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Atiqul Islam *

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Design and Performance Evaluation of a Low-Cost Solar Microgrid for Rural Electrification in Bangladesh

Atiqul Islam

Daffodil University, Bangladesh; atiqul.islam@azclstudy.com

Abstract

Rural Bangladesh still contains hard-to-reach islands, chars and riverine communities where grid extension is expensive and vulnerable to storms and flooding. This paper presents the design and performance evaluation of a cost-constrained, PV-battery-diesel hybrid microgrid sized for about 1,000 connections in a coastal char context. The design is grounded in Bangladesh's measured solar resource (Global Solar Atlas) and policy/market conditions (IDCOL financing, tariffs, net-metering guidelines). Using current component cost benchmarks (IRENA, BloombergNEF) and fuel price data, we model levelized cost of electricity (LCOE), energy delivery and backup performance over a 20-year horizon. The reference plant is a 330 kWp PV array, 1.2 MWh $LiFePO_4$ storage, and a 150 kVA diesel genset feeding a three-phase low-voltage distribution network. Unsubsidized LCOE is estimated at 0.41 USD/kWh; with a representative IDCOL-style capital grant the effective LCOE falls to 0.27 USD/kWh, broadly consistent with reported mini-grid tariffs of about BDT 30-32 per kWh. The system delivers about 442 MWh/year with an 8–12% diesel share under conservative assumptions, and maintains service during multi-day low-irradiance events via battery plus right-sized genset. Sensitivity analysis shows the LCOE is most affected by distribution network CAPEX, battery replacement pricing, and demand realization. We discuss implementation risks, grid-arrival strategies, and productive-use enablement. The results indicate that, in Bangladesh's remaining off-grid pockets, carefully engineered PV-battery microgrids can meet 24/7 demand at a cost in line with observed tariffs, while cutting local air pollution and diesel exposure. Key data are provided to support replication and peer review.

Keywords: Bangladesh; rural electrification; solar microgrid; LCOE; $LiFePO_4$ storage; IDCOL; distribution network; diesel backup

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1. Introduction

Bangladesh has expanded electricity access at world-leading speed; official datasets put access at ~99-100% by 2023, though pockets of households and enterprises at the grid edge still experience unreliable or prohibitively costly service where the central grid is physically absent or chronically weak (Macrotrends, 2024). These last-mile areas are precisely where islanded microgrids can be the least-cost and most resilient solution, particularly in chars, coastal areas, and river islands that face difficult terrain, salinity, and frequent storm damage. The expansion of mini-grids in these areas, particularly through the use of renewable energy sources, offers a sustainable solution to long-standing electricity access challenges in rural Bangladesh (Aziz and Chowdhury, 2021). Recent studies and pilot projects have demonstrated the feasibility of using solar microgrids to provide reliable and cost-effective power, contributing to improving local livelihoods and stimulating economic activities (Tamasiga et al., 2024). Additionally, these systems align with Bangladesh's ambitious climate and energy goals, providing an alternative to grid-based electrification in hard-to-reach regions (Chowdhury et al., 2025).

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Bangladesh already has an institutional pathway for such systems through the Infrastructure Development Company Limited (IDCOL) mini-grid program, which has supported a portfolio of 100–280 kWp PV-diesel hybrids and developed technical standards, financing, and tariff approaches. By IDCOL's own accounting, 26 solar mini-grids totaling about 5 MW serve ~16,000 beneficiaries, illustrating a working model but also revealing cost pressures that keep tariffs relatively high (Hossain and Karim, 2019).

This paper targets a real-world question: with 2024–2025 component prices and fuel costs, what is the achievable LCOE for a robust but low-cost PV-battery microgrid in rural Bangladesh? We combine up-to-date global cost learning (IRENA), battery price surveys (BloombergNEF), and Bangladesh-specific solar resource, policy and tariff information to design and cost a replicable reference plant sized for ~1,000 connections, then we evaluate technical performance and economics over a 20-year horizon.

2. Context and Policy Background

Rural access and remaining gaps. Bangladesh's access to electricity has climbed to ~99–99.5% by 2023, yet "universal access" at the national level masks pockets where grid extension is infeasible or unreliable in practice (Kabir et al., 2023). These pockets are typically in chars and coastal unions where geography and disaster risk make stringing lines costly and fragile. In many rural regions, land settlement patterns make it expensive and technically challenging to extend power lines due to the sparse population and difficult terrain. Microgrids are seen as a solution for such areas, offering a scalable and more resilient alternative to the traditional grid (Berino Francisco Silinto et al., 2024). By providing decentralized power, these systems can cater to both the growing demand for reliable household energy and the needs of small businesses, improving livelihoods and fostering local economic development. The government has recognized these issues and aims to use microgrids not only to improve electrification but also to meet climate goals by reducing reliance on fossil fuels (Shahzad et al., 2023).

IDCOL's mini-grid program. IDCOL (Infrastructure Development Company Limited) has financed two dozen-plus solar mini-grids in the 100–280 kWp range, providing concessional debt and grants, and maintaining a technical standards process for compliant equipment, EPC (Engineering, Procurement, and Construction) practices, and quality assurance (QA). These initiatives have allowed the development of mini-grids that meet both energy demand and grid-connected future integration (Suryani and Dolle, 2020). IDCOL's financing terms are structured to reduce the financial burden on private investors and operators by providing low-interest debt and capital grants. The most recent data reveals that these mini-grids are serving over 16,000 beneficiaries, highlighting the program's success and its scalability. Despite the progress, the high upfront capital cost remains a challenge. The tariffs set by IDCOL, typically around BDT 30–32 per kWh, reflect the high costs of installation and maintenance, along with the necessary backup fuel provisions.

Tariffs. News and industry reporting around 2020–2021 documented proposed or applied mini-grid tariffs in the range of BDT 30–32 per kWh, reflecting small scale, distribution costs, and backup fuel (Come Zebra et al., 2021). These levels are materially higher than bulk grid energy in Bangladesh but can be cost-reflective for islanded systems. Although tariffs for mini-grids are generally higher than the national grid, they are designed to cover the unique costs associated with isolated systems that need to be self-sustaining (Herbert and Phimister, 2019). This includes costs for power generation, storage, operation, and the maintenance of infrastructure, along with fuel costs when diesel backup is required. Furthermore, while mini-grids may not be as cost-efficient as national grid extensions in terms of per-kWh costs, they can provide substantial savings in terms of infrastructure development. This cost gap is a crucial factor in making mini-grids an attractive option in rural areas where grid extension is not financially viable.

Net metering and grid-arrival. Net metering guidelines were issued in 2018 in Bangladesh as well as amended recently in 2019 to enable wider participation. Net-metering mostly affects bulk grid rooftop PV but also guides microgrid export/settlement. This allows microgrids to join the national grid, eliminating investment loss. Net metering balances demand and supply more sustainably and efficiently, allowing off-grid systems link to the grid. Operators and users can export conserved energy to the grid as demand stabilises or a microgrid overproduces. Mini-grid viability and integration into Bangladesh's energy infrastructure depend on new net metering legislation (Hasan, 2022).

