementarity in Islanded Microgrid Design

3) *Deployment constraints*

The design and operation of a hybrid microgrid for Neduntheevu are strongly influenced by its strict physical and environmental constraints. Being a coral island at a very low level of elevation and only reachable by small boats, energy generation and storage equipment need to be carried out with shallow-draft vessels, which quite appropriately limits the size, weight, and packing of the equipment [5]. These limitations directly impact the choice of technology and the sizing of equipment thereby giving rise to the necessity of planning frameworks that incorporate physical viability explicitly just as it is noted that sizing problems determine the optimum amount of generation needed to meet load and the desired level of reliability and that Proper planning of ESS is essential for secure, reliable, and economic operation of islanded microgrids [10].

Operating maintenance can be challenging, especially if the work environment is very corrosive: the salt spray, the humid air, and the continuous exposure to the seaside all contribute to hastening the corrosion of not only the inverters but also the wiring and the structures of the mounts. The authors stress that hybrid microgrids in remote locations should not only adapt themselves to the environment and degradation factors but also to the increase in O&M costs, these factors should be considered even during the design phase if the objective is to achieve long-term sustainability as it is through the alignment of technology choices with local conditions and community capacity that the long-term sustainability of the project is made possible [11]. Other than the technical constraints, in a rural context the designer is concerned with structural feasibility indeed most buildings in island communities are light roofs as the rural HRES case studies mentioned where the selection of the technology was made in such a way as to not offend the beneficiary resources, culture, energy needs, social system, and especially beneficiary autonomy [11]. That is why considerations of roof loading limits, anchoring strength, and wind uplift risks should be part of the evaluation process before making any decisions about rooftop PV; ground mount systems need to be designed to withstand cyclone winds, saline soils, and land limitations, should a rooftop PV system be out of the question.

Finally, constraints for deployment should be incorporated into the microgrid's energy management system and planning. Stochastic EMS models focus on reducing power failures and the risk of operations in an unpredictable environment [12]. This concept applies to islands in particular, where replacing damaged goods takes time and is expensive. Overall, Neduntheevu's difficulties in transportation maintenance, exposure to salt, and the structural limitations of the building are not just minor problems; they are the main factors in the design that should determine the selection of the structures and facilities, as well as the strategies of operation and scheduling.

IV. TECHNOLOGY & ARCHITECTURE REVIEW

A. *Taxonomy of Hybrid Microgrid Architectures for Islanded Applications*

In the case of hybrid microgrids for remote sites, these can only function by: defining bus configurations; selecting how converters are linked and designing various levels of control. On island sites such as Neduntheevu the nature of supply interruptions and hardware failure means that these design decisions will define stability and the allocation and difficulty of energy distribution [15].

1) *AC-Coupled Hybrid Microgrids*

AC-coupled configurations are still the preferred ones for standalone systems since they are the most natural way to combine diesel generators, AC loads, and inverter-based renewables. In this arrangement, the PV and wind systems generate power via inverters and feed it to a common AC bus, whereas the BESS devices are linked through bidirectional AC/DC converters [14]. Voltage-source inverters (VSIs) serve as the grid-forming elements, which means that they provide frequency and voltage control when the system is isolated. This is in principle the same as the droop-based decentralized control, where each unit changes its frequency and voltage by measuring power locally without the need for communication links [14]. Such independence is crucial for remote islands where communication infrastructure is scarce.

TABLE II. AC-Coupled Hybrid Microgrid Characteristics [14].

Feature	**Hybrid Microgrid Characteristics**
	Description
Grid-forming units	BESS or diesel VSIs
RES interfacing	PV/wind via individual inverters
Strengths	Mature protection, simple integration, robust droop control
Limitations	Multiple conversion stages, lower efficiency for DC loads

2) *DC-Coupled Hybrid Microgrids*

DC coupling of photovoltaic cells, battery banks and DC loads onto a single DC bus allows lower power losses and enables simple maximum power point tracking [15]. In such a configuration, the wind turbines and AC loads are integrated via the inverters. The arrangement is well suited for grid disconnected power generation with high sunlight and high DC load demand e.g. In data centers and smart lighting applications, although DC fault protection is problematic.

