FEASIBILITY ANALYSIS OF BATTERY ENERGY STORAGE SYSTEMS IN NEPAL: A TECHNO-ECONOMIC CASE STUDY OF CHANAULI 33 KV SUBSTATION

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Abstract

Nepal's electricity system is dominated by RoR hydropower which leads to significant seasonal imbalances and transmission and distribution networks are also oper-ating with congestion due to not having effective implementation of transmission and dis-tribution expansion plan. Conventional grid reinforcement options such as line upgrading or new transmission construction has many limitations like high capital costs, long imple-mentation periods and environmental and social challenges. In this scenario, Battery Energy Storage Systems (BESS) could be a promising alternative for enhancing grid flexibility and reliability. This study highlights a techno-economic analysis of BESS placement at the Chanauli 33/11 kV substation in Nepal. The analysis is based on actual hourly load data obtained from the Nepal Electricity Authority, projected load growth and transmission line loading limit. MATLAB based iterative optimization approach is used to determine BESS Size and capacity considering operational constraints and battery degradation over a 2 year planning horizon. The results demonstrated that BESS with rated capacity of 1.9 MW / 9.1 MWh is sufficient enough to mitigate projected summer peak overloads through effective peak shaving within depth of discharge and state of charge design limits.

Keywords: Battery energy storage system, Overload mitigation

1. Introduction

Nepal's energy sector is endowed with substantial hydropower resources, with an estimated theoretical potential exceeding 83,000 MW. Nepal Electricity Authority (2025) report that, despite this abundance, electricity generation is dominated by seasonal run-of-river (RoR) hydropower plants. While these plants produce significant energy during the monsoon, limited storage constrains dry-season generation, causing pronounced seasonal supply–demand imbalances and difficulties in meeting peak load requirements (Shrestha, 2023). Rising electricity demand further highlights the need for flexible system resources capable of enhancing operational resilience and reliability.

The country's transmission and distribution infrastructure faces increasing stress. Much of the network was designed decades ago and now operates near thermal and voltage stability limits, particularly during seasonal agricultural peaks (Nepal Electricity Authority, 2025). Conventional reinforcement measures, such as conductor uprating or new transmission lines, are capital intensive, time consuming, and often constrained by geography, environmental concerns, and social factors (Kishore and Singal, 2014). In this context, non-wire alternatives (NWAs), including Battery Energy Storage Systems (BESS), offer a promising approach to relieve network congestion and defer costly upgrades.

Electrical Energy Storage (EES) encompasses technologies such as pumped hydro, flywheels, compressed air, and batteries. Among these, lithium-ion batteries have emerged as a leading solution for grid-scale applications due to declining costs, high efficiency, and modular scalability (Hesse, 2017; Luo et al., 2014; Mongird et al., 2020). Stationary BESS design considerations—including system architecture, power conversion, and thermal

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management—are critical for safe and reliable operation (Nehrir, 2022). Despite growing global adoption, studies on BESS deployment in Nepal's hydropower-dominated, seasonally constrained grid remain limited.

BESS can provide multiple services, including peak shaving, frequency regulation, voltage support, congestion management, and renewable integration. Multi-service operation generally yields greater economic benefits than single-service applications (Engels et al., 2020; Nick et al., 2014; Pandžić et al., 2015; Yang et al., 2014), while simpler strategies—charging off-peak and discharging during peak hours—can effectively reduce demand charges and defer network upgrades (Hoon and Hkn, 2020; Shrestha, 2023; Srujan et al., 2019). Stacking services further enhances financial returns when operational constraints are properly modeled (Gantz et al., 2015; He, 2016; Mohsenian-rad, 2016; Nair et al., 2021).