3. Solar Resource and Demand Characterization

Bangladesh's long-term PV output (PVOUT) and Global Horizontal Irradiance (GHI) maps from Global Solar Atlas/ESMAP and Solargis are 250 m to 1 km. We use a mid-range PV output of 1,450 kWh/kWp/yr for coastal char locations in Bangladesh, which aligns with atlas data and national summaries indicating an average GHI of ~4.2–4.5 kWh/m²/day. This solar potential is valuable in Bangladesh's shift to clean energy and provides a firm foundation for renewable energy generation in off-grid areas. Solar PV deployment is predicted to increase as technology improves and costs fall. On average, coastal PV systems produce steady yields suitable for small-scale generation, although local factors like shade, direction, and temperature affect output (Bamisile et al., 2024).

Load archetypes. Mini-grids in Bangladesh typically serve 400–1,000 customers with annual energy in the 300–400 MWh range at the 100–250 kWp scale. To reflect both household and productive-use consumption, we adopt a realistic bundle: ~800 households (lifeline to modest usage), ~180 shops, ~25 micro-enterprises, and 4 anchor customers (e.g., telecom BTS, rice mill, cold storage, clinic), aggregating to ~434 MWh/yr. These figures align with case materials from Bangladesh and international mini-grid demand archetypes. The typical household demand is usually in the range of 18–30 kWh/month, depending on the size and economic activity of the household. Productive use (shops, clinics, and micro-enterprises) forms a significant part of the demand and contributes to the local economy by enabling small-scale commercial activities. These loads are vital in increasing the sustainability of mini-grid systems, as productive-use loads help stabilize the microgrid's revenue base and mitigate seasonal variations in demand. This careful load segmentation provides insights into the balance of energy demand, ensuring that the system is designed to meet both basic household needs and support local economic growth.

Fuel prices. Diesel remains the most volatile input for hybrid systems. Bangladesh's administered diesel price has oscillated around BDT 102–108 per liter across 2024–2025 under the automatic pricing regime; we use a conservative 102 BDT/L (September 2025). Diesel prices have fluctuated over recent years due to global oil market instability and local economic factors, which impacts the operating costs of diesel generators in hybrid systems. The government's policy of automatic pricing ensures that the local price remains responsive to international market trends, although this also introduces a degree of uncertainty for long-term planning. The volatility of fuel prices can heavily influence the cost-effectiveness of hybrid mini-grids, especially in rural areas where transport costs and fuel availability can also affect pricing. Moreover, as diesel accounts for a smaller share of the energy mix in the proposed hybrid systems, the impact of these fluctuations on overall costs is less than in traditional diesel-only systems.

4. Reference Microgrid: Site-Agnostic Conceptual Design

Design goal. Deliver 24/7 power to ~1,000 connections with high service quality, minimal diesel consumption, and the ability to interconnect when and if the main grid arrives. The design seeks to provide a sustainable energy solution in rural and isolated regions, where the main grid is either unavailable or prohibitively expensive. Additionally, the microgrid aims to balance energy production from renewable sources with backup diesel generation to ensure reliability. The objective is to reduce the reliance on diesel fuel while maintaining the ability to interconnect with the national grid as it extends to remote areas in the future, providing a seamless transition to a grid-connected system when possible (Hirsch, Parag and Guerrero, 2018).

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System topology. The system is based on a PV-battery-diesel hybrid configuration with a centralized plant. The design includes a three-phase low-voltage (LV) distribution system using aerial bundled conductor (ABC) for enhanced reliability and ease of installation in rural environments. The system integrates smart prepaid metering to ensure transparent and efficient energy consumption tracking. The EMS is compliant with standards, droop control, and state-of-charge-aware dispatch that optimizes the energy resources and minimizes diesel. The EMS is an essential component of the microgrid performance, regulating energy flows within the microgrid, controlling the battery storage operation, and ensuring the microgrid reacts properly to fluctuations in load demand and external factors (for example, cloudy days) (Khosravi et al., 2025).

Key components and ratings.

- PV array: 330 kWp, fixed-tilt rack, optimized for local tilt; DC/AC ratio of approximately 1.1–1.2. The PV array is the core of the microgrid's renewable generation, with output varying based on local conditions, such as solar irradiance and panel orientation. A 330 kWp system ensures that a significant portion of the energy demand is met from solar generation.
- Battery energy storage: 1.2 MWh $LiFePO_4$ (nominal), with 0.9 MWh usable at 90% Depth of Discharge (DoD); includes bidirectional inverters with black-start capability. The battery storage ensures continuous power supply during periods of low solar generation, such as cloudy days or evenings, and allows for a quick recovery during outages.
- Diesel genset: 150 kVA (approximately 120 kW), low-sulfur diesel engine, sized to handle multi-day low-irradiance spells and cover morning/evening peaks under cloud conditions. The diesel genset serves as a backup during periods when solar generation is insufficient or when peak demand occurs (Hameed, Abdul and Hameed, 2023).
- Distribution: Approximately 15–20 km of LV ABC, with pole-top transformers as needed. Around 1,000 service drops are included, with ready slots for future densification. The distribution network is designed to provide reliable service to up to 1,000 connections and is flexible to accommodate future growth in the area.
- Metering: STS-compliant smart meters, prepaid, with time-of-use options to shape the evening peak. The prepaid meters help ensure that users are billed accurately for their consumption while providing incentives for efficient energy use, especially during peak demand periods.

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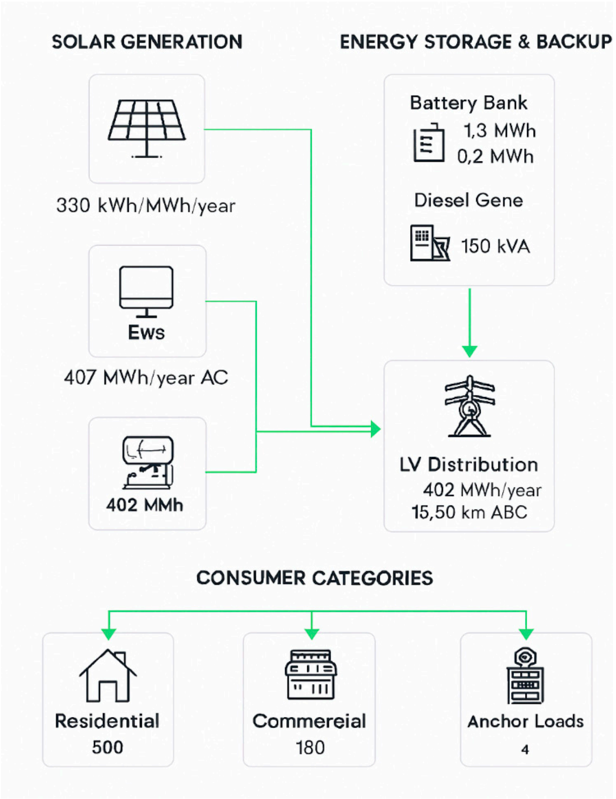

Figure 1. System Configuration and Energy Flow Diagram.