TABLE III. DC-Coupled Hybrid Microgrid Characteristics[15]

Feature	**Hybrid Microgrid Characteristics**
	Description
Grid-forming units	DC-DC converters + AC inverter
RES interfacing	PV directly, wind via AC/DC stage
Strengths	High efficiency, fewer conversion steps
Limitations	Immature DC protection, complex stability management

3) *Hybrid AC-DC Microgrids*

Hybrid AC-DC system consists of both buses using two-way converters to allow flexibility in the direction of energy flow and dispatch optimization [13]. This type of system can cater to both constant and peak loads by employing a combination of solar, wind, and battery systems. Currently, it is a good solution for off-grid village applications, where there is fast-changing demand for energy. Smooth switching droop control allows renewable and battery sources to transition from grid-forming to grid-following modes automatically [13]. System response stays solid during sudden weather changes.

TABLE IV. Hybrid AC-DC Microgrid Characteristics [13]

Feature	**Hybrid Microgrid Characteristics**
	Description
Grid-forming units	ESS or RES via SSDC-enabled VSIs
RES interfacing	PV on DC bus; wind on AC bus
Strengths	High flexibility, reduced losses, supports mixed loads.
Limitations	Higher design complexity requires advanced EMS.

4) *Control Hierarchy and Architecture Integration*

Architecture is linked with the control hierarchy. Modern isolated micro-grids rely on a three level control structure of primary droop, secondary restoration and tertiary dispatch, which follow a large grid practice, in the converter dominated systems [14]. Primary droop function controls the power sharing only. Secondary level operations ensure the frequency and voltage to regain. Tertiary level selects the optimum dispatch of resources.

Wu et al has shown that co-ordination between RE and EE operations in SSDC mode, utilizing FBS, may switch operation in decentralized manner without any communication links which enhances resilient operation in islanded mode [13]. Shezan et al also confirms that in hybrid micro grid system, frequency deviation, voltage fluctuation and unpredictable behavior of solar-wind source can be dealt by a secure control strategy [15].

5) Architecture Selection for Islanded Communities

Hybrid AC-DC setups serve remote spots like Neduntheevu well. They manage shifting demands and reduce wasted power. Renewables link smoothly to storage when conditions go wild. Local droop settings help systems react fast. SSDC boosts stability during storms or strain. It tends to work better under real-world stress. Probably not flawless every time, but fits where it's needed [13]-[15].

B. Solar PV

Factors that determine the choice of the best solar PV technologies for islanded microgrids include efficiency, material durability, cost, and the ability to work well with hybrid energy management strategies. Latest improvements in PV materials like highly efficient crystalline silicon, perovskites, and bifacial modules have allowed higher performance even when exposed to variable sun conditions, which is very important for self-sufficient microgrid operation [16]. Crystalline silicon is still considered the most dependable choice for the reasons of its being mature, having a long lifespan, and its behavior being quite predictable in decentralized control environments [17]. New technologies such as perovskite and organic PV offer high power-to-weight ratios and are more flexible in terms of deployment, but their instability issues that limit their suitability for long-term islanded applications still need to be addressed [18]. So, technology choice should be a trade-off of efficiency, durability, and the ability to be integrated with storage and control architectures such as SSDC-based coordinated microgrid control [18].

C. Wind Subsystem

Processing wind data shapes island energy plans. Without real-time inputs, decisions stall. Turbines and landforms alter how much power flows. Winds shift suddenly, sometimes within minutes, and differ over short ranges. Forecasting fails without strong records. ERA5, MERRA2, and local models help fill gaps where sensors fall short. In remote spots, reliable data remains absent. Accuracy drops if you ignore site differences. Proper placement matters more than theory alone. However, even then, one has to take into account local terrain effects, roughness, and micro-siting to prevent underperformance. Besides that, SWT brings about a few challenges related to power curve uncertainty, certification, and manufacturers' limited availability, all of which have an impact on the long-term reliability and cost-effectiveness of the wind turbines [20].