Optimal BESS sizing, considering both power and energy capacity, is critical for economic viability and can employ rule-based or stochastic optimization accounting for load and renewable uncertainties. Battery degradation, including calendar and cycle aging, impacts long-term performance and lifecycle costs. Other emerging strategies, such as continuous-time distributed unit commitment, have also been explored to coordinate generation and storage under variable renewable output and seasonal constraints (Lamichhane et al., 2025). Degradation-aware sizing has been shown to improve operational reliability, reduce network losses, and defer infrastructure investments.

Economic evaluation of BESS typically relies on metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Storage (LCOS), with comparisons to conventional alternatives like diesel generators (Shrestha, 2023). Sensitivity analyses on cost, electricity prices, and degradation rates are critical, particularly when accounting for Nepal-specific factors such as import duties, local labor costs, and socio-economic benefits of avoided load shedding.

In hydropower-dominated systems like Nepal's, BESS provides a strategic opportunity to complement existing generation, mitigate seasonal variability, and support peak load management. Motivated by this potential, this study investigates the deployment of a lithium-ion BESS at the Chanauli 33/11 kV substation operated by the Nepal Electricity Authority, a critical power hub for southwestern Chitwan. Technical feasibility, economic viability, and operational benefits are evaluated using key performance indicators including optimal power and energy sizing, round-trip efficiency, capital and operational expenditures, and levelized cost of storage/energy (LCOS/LCOE).

2. Methodology

This section delineates the research framework employed to achieve the techno-economic optimization of Battery Energy Storage System (BESS) at the Chanauli 33 kV substation. The methodology integrates load data processing, MATLAB based iterative sizing, and a comprehensive financial modeling approach to compare BESS against traditional Diesel Generator (DG) solutions.

2.1. Data Collection and Processing

Chanauli Substation is distribution substation situated in south west of Chitwan district with its total capacity of 24 MVA (16+8). One circuit of 33 kV transmission/distribution line is feeding power to this substation from Nepal Electricity Authority existing high voltage grid substation namely Bharatpur 132 kV substation with its capacity of 60 MVA of 132/33 kV and 45 MVA of 132/11 kV. From Chanauli 33/11 kV substation, one 33 kV line is also leaving towards Madi 33 kV substation. The power demand in in the summer in the Chanauli substation exceeds its line loading capacity. As per the record of existing substation data, the maximum loading of Bharatpur-Chanauli 33 kV line is 297 A (2082/04/06 and 7) which is maximum limit for existing DOG ACSR conductor.

Historical hourly load data for Chanauli 33/11 kV substation was obtained from Nepal Electricity Authority (NEA) operational records spanning fiscal year 2080/81 (2023/24). The dataset comprises 8,760 hourly measurements, enabling detailed analysis of daily, weekly and seasonal patterns.

Technical specifications of the existing 33 kV transmission line were extracted from NEA design documents and operational manuals. Key parameters include:

- Conductor type: ACSR DOG (6/1/3.35 mm)
- Maximum current rating: 280 A
- Line Length: 21 km
- Resistance: 0.2732 Ohm/km at 20 degree Celsius
- Reactance: 0.401 Ohm/km

Cost parameters were collected through ADB Report and Manufacturer/Supplier data, NEA tariff Data and Local supplier data for diesel generator systems. Battery performance characteristics were obtained from technical datasheets of commercial LFP (Lithium Iron Phos-phate) battery systems, including efficiency curves, degradation profiles and operational limits. Future load profiles were generated by applying compound annual growth rates (CAGR) of 8% based on NEA's historical demand growth trends, while preserving the underlying daily load shape.

2.2. Technical Analysis Framework

The maximum power transfer capacity of the existing transmission line is calculated using standard power system relationships:

$$P_{\max} = \sqrt{3}\, V_{LL}\, I_{\max}\, \cos\phi \tag{1}$$

where $V_{LL} = 33$ kV is the line-to-line voltage, $I_{\max} = 280$ A is the maximum continuous current rating of the ACSR DOG conductor, and $\cos\phi = 0.95$ is the assumed operating power factor based on NEA standards. Using Equation (1), the maximum active and apparent power transfer limits are

$$P_{\max} = 15.2 \text{ MW}, \qquad S_{\max} = 16 \text{ MVA}. \tag{2}$$

These values establish the baseline transmission constraint against which load profiles are evaluated.