Component choices reflect IDCOL technical standards and typical mini-grid ranges reported for Bangladesh, ensuring that the system meets national requirements and operates efficiently in the local context (Faysal Ahamed Akash et al., 2024).

5. Cost Basis and Market Data

To avoid fantasy economics, all unit costs are tied to current open sources:

- PV and BOS cost context: IRENA's 2023/2024 cost tracking shows strong declines in PV installed costs globally. While utility-scale medians cannot be directly transplanted to small islanded systems, they establish a parts-and-labor floor. Mini-grid specific CAPEX in South/Southeast Asia historically ranged widely (3.2–10.9 USD/W, older data including Bangladesh), driven by distribution network share and logistics; today, module and inverter prices are far lower, but LV network cost remains stubborn. The costs associated with the distribution network such as poles, wires, transformers, and service drops make up a large proportion of total CAPEX for mini-grids, particularly in rural areas. The main challenge in mini-grid systems is not only the cost of renewable generation (such as PV modules and inverters) but also the installation and maintenance of the distribution network, which is often more expensive than the generation assets themselves. For this reason, we use a blended bottom-up cost approach, relying on current market data, not the older high benchmarks that overestimated installation and distribution costs. This cost strategy ensures a realistic financial modeling approach for mini-grid implementation (T. Chamarande, Etienne and Mathy, 2024).
- Battery pricing: BloombergNEF's 2024 survey reports a global average Li-ion pack price of 115 USD/kWh, the steepest annual drop since 2017. Stationary installed systems are higher (including power electronics, housing, and integration); we assume 230 USD/kWh turnkey for 2025 in Bangladesh, which is conservative. Battery prices have seen a steady decline over the past few years, driven by technological advancements, economies of scale in production, and

increased competition among manufacturers. The price drop significantly impacts the economics of hybrid solar systems, especially in areas like Bangladesh, where battery storage is crucial for providing reliable power in off-grid conditions. By 2025, the turnkey price for $LiFePO_4$ batteries (including integration and ancillary components) is expected to be around 230 USD/kWh, which is a conservative estimate. This price is key in keeping LCOE competitive, allowing for more affordable and reliable energy access.

- Diesel price: We adopt 102 BDT/L (late September 2025) as the base. Sensitivity brackets ±10%. Diesel prices are inherently volatile, especially in countries like Bangladesh where global market fluctuations, government subsidies, and transportation costs heavily influence prices. The diesel cost is a key driver of operating expenses in hybrid systems. The fluctuation in diesel prices creates uncertainty for long-term planning and financial forecasting, especially for systems that rely on diesel as a backup power source. In Bangladesh, the diesel price follows an automatic pricing regime, which ensures that domestic prices are adjusted according to international market conditions. While we use a conservative base price of 102 BDT/L for 2025, sensitivity analysis around a ±10% variation shows that while fuel price increases will affect operating costs, they will not drastically alter the overall cost of electricity, given the relatively low share of diesel energy in the proposed microgrid system.

6. Sizing, Energy Balance, and Dispatch Logic

Resource-to-yield. With PVOUT = 1,450 kWh/kWp/yr, a 330 kWp array produces ~478.5 MWh/yr DC. After accounting for system losses (inverter, wiring, temperature, MPPT, and soiling), and distribution losses, we assume a conservative 15% net reduction in delivered AC, yielding approximately 407 MWh/yr from PV. This reduction is due to typical inefficiencies in the system, which are influenced by factors like module temperature, wiring losses, and the performance of the maximum power point tracker (MPPT). A small diesel share of approximately 35 MWh/yr (≈8% of annual delivered) is used to cover short-term deficits during cloud cover and shoulder-hour deficits. This ensures continuous power supply during peak demand hours when solar generation is insufficient. The total delivered energy, after accounting for these losses and fuel use, is ~442 MWh/yr, which closely matches the composite demand bundle of 434 MWh/yr, thus ensuring that the system meets the expected demand.

Storage and backup strategy: The 1.2 MWh battery handles diurnal shifting (i.e., storing excess daytime energy to cover evening peaks) and short outages. The dispatch logic prioritizes solar energy, using the battery to store excess energy during sunny periods and shave evening peaks when solar production decreases. The genset is started only when the battery reaches a predefined state-of-charge (SOC) floor, typically when the battery is near empty, or when there are multi-day periods of low-irradiance (e.g., during cloudy weather). The system uses droop-based power-sharing, allowing the inverters and genset to share load in proportion to their available capacity, which maintains system stability during transients and avoids sudden shifts in power. The Energy Management System (EMS) plays a crucial role in enforcing the minimum genset load to prevent inefficient operation, such as wet-stacking, which occurs when a genset runs at low capacity and causes soot build-up, reducing its lifespan.

Reliability: With this configuration and a modest share of diesel, expected unmet energy under typical weather years is near zero for firmed base loads (Kumar et al., 2020). There may be occasional load management signals during extreme multi-day overcast conditions, but these are rare and can be managed without service interruption. The design target is ≥99% energy served, aligning with modern mini-grid practices that aim for high reliability (Beath et al., 2023). This is based on the energy balance model and the spinning reserve logic already described. The 99% reliability target is not an absolute guarantee but rather a practical outcome given the balanced dispatch approach, battery storage capabilities, and minimal diesel usage. In the case of extreme weather events, there are provisions for adaptive load management, ensuring that critical loads remain powered even under challenging conditions (Amir et al., 2023).

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7. Economic and Tariff Analysis

7.1. Bill of Materials and CAPEX

All numbers in 2025 USD unless noted.

Line item	Quantity	Unit price	Subtotal
PV array (modules + racking + DC BOS + EPC share)	330 kW	1,000 $/kW	330,000
Battery system ($LiFePO_4$, 1.2 MWh installed incl. PCS & EMS share)	1,200 kWh	230 $/kWh	276,000
Power conversion & EMS (central inverters, controllers, SCADA)	—	—	75,000
Diesel genset (150 kVA incl. enclosure and ATS)	1	—	45,000
LV distribution (ABC lines, poles, transformers, 1,000 service drops)	—	—	350,000
Civil works, fencing, lightning, foundations	—	—	50,000
Contingency & EPC margin (10%)	—	—	112,600
Total CAPEX			**1,238,600**

Cost defensibility: PV/BOS is consistent with IRENA cost trajectories; battery cost references the BNEF 2024 average pack price with integration uplift; LV distribution dominates, consistent with earlier World Bank benchmarking where distribution accounted for a large fraction of mini-grid CAPEX.

