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Techno Economic Analysis of Battery Energy Storage System (BESS) in Chanauli 33 kV Substation, Nepal

by
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The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis entitled “Techno Economic Analysis of Battery Energy Storage System (BESS) in Chanauli 33 kV Substation, Nepal “submitted by Shiva Ram Tamrakar in partial fulfillment of the requirements for the degree of Master of Science in Energy System Planning and Management.

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ABSTRACT

Nepal's electricity system is dominated by Run of River (RoR) hydropower which leads to significant seasonal imbalances and transmission and distribution networks are also operating with congestion due to not having effective implementation of transmission and distribution expansion plan. Conventional grid reinforcement options such as line upgrading or new transmission construction has many limitations like high capital costs, long implementation 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 the optimal BESS power and energy capacity considering operational constraints and battery degradation over a two year planning horizon. The results shows that a BESS with rated capacity of 1.9 MW / 9.1 MWh is sufficient to mitigate projected summer peak overloads through effective peak shaving within depth of discharge and state of charge design limits for the Chanauli Substation considering next two years load growth.

A comparative financial evaluation between BESS and diesel generation is conducted using financial parameters such as Net Present Value, Cost Benefit Ratio, Payback Period, Internal Rate of Return and Levelized Cost of Storage/Energy. Although the BESS requires higher upfront capital investment (NRs. 159.49 million) compared to diesel generation (NRs. 44.71 million), it demonstrates significantly lower operating costs over the project lifetime. The total operating expenditure of BESS is estimated at NRs. 215.44 million, whereas diesel generation incurs a substantially higher OPEX of NRs. 7,630.37 million, mainly due to escalating fuel costs. The LCOS of BESS is around NRs. 12.75/kWh, which is less than half of the diesel LCOE of about NRs. 30.74/kWh. The findings show that BESS has lower lifecycle costs and improved long term economic performance compared to diesel based alternatives. The study concludes that BESS placement at distribution substations is a technically feasible and economically viable solution for congestion management in transmission/distribution lines.

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LIST OF ABBREVIATIONS

BESS : Battery Energy Storage System

CAPEX : Capital Expenditure

DC : Direct Current

DOD : Depth of Discharge

DoED : Department of Electricity Development

DG : Diesel Generator

EES : Electrical Energy Storage

ESIA : Environmental and Social Impact Assessments

FY : Fiscal Year

GWh : Gigawatt-hour

HEP : Hydroelectric Project

IEE : Initial Environmental Examination

LCOE : levelized Cost of Energy

LCOS : levelized Cost of Storage

MATLAB : Matrix Laboratory

MoEWRI : Ministry of Energy, Water Resource and Irrigation

MVA : Mega Voltage Ampere

MW : Megawatt

MWh : Megawatt Hour

NEA : Nepal Electricity Authority

OPEX : Operational Expenditure

RET : Renewable Energy Technology

RoR : Run-of-River

SOC : State of Charge

CHAPTER ONE: INTRODUCTION

1.1. Background

Nepal's energy sector is endowed with immense hydropower potential, estimated at over 83,000 MW, yet its electricity generation remains dominated by seasonal Run-of-River (RoR) hydropower plants (NEA, 2025). While RoR plants provide substantial energy during monsoon season they are not capable of meeting dry season demand and peak load requirements, leading to a pronounced seasonal supply demand imbalance (Narayan Shrestha, 2023). This seasonal imbalance in hydropower generation, coupled with growing electricity demand and increasing integration of variable renewable energy sources, has highlighted the need for energy storage systems that can enhance grid stability, reliability, and flexibility.

Furthermore, Nepal's transmission and distribution infrastructure faces significant stresses as many lines are designed and built decades ago and are operating near or beyond their thermal and stability limits, especially during seasonal agricultural peaks when irrigation loads surge (NEA, 2025).Upgrading this infrastructure through conductor upgradation, new lines construction, or circuit addition is often a capital intensive, time-consuming process fraught with logistical, environmental, and social challenges. In such scenarios, non-wire alternatives like BESS offer a compelling strategic option.

As global energy landscape is undergoing a profound transformation to decarbonize power systems and enhance grid resilience. Within this context, Electrical Energy Storage (EES) has emerged as a critical enabling technology, facilitating the integration of renewable energy sources, improving grid stability, and optimizing power delivery(Luo et al., 2014)

Among EES technologies, Lithium-ion Battery Energy Storage Systems (BESS) have gained significant commercial traction due to their declining costs, high energy density, rapid response times, and modular scalability (Hesse, 2017). BESS applications span from utility-scale frequency regulation and renewable firming to behind-the-meter peak shaving and backup power, demonstrating their versatility in modern power grids (Nehrir et al., 2022).

By storing electrical energy in chemical form and releasing it when needed, BESS can effectively balance supply and demand, provide frequency regulation, and support peak load management. In the context of Nepal, where hydropower is the backbone of the electricity system, BESS presents a strategic opportunity to complement existing generation, ensure energy security, and support long-term power sector planning. The proposed study focuses on the installation of a Battery Energy Storage System (BESS) at the existing Chanauli 33/11 kV substation operated by the Nepal Electricity Authority (NEA), a power hub for the south west of Chitwan district. Through a comprehensive techno-economic analysis, the thesis aims to evaluate the technical feasibility, economic viability, and operational benefits of implementing BESS at this strategic location. Key parameters to be assessed include battery sizing, energy storage capacity, round-trip efficiency, capital and operational expenditures, and the Levelized Cost of Storage/Energy (LCOS/LCOE). The findings of this research are expected to offer valuable insights for policymakers, system planners, and investors, supporting Nepal's transition toward a more resilient, flexible, and sustainable power system.

1.2. Problem statement

Despite Nepal's significant hydropower potential, the dominance of run-of-river plants in its energy mix leads to seasonal and daytime supply-demand mismatches. During dry seasons and peak demand periods, the country experiences power deficits, forcing it to rely on imports or expensive alternatives. Moreover, as Nepal aims to integrate more renewable sources and expand its electricity export potential, the need for grid flexibility and energy storage becomes more urgent. Battery Energy Storage Systems (BESS) offers a proven solution for energy storage and grid balancing.

While the technical potential of BESS for peak shaving is well established in international literature its application in the specific context of Nepal's distribution network characterized by radial topology, seasonal hydrology and constrained infrastructure remains critically understudied. There is a significant knowledge gap regarding the techno-economic feasibility of BESS as a solution to improve transmission congestion and prevent load shedding in scenarios where conventional grid reinforcement is not immediately feasible.

NEA, Chanauli 33/11 kV substation is a distribution substation with its capacity of total 24 (8+16) MVA. One circuit of 33 kV transmission/distribution line with ACSR DOG conductor is feeding power to this substation from Bharatpur 132 kV grid substation. One 33 kV line is also leaving towards Madi 33 kV substation through this Chanauli33/11 kV substation. At present, the load demand in summer season is nearly its line loading capacity. Considering the load growth as per NEA present scenario, this existing line could not fulfill the projected load during summer in the next two years. Similarly, the upgradation of this single circuit with its equivalent High Temperature Low Sag (HTLS) conductor will take substantial shutdown time and the construction of new 33 kV line will also take around 2-3 years from now. Therefore, Chanauli 33/11 kV substation is identified as a potential location for mobile type BESS which is immediate solution to mitigate above problems in the next two years until grid reinforcement. A detailed assessment of BESS's technical parameters, economic performance, and system integration potential has yet to be conducted. Hence, a comprehensive techno-economic analysis of the implementation of BESS in comparison with Diesel Generator at Chanauli 33/11 kV substation is crucial to determine whether it is a viable and strategic solution for addressing Nepal's current and future power system challenges.

1.3. Objectives

The main objective of this study is to conduct a techno-economic analysis of the implementation of BESS at Chanauli 33/11 kV substation in Nepal to overcome the transmission line congestion and prevent from load curtailment. Specific objectives of this dissertation are:

- ❖ To determine the optimal size of Battery Energy Storage System (BESS) regarding charging and discharging schedules based on the load profiles of assigned substation to reduce transmission line congestion.
- ❖ To conduct a comprehensive financial analysis of the BESS placement, considering optimized seasonal operations, capital and operational expenditures, and potential cost savings and its comparison with alternative Diesel Generator.
- ❖ To perform the environmental benefit of BESS against diesel generation using key metrics (toe).

1.4. Scope

- This study focuses specifically on the Chanauli 33 kV substation's incomer line loading.
- The technical analysis utilizes MATLAB based iterative modeling for BESS sizing based on historical load curves.
- The economic analysis considers current market data from global BESS manufacturers and local diesel fuel price trends in Nepal.
- The analysis focuses on Lithium-ion BESS technology due to its market dominance and suitability for peak-shaving applications.
- The technical study period spans a 15 year operational horizon to adequately account for battery degradation.

1.5. Limitations

- The study relies on secondary load data obtained from NEA records. While deemed accurate, the absence of real-time SCADA data may introduce minor uncertainties in the load profile's resolution.
- Battery cost, performance, and degradation parameters are based on global manufacturer datasheets and literature, as locally verified data for utility-scale BESS in Nepal is scarce. Economic results are therefore sensitive to these input assumptions.
- The analysis assumes a standalone BESS performing peak shaving as its primary service. Potential revenue streams from ancillary services (e.g., frequency regulation) or multi-use applications are not monetized in the base-case financial model, potentially understating the BESS's value.
- Detailed Environmental and Social Impact Assessments (ESIA), site-specific geotechnical investigations, and minute engineering design details (e.g., exact footprint, cooling system design) are beyond the scope of this planning-level feasibility study.
- The findings are specific to the load patterns, grid topology, and constraints of the Chanauli case. While the methodology is transferable, direct generalization to other substations in Nepal requires careful re-application with local data.

1.6. System under consideration

The system under consideration is a BESS at the proposed Chanauli 33 kV substation. The primary function of a BESS is to store excess electrical energy during off-peak periods and discharge it during peak demand hours to support the grid. This enables effective load balancing, enhances grid reliability.