2.2.1 BESS power rating determination

The instantaneous power deficit at time t is defined as

$$P_{\text{def}}(t) = \max\left(0,\, P_{\text{load}}(t) - P_{\max}\right), \tag{3}$$

where $P_{\text{load}}(t)$ is the system load. The minimum required BESS power rating is then obtained as

$$P_{\text{BESS}}^{\min} = \max_{t\in\mathcal{T}} P_{\text{def}}(t), \tag{4}$$

with $\mathcal{T}$ representing the entire study period (typically one year of hourly data).

2.2.2 Energy storage requirement

The daily energy deficit is computed by integrating the power deficit over a 24-hour period:

$$E_{\text{daily}}^{\text{def}} = \sum_{t=1}^{24} P_{\text{def}}(t)\, \Delta t, \tag{5}$$

where $\Delta t = 1$ hour.

Accounting for round-trip efficiency and operational depth-of-discharge limits, the base BESS energy capacity is calculated as

$$E_{\text{BESS}}^{\text{base}} = \frac{E_{\text{daily}}^{\text{def}}}{\eta_{\text{rt}} \times \text{DoD}_{\max}}, \tag{6}$$

where $\eta_{\text{rt}} = 0.85$ is the round-trip efficiency and $\text{DoD}_{\max} = 0.80$ is the maximum allowable depth of discharge.

This study uses iterative sizing approach that explicitly accounts for battery degradation over the project lifetime. Unlike conventional methods that size for initial conditions only, this approach ensures the BESS remains capable of perform-ing its intended function throughout its design life. The optimization function is a loop that performs a forward simulation and degradation analysis, manually increasing the energy size until the lifetime capacity constraint is satisfied. It finds the smallest BESS (starting from a theoretical minimum) that is feasible across all constraints, with the degradation constraint being the active one that drives the size up from the base case. The block diagram is as per figure. The core optimization logic, its objective, variables, constraints, and the algorithm is in following section.

2.3. BESS Optimization Objective and Sizing Methodology

The objective is to determine the minimum-cost battery energy storage system (BESS) that satisfies power, energy, and lifetime constraints over the design horizon.

2.3.1 Optimization constraints

The BESS sizing is subject to the following constraints:

- **Power constraint:**

$$P_{\text{BESS}} \geq \max\left(\text{Load}_{24h} - \text{Transmission Limit}\right) \tag{7}$$

- **Energy constraint:**

$$E_{\text{BESS}} \geq \frac{E_{\text{deficit}}}{\text{DoD}_{\max} \times \eta_{\text{rt}}} \tag{8}$$

- **Lifetime constraint:**

$$C_{\text{remaining}}(Y_{\text{design}}) \geq C_{\min} \tag{9}$$

- **Minimum sizing constraints:**

$$P_{\text{BESS}} \geq 0.5 \text{ MW}, \qquad E_{\text{BESS}} \geq 1.0 \text{ MWh} \tag{10}$$

2.3.2 Objective function

The implicit optimization problem is formulated as

$$\min\ \text{Cost} = c_{\text{inv}} P_{\text{BESS}} + c_{\text{bat}} E_{\text{BESS}}, \tag{11}$$

where c_{inv} and c_{bat} denote the inverter and battery energy costs, respectively. The decision variables are P_{BESS} and E_{BESS}.

2.3.3 Iterative energy oversizing approach

Due to the coupling between operational dispatch and battery degradation, a direct analytical solution is not pursued. Instead, an iterative energy-oversizing approach is employed. The base energy requirement is computed as

$$E_{\text{base}} = \frac{E_{\text{deficit}}}{\text{DoD}_{\text{max}} \times \eta_{\text{rt}}}, \qquad (12)$$

which represents the minimum theoretical energy capacity neglecting lifetime degradation.