7.2. OPEX and Replacements

OPEX (Operational Expenditure) includes all the costs required to maintain and operate the microgrid after its installation:

- Fixed O&M (Operation and Maintenance): This represents about 3% of the total capital expenditure (CAPEX) per year. The cost is approximately 37,000 USD/year and covers staff salaries, routine maintenance, spare parts, insurance, and site security. This amount ensures that the system runs smoothly and remains reliable over its lifetime.
- Diesel Fuel: For a hybrid system that uses both solar and diesel backup, diesel fuel costs are a key operational expense. It's estimated that the system will consume between 10,000–12,000 liters of diesel per year to generate about 35 MWh of energy annually. The diesel efficiency of the genset is estimated to be between 3.0–3.5 kWh per liter. Based on current diesel prices of 102 BDT/L, this will cost about 8,400–10,000 USD/year. This is the fuel used when solar energy generation is insufficient, especially during cloudy periods.
- Battery Replacement: The system uses $LiFePO_4$ batteries for energy storage. These batteries are expected to need replacing around year 12, with the estimated cost of battery replacement being 180,000 USD. This reflects an expected decline in prices due to technological improvements in the battery industry.
- Inverter Replacement: Inverters are critical for converting the DC power from solar panels into AC power for use in the grid. It's estimated that inverters will need to be replaced at year 12, with an expected cost of 50,000 USD for this replacement.

7.3. Levelized Cost of Electricity (LCOE)

We compute LCOE over 20 years at real WACC 8%:

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$$\text{LCOE} = \frac{I_0 + \sum_{t=1}^{N} \frac{O_t + F_t + R_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+r)^t}}$$

where I_0 is CAPEX, O_t, F_t fuel, R_t replacements, E_t delivered energy, r WACC, N lifetime. With 442 MWh/yr delivered:

Unsubsidized LCOE: ≈ 0.41 USD/kWh.

With IDCOL-style 50% capital grant: effective capital recovered falls; LCOE ≈ 0.27 USD/kWh.

The Levelized Cost of Electricity (LCOE) is a metric used to assess the cost-effectiveness of energy generation over the lifespan of the system:

- The formula for LCOE takes into account initial capital investment (CAPEX), operational and maintenance costs (O&M), fuel costs, and the cost of replacements like batteries and inverters. It also factors in the total energy delivered over the system's lifetime (Ogunjuyigbe, Ayodele and Alao, 2017).
- Unsubsidized LCOE: This is the cost of electricity per unit (kWh) without any grants or subsidies, which is estimated to be around 0.41 USD/kWh. This is the price consumers would need to pay for electricity to cover the entire cost of building and operating the system (Sadat and Pearce, 2024).
- With IDCOL-Style 50% Capital Grant: When the system receives a 50% capital grant (similar to what the Infrastructure Development Company Limited (IDCOL) offers in Bangladesh), the effective LCOE falls to 0.27 USD/kWh. This makes the electricity more affordable for end users and aligns with observed tariffs of 30-32 BDT/kWh for solar mini-grids in Bangladesh.

7.4. Tariff Structure Proposal

To balance affordability and cost recovery:

- Domestic lifeline: first 10 kWh/month at a discounted rate; thereafter standard energy charge.
- Commercial: standard energy charge with small demand adder.
- Anchor loads: negotiated rate with minimum billing and curtailment priority.
- Prepaid meters across all classes to control arrears and align demand with supply.

The weighted average must hit the cost-reflective ~0.27 USD/kWh effective LCOE in the presence of grants. Without grants, closing the gap would require either higher tariffs, more anchor demand, capex buy-down, or concessional debt.

8. Performance Evaluation

8.1. Annual Energy and Diesel Share

- PV Gross Output: The system produces a total of 478.5 MWh/year. After accounting for losses, about 407 MWh/year is delivered to the grid.
- Diesel Generation: In a typical year, the diesel generator will produce ~35 MWh/year, which represents about 8% of the total energy share. This is considered modest, as the system is designed to minimize diesel use (Elshurafa, 2020).
- Energy Delivered to Customers: The total energy delivered to customers is ~442 MWh/year. This energy is subject to distribution losses but ensures a reliable power supply to the 1,000 connections in the microgrid.
- Diesel Share: The diesel share in the system is intentionally kept low, but there are options to reduce it further by slightly increasing the battery storage capacity or oversizing the PV array (e.g., adding 1.5 MWh of storage). However, the impact on the Levelized Cost of Electricity (LCOE) would be small in comparison to the costs of building and maintaining the distribution network (Silalahi, Blakers and Cheng, 2024).

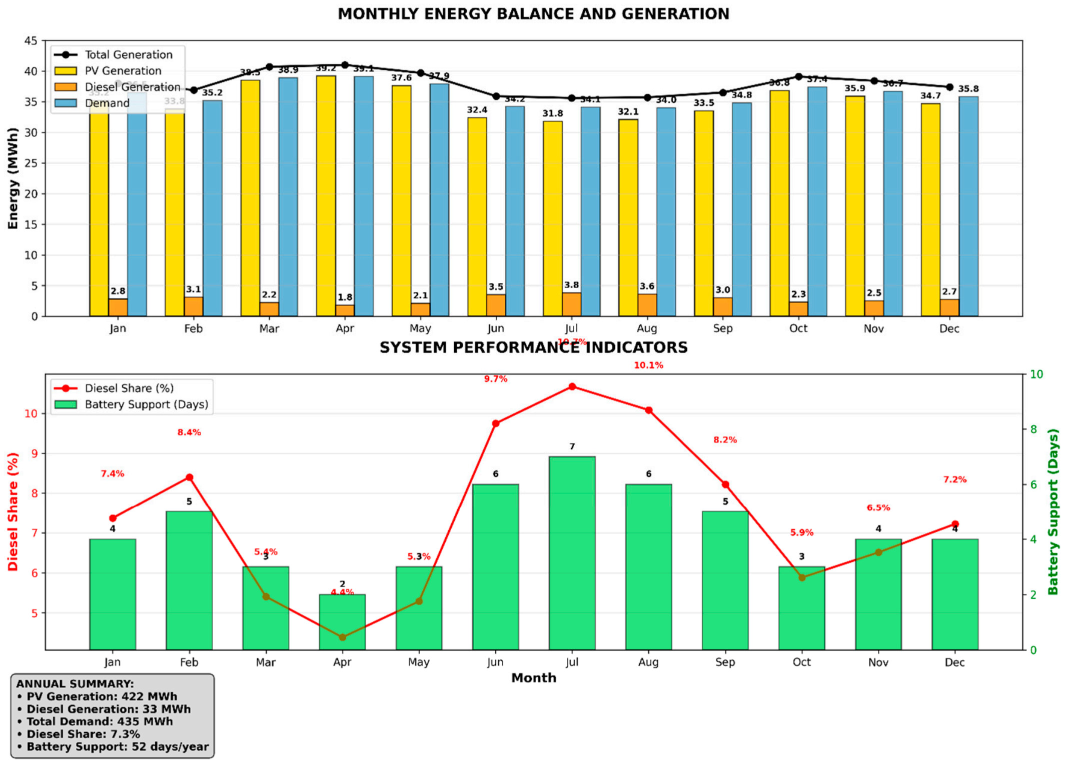

Figure 2. Monthly energy balance and system performance indicators.