Key components of the system include:

- Battery Modules (e.g., Lithium-ion, LFP, or other chemistries)
- Power Conversion System (inverters and converters)
- Battery Management System (BMS)
- Energy Management and Control Systems
- Cooling and Fire Protection Systems
- Switchgear and Protection Equipment
- Grid Interconnection Infrastructure

The system is designed to operate on daily or hourly cycles, providing services such as peak shaving, load leveling, frequency regulation, and renewable energy integration. In the context of Nepal's evolving power sector, BESS offers a scalable and flexible solution to enhance grid stability, improve power quality, and support a more resilient and sustainable energy future.

1.7. Report structure

The remainder of this thesis is organized as follows:

Chapter 2: Literature review provides a critical review of relevant literature on transmission line loadability, energy storage technologies, BESS applications, degradation modeling and techno-economic analysis methods.

Chapter 3: Methodology details the data sources, the analytical and iterative optimization framework for BESS sizing and the financial analysis model.

Chapter 4: Results and discussion presents the optimized BESS size, the simulation results of its operation and the comprehensive financial metrics.

Chapter 5: Conclusions and recommendations summarizes the key findings, states the conclusions regarding the feasibility of BESS at Chanauli and provides recommendations for NEA, policymakers and future research.

CHAPTER TWO: LITERATURE REVIEW

This chapter reviews existing literature relating to BESS for grid applications, transmission line limitations, and techno-economic analysis methods. The review is structured to provide background on key concepts, assess current research, identify gaps in knowledge regarding BESS placement in Nepal's distribution networks, and clarify this study's contribution.

2.1. Line parameters of transmission line

Any transmission line has four parameters- Resistance, Inductance, capacitance and Shunt conductance. Shunt conductance is leakage current which is very small so can be neglected. Resistance is responsible for power loss and inductance is the one which govern capacity of line. The shunt capacitance causes the charging current to flow in the line and is significant for medium and long lines i.e. line of length more than 80 km.

Line resistance: Resistance is proportional to the resistivity of the conductor which depends upon nature of the element. It is depended upon length, area, temperature and frequency applied to the conductor. In most case, DC resistance is specified at standard temperature. DC resistance at higher temperature can be calculated by using this relation:

$$R_{dc} = R_0(1 + \propto_0 t) \qquad \text{Equation 2-1}$$

Where,

R_{dc} is the resistance at any temperature

R_0 is the resistance at specified temperature

α is the temperature coefficient of resistance

And t is the temperature at which R_{dc} has to be calculated

At 50 Hz, the resistance can increase from 3-5%(B. R. Gupta, 2016).

In most cases, conductor manufacturer specifies the R_{dc} and R_{ac} at standard temperature.

Line Inductance: Inductance is due to magnetic flux linkage created due to flow of current. It depends upon the line spacing and diameter of the conductor. The inductance per phase per km is given by the relation:

$L = 2 \times 10^{-7} \ln\left(\frac{GMD}{GMR}\right) \frac{H}{phase}/m$ Equation 2-2

Where GMD is geometric Mean Distance given by

$D_{eq} = \sqrt[6]{D.m.D.m.2.D.h}$ Equation 2-3

And

GMR is Geometric Mean Radius given by

$D_s = [r'^{1/2}.n^{1/3}.h^{1/6}]$ Equation 2-4

And r' =0.7788.r

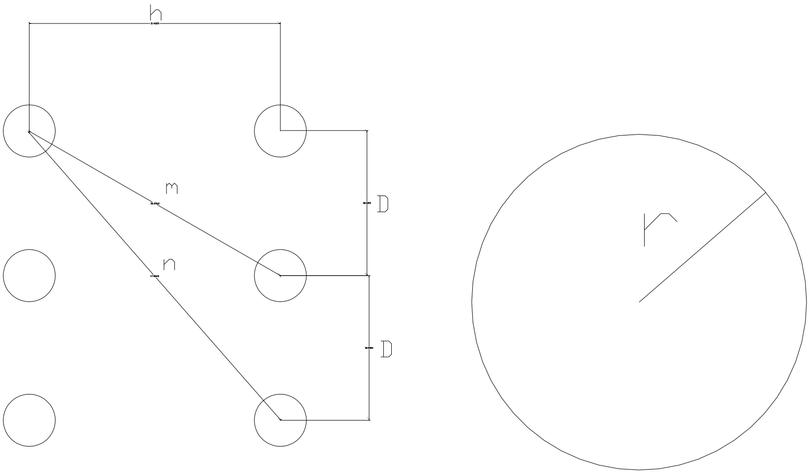

Figure 2.1: Spacing between conductors in double circuit line

Line capacitance: Capacitance is the due to charge in the conductor which also depends upon line spacing and line height. It is given by

$C = \frac{2\pi\epsilon}{\ln(GMD/GMR_c}$F/m Equation 2-5

GMR$_c$=GMR but in this case r is used instead of r' in above formula of inductance.

Inductive Reactance of the line is calculated by using inductance which is given by:

$X_L = 2\pi fL$ Equation 2-6

where f is the power frequency.

Impedance can be calculated as:

$Z = R + jX_L$ Equation 2-7

where Z is the impedance of the line

Similarly, Admittance is calculated which is given as:

$Y = j2\pi fC$ Equation 2-8

Where Y is the admittance of the line.

So using above parameter voltage and current calculation of line can be done which is given by:

$\begin{pmatrix} V_R \\ I_R \end{pmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{pmatrix} V_S \\ I_s \end{pmatrix}$ Equation 2-9

Where A= 1+ZY/2

B=Z

C=Y(1+ZY/4)

D=1+ZY/2

For short lines, ZY/2 and Y(1+ZY/4) is almost equals to zero.

(Gupta, 2006)

$Voltage\ Regulation = \frac{V_{rNL} - V_{rFL}}{V_{rFL}} * 100\%$ Equation 2-10

That becomes

$Voltage\ Regulation = \frac{AV_S - V_r}{V_r} * 100\%$ Equation 2-11

2.2. Loss in transmission line

The transmission line has its resistance which is responsible for line loss. This loss is given by:

$P_{loss} = I^2 R_{ac}$ Equation 2-12

Where P_{loss} is power per phase and has to be multiplied by 3 for 3 Phase

I is the current flowing in the line and

R_{ac} is the effective resistance of the line.

This loss depends upon load current. The load of the system cannot remain constant.

So, the average load has to be calculated. The average load can be calculated by using this formula(J. Duncan Glover, Mulukutla S. Sarma, 2011):

$$Load\ factor = \frac{Average\ Demand}{Maximum\ Load} \qquad \text{Equation 2-13}$$

Similarly, loss factor also known as loss load factor is given by:

$$Loss\ Load\ factor = \frac{Loss_{avg}}{Loss_{peak}} \qquad \text{Equation 2-14}$$

In case, only load factor is known, it is given by:

$$LLF = a \times LF + (1 - a) \times LF^2 \qquad \text{Equation 2-15}$$

Where LLF is loss load factor,

LF is load factor and.

a is the constant whose value is are 0.3 for sub transmission line, 0.2 for medium voltage feeders and distribution substations(Baitch, 2004).

2.3. Factors affecting transmission line

According to (Gonen Turan, 2014), following factors affects EHV transmission line design:

1. Voltage level: The choice for a particular type of line or voltage level depends on the amount of power to be transmitted over the line. Power transmission is usually done through AC systems at high voltage to minimize the transmission losses. The power transfer capability of the line increases and the transmission losses are minimized as the transmission voltage level is increased. This is one of the obvious reasons which are in favor of the utilities aiming for higher transmission voltages. While there are several advantages of preferring high voltage for transmission such as reduced line losses, increased transmission efficiency and better voltage regulation, there are also some parameters which limit higher voltage level. These are increase in insulation required between the conductors and the earthed tower, increase in clearance required between conductors and ground resulting in increased height of towers and increase in distance required between the conductors resulting in requirement of longer cross-arm, all of these contribute in escalating the construction cost of the line. Every transmission line possesses a superior limit fixed for the voltage level to be employed, beyond which it is not economical(Kishore & Singal, 2014).

2. Conductor type and size: It is responsible for different line parameters like Inductance, capacitance and resistance which are very important in line design. Different Types of conductors are available in which ACSR is mostly used conductor. Line parameters are also affected by line spacing and their configuration.
3. Line regulation and voltage control : Voltage regulation is the rise in voltage when full load is removed and is given by:

   $Voltage\ Regulation = \frac{V_S - V_r}{V_r}$ or

   $Voltage\ Regulation = \frac{V_{rNL} - V_{rFL}}{V_{rFL}} * 100$ Equation 2-16

4. Corona and losses, Proper load flow and system stability, Grounding, System protection, Insulation coordination, Mechanical design and Structural design

2.4. Loadability of transmission line

According to (Bstract, 1979), transmission line loadability depends upon following factor:

1. Thermal limitation
2. Line voltage drop limitation
3. Steady state stability limit

Thermal capacity is the ultimate capacity of a line, corresponding to its capability to withstand the heat generated due to line loss. It depends on the type of conductor, maximum permissible conductor temperature, ambient condition and other environmental factors(Nayak et al., 2006). This thermal capability is significant only for very short lines less than 50 miles at 138-kV and below. For EHV and UHV transmission lines of length longer than 50 miles (80m), the only practical limitations to line loadability are provided by line-voltage-drop and by steady-state-stability considerations.

Equation 1 can be written as(B. R. Gupta, 2016):

$$Voltage\ Regulation = \frac{I_r\, R\, cos\emptyset + I_r\, X\, sin\emptyset}{V_r} \qquad \text{Equation 2-17}$$

Where I_r is Receiving end current

R is resistance of line.