TABLE V. Comparison of Solar PV Technologies for Islanded Microgrids [16]-[18]

PV Technology	**For Islanded Microgrids**		
	Key Advantages	**Limitations**	**Suitability**
Monocrystalline Silicon	High efficiency, long lifespan, stable performance	Higher cost than poly-Si	Highly suitable, reliable under decentralized control, and variable loads
Polycrystalline Silicon	Lower cost, mature technology	Lower efficiency, larger temperature losses	Moderately suitable, good for cost-sensitive microgrids
Perovskite Solar Cells	Very high efficiency potential, low manufacturing cost	Stability issues (moisture, heat), degradation	Limited suitability promising but not yet robust for islanded systems
Organic PV (OPV)	Lightweight, flexible, easy integration	Low efficiency, short lifespan	Low suitability best for portable or auxiliary applications
Bifacial PV Modules	Higher energy yield using reflected light	Requires optimized installation surfaces	Highly suitable increases the generation in limited land areas

Moreover, proper siting, i.e., making sure that the hub height is adequate, the turbulence is minimal, and the wind turbine is a sufficient distance away from any obstacles, plays a major role in achieving the expected energy yields. Wind systems, when part of hybrid microgrids, need to be compatible with different control strategies such as droop control, synchronization, or isochronous operation so that the system can be in a stable state even if the wind is variable [21]. In conclusion, to deploy successfully, a combination of accurate resource assessment, certified turbine selection, and robust control integration is required. Constantly changing wind conditions can only be handled by a control system if these three components are in place. Otherwise, the control strategies would only be theoretically optimal and not practically feasible.

D. Battery Energy Storage Systems (BESS)

BESS are key players in stabilizing island microgrids as they help to soak up the fluctuations of renewables, enhance power quality, and provide the system with more flexibility. Among different battery types, lithium-ion batteries remain the leading one because of their high energy density, quick response, and long cycle life. Besides that, lead-acid, Ni-Cd, Ni-MH, and supercapacitors are also being used in some specific applications based on the requirements of cost, safety, and power density [21].

Battery chemistries,

- Li-ion: high round-trip efficiency (90-95%), strong cycling capability, sensitive to temperature.
- Lead-acid: low cost, lower efficiency (70-85%), limited cycle life at high DOD.
- Ni-Cd / Ni-MH: robust thermal tolerance, moderate efficiency, environmental concerns (Ni-Cd).
- Supercapacitors: extremely high power density, excellent for fast transients, but low energy density.

And extreme heat or cold can drop Li-ion power by half, down to 50% at 40 °C or 80 °C. Thermal control keeps batteries safe and stable during wide swings in climate. Active cooling or heating helps stop damage from temperature stress. Without it, battery life falls fast. Li-ion still wins on frequency support and smoothing for microgrids. Dispatch planning relies heavily on this behavior.

Lifetime also largely relies on choice of the SOC window and cycling regime. By keeping within a mid-range SOC (20-80%) degradation rates were significantly attenuated by reduced stress on electrode and limited SEI layer growth. Rapid capacity fade and increase in internal resistance was seen in deep cycling (high DOD), high Crates, and the volatile nature of cycling in renewable-rich microgrids. Experiments show that operation at high SOC or high temperature led to a rapid mechanical and chemical degradation, but good dispatch control and intelligent BMS algorithms are key in extending useful lifetime by controlling charge/discharge currents and maintaining the battery within allowable SOC range [21].

V. EMS, RELIABILITY, AND STABILITY

In a microgrid, the Energy Management System (EMS) is the key element that ensures the microgrid is operating in an economically efficient way, is reliable, and remains dynamically stable even when the grid is connected or when it is in island mode. Current EMS architectures have transformed from simple rule-based dispatch to complex optimization and AI-driven frameworks, which differ in their ability to handle computational workload, adaptability, and reliability. Rule-based EMS strategies generally follow a renewable generation first logic, then charging the battery when there is a surplus, and discharging when there is a deficit. Although these methods are simple and robust, they are not effective under high renewable variability as they do not have predictive capability and cannot guarantee optimality under uncertainty [25].

Optimization-based EMS frameworks address this limitation by formulating multi-objective problems, minimizing operational cost, reducing emissions, and improving reliability using methods such as MILP, nonlinear programming, or hybrid metaheuristics. These techniques provide near-optimal scheduling but may face scalability issues in large microgrids with many distributed resources [26],[27]. Fig.6 shows the types of forecasting techniques available in the EMS of a microgrid.