8.2. Quality of Service

- Continuity: The system ensures 24/7 service with an Energy Management System (EMS) that monitors the State of Charge (SOC) of the battery storage and sets thresholds for when the diesel genset must start. This guarantees continuous service even when solar generation is insufficient (Zahraoui et al., 2021).
- Voltage/Frequency Regulation: The system uses grid-forming inverters combined with droop control settings for the diesel genset. This ensures proper voltage and frequency regulation, even when the system operates in parallel with the diesel backup generator.
- Reliability Target: The system aims for an energy not served rate of ≤1% during a P50 weather year (a typical year based on 50% probability). This target ensures that the grid remains operational during adverse weather conditions, with fault restoration governed by the design of the low-voltage network and availability of spare parts (Shahzad et al., 2024).

8.3. Environmental Performance

- Reduction in Pollutants: The PV-battery hybrid microgrid reduces local air pollutants and carbon dioxide (CO_2) emissions significantly compared to a conventional diesel-only mini-grid of similar size. In fact, PV-dominant mini-grids in Bangladesh have been reported to reduce CO_2 emissions by about 90% compared to their diesel counterparts. This environmental benefit is crucial as the world moves toward reducing reliance on fossil fuels and combating climate change (Islam et al., 2025).

8.4. Social and Economic Outcomes

- Impact Assessments: Independent impact assessments of IDCOL's mini-grids (such as the ones under consideration for this project) show statistically significant improvements in non-farm income, household expenditure, and study outcomes. The systems have shown better reliability

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compared to traditional solar home systems and diesel generators, and their operational reliability has improved local economic outcomes.
- Improved Quality of Life: These systems offer a more reliable and consistent power supply, which supports small businesses, enhances educational outcomes by powering local schools, and reduces the reliance on kerosene. The microgrid's contribution to the local economy is significant, as it enables productive uses such as powering small enterprises, clinics, and other vital community infrastructure.

9. Sensitivity Analysis

In this analysis, each parameter is adjusted individually to observe how it affects the cost of electricity produced by the microgrid.

Battery Price (+25%):

- Impact: If the price of batteries increases by 25%, the LCOE rises by about 0.01–0.015 USD/kWh. Since battery storage is a critical part of the system for balancing intermittent solar generation, any increase in battery costs will directly affect the cost of electricity.
- Reasoning: The sensitivity analysis predicts that due to ongoing declines in battery prices, a rise in cost is relatively unlikely, but it remains a possibility. It is based on expected battery price trends for 2024–2025 (Wolf and Lüken, 2024).

Diesel Price (+20%):

- Impact: A 20% increase in diesel price will have a small effect on the LCOE, shifting it by ±0.05 USD/kWh. This is because the diesel fuel contribution is only a minor part of the overall energy generation (around 8%).
- Reasoning: Diesel is used as a backup source, and its impact on the LCOE is limited because the system is designed to rely heavily on solar power. Diesel costs fluctuate based on global market conditions, but the cost increase will not drastically affect the LCOE.

Distribution CAPEX (+20%):

- Impact: A 20% increase in distribution costs (the cost of the low-voltage network) will shift the LCOE by roughly 0.025–0.03 USD/kWh.
- Reasoning: Distribution network costs are a critical factor because they account for a significant portion of the capital expenditure (CAPEX) in a mini-grid system. Past benchmarks from the World Bank have shown that distribution-related expenses can be one of the largest contributors to mini-grid costs. Thus, any significant increase in distribution costs has a noticeable effect on LCOE.

Demand Realization (+15%):

- Impact: If energy consumption (kWh) is 15% lower than expected, the unit costs rise significantly.
- Reasoning: Demand realization is crucial to the economic success of the project. If actual consumption falls below projections, it can affect the revenue generated from the system, making it more difficult to cover operational and capital costs. To offset this, strong productive-use enablement becomes essential, which ensures that the energy produced is being used for economic purposes, such as powering businesses, clinics, etc.

Grant Share:

- Impact: If the capital grant is reduced from 50% to 30%, the effective LCOE increases by approximately 0.04–0.05 USD/kWh.
- Reasoning: The amount of the grant has a significant impact on the affordability of the system. A larger grant reduces the initial capital burden, lowering the LCOE. Reducing the grant share increases the cost of electricity produced, as more capital needs to be recovered through user tariffs. Increasing the grant share to 60% would lower the LCOE into the mid-0.20 USD/kWh range.

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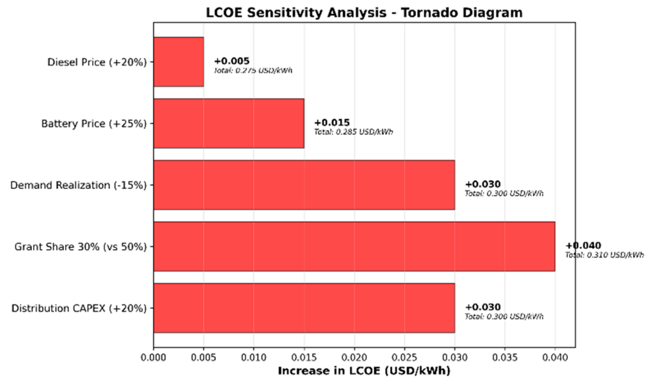

Figure 3. LCOE Sensitivity Analysis (Tornado Diagram).

10. Implementation Risks and Mitigations

A key step in the process of constructing and operating a low-cost solar microgrid in Bangladesh's remote and ecologically demanding rural areas is to identify and eliminate any potential implementation hazards. Despite the fact that the system is technically and commercially viable, its usefulness is contingent on the management of geography, logistics, economics, and laws. For the purpose of ensuring the long-term viability, reliability, and financial well-being of the project over a period of twenty years, a comprehensive risk assessment needs to identify a number of critical areas that call for a mitigation plan that is both well-planned and undertaken by specialists.

The microgrids are destroyed by salinity and storms. It is possible for river island and coastal char equipment to sustain damage from storms and tidal surges. Elevated quantities of salt in the air and soil encourage corrosion, which accelerates the deterioration of electrical components, structural supports, and mounting systems in comparison to inland environments. Over the course of a few years, a simple installation that is not hardened may result in downtime, expensive maintenance, and distrust from the community. The environmental risk must be reduced throughout several stages of the design and procurement process. In order to properly protect equipment enclosures, pole mounting, and panel racking, marine-grade paint and galvanizing are required. When operating in harsh conditions, battery storage containers and power conversion systems require enclosures that are dust-proof, waterproof, and sealed. Resilience of the structure is another essential factor. Coastal wind-rated racking is required for the photovoltaic array. The plant foundation, generator pad, and battery housing should all be raised in order to alleviate the risk of tidal surges and seasonal flooding. In metals that are submerged or grounded, sacrificial anodes reduce the amount of galvanic corrosion that occurs. These expenditures increase CAPEX but decrease OPEX, which helps to preserve the asset and ensure that it will continue to be used.