From above, voltage drop in the line depends upon current flowing in the line which increases as the load increases, resistance and reactance of the line. The limitation in the allowable voltage drop is voltage drop limitation which is determined to be 5% which adequately represent the condition of a carrying heavy line. It is the controlling factor for line upto 200 miles. For line longer than 200 miles, stability limit governs its loadability which can be seen in Figure 2.2(Bstract, 1979).

$$\text{Stability Margin} = \frac{P_{max} - P_{Rated}}{P_{max}} x\ 100 \qquad \text{Equation 2-18}$$

$$\text{Where } P = \frac{|V_r||V_s|}{X} sin\delta \qquad \text{Equation 2-19}$$

(B. R. Gupta, 2016)Where

V_r is receiving end bus voltage

Vs is sending end bus voltage

X is Reactance of the line

δ is angular displacement called power angle from Figure 2.2.

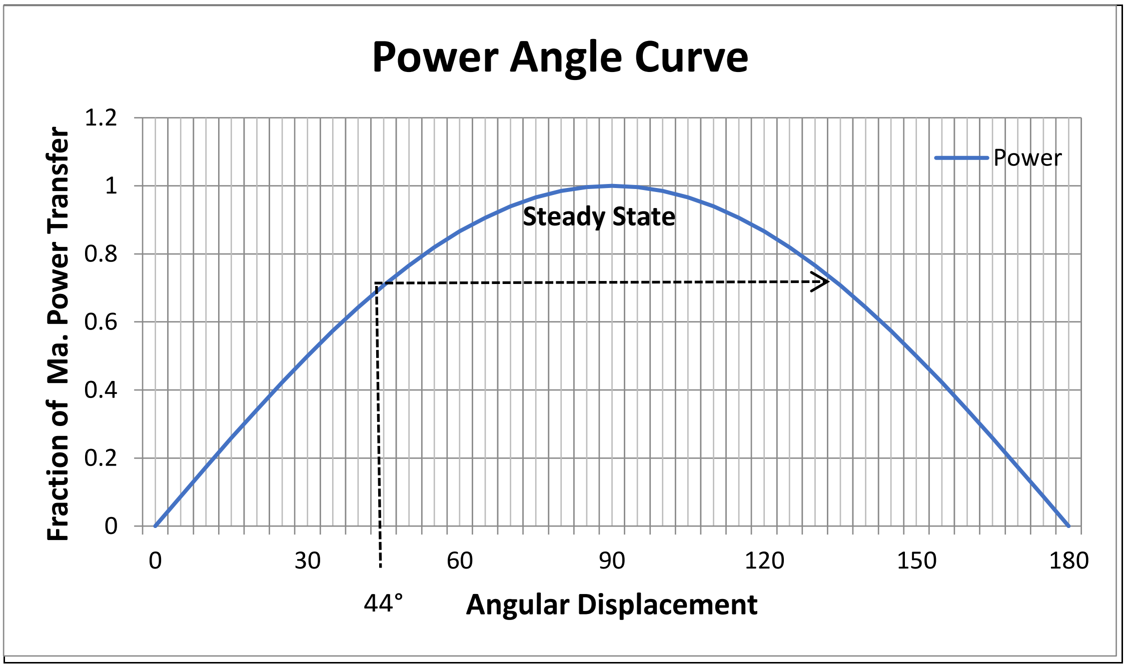

Figure 2.2: Power angle curve

P_{max} is P when δ is 90° and P_{Rated} is value of P corresponding to δ is 44 ° for American power system and 30°for Nepalese and Indian power system.

This margin is chosen so as to provide for stable system operating performance following a variety of credible contingencies which may cause steady state and or transient increases in a given line loading. Such changes in loading may be caused by line switching operations, by changes in generation-dispatch, and by transient disturbances such as temporary faults or loss of generation(Bstract, 1979).

Transmission line loading is limited by thermal, voltage, and stability constraints. For distribution-level lines like the 33 kV feeder to Chanauli, the thermal limit of the conductor often governs maximum power transfer. Studies by (Bstract, 1979) and(J. Duncan Glover, Mulukutla S. Sarma, 2011) establish methods for calculating these limits, noting that exceeding them necessitates either load shedding or infrastructure upgrades. In contexts where traditional upgrades are infeasible due to cost, terrain, or operational constraints non wire alternatives such as energy storage become relevant (Kishore & Singal, 2014) .Research in this area, however, has largely focused on transmission-level solutions in developed grids, with limited attention to distribution-level congestion in developing countries like Nepal.

2.5. Electrical energy storage

Electrical Energy Storage (EES) technologies include pumped hydro, flywheels, compressed air, and various battery types. Among these, lithium-ion batteries have emerged as a leading solution for grid-scale storage due to their declining costs, high efficiency, and scalability (Luo et al., 2014). Cost analyses by (Kendall Mongird, Vilayanur Viswanathan , Patrick Balducci , Jan Alam, Vanshika Fotedar, 2020) show that lithium-ion battery prices have fallen dramatically, making them increasingly viable for peak shaving and grid support. Stationary BESS design considerations such as system architecture, power conversion, and thermal management are detailed by (Hesse, 2017). While global adoption is growing, specific studies on BESS in Nepal’s hydropower-dominated, seasonally constrained grid remain sparse.

2.5.1. BESS applications

BESS can provide multiple grid services, including peak shaving, frequency regulation, voltage support, and renewable integration. (Hesse, 2017) demonstrate that BESS used for combined peak shaving and frequency regulation can yield greater economic benefits than single-service operation. In developing contexts, simpler applications like daily peak shaving charging during off-peak periods and discharging during peaks have proven effective in reducing demand charges and deferring network upgrades (Hoon & Hkn, 2020) Studies by (Srujan et al., 2019), (Engels et al., 2020)also show BESS supporting solar PV integration and microgrid stability evaluated combined peak shaving and frequency control using battery storage and concluded that stacking multiple services substantially enhances financial returns, provided operational constraints are properly modeled. However, most applications assume advanced market structures or control systems not yet present in Nepal.

2.5.2. BESS sizing and degradation modeling

Determining the optimal size (power and energy) of a BESS is critical for economic viability. Methods range from rule-based approaches to sophisticated stochastic optimization that accounts for forecast uncertainty (Baker et al., 2016),(Ravichandran et al., 2016)Equally important is modeling battery degradation over time, as capacity fade affects long-term performance and economics. (Xu et al., 2018) provide a comprehensive degradation model that considers calendar and cycle aging. Despite advances, few studies apply degradation aware sizing to distribution level congestion problems in settings with limited data.

(Nick et al., 2014) presented an optimization framework for allocating battery energy storage in active distribution networks and demonstrated that properly sized storage can reduce network losses and defer infrastructure upgrades, leading to measurable operational cost savings and improved investment justification.

(Yang et al., 2014)investigated optimal sizing of battery storage for peak shaving and voltage regulation and showed that economically optimal storage capacity strongly depends on load profiles, highlighting the financial benefits of load-based sizing strategies in distribution substations.

(Pandžić et al., 2015)developed a near-optimal method for siting and sizing storage in transmission networks and demonstrated that congestion relief and deferred transmission expansion can significantly improve the economic viability of grid-scale BESS.

(Mohsenian-Rad, 2016)analyzed optimal scheduling and market participation of battery storage and showed that revenue from energy arbitrage and optimized dispatch plays a key role in recovering capital investment and improving long-term financial performance.

2.6. Financial and economic evaluation

Economic assessment of BESS projects typically uses metrics such as Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Storage (LCOS). Comparative analyses against alternatives like diesel generators are common, with findings indicating that BESS can be cost-competitive when considering lifetime fuel and maintenance costs(Nair et al., 2021). Sensitivity analyses on cost, electricity prices, and degradation rates are essential for robust conclusions. However, most financial models rely on generalized cost assumptions and do not account for location-specific factors such as Nepal's import duties, local labor costs, or the socio-economic value of avoided load shedding.

(He et al., 2016)proposed an optimal bidding strategy for battery storage considering battery degradation and cycle life, emphasizing that degradation-aware operation is essential for realistic financial evaluation and lifecycle cost minimization.

(Gantz et al., 2015)studied multi-use energy storage systems and demonstrated that partitioning storage capacity across multiple services improves overall project profitability compared to single-service operation.

(Wen et al., 2015)presented an economic allocation model for energy storage in systems with renewable variability and showed that optimal storage operation reduces system operating costs, particularly under seasonal generation and demand variations

(Akhavan-hejazi et al., 2014)analyzed optimal operation of storage in energy and reserve markets and highlighted the importance of coordinated scheduling for maximizing revenue while maintaining acceptable operating costs.

2.7. Nepal's energy context literatures

Nepal's electricity sector is characterized by seasonal hydropower generation, growing demand, and transmission bottlenecks. Reports by (NEA, 2025) and (MoEWRI, 2025) highlight dry-season deficits and the need for storage solutions. Academic research within Nepal has begun exploring BESS, primarily for solar PV integration (Narayan Shrestha, 2023)or theoretical feasibility studies. However, a detailed, case-based techno-economic analysis of BESS for distribution-level congestion relief considering real load data, line constraints, battery degradation, and comparative economics has not been conducted. BESS can be categorized based on their chemical composition, with common types including lithium-ion, Sodium-Sulphur, and lead-acid batteries. Each type of battery comes with unique characteristics such as cost, performance, lifespan and safety. Out of these LI-ion batteries are often the preferred choice for BESS due to their high energy density, long lifespan, rapid charge and discharge rates, low maintenance requirements, and environmental advantages.

2.8. Identified research gaps

- Limited studies on BESS for distribution level congestion relief in developing countries particularly in hydropower dominated grids like Nepal where radial distribution feeder reached congestion level.
- Most BESS sizing studies use complex stochastic optimization requiring extensive data so simple and robust method suitable for data scarce environments are underexplored.
- Lack of localized financial analyses comparing BESS against realistic alternatives (e.g., diesel generators, continued load shedding) using Nepal specific cost and tariff data.
- Few studies integrate battery degradation constraints explicitly into sizing for long-term reliability in peak shaving applications.