Starting from $E_{\text{BESS}} = E_{\text{base}}$, time-domain simulations are performed to estimate the total number of charge–discharge cycles over the evaluation period. The remaining usable capacity at the design year is projected using a multiplicative degradation model:

$$C_{\text{remaining}} = (1 - D_{\text{calendar}})^{(Y_{\text{design}}-1)} (1 - D_{\text{cycle}})^{N_{\text{cycles}}}, \qquad (13)$$

where D_{calendar} and D_{cycle} represent calendar and per-cycle degradation rates, respectively.

If the lifetime constraint in Equation (9) is violated, the energy capacity is increased by a fixed oversizing factor of 10%, and the procedure is repeated. The smallest BESS size satisfying all constraints is selected, with the oversizing factor capped at 3.0 to ensure practical and economically reasonable designs.

2.4. Techno-Economic Evaluation Framework

A techno-economic evaluation framework is developed to assess the feasibility of deploying a Battery Energy Storage System (BESS) at the Chanauli 33 kV substation. Optimal sizing results obtained from MATLAB simulations (1.9 MW / 15.9 MWh) are converted into a discounted cash flow model over a 10-year project lifecycle.

The financial model incorporates realistic cost and tariff assumptions derived from global BESS suppliers, local equipment vendors, and the Nepal Electricity Authority (NEA). The key economic components considered in the analysis are summarized as follows:

- **Capital Expenditure (CAPEX):** Battery modules (LFP), power conversion system, balance-of-plant, civil works, and grid interconnection at the Chanauli 33 kV bay.
- **Operating Expenditure (OPEX):** Off-peak charging costs based on NEA Time-of-Day tariffs and annual operation and maintenance costs.
- **Revenue Streams:** Avoided diesel generation costs and value of energy supplied during peak hours constrained by line limits.

Project viability is evaluated using standard discounted cash flow–based financial performance indicators, enabling direct comparison between the BESS and a diesel generation alternative:

- **Levelized Cost of Storage/Energy (LCOS/LCOE):** Measures the average cost of delivered energy over the system lifetime, accounting for battery degradation.
- **Net Present Value (NPV):** Indicates the net economic value created by the project considering the time value of money.
- **Internal Rate of Return (IRR):** Represents the effective annual return on investment.
- **Payback Period:** Estimates the time required to recover the initial capital investment.

A comparative decision framework is adopted to determine economic preference between BESS and diesel generation based on NPV and LCOS, supplemented by qualitative considerations such as emissions, operational flexibility, and fuel dependency. This framework provides a transparent and consistent basis for investment decision-making for grid-scale BESS deployment in Nepal's distribution network.

3. Results and Discussion

This section presents the results of the techno-economic assessment of Battery Energy Storage System (BESS) integration at the Chanauli 33/11 kV substation, based on measured substation load data, projected demand growth, and existing network capacity constraints. MATLAB-based analytical and iterative methods are employed to analyze seasonal load behavior, identify congestion periods, and evaluate the suitability of BESS as a non-wires alternative to conventional network reinforcement.

Analysis of historical operating data shows a pronounced seasonal variation in demand. During the summer season, driven mainly by residential and irrigation loads, the Chanauli 33 kV feeder operates close to its thermal limit of 16 MVA for extended periods, whereas winter demand remains significantly below the line capacity. A representative daily load profile illustrating this seasonal disparity is shown in Figure 1. This contrast establishes the baseline operating condition of the substation and highlights the inefficient utilization of network capacity across seasons.