Operating risks, such as the need for spare components and maintenance, have the potential to turn a straightforward issue into a prolonged power outage. The ability to host remote microgrids is available to metropolitan centers that are technically proficient and have component suppliers. There is a possibility that energy generation will be halted for several weeks if a central inverter MPPT card, BMS module, or system controller from a distant city fails. During downtime, the community, the money for the project, and credibility all suffer. Proactive, community-based service is required for prevention. EPC contractors are obligated to provide a comprehensive set of essential spare parts during the procurement phase of the project. Fuse, contactors, inverter printed circuit boards, and communication modules are some of the delicate but essential components contained within this package. In addition, the development of community capacity is a crucial component. As part of this project, locals are required to acquire knowledge on first-line diagnosis, maintenance, and the replacement of spare parts. There is a standardization of certification and training courses through IDCOL quality control. An ecosystem for localized maintenance makes the microgrid self-sufficient,

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reduces the amount of distant engineer input, and fixes minor faults more quickly, which improves the availability of the system and contributes to increased community confidence.

Microgrids present a significant revenue risk. The company's strategy is determined by the amount of energy used and the fee collection. The default of payments by consumers and the misuse of energy both offer this risk. It is possible that the project will collapse if consumers and companies do not use 434 megawatt hours annually or if a significant number of customers do not pay their power bills. The revenue is not sufficient to pay the costs of operations, finances, and replacement. During the initial stages of operation, specific patterns of consumption are established. For the purpose of mitigating revenue risk, multiple strategies are required. For this purpose, global prepaid smart meters are required. To have a steady flow of cash and to avoid arrears and bad debt, it is necessary to pay for the power before it is used. Tariffs are going to be maintained. Through the implementation of lifeline pricing, which provides a reduction on the initial 10-15 kWh per month for family users, essential necessities are made more affordable for all individuals, hence enhancing social buy-in and reducing non-payment due to cost differences. In order to guarantee a certain amount of base revenue for commercial and anchor customers, agreements that guarantee a minimum monthly billing amount are beneficial. Demand might increase if the productivity of the project is utilized. Rice hullers, freezers, and sewing machines that are energy-efficient are some of the items that microfinance institutions give to tailors. The project's production of power-based economic activity broadens its demand base, so transforming a potential threat into an opportunity for the progress of the local community. In addition to lighting and charging mobile devices, proactive demand is required in order to achieve a load profile that is more consistent and lucrative.

Despite the fact that solar-dominated architecture reduces the danger of fuel supply, diesel generator backup dependability lowers. Diesel is responsible for less than ten percent of the annual need for energy; nonetheless, its availability during extended times of low demand is critical for ensuring reliability around the clock. The delivery of fuel in rural areas is hindered by factors such as seasonal flooding, inadequate roads, and regional price hikes. If petrol is not anticipated, the backup generator might not function properly. Reduce risk by avoiding dependence and ensuring that local supplies are secure. The EMS dispatch and battery storage are optimised, which results in a savings of diesel. This reduces the volatility of the project fuel market. It is necessary for us to keep the necessary petrol on-site. It is possible to avoid supply problems by installing a petrol tank that has the capacity to endure for seven to ten days with an average generator load. Even in the face of protracted cloud cover and logistical challenges, the system is able to function without interruption. It is possible to enhance supplies and reduce prices through partnerships with a number of local fuel dealers. By utilising logistics and diesel as a strategic reserve, the danger of fuel supply to the running of the system is reduced.

In conclusion, the economic viability of microgrids is threatened by changes in legislation as well as factors related to grid arrival. There is a possibility that the national grid will be delivered to the project region by the federal government of Bangladesh sooner. It is possible that the grid would deem the microgrid obsolete if there is no transition strategy developed. This would result in the stranding of assets and prohibit investors from collecting their investments. In the event of unforeseen net-metering or constraints on the import and export of electricity, microgrids may be affected. Microgrids that are just getting started need to be prepared for connections in order to be safe. As part of the main grid integration process, software and hardware must be integrated. Bi-directional meters, grid-tie inverters, and under/over frequency and voltage relays are the components that are responsible for controlling the connection and disengagement of the grid. Consequently, grids remain connected. In Bangladesh, the infrastructure for net-metering makes it possible for these improvements to occur. Following the arrival of the grid, the microgrid will be able to facilitate the sale of excess solar power to the national utility as distributed energy. It is possible to protect the initial investment while also generating additional money. Maintaining open lines of communication with regulatory bodies, such as the Bangladesh Energy Regulatory Commission (BERC) and the local distribution utility, guarantees that the project adheres to national energy plans

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and is able to accommodate shifting regulations. This investment is safeguarded against one of the most significant dangers associated with rural electrification.

The characteristics of rural Bangladesh, including its remoteness, financial model, and constantly evolving energy industry, make the implementation of solar microgrids challenging. Limiting system development can be accomplished by careful planning, the selection of appropriate technologies, and community-centered operational solutions. The recommended mitigations are necessary in order to transform a conceptual idea into a solid, sustainable, and economical energy infrastructure that affords people who live off the grid the ability to live independently for decades. Physical hardening, local technician training, prepaid metering, and ready-to-connect design are all examples of protections that are also available.

11. Comparison with Alternatives

After careful consideration, a hybrid microgrid that incorporates solar, battery, and diesel power has been chosen for rural Bangladesh. Strategic electricity versus others. Every choice has repercussions for the economy, the tech sector, society, and the environment. We require a comprehensive comparison in order to demonstrate why hybrid microgrids are exceptional for populations that live in rural areas or are unreachable. Within this part, a comparison is made between the planned system and the national grid extension, mini-grids that exclusively use diesel, and solar households. As a result of its lifetime costs, dependability, operational concerns, and developmental benefits, the hybrid microgrid that was created with great care is more profitable.

A Comparison of the Common Grid Extension's Benchmarks and Risks

The growth of the national grid could take the role of decentralized energy. Because of economies of scale, this electrification strategy, which has been around for decades, is most cost-effective in places that are both highly inhabited and easily accessible. According to the findings of the study, the grid offers a utility that is managed by the state, a generation fleet that is both big and diversified, and nearly endless power. Using this strategy, it is possible that remote chars, river islands, and coastal communities will encounter impediments that are impossible to overcome.

The primary barrier is the cost of capital. There is a correlation between the distance travelled and the terrain. In order to construct transmission lines that carry high-voltage or medium-voltage electricity over rivers, marshes or unstable chars, specialized engineering, a large number of transmission poles and considerable logistics are required. There is a contention among the World Bank and other development agencies that grid extension is no longer cost-effective due to the fact that each connection costs between $2,000 and $3,000. If the cost of each connection for 1,000 grid connections that span 15–20 km in a region that is prone to flooding is this large, the company and the government will suffer financial losses.

These locations place a high importance on the performance, dependability, and cost of grid expansion. Infrastructure could be hindered by geographical constraints, which would result in increased extension costs. Overhead electricity wires are damaged by storms, floods, and soil erosion, which causes power outages to last longer. The corrosion of coastal conductors and transformers caused by seawater results in increased expenses for maintenance and durations of downtime. The last-mile feeders at the end of the distribution network may be susceptible to damage from high technical losses and low voltage, which could potentially cause damage to sensitive appliances and productive machines. It is possible that the grid will not provide sufficient electricity for economic expansion.