2.9. Methodology and contribution

This thesis addresses these gaps by:

- Conducting techno-economic analysis of BESS for the Chanauli 33 kV substation, using actual load data and line parameters.
- Developing a practical, iterative BESS sizing methodology in MATLAB that accounts for load growth, line limits, and battery degradation.
- Performing comparative financial analysis between BESS and DG using economic metrics (NPV, IRR, Payback Period and LCOS/LCOE).
- Providing actionable recommendations for NEA on BESS placement as a non-wire alternative for congested distribution feeders.
- Suggesting NEA for implementation of Mobile BESS that can be rapidly deployed, relocated and connected to different distribution/transmission substation to provide temporary grid support.

CHAPTER THREE: METHODOLOGY

This chapter 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 iteration for battery and converter sizing, and a comprehensive financial modeling approach to compare BESS against traditional Diesel Generator (DG) solutions. The overall methodology is shown below.

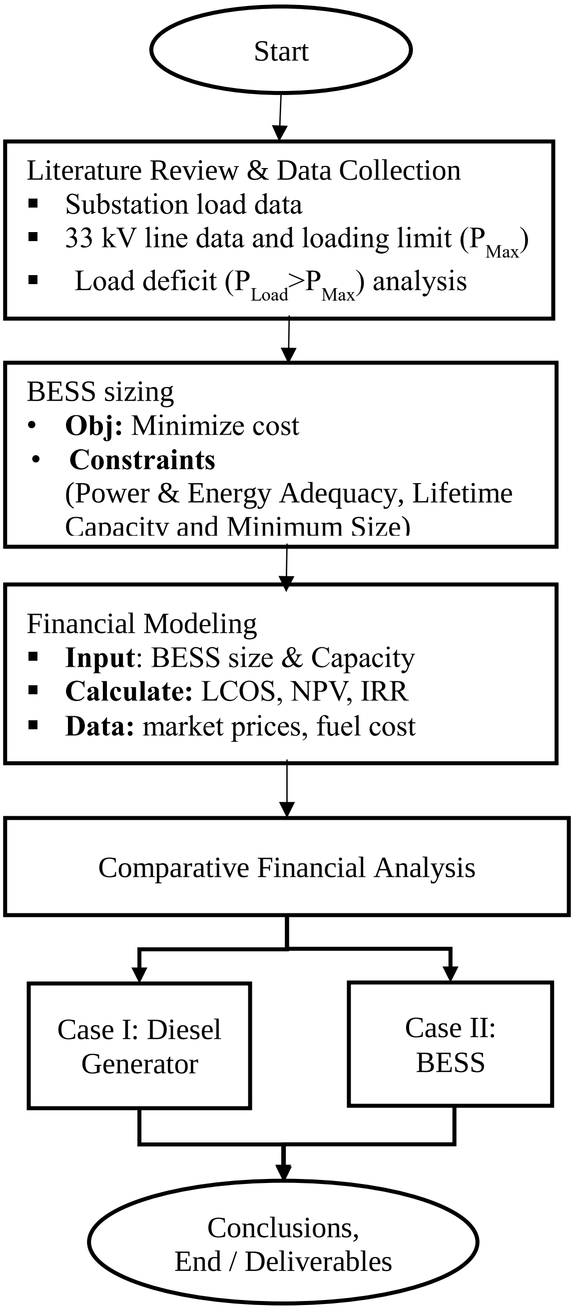

Figure 3.1: Methodology flowchart

3.1. Data collection and processing

3.1.1. Chanauli 33 kV Substation

This substation is distribution substation situated in south west of Chitwan district with its total capacity of 24 (16+8) MVA. 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 & 7) which is maximum limit for existing ACSR DOG conductor. The single line diagram of existing Chanauli 33 kV substation is as follows

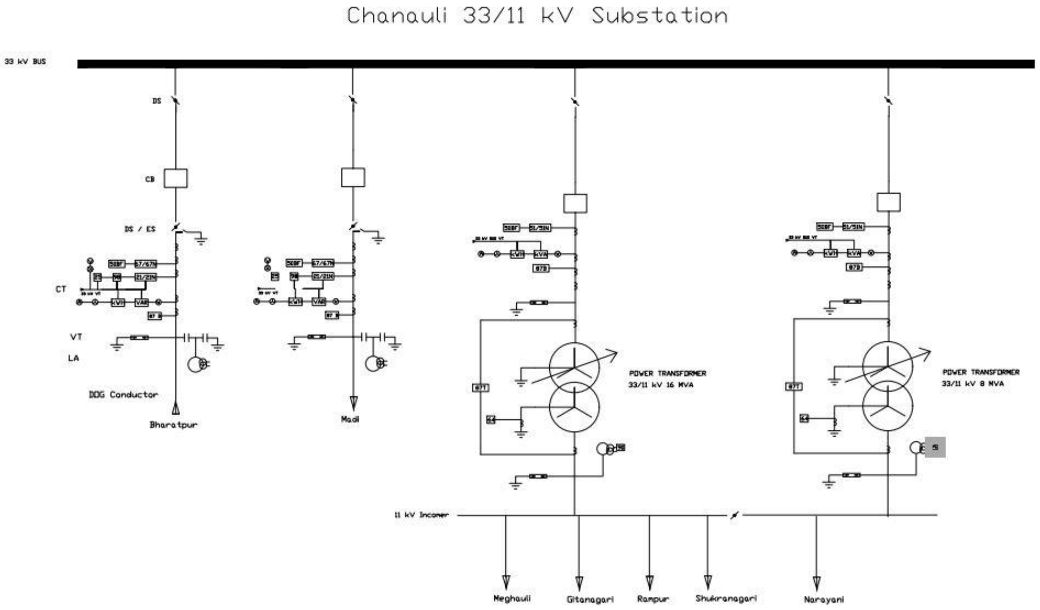

Figure 3.2: SLD of Chanauli Substation

3.1.2. Load profile data

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

3.1.3. Transmission system parameters

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 Ω/km at 20°C
- Reactance: 0.401 Ω/km

3.1.4. Economic data

Cost parameters were collected through:

- ADB report and Manufacturer/Supplier data
- NEA tariff data
- Local supplier data for diesel generator systems

3.1.5. Technical parameters

Battery performance characteristics were obtained from technical datasheets of commercial LFP (Lithium Iron Phosphate) battery systems, including efficiency curves, degradation profiles, and operational limits

3.1.6. Growth projection

Future load profiles were developed by applying a compound annual growth rate (CAGR) of 8%, derived from NEA's historical demand growth trends, which reflect past load evolution driven by population growth, urbanization, economic activity and appliance penetration. The temporal (daily) load shape of the base year was preserved to maintain consistency with observed consumption behavior. However, this growth-based extrapolation represents conventional demand expansion only and does not explicitly account for additional policy-driven loads, such as the rapid deployment of electric vehicle (EV) charging infrastructure.

3.2. Technical analysis framework

3.2.1. Transmission line capacity analysis

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

$$P_{MAX} = \sqrt{3} * V_{LL} * I_{Max} * \cos\varphi \qquad 3\text{-}1$$

Where,

V_{LL}=33 kV (line-to-line voltage)

I_{Max}=280 A (maximum continuous current for ACSR DOG)

$\cos\phi$=0.95 (assumed power factor based on NEA operational standards

P_{MAX}=$\sqrt{3} * 33 * 280 * 0.95/1000$ = 15.2 MW

S_{MAX}=$\sqrt{3} * 33 * 280 * /1000$= 16 MVA

This establishes the baseline constraint against which load profiles are evaluated.

3.2.2. BESS power rating determination

The minimum power rating required from the BESS is determined by analyzing the maximum instantaneous power deficit:

$$P_{deficit}(t) = Max\ (0, P_{load}(t) - P_{Max}) \qquad 3\text{-}2$$

$$\mathrm{P}_{\mathrm{BESS}}^{\mathrm{MIN}} = \max_{t \in T} \mathrm{P}_{\mathrm{deficit}}(\mathrm{t}) \qquad 3\text{-}3$$

Where T represents the entire study period (typically one year of hourly data).

3.2.3. Energy storage requirement calculation

The daily energy storage requirement is computed by integrating the power deficit over time

$$E_{Daily}^{Defecit} = \sum_{t=1}^{24} P_{deficit}(t) * \Delta t \qquad 3\text{-}4$$

Where Δt=1 hour

Considering system efficiency and operational constraints

$$E_{BESS}^{Base} = \frac{E_{Daily}^{Defecit}}{\eta_{rt} * DoD_{Max}} \tag{3-5}$$

Where:

- η_{rt}=0.85 (round-trip efficiency)
- DoD_{max}=0.80 (maximum depth of discharge)

3.2.4. BESS optimal sizing

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 performing 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 as following.

3.2.5. Optimization objective

The primary goal is to find the smallest (cheapest) BESS that satisfies all operational constraints, primarily:

- ❖ **Power Constraint:** It must be able to supply enough power to shave the peak load down to the transmission line limit for the present and future load demands until the designed year.
- ❖ **Energy Constraint:** It must have enough energy capacity to perform this peak shaving throughout the day, considering its efficiency and maximum Depth of Discharge (DoD) for considerable time.
- ❖ **Lifetime Constraint (The Key Sophistication):** Its size must be large enough so that after degrading until the designed year will still have at least the minimum BESS health of its original capacity remaining to perform its job as specified by the designer.