Forecasting-driven EMS, especially MPC, improves reliability through the use of short-term load and renewable power forecasts allowing the decision-making to be made with an appropriate rolling horizon, which accommodates for real time deviations [28]. Artificial intelligence/machine learning-based EMS, using for example, ANN forecasting, fuzzy logic control and reinforcement learning, are able to offer effective performances in stochastic conditions, however, these algorithms are all reliant upon available data sets, have inherent explainability problems and make it difficult to prove the stability necessary in safety critical micro grid operations. [29], [30].

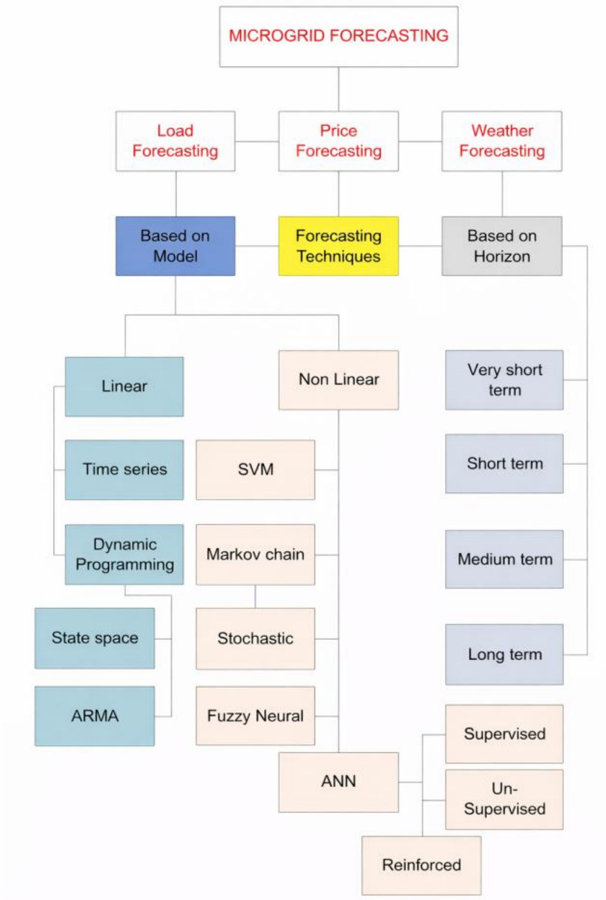

Fig. 6. Forecasting techniques in EMS [26]

Reliability assessment is a fundamental part of figuring out the performance of an energy management system (EMS), particularly in off-grid or weak-grid communities where the consequences of supply interruptions can be quite severe. Fundamental reliability metrics are the Loss of Load Probability (LOLP), which is a measure of how likely it is that the available generation will not be sufficient to meet the demand; the Expected Energy Not Supplied (EENS), which is a measure of how much load is unmet; and Unmet Load Hours (ULH), which are a measure of the time supply shortfalls last. These metrics are instrumental in deciding if a microgrid is fulfilling the reliability requirements one would expect in rural electrification or remote communities, where the value of LOLP has to be close to zero to guarantee uninterrupted service for critical loads [31]. Methods of EMS that take into account reliability limits like keeping minimum state-of-charge levels or giving priority to critical loads are well above the performance of only cost-based approaches, particularly in the case of renewable energy variability. Fig. 7 shows the problems encountered in MGs that are solved using an EMS.

Uncertainty and sensitivity analyses strengthen EMS resilience by testing system performance under extreme or limiting conditions. Variations in renewable output, rising energy demand, and component aging especially battery deterioration can significantly alter dispatch patterns and long-term reliability. Stress tests, such as multi-day no-wind periods, prolonged cloudy days, or reduced battery capacity, ensure the microgrid can supply power even in worst-case scenarios [32]. Besides, these kinds of analyses point out how important hybrid storage, flexible loads, and adaptive EMS algorithms are that are able to react to rapidly changing operating conditions [32].