Future load projections assuming an annual growth rate of 8% indicate that while the existing feeder can continue to satisfy winter peak demand over the next two years, summer peak demand increasingly violates the 16 MVA line limit. As illustrated in Figure 2, congestion first appears during peak irrigation hours in the first projected year and becomes persistent thereafter. Considering the long implementation timelines, environmental clearance requirements, and right-of-way challenges associated with line upgradation or new line construction, these results

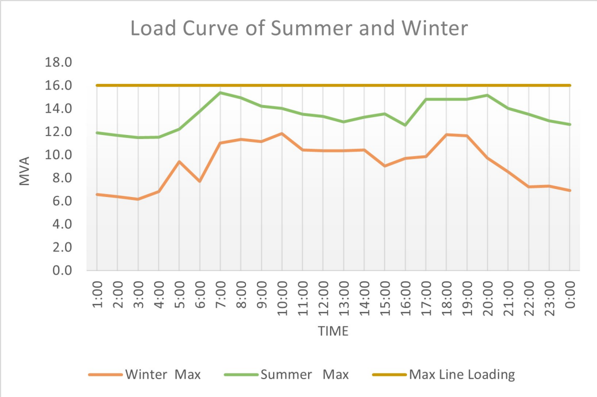

Figure 1. Representative daily load profile of the Chanauli 33/11 kV substation.

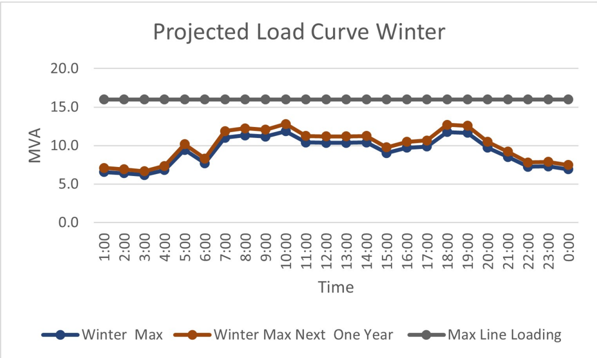

Figure 2. Projected summer peak load under 8% annual demand growth.

demonstrate the technical necessity of deploying BESS to mitigate summer peak congestion and avoid mandatory load shedding.

3.1. BESS Sizing and Configuration Results

The optimal BESS size is determined using an iterative techno-economic sizing algorithm based on summer peak load conditions, projected demand growth, and battery degradation constraints. Key input parameters include transmission capacity, allowable depth of discharge, battery and inverter costs, degradation rates, discount rate, and the target design year. These parameters are selected to reflect realistic operating conditions and economic assumptions for utility-scale BESS deployment at the Chanauli substation.

Using a representative 31-day summer load profile, the optimization yields an optimal BESS rating of 1.9 MW with an energy capacity of 9.1 MWh. The solution satisfies all operational constraints, including an allowable depth of discharge of 80% and a minimum remaining capacity requirement of 60% in the design year. Accounting for both calendar and cycle degradation, the available energy capacity in the second year remains above 97% of the nominal value, confirming adequate margin for reliable operation. The optimized configuration represents the least-cost solution capable of mitigating projected summer congestion without load curtailment over the planning horizon.

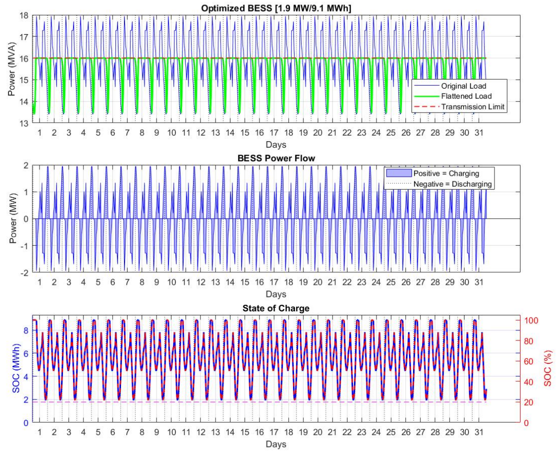

Figure 3. BESS optimization curve for 31 days in designed year

The operational behavior of the optimized BESS is illustrated through simulated charge–discharge profiles and state-of-charge (SOC) trajectories for different time windows. Figure 3 presents the BESS operation over 31 days in the design year, while Figure 4 and Figure 5 provide zoomed-in views over 5-day and 1-day periods, respectively. The results show that the BESS consistently charges during NEA off-peak hours and discharges during morning and evening peak demand periods, effectively reducing transmission congestion without violating SOC or depth-of-discharge limits. Battery degradation trends and absolute capacity reduction over the design period are shown in Figure 6, confirming that degradation remains within acceptable limits.