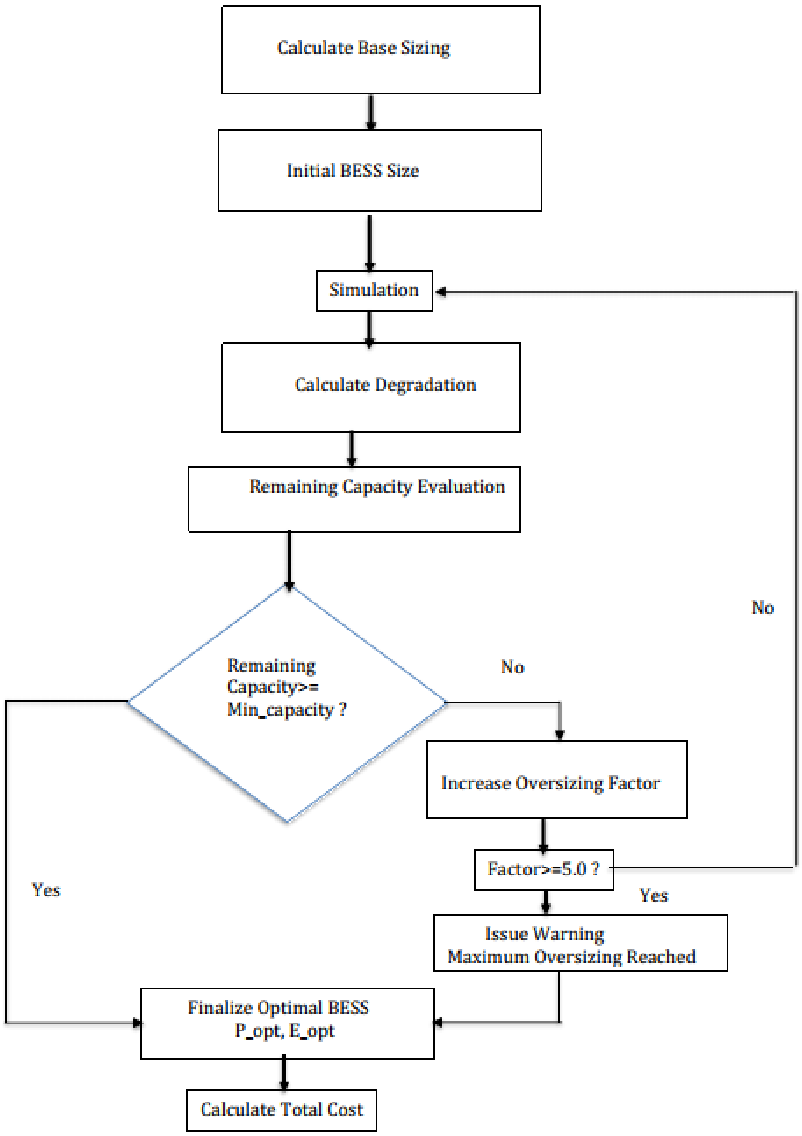

Figure 3.3: Optimization methodology

Therefore, the implicit objective is to minimize the BESS cost function:

Minimize Cost = $\text{Inverter}_{\text{cost}} * \text{Power} + \text{Battery}_{\text{cost}} * \text{Energy}$

subject to the constraints below.

Design variables

The algorithm searches for two optimal variables:

1. BESS size in MW (Power Capacity in MW)
2. BESS capacity in MWh (Energy Capacity in MWh)

Constraints

The solution must adhere to these hard constraints:

1. **Power adequacy:** BESS size in MW >= maximum load above the transmission limit
2. **Energy adequacy (Initial):** BESS capacity in MWh >= (total deficit energy) / (maximum DoD * charging η^2)
3. **Lifetime capacity:** Remaining Capacity for the design year >= minimum capacity at design year specified by the designer.
4. **Minimum size:** Power >= 0.5 MW, Energy >= 1.0 MWh (to avoid trivial solutions).

Optimization algorithm

The function uses a **manual iterative search with an "oversizing factor"**:

1. **Calculate Initial "Base" Size:**
    - Required power = max (design load for 24h – MVA of the line) for any year in the designed period.
    - Base energy = total deficit energy / (max DoD * charging η^2)

This is the smallest BESS that could theoretically handle one day without any degradation.

2. **Enter the Iterative Loop (up to 20 iterations):**

    a. **Propose a Candidate BESS:** Start with the base size (oversizing factor = 1.0). i.e 100% of base energy value is taken initially.
    b. **Simulate Operation:** Perform the simulation for the required period with the candidate size. This returns key performance data, most importantly the number of cycles the BESS would undergo to oversee if the capacity is enough or not for multiple days.

c. **Forecast Degradation:** Using the results from the simulation (cycles per day/year), project the total degradation for the design year using the multiplicative model:

Remaining BESS capacity = (1 – calendar degradation)$^{(\text{year-1})}$ * (1 – cycle degradation)$^{\text{total\_cycles}}$

d. **Check the Key Constraint:** Compare the forecasted remaining capacity to the required minimum capacity for the design year.

e. **Decision:**

* **If Constraint Met (**remaining BESS capacity >= minimum capacity required for the designed year input by the user**):** Exit the loop. The current candidate size is the optimal solution.

* **If Constraint Not Met:** Increase the oversizing factor (by 10%). The energy capacity is recalculated as base energy * oversizing factor. A larger battery will degrade more slowly on a per-cycle basis, thus meeting the lifetime requirement. The loop repeats with this new, larger candidate.

3. **Termination:** The loop exits when the constraint is met or the oversizing factor hits a safety cap (the value taken is 3.0). This means the loop terminates if the Battery sizing 300% of base energy and issues warning to the user.

The results of battery and converter sizing is provided in Chapter 4: Results and Discussion. With the objective to minimize the BESS cost function and the limitation of Power Constraint, Energy Constraint and Lifetime Constraint (degradation), the minimum size of BESS was computed.

Further, considering the uncertainties of load growth, BESS size was calculated at ± 10 % of the assumed growth rate i.e 7.2% and 8.8%. The BESS size in MW, MWh, remaining capacity, LCOS and cost of BESS for the abovementioned load growth was compared to the original load growth projection of 8 %.

3.3. Technoeconomic evaluation framework

The analysis utilizes optimal sizing parameters derived from MATLAB simulations based on an 8% load growth projection. Considering market availability, the corresponding BESS power and energy capacity were selected for the study. This BESS configuration is used for the economic evaluation and a multi-year cash flow model over a 15 year project lifecycle is developed. The financial performance of the BESS is then compared with that of a diesel generator providing equivalent grid support.

3.3.1. Input data and cost assumptions

To ensure a high fidelity report the framework utilizes realistic cost data sourced from global BESS manufacturers, local equipment suppliers, and Nepal Electricity Authority (NEA) tariff structure

- **CAPEX (Capital Expenditure):** Includes the total upfront investment required for the system. This encompasses the cost of Lithium-ion battery modules (LFP), the Power Conversion System (PCS/Inverters), the Battery Management System (BMS), site preparation (civil works), and grid interconnection costs at the Chanauli 33 kV bay.
- **OPEX (Operating Expenditure):**
  Represents the ongoing costs to maintain and operate the system.
  - **Charging Cost:** Calculated using the NEA Time-of-Day (ToD)
  - **Tariff**. The system is modeled to charge during the "Off-Peak" window (11:00 PM – 5:00 AM) to minimize energy input costs.
  - **Maintenance:** Annual fixed O&M costs (typically 1.5–2% of CAPEX).
- **Revenue Streams:**
  - **Avoided Diesel Fuel Cost:** The primary economic benefit is the displacement of high-cost diesel generation.
  - **Energy Arbitrage & Sales:** Value of energy units (kWh) served during peak hours that would otherwise be curtailed due to line limits.

3.3.2. Financial performance indicators

The evaluation benchmark for BESS and Diesel Generator is established through four key financial metrics, calculated using a Discounted Cash Flow model.

a. Levelized Cost of Storage/Energy (LCOS/LCOE)

LCOS/LCOE represents the average cost per kilowatt-hour of electricity discharged from the storage system over its entire operational lifetime, incorporating all capital and operational expenditures discounted to present value

$$LCOS/LCOE = \frac{\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{E_{Discharge}(t)}{(1+r)^t}} \qquad 3\text{-}6$$

LCOS/LCOE enables direct comparison between storage technologies with different cost structures, lifetimes, and performance characteristics. For BESS, it captures the critical impact of battery degradation on usable energy output over time. A lower LCOS indicates more economical storage delivery, crucial for justifying BESS investments against conventional alternatives in Nepal's cost sensitive energy sector.

b. Net Present Value (NPV)

NPV quantifies the net economic value created by a project by discounting all future cash flows to their present value and subtracting initial investment

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t} \qquad 3\text{-}7$$

Where $CF_0 = -C_0$(initial investment) and CF_t are net cash flows in subsequent years

Positive NPV indicates that the BESS project generates value exceeding its costs when considering the time value of money. For the Chanauli application, NPV measures whether the combined benefits of avoided load shedding, deferred infrastructure investment, and energy arbitrage outweigh the substantial upfront cost of battery technology, providing a clear go/no go decision criterion for NEA investment committees

c. Internal Rate of Return (IRR)

IRR is the discount rate that makes the NPV of all project cash flows equal to zero, representing the project's effective annual return on investment.

$$0 = \sum_{t=0}^{T} \frac{CF_t}{(1+IRR)^t} \qquad 3\text{-}8$$

IRR provides a percentage-based measure of investment efficiency, allowing comparison across different project types and scales. For BESS projects with high initial costs and long term revenue IRR must exceed NEA's minimum required rate of return to justify capital investment. The parameter is particularly sensitive to battery degradation rates and electricity price differentials making it a critical indicator of BESS economically viable.

d. Payback Period

Payback Period measures the time required for cumulative project cash inflows to recover the initial investment.

$$Payback = \frac{Total\ CAPEX}{Annual\ Net\ Cash\ Inflow} \tag{3-9}$$

In Nepal's capital-constrained electricity sector, payback period indicates investment risk and liquidity recovery speed. Shorter payback reduces exposure to long-term uncertainties like technological obsolescence or regulatory changes. For BESS with substantial upfront costs, achieving reasonable payback requires optimized operational strategies and may benefit from policy support mechanisms during early market placement

3.3.3. Decision framework

- If $NPV_{BESS} > NPV_{DG} > 0$ then BESS is economically superior
- If $NPV_{DG} > NPV_{BESS} > 0$ then DG is economically superior
- If both NPV < 0 then Neither viable; reconsider project
- If $LCOS_{BESS} < LCOS_{DG}$ then BESS delivers cheaper energy

Additional considerations

- Environmental benefits (zero emissions for BESS)
- Operational flexibility (fast response for BESS)
- Noise pollution (silent operation for BESS)
- Fuel dependency (import risk for DG)

This techno-economic framework provides a rigorous and transparent methodology for evaluating BESS placement at Chanauli substation enabling the decision maker for the investment with financial returns.