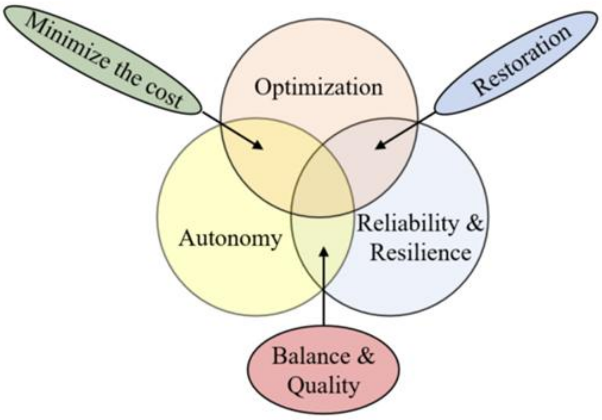

Fig. 7. Types of problems solved by the EMS [30]

In addition to steady state reliability, the transient and dynamic stability aspects are of importance in inverter dominated microgrids. The large numbers of power-electronic interfaces can give rise to unusual fluctuations in voltage/frequency, low inertia and lack of synchronism [33]. Power quality, fault tolerance and ride through capability are functions of EMS decisions such as storage dispatch, diesel generation schedule and inverter droop control [33]. Hence, protection, fault detection and ride through should be coordinated with the EMS planning to guarantee overall stability.

EMS operation heavily relies on forecasting, and load prediction is a major forecasting task that is usually accomplished by ARMA, machine learning, or ANN models, while renewable forecasting is mainly done by weather-based, persistence, or hybrid methods. Correct forecasting can greatly lessen the inconvenience caused by the unknown factors, thus making the production cheaper and more reliable [34]. Besides control, the EMS control strategies also include centralized, decentralized, and distributed frameworks, which can strike a balance between global optimality, scalability, and resilience [25],[27]. These systems are essentially responsible for economic dispatch, unit commitment, storage scheduling, and demand response.

VI. TECHNO-ECONOMIC ASSESSMENT & OPTIMIZATION TOOLS

The techno-economic evaluation of hybrid renewable energy systems depends on a few key economic indicators that measure long-term financial sustainability and, at the same time, reflect the operational characteristics. Among all the studies analyzed, the Net Present Cost (NPC) is the metric most commonly used. It is the present value of all capital replacement operations and maintenance, and fuel costs over the system's lifetime, less salvage value. NPC is a very handy metric because it allows direct comparison of different system configurations [31]. The Levelized Cost of Energy (LCOE) is another economic indicator that is normally considered. It basically measures the average total system cost per unit of energy delivered and makes it possible to compare very different technologies, even when renewable resources are available only seasonally [32]. The indicators related to system operation, such as renewable fraction, capacity deficit, surplus generation and curtailment provide complementary information to solely economic ones to characterize the reliability of the system and the usage of the resources [33]. Several papers point out that it is very important to identify the system boundaries very clearly, especially if the systems include the fuel logistics, transport costs, or grid-extension options, since these assumptions have a great impact on the comparative economics of off-grid versus grid-connected systems [34]. Sensitivity analysis is equally emphasized as necessary, as changes in fuel prices, solar wind interannual variability, and battery replacement cycles may greatly affect NPC and LCOE results [35].

The net present cost (NPC) represents the total cost to the system of the installation including repairs and subtracting the residual value. The LCOE can represent the mean energy cost which facilitates comparison of solar-wind power without considering the time dependence of weather. The amount of a low renewable fraction means some of the power isn't used, while a high value for curtailment means output is being lost. It is difficult to forecast hidden costs such as the expense of reinforcing the grid, slow delivery of fuel and transmission, which increase final prices significantly [35].

Techno-economic studies emphasize reporting key assumptions such as discount rate, inflation, component lifetime, replacement schedules, and fuel escalation to enable proper interpretation and comparison [31], [34]. To ensure a proper global comparison, currencies should be normalized. If applicable, it is also necessary to mention the methods of load-profile construction, the sources of resource data and the rationale behind the dispatch algorithm choice when discussing a hybrid microgrid, since these all have a large impact on the results of NPC and LCOE. Lastly, to make sure a dynamic EMS, an economic optimization tool or a transient-stability simulator are used in a correct domain, its features must be matched with the purpose of a given study [33],[35].