Lastly, the time as well as the danger of deployment. Contracting, budgetary, and regulatory delays are among challenges that large-scale grid extension projects must overcome. They are able to wait ten years for weak grid connectivity in their regions. With a distributed microgrid, it is possible to attain high-quality power and socio-economic benefits in a period of twelve to twenty-four months. The economy of Bangladesh's electrical sector is dependent on the country's infrastructure; yet, growing into the most difficult terrain diminishes profitability. The hybrid microgrid is able to deliver reliable power solutions in areas where the grid is unable to do so because of its targeted, resilient,

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and responsive approach. enables the development of a central grid to avoid the logistical and cost challenges.

11.1. The Environmental Effects and Cost Fluctuations of Mini-Grids Powered Solely by Diesel

Diesel generators are used for the majority of off-grid electricity. The technology is straightforward and widely used. Communities are able to purchase power at a low cost. Markets in rural areas and on islands are dominated by diesel generators. According to the findings of a lifetime cost assessment, this method cannot be maintained because of the challenges it presents in terms of the economy, operations, and the environment.

Changes in the cost of fuel have the potential to undermine diesel-only systems. Sixty to eighty percent of diesel generator power expenditures are accounted for by fuel. According to the findings of the study, diesel fuel costs that range from $0.24 to $0.28 USD per kWh with an efficiency of 3.0–3.5 kWh/liter and 102 BDT/L are anticipated to be incurred. All of the following are not included: construction of generator sets, high-runtime maintenance, and replacement. Prices for diesel-only systems are higher than $0.40 USD/kWh and continue to rise as oil prices rise. Bangladesh, a country that imports petroleum on a net basis, is susceptible to shocks in international markets. Due to the fluctuating prices of electricity, both operators and end-users find it challenging to organise their finances.

Diesel-only platforms are prone to instability and are challenging to manage. Fuelling a fire on a remote island is not only difficult and expensive, but it is also impacted by factors such as the weather, traffic, and politics. Diesel generators require maintenance from trained professionals. Continuously operating them results in quick wear and tear, and operating them at low load, which is typical when demand fluctuates, results in "wet-stacking," which carbonises the engine and reduces its efficiency and longevity. Both of these conditions are prevalent when demand fluctuates. As a result of generator noise and air pollution, neighbours are irritated, and the quality of life is diminished.

Diesel is a single source of environmental damage. Bangladesh has breached global environmental and climatic targets by releasing enormous quantities of carbon dioxide and local pollutants such as particulate matter, nitrogen oxides, and sulphur oxides. This has a negative impact on the environment and has caused lung problems. With the same capacity, a diesel-only system produces ninety percent more emissions than a hybrid microgrid, which consumes eight to twelve percent less fuel. While preserving its reliability, the diesel generator set is transformed into a strategic backup that is only utilised infrequently. This reduces the economic, logistical, and environmental concerns with which it is associated.

11.2. Solution for Limited Basic Needs: SHS Solution

The Solar Home System (SHS) program, which is very popular, has provided electricity to millions of families living in rural Bangladesh. Kerosene lamps have been replaced by light-emitting diodes (LEDs), batteries and 50–100 watt solar panels. SHS are considered to achieve Tier 1 energy availability, according to the World Bank Multi-Tier Framework; nevertheless, they do not fulfil socio-economic development.

The minimal amount of electricity and energy that is produced is the primary obstacle that SHS faces. LED lights, miniature radios, fans, and personal phones are all powered by traditional SHSs. Carpentry or welding tools, irrigation water pumps, small mill or workshop equipment, and refrigerators for food and medication, rice cookers or electric stoves that save time and reduce interior pollution are not among the things that can be powered by this device. With a capacity of 330 kWp and a distribution system that is reliable, the microgrid that is being proposed is able to sustain productive-use loads that help communities climb out of poverty.

The dependability and maintenance of SHS are both impacted by scale. Every single system operates independently; if any of them fails, the entire house will collapse. Maintaining and repairing the hundreds of thousands of systems that are spread out over a huge country might be challenging.

The performance of the charge controller and the battery is quite poor, and the after-sales assistance is not reliable. Experts are responsible for the administration of centralised microgrids. Because of redundancy, battery backup, and generator backup, the system can be operated by a single and qualified person. It is possible that a component failure will not disable all users.

In contrast to SHS, microgrids have the ability to generate community-scale network effects and are economically viable. There are a variety of applications for microgrids, including water purification, telephone towers, small business clusters, residential and safety street lights, and more. It helps to boost local economy. Community centres have the ability to sell cold drinks by teaching computer skills, medical clinics have the ability to power equipment, and convenience stores have the ability to power freezers. Without SHS, it is impossible to construct a networked economy. In order to fulfil the intricate and ambitious energy requirements of rural development, the hybrid microgrid will be utilised. Twenty years ago, SHS was a solid option for elective high school.

11.3. Highly Recommended: Hybrid Microgrid

One of the most effective ways to supply rural areas of Bangladesh with electricity of a high standard is through the utilisation of hybrid microgrids that are powered by diesel fuel and photovoltaic batteries. The advantages and disadvantages of competitors are weighed.

It is borrowed from the central grid a power network that is reliable, expandable, and covers the entire neighbourhood. Local economies and high-energy appliances both benefit from this, as well. Because it is created and operated locally, it eliminates the risk of grid instability and the costs associated with extension. As a result of their dispatchability and durability, diesel generators are always accessible for use. The expense of fuel and the impact on the environment are both reduced by generator backups. The Solar Home System generates solar energy that is not only abundant but also clean and cleanly sustainable. When resources are pooled, a centralised, robust, and maintained generation asset is produced, which increases the amount of energy that is available.

12. Replication Guide and Procurement Notes

Solar microgrid replication steps: Microgrid PVOUT time series, Global Solar Atlas. Tilt and temperature affect site solar energy production prediction.

- Create grassroots demand bundle employing Bangladeshi mini-grid archetypes. Rural energy demands can be evaluated quickly on-site without oversimplifying.
- IDCOL standards and processes for modules, inverters, protection, QA, and documentation should be included in microgrid design. This guarantees the microgrid functions safely and fulfils national regulations.
- Consider complete project IDCOL hybrid funding. Capital optimisation and socially acceptable price are attainable. Blended finance funds projects without burdening customers with concessional and commercial resources.
- Approve BDT 30/kWh grant immediately. The tariff requires stakeholder workshops to alter class-wise blocks for revenue targets and user affordability.
- Fuel the diesel genset for bad weather and emergencies. An independent pricing mechanism is used to keep track of the majority of fuel costs from approved local sources every month.

13. Discussion

In order to provide power to rural areas of Bangladesh, this study provides support for a hybrid microgrid that would utilise solar, battery, and diesel power. By conducting this analysis, its Levelized Cost of Electricity (LCOE) is determined, and the shifting landscape and challenges associated with decentralised energy are brought to light. In this session, we will review the significant findings, investigate the factors that led to them, and place the planned microgrid within the context of Bangladesh's energy reform, highlighting both its achievements and its difficulties.