CHAPTER FOUR: RESULTS AND DISCUSSION

This chapter discusses the results obtained from the techno economic assessment of Battery Energy Storage System (BESS) integration at the Chanauli 33 kV Substation. The analysis is based on actual substation load data, projected demand growth, and network capacity constraints. MATLAB based analytical and iterative techniques are employed to determine the optimal BESS size and operating strategy. The chapter further evaluates the technical effectiveness of BESS in mitigating peak load violations and compares its economic feasibility against a diesel generator alternative using standard financial indicators.

4.1. Load profile analysis

The daily load curve of 24 hours for last one year was obtained from the existing substation record book of Nepal Electricity Authority, Chanauli Substation. The baseline of this study is the current operational state of the Chanauli substation.

4.1.1. Daily and seasonal load profile

This section presents the measured load curve of the Chanauli 33/11 kV substation under current operating conditions.

The load curve of summer in the month of Shrawan 02, 2082 when the summer peak was recorded and is plotted as follows;

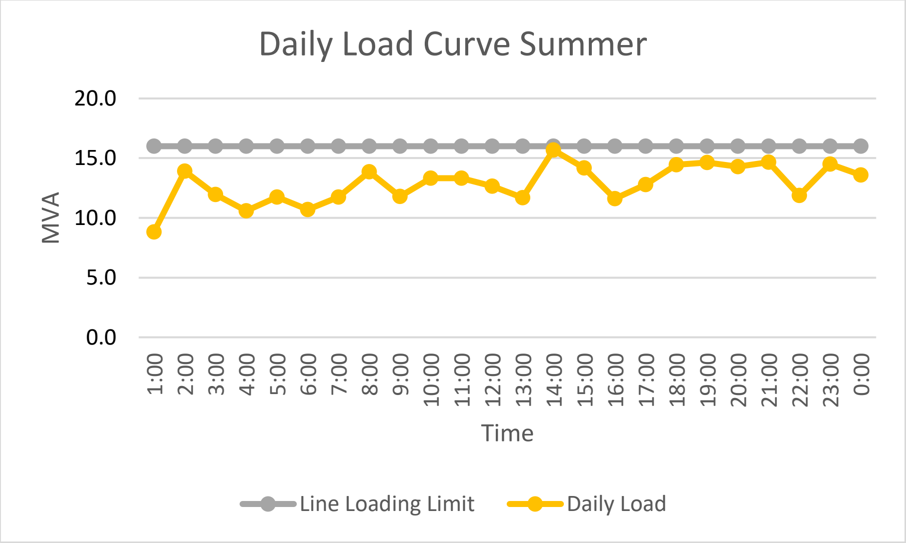

Figure 4.1: Typical load curve during summer

Similarly, the winter load curve of Mangsir 13, 2081 when the substation experience minimum load compare to other months of winter and plotted as follows;

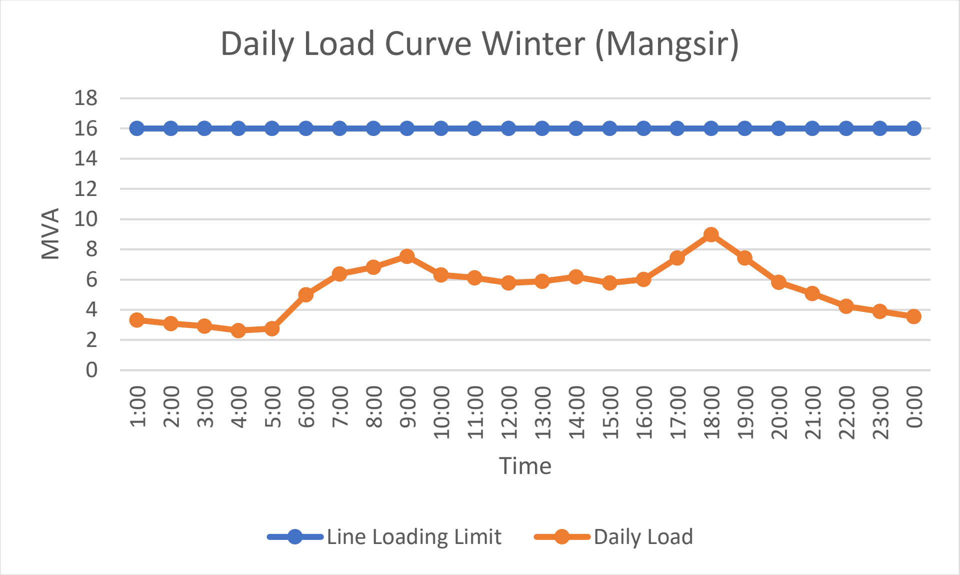

Figure 4.2: Typical load curve during winter

Likewise, the log sheet data of each months of winter and summer seasons of Chanauli 33 kV Feeder is processed in spreadsheet. The maximum winter and summer season loading is plotted as follows:

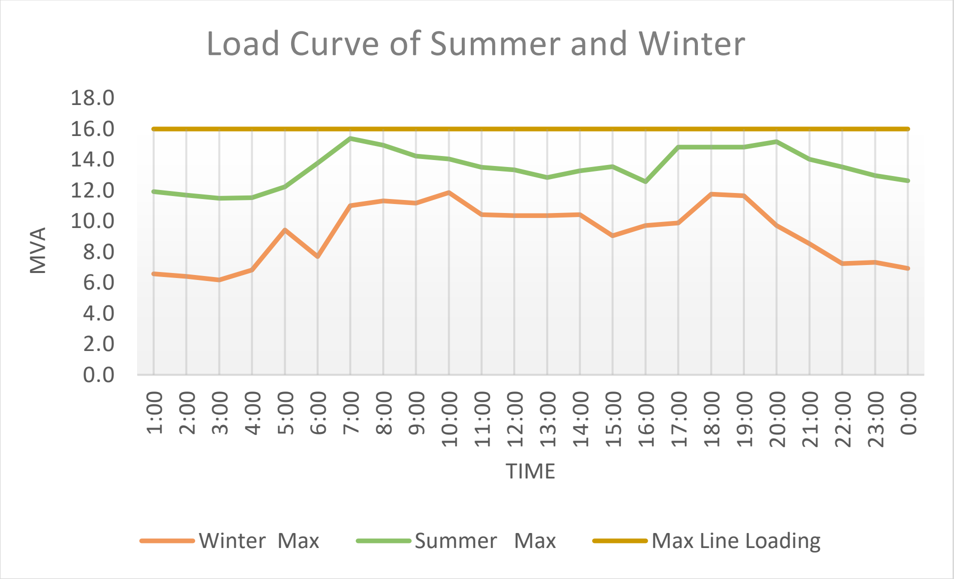

Figure 4.3: Load curve of summer and winter

From the above load curve, the existing Chanauli 33 kV line is operating in its almost full load capacity during summer season due to the high residential and irrigational loads. But, during the winter season, load is found to be below the line loading capacity of 16 MVA.

4.2. Load growth projection and future congestion

From substation obtained log sheet data, the load growth of next one year and next two fiscal years is forecasted with load increment of eight percent each year as per current load growth scenario of Nepal Electricity Authority data. The summer and winter load curve for next one year is plotted as follows;

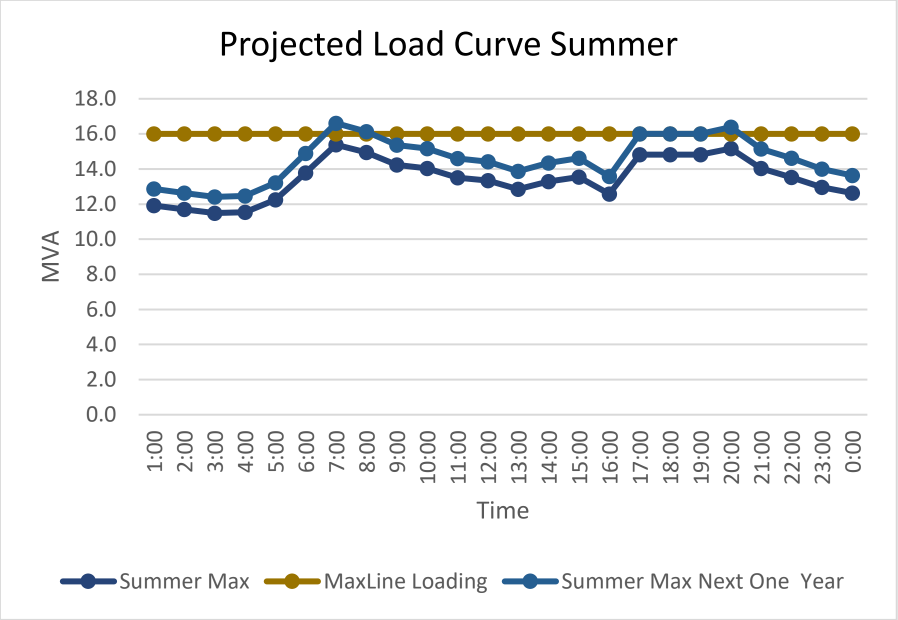

Figure 4.4: Projected load curve summer for one year

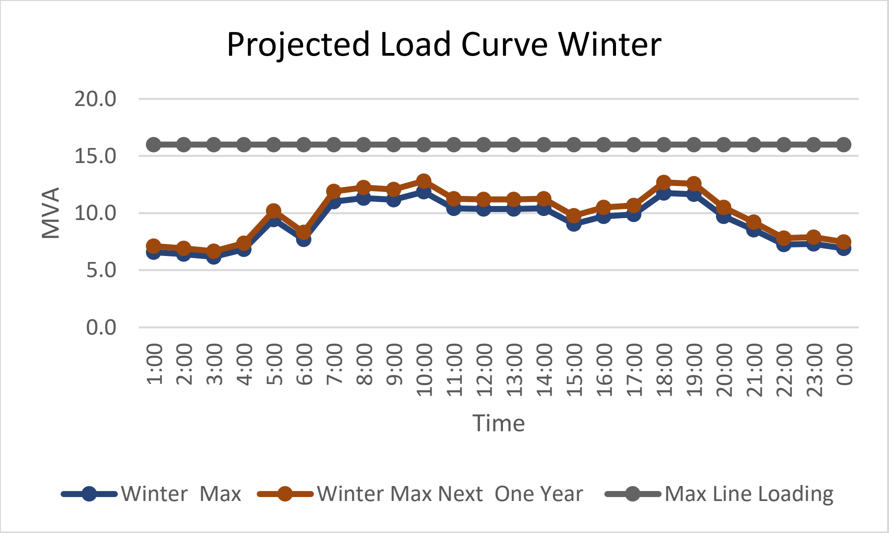

Figure 4.5: Projected load curve winter for one year

Similarly, the load for next two fiscal years is forecasted with load increment of eight percent each year as per current load growth and the summer and winter load curve is plotted as follows;