VII. ENVIRONMENTAL ASSESSMENT

Environmental impact of microgrid is significantly driven by lifecycle impacts of solar PV, wind turbines and batteries. Cradle-to-grave LCA boundary is required because the cradle-to-gate studies tend to underestimate the impacts as end-of-life, transport and batteries disposal have been excluded from most. Multiple microgrid LCAs use cradle-to-gate boundary excluding the operation processes, replacement cycles and waste, causing confusing and inaccurate result on microgrid sustainability [36]. It is possible to see that the batteries have caused 74% of the impacts to human health and 78% of impacts to ecosystem for the PV-driven microgrid in Mahmud et al results with consideration of all lifecycle flows [37]. Also, Wang et al show that the microgrid is only better than the diesel and the grid extension case when the whole cradle-to-grave cycle (including the transport of components to the remote islands and battery replacement for 20 years) is considered [36].

The LCA boundary for microgrids needs to span from raw materials acquisition through to end-of-life recycling including manufacturing, transportation, installation, operation and maintenance stages. The treatment of end-of-life components, especially batteries (release hazardous materials if both lead acid and lithium-ion are used) and PV panels (contain harmful chemicals such as cadmium and arsenic), present recycling challenges [38] and also end-of-life treatment difficulties. Incorporating end-of-life impacts for second life EVs avoids the upstream impact of the creation of a new battery, however it introduces a degree of uncertainty into terms of the capacity, internal resistance and long term degradation, and eventual waste. From an environmental perspective, solar-wind hybrid systems reduce reliance on fossil fuels, lowering greenhouse gas emissions and enhancing local air quality, as summarized in Table VI [38].

TABLE VI. Comparison of greenhouse gas emissions for different energy generation systems [38]

Energy System	Comparison of greenhouse gas emissions
	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

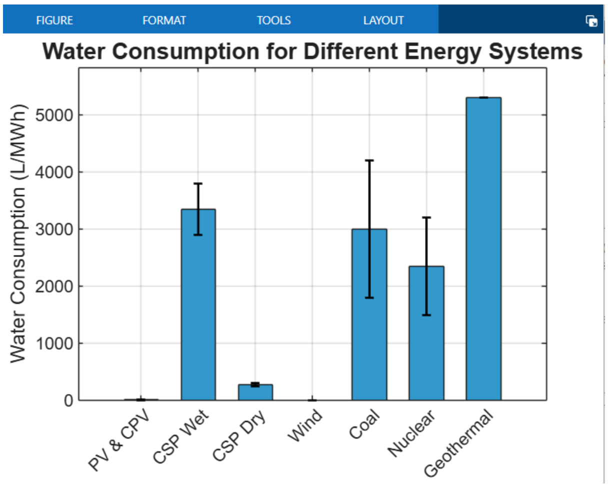

Fig. 8. Water consumption across major power-generation technologies [38]

LCAs of microgrids normally focus on GWP, water use, particulate emissions, ecotoxicity, and resource depletion. GHG emissions are mainly from batteries and their effects are significantly lowered compared to diesel if the electricity is provided by solar and wind [37]. Diesel-only systems show 4-8 times higher GWP, and PV/ wind microgrids consume far less water, offering advantages in arid regions [36],[38]. Renewable-based microgrids also cut local pollutants, eliminating NO_x, SO_2, particulate matter, and CO_2 emissions, improving air quality and reducing health burdens in remote communities [36],[40] [41]. Fig. 8 shows water-use intensity across power-generation technologies.

TABLE VII. Key Environmental Indicators for Microgrid LCA [36]-[40]

Indicator	Indicators for Microgrid LCA
	Findings from Literature
Global Warming Potential (GWP)	Diesel systems emit 4.3–7.8× more GWP than renewable microgrids.
Battery Environmental Burden	Batteries contribute 74% of human-health impacts and 78% of ecosystem damage.
Water Consumption	PV ≈ 0.02 m^3/MWh; CSP up to 3 m^3/MWh.
GHG Composition	CO_2 (48%), CH_4 (37%), and N_2O (48%) from the battery life cycle.
Emission Reduction vs Diesel	Hybrid microgrids reduce CO_2 emissions by ~68%.
Circularity Benefit	Second-life batteries reduce cumulative energy demand by up to 70%.