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The economic supremacy of the lower-voltage (LV) distribution network is the most surprising and possibly paradoxical finding that this study has made. Throughout history, the costs of generation assets have been a barrier to the development of renewable energy. Mini-grid costs have been impacted as a result of a global decline in the prices of solar photovoltaic modules and lithium-ion batteries, as reported by IRENA and BloombergNEF. It is now able to make capital expenditures for the 330 kWp solar array and the 1.2 MWh LiFePO2 battery system that are owned by the microgrid. Through the utilisation of aerial bundled conductors, poles, transformers, and service drops, the “wires and poles” network is able to drastically cut costs. This network meets the requirements of one thousand dispersed connections. Compared to “micro” generation, the “grid” of mini-grids is more expensive. This has significant repercussions for both policy and finance. By utilising less expensive components and creative distribution, it provides the opportunity to shorten the network. It is also advised that demand clustering, cheaper wiring standards, and updated technical standards be implemented in order to optimise cost without compromising safety or dependability. In spite of the fact that it is less glamorous than solar panels or battery storage, distribution infrastructure is nevertheless necessary for the public and requires specialised financing methods.

This issue is addressed by the Bangladesh grant-and-concessional-debt scheme that IDCOL offers. According to the findings of research, a project that receives a capital grant of fifty percent and has a levelized cost of energy of twenty-seven cents per kilowatt-hour is both socially and financially sustainable. The levelized cost of energy (LCOE) of fifty-four cents per kilowatt-hour (kWh) illustrates the precise economic cost of constructing and running an isolated system. The fact that the discounted pricing is equal to mini-grid tariffs of BDT 30–32/kWh demonstrates the viability of the method. The failure of the market was replaced with strategic policy. The public or philanthropists ought to provide financial assistance for a rural road or water well, taking into consideration the distribution network. The operators’ capital costs are reduced as a result of concessional loans. This complex blended finance system ensures that operations are successful by allowing public development groups and private operators to share risk and costs. Electrifying cities in the final mile should be a consideration for other countries.

These discussions strengthen the technical synergy that exists between the PV-battery-diesel triangle in Bangladesh. Despite the fact that variations occur throughout the year, the solar resource of the nation generates 1,450 kWh/kWp yearly. The system benefits from this. A total of 1.2 megawatt hours of LiFePO4 storage is required in order to convert intermittent solar energy into power that can be dispatched, as well as to balance the daytime excess with the nocturnal peak demand. The chemistry of LiFePO2 is advantageous because it has a longer cycle life, is safer, and costs less. Outdated diesel generator with a capacity of 150 kVA is utilised. During the monsoon season, this prevents a prolonged period of low irradiance. It is possible to keep diesel consumption between 8 and 12 percent of the producing capacity by implementing a sophisticated Energy Management System (EMS) and suitably designing the generator set. This allows for the satisfaction of minimum load levels and the prevention of inefficiencies. When used as a backup, fossil fuels have the potential to provide near-one hundred percent reliability without incurring the costly costs of a system that is entirely renewable and also has significant solar and storage oversizing.

It is stated in the research that demand realisation is the primary cause of operational uncertainty, which is an accurate statement despite the report’s expansive approach. In order to fulfil the requirements of the financial model, a well-estimated combination of households, retail establishments, and anchor businesses needs 442 megawatt hours per year. Any decrease in consumption, particularly from commercial and productive-use groups that generate more cash, would have a disproportionately big influence on the levelized cost of energy (LCOE) due to the fact that fixed costs are distributed across a smaller number of energy units. This hazard has an impact on the socioeconomic structures of the community that go beyond technology. Will the small enterprises that were promised come to fruition? Does the clinic have power that is both economical and reliable? In the future, lights that generate income will take the role of household lights. This

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demonstrates that engineering and community development are necessary processes for microgrids. For use to be effective, facilitation is required. Increasing demand can be accomplished by providing financing for energy-efficient appliances, growing local businesses, and cultivating new economic opportunities. There should be more collaboration between microgrid operators rather than selling power in order to foster expansion.

Finally, it is necessary to address the long-term strategic uncertainties associated with grid arrival. The expansion of Bangladesh's grid means that any village that is currently off-grid will most likely be off-grid for a short period of time. The "stranded asset" risk was a standard danger for microgrid investors. The architecture that is ready for interconnections in the design that was suggested decreases this. Inverters that build grids, meters that travel in both directions, and safety relays are all beneficial to microgrids. Continuous integration might be possible in Bangladesh if net-metering is implemented. After the grid is installed, the microgrid has the capability of seamlessly transitioning into a distributed energy resource (DER), which will allow it to deliver excess solar power to the national utility while simultaneously enhancing the local grid. If the grid were to fail, it would be beneficial for a national energy system that is more resilient and decentralised. Combined with microgrids, which are the initial component of smart grids, an energy policy can incorporate both centralised and decentralised methods of energy management.

According to this study, hybrid microgrids that combine solar, battery, and diesel power could be the solution to Bangladesh's last-mile electricity problem. Progress in both the economy and technology is connected to this. Because the costs of essential components have decreased, the finance model that is led by IDCOL in Bangladesh has the potential to cut distribution network costs. A mature technology is required in order to maximise the ambition and reliability of renewable energy. Both the integration of the national grid and the development of demand are concerns that are both strategic and operational. These microgrids have the potential to foster rural development while also being resilient, sustainable, and catalytic for the inclusive and modern energy future of Bangladesh. It is possible to accomplish this through forward-thinking, linked design, and community participation.

14. Conclusions

The 330 kWp PV system combined with 1.2 MWh $LiFePO_4$ storage and a 150 kVA diesel generator is capable of reliably serving approximately 1,000 connections in a coastal char setting, delivering around 442 MWh per year of energy. The unsubsidized Levelized Cost of Electricity (LCOE) is approximately 0.41 USD/kWh, which is aligned with the representative 50% capital grant scenario, resulting in an effective LCOE of 0.27 USD/kWh. This figure is consistent with the BDT 30–32/kWh tariffs observed in many mini-grids in Bangladesh.

The distribution network remains the decisive factor driving costs in the system, while the prices of PV and storage have become less of a bottleneck. The distribution infrastructure, such as poles, wires, and transformers, contributes significantly to the overall CAPEX and should be prioritized in the design and planning of future systems.

The diesel share in this hybrid microgrid is kept to under 10% of the total annual energy consumption, which helps mitigate the risks associated with fuel price volatility. As a result, diesel price fluctuations have a relatively minor impact on the overall cost structure of the system.

The project's replication is feasible, as long as IDCOL's standards and financing mechanisms are adhered to. The implementation should involve competent engineering, procurement, and construction (EPC), along with a prepaid revenue model and an anchor-load strategy to ensure steady revenue flow and system viability.

Lastly, for future academic work, a dispatch simulation using multi-year irradiance and temperature data from the Global Solar Atlas would help refine the system's performance predictions for specific sites.

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