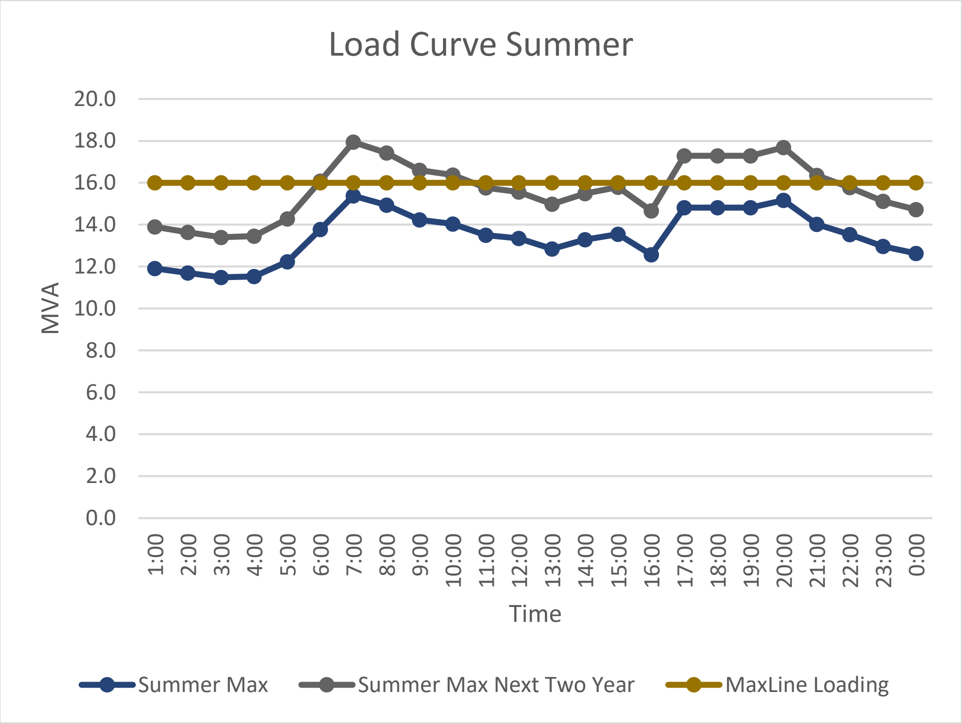

Figure 4.6: Projected load curve of summer for two year

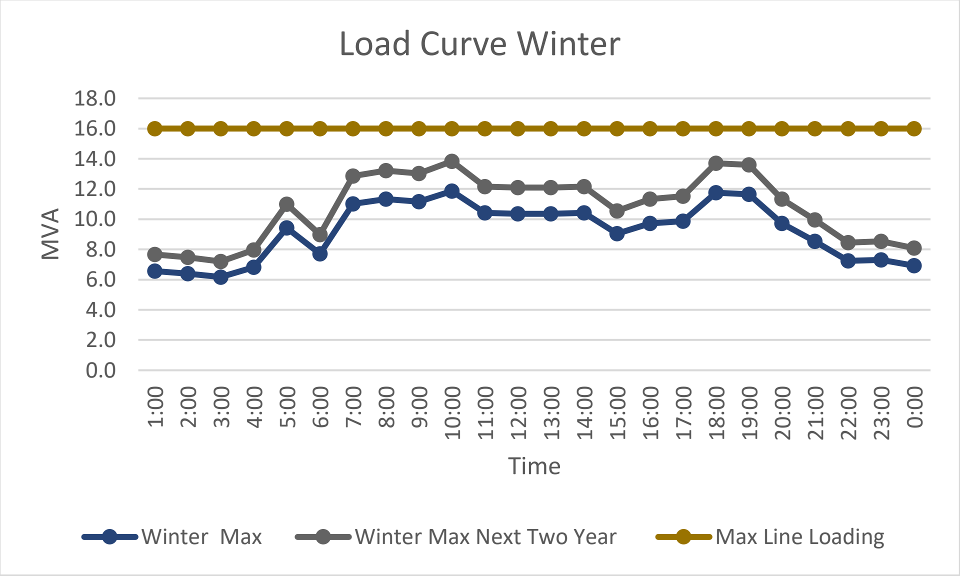

Figure 4.7: Projected load curve of winter for two year

From the above load curve, it is observed that the existing line can fulfill the winter peak in the next two year also but the summer peak will not be fulfilled from the existing line. For summer season, the peak load begins to touch the 16 MVA line limit during peak irrigation hours in the projected year 1. Furthermore, demand consistently violates the 16 MVA line limit, indicating that without BESS or line upgradation or addition of new line, the NEA must implement mandatory load shedding.

Upgradation of existing 33 kV line with equivalent new HTLS conductor will take significant time of power curtailment for reconductoring of HTLS conductor and construction of new line will take more than two years of time as Initial Environment Examination (IEE) or Environment Impact Assessment (EIA) is mandatory for the line route passes through conservation area and social issues regarding Right of Way (RoW) clearance. Furthermore, the substation is supplied via single circuit transmission line, hence upgrading the line means cutting the power for whole day which is not possible given the importance of the load center. Therefore, alternative to address the above issue is the implementation of mobile Battery Energy Storage System (BESS) or Diesel Generator for supplying power during summer season.

4.3. BESS sizing and configuration results

4.3.1. Optimization input parameters

The following table summarizes the key technical, operational and economic input parameters used for the BESS modeling and analysis. These parameters define the system design limits, cost assumptions, degradation behavior and planning horizon considered in the study and serve as the basis for simulating BESS performance under future load and network constraints.

Table 4-1: Input parameter for BESS design

S.N.	Parameter	Input Value
1	Enter no. of days for Plot (1-31)	31/ 5/1
2	BESS DC voltage (kV)	1.2
3	Max Depth of Discharge (80-20) (%)	80
4	Transmission capacity (MVA)	16

5	Battery cost ($/kWh)	84
6	Inverter cost ($/kW)	31
7	Discount rate to calculate present value (%)	10
8	Total service life (years)	15
9	Annual calendar degradation rate (%)	0.5
10	Cycle degradation rate (% per full cycle)	0.01
11	Which year to design for (1-15)	2
12	Minimum remaining capacity in design year (90-30) (%)	60

4.3.2. Optimal BESS sizing results

The input load curve for the summer of 31 days resulted in the BESS size (MW) and Capacity (MWh) as following table;

Table 4-2: Result with BESS size and capacity

S.N.	Parameter	Output Value
1	Optimized Power (MW)	1.9
2	Optimized Energy (MWh)	9.1
3	Actual DoD achieved (%) with accounting battery degradation at the designed year.	80
4	Current Capacity in Year 2 (MWh)	8.88 (97.5%)

The output of optimum BESS sizing for the least cost as the optimizing function and the given constraints was obtained. The results provided the cheapest BESS which fulfills the job without load curtailment in next two years for the Chanauli 33kV substation accounting for load growth projection of 8 %.

4.3.3. Operational dynamics

The simulation starts with the consideration that the battery is initially fully charged. The output curve for BESS optimization with load curve Battery Charge/discharge cycle and Battery state of charge for 31 days considering the design period of 2 years and the size of BESS accounting with battery degradation, remaining capacity, and allowed DOD is as per following figure;

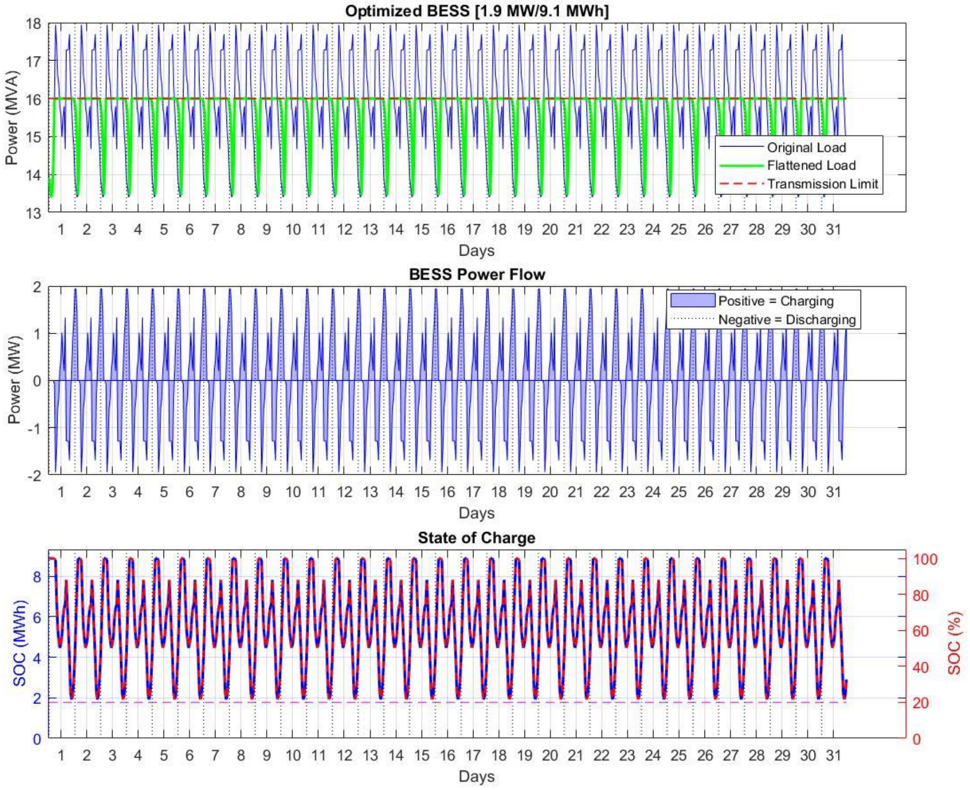

Figure 4.8: BESS optimization curve for 31 days in designed year

For the better observation purpose, the output curve for BESS optimization with load curve Battery Charge/discharge cycle and Battery state of charge during operation for 5 days is as per following figure;