Overall, the results demonstrate that a properly sized mobile BESS can serve as an effective non-wires alternative for congestion relief at substations supplied by overloaded transmission lines. Such a solution provides operational flexibility and sufficient lead time for permanent network reinforcement, after which the BESS can be relocated to other constrained substations within the distribution network.

3.2. Financial and Economic Analysis

The optimized BESS configuration is evaluated using a discounted cash flow–based financial model incorporating cost data from international reports (ADB, IRENA, EMBER), manufacturer quotations, and Nepal Electricity Authority (NEA) tariff structures. The analysis compares the economic performance of the BESS against a diesel generator (DG) alternative over a 15-year project horizon

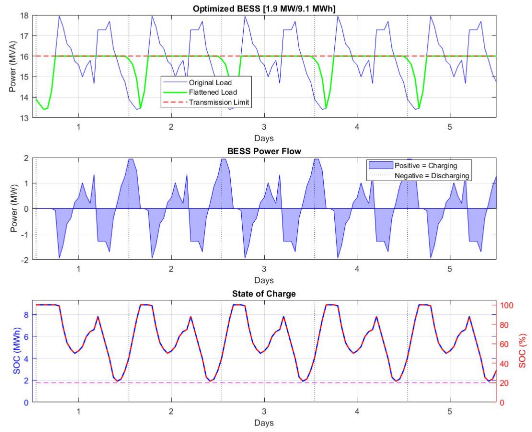

Figure 4. BESS optimization curve for 5 days in designed year

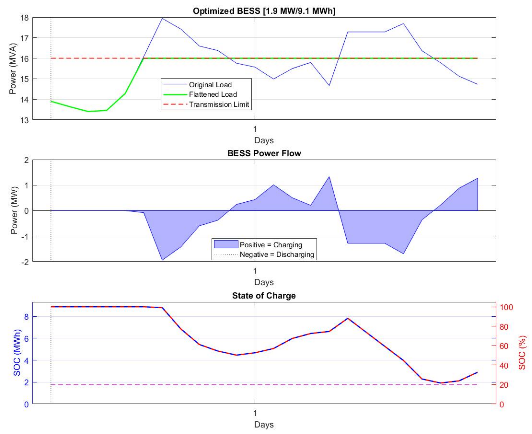

Figure 5. BESS optimization curve for 1 days in designed year

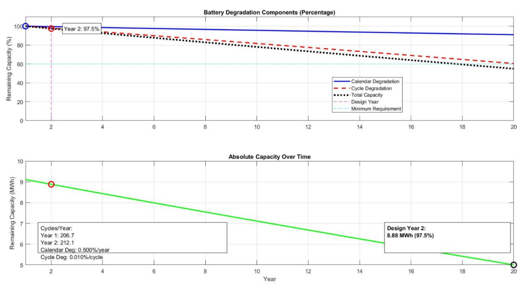

Figure 6. Battery degradation and absolute capacity for designed year

using a discount rate of 10%.

Capital and operating cost comparisons indicate a clear economic distinction between the two technologies. While the BESS requires a lower upfront investment (NRs. 159.49 million) compared to the diesel generator (NRs. 44.71 million), the most significant difference arises

Table 1. Lifecycle Cost Comparison

Cost Component	BESS	Diesel Generator
Total CAPEX (M NRs.)	159.49	44.71
Total OPEX (M NRs.)	215.44	7,630.37
LCOS/LCOE (NRs./kWh)	12.75	30.74

in operating costs. The BESS incurs relatively low lifecycle operating expenditure, primarily associated with off-peak charging and routine maintenance, whereas the diesel generator exhibits extremely high OPEX driven by fuel consumption and fuel price escalation. As a result, diesel generation becomes economically unsustainable for frequent or long-term operation.