Compared to brand-new cells, the second-life EV battery would decrease consumption up to 70% than new lithium ion battery [39]. However, there are questions about the prior usage, internal resistance, recycle etc. In case of PV, to recycle toxic components such as cadmium, lead etc. is still a limited part and those metals would need to be recovered in a safe manner [36]. Island and coastal grids also risk marine disruption from cables and shipping. Including these factors in the LCA ensures sustainability reflects real local conditions.

VIII. Cross-Study Synthesis with Neduntheevu’s Design Implications

Load profiles, evening peak demand, ramp increase and annual cycles are simulated by the model. Solar and wind data for one year provides a description of the extent of variability. In AC vs DC coupling, choice is based on the most appropriate configuration according to efficiency and flexibility. Sizing the system means finding appropriate sizes for photovoltaic and battery and back-up power so that objectives for reliability and minimum levelized cost of electricity (LCOE) are met. EMS performs daily scheduling operations and dynamic controls to minimize amounts of energy waste, fuel waste and machine idleness. The stress test helps system robustness assessment when peak loads occurs. Cost benefit analysis of reliability is one way to reconcile performance and environmental issues. Boundaries must be drawn up to evaluate the impact of energy unit for emissions, and recycling/waste of components.

Clear evening and night peaks and low daytime industrial loads were identified for Neduntheevu, so storage would be required to provide continuity. There are clearly periods during the night where PV cannot supply loads. Appropriately sized batteries shift excess midday power to the evening and morning peak, reduce needed standby capacity and provide fast response to cloud transients or generator trips. For new builds with substantial marine cabling losses, DC coupled PV-battery systems are appropriate. AC coupling is more suitable for retrofits. To provide supply without high emissions or high LCOE, optimization must consider logistically dependent issues such as refueling times and capacities of ships, weather-dependent access, and limits on crew transfers..

Research Gaps

Island Microgrid studies usually focus on only LCOE, Reliability or LCA, lacking integrated assessment. A unified reporting format, which lists LCOE with uncertainties, reliability (LOLP, LOLE, EENS) and LCA indices within the same system boundaries and scenario, is desired. Dynamic and transient stability, involving fault conditions, motor start up and generator tripping, is seldom considered although it is critical during islanded operation. Finally, logistics challenges including fuel delivery, spares and crew access is typically examined in a qualitative manner. A systematic and integrated logistics-aware design and operational framework, where delivery schedules, storage capacity and weather window are hard constraints, is highly recommended.

IX. CONCLUSION

This review synthesizes technical, economic, and environmental insights on hybrid microgrid deployment for off-grid island communities, with Neduntheevu serving as a representative case study. Hybrid systems mixing solar PV, wind, and batteries work better together less overbuilt storage, lower LOLP, smaller EENS. Solar and wind naturally oppose each other in Neduntheevu. This cuts down on energy gaps even through seasons. Probably not always perfect, but it keeps the grid running steady at night or during dry months. AC-DC microgrids with smart EMS tools, forecast-based or AI-powered - handle swings smoothly. Real-time adjustments help manage battery life and state of charge under changing weather. The rate of penetration for renewables more or less impacts the reliability over time. Appropriate control systems and correctly dimensioning the storage are perceived as the most critical points. Techno-economic results indicate that hybrid (hybrid micro-grid) can offer lower NPC and LCOE with respect to the case fueled only by diesel, assuming that correct hypotheses are made about fuel supply, replacement of the components and constraints due to the island's particular context. Environmental evaluation reveals a reduction of CO2 emissions (-68%), of water usage and local pollutants; although battery lifecycle impacts prevail, highlighting benefits from second-life battery applications to improve circularity.

In conclusion, When designed with a focus on reliability, an integrated EMS, and deployment strategies that work for the situation, low-carbon hybrid microgrids can provide sustainable, cost-effective, and resilient electrification for remote islands. The results offer a transferable framework for analogous off-grid communities encountering logistical, environmental, and economic challenges, while underscoring the necessity of explicitly integrating lifecycle and operational factors to achieve authentic sustainability.

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