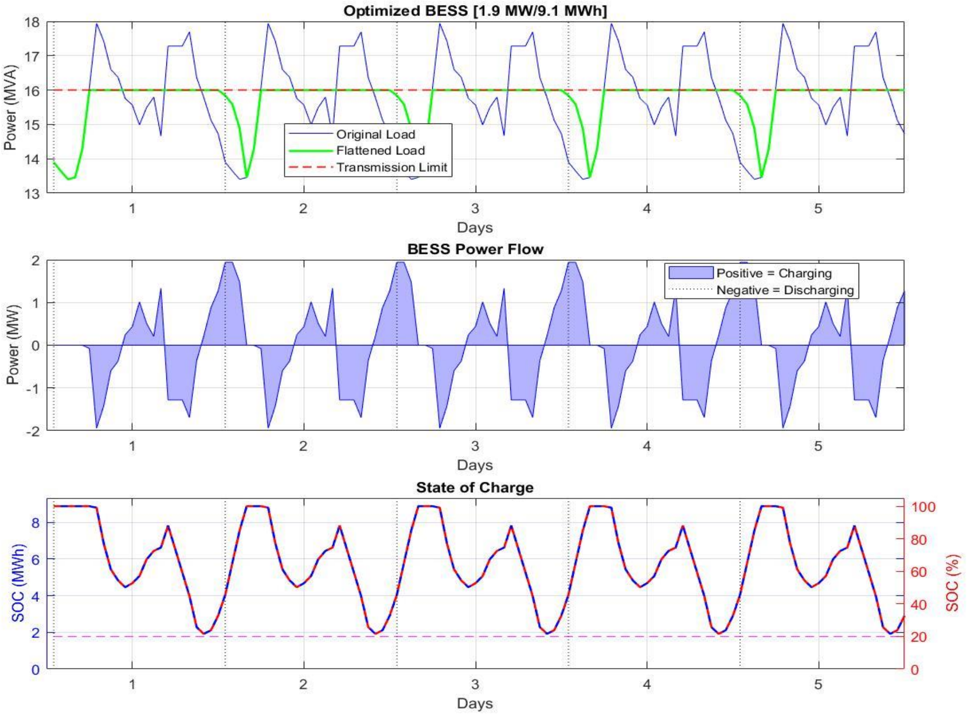

Figure 4.9: BESS optimization curve for 5 days in designed year

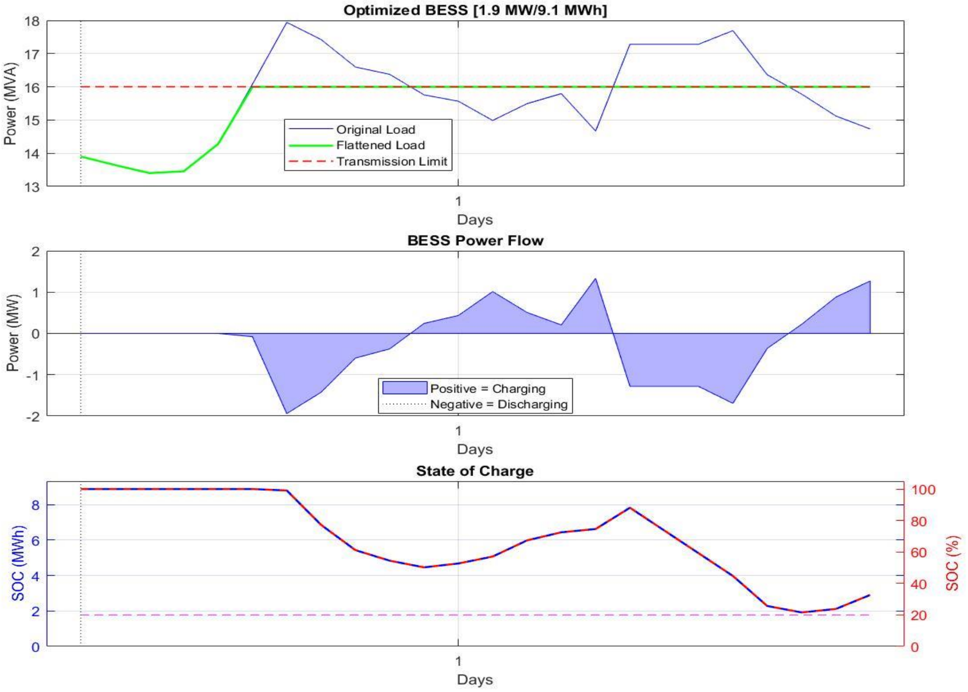

Figure 4.10: BESS optimization curve for 1 days in designed year

The above figures 4.8, 4.9 and 4.10 illustrate the operational performance of the optimized 1.9 MW / 9.1 MWh BESS in mitigating transmission or substation congestion while maintaining feasible battery operation. The top panels show that the original load periodically exceeds the 16 MVA transmission limit, whereas the BESS effectively flattens the load profile by shaving peaks and keeping the net load within the allowable limit. The middle panels depict BESS power flow, where positive power indicates charging during low-load periods (off peak) and negative power indicates discharging during peak demand, demonstrating a consistent peak-shaving strategy. The bottom panels present the state of charge (SOC), confirming that the BESS operates within defined SOC bounds and cycles regularly without violating minimum capacity constraints. Overall, the above figures demonstrate that the optimized BESS size is sufficient to relieve congestion, smooth load variability, and sustain reliable operation over daily to monthly time scales.

The component wise battery degradation and absolute capacity consumption over design period is per the following figure;

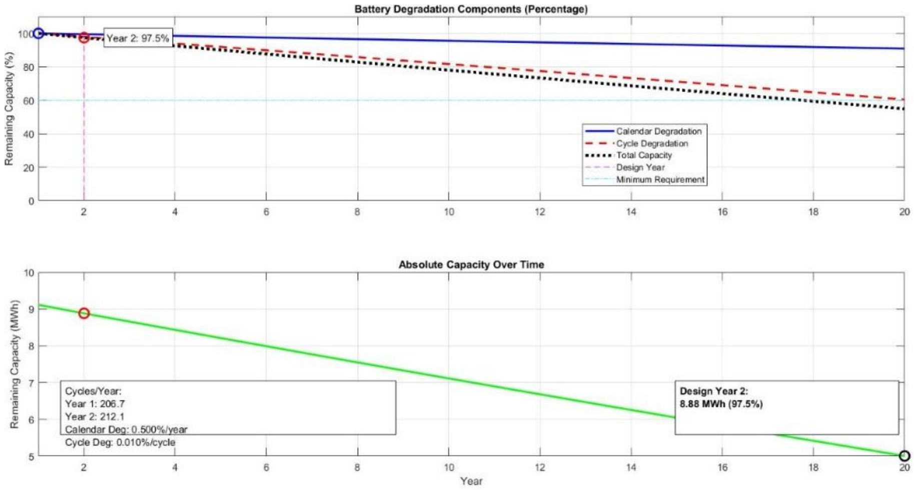

Figure 4.11: Battery degradation and absolute capacity for designed year

This figure illustrates battery degradation over time in two parts. The top panel shows capacity loss percentage from calendar and cycle aging with total capacity declining until it meets the minimum requirement. The bottom panel displays absolute capacity in MWh, using specific yearly cycle counts and degradation rates to quantify the loss. At Year 2, the battery retains 8.88 MWh, or 97.5% of its original capacity. Together, these panels help visualize both relative and absolute battery health across its lifespan.

From the above output figure and result, we can conclude that the BESS is sized such that it does not violate the maximum allowable depth of discharge (DOD) and maintains the minimum required state of charge (SOC) for the designed operating period. This type of mobile BESS serves as a temporary solution and is installed at substations supplied by overloaded transmission lines or at substations expected to experience overloading in the near future. The mobile BESS provides the utility with sufficient time to construct a new transmission line after which the BESS can be relocated to another substation facing a similar constraint.

4.3.4. Sensitivity analysis

A sensitivity analysis of BESS sizing under different load growth projections to account for future demand uncertainty at the substation. Load growth of $\pm 10\%$ of assumed load growth of 8% i.e 7.2% and 8.8% along with assumed load growth projection of 8% are considered to represent low, medium and high demand expansion scenarios. For each scenario, the required BESS power and energy capacities are reassessed to ensure effective mitigation of peak load violations and line congestion. The analysis highlights how increasing load growth directly influences the optimal BESS size, cost and LCOS. The results are summarized in the following table to facilitate comparison across scenarios.

Table 4-3: Sensitivity analysis of BESS

S.N.	**Parameter**	**7.2% Load Growth**	**8.0% Load Growth**	**8.8% Load Growth**
1	Optimized Power (MW)	1.7	1.9	2.2
2	Optimized Energy (MWh)	7.1	9.1	11.0
3	Current Capacity in Year 2 (MWh)