Financial performance indicators further reinforce the comparative advantage of BESS. At the prevailing NEA energy selling rate of NRs. 13.5/kWh, the BESS project shows marginal financial viability with a low IRR, while diesel generation exhibits large gross revenues but strongly negative net NPVs due to excessive fuel costs. As the selling tariff increases, the BESS performance improves significantly, achieving an IRR of 9.15% and a simple payback period of approximately 7 years at NRs. 18.0/kWh. In contrast, the diesel generator approaches breakeven only at very high tariffs and remains highly sensitive to fuel price volatility.

In addition to direct financial metrics, the BESS provides substantial energy displacement benefits. The annual energy delivered by the BESS corresponds to approximately 168 tonnes of oil equivalent (toe) of avoided diesel consumption, highlighting its contribution to fuel import reduction and emissions mitigation. Overall, the results demonstrate that while both technologies face tariff sensitivity, the BESS offers significantly lower lifecycle costs, superior economic resilience, and stronger long-term viability compared to diesel generation for grid support applications in Nepal.

4. Conclusion and Recommendations

4.1. Conclusion

This study assessed the techno-economic feasibility of deploying a Battery Energy Storage System (BESS) at the NEA Chanauli 33/11 kV substation to mitigate present and future transmission congestion. Analysis of historical load data and projected demand growth of 8% per annum indicates that the existing 33 kV feeder operates close to its thermal limit during summer peak periods and is expected to violate the 16 MVA constraint within the next two years without corrective action, despite adequate winter capacity.

Using a MATLAB-based iterative optimization framework, an optimal BESS size of 1.9 MW / 9.1 MWh was identified, satisfying depth-of-discharge and state-of-charge constraints while accounting for battery degradation over the design horizon. The optimized BESS effectively mitigates summer peak congestion by charging during off-peak hours and discharging during peak demand, thereby preventing line overloading without load curtailment. The operational behavior closely resembles that of pumped storage, enabling efficient energy shifting without increasing transmission stress.

Economic analysis demonstrates that BESS offers a clear lifecycle cost advantage over the diesel generator alternative. Although both options require significant upfront investment, diesel generation incurs extremely high operating costs due to fuel consumption and price escalation. The BESS exhibits substantially lower and more predictable operating costs, with a levelized cost of storage of approximately NRs. 12.75/kWh, less than half of the diesel generator's levelized cost of energy. In addition, the BESS displaces approximately 168 tonnes of oil equivalent annually, contributing to reduced fuel imports and emissions. Overall, the results confirm that mobile BESS provides a technically effective, economically robust, and environmentally sustainable interim solution for congestion management at constrained substations.

4.2. Recommendations

Based on the findings of this study, the following recommendations are proposed:

- NEA should deploy a mobile BESS of approximately 2 MW / 10 MWh at the Chanauli substation as an immediate mitigation measure to address summer peak congestion and avoid forced load shedding.
- BESS should be treated as a relocatable, temporary asset that can be redeployed to other substations facing similar constraints once permanent transmission upgrades are completed.
- Diesel generators should be avoided for routine grid support due to high operating costs, fuel price volatility, and environmental impacts.
- Appropriate tariff mechanisms, peak-shaving incentives, or ancillary service compensation should be considered to improve the financial viability of BESS investments.
- Future studies should investigate co-optimization of BESS with renewable energy sources, such as solar PV, and evaluate additional system benefits including voltage regulation, loss reduction, and ancillary services.

The methodology presented in this study can be readily replicated across other constrained substations within the NEA network to systematically identify locations where mobile BESS deployment can defer costly transmission infrastructure investments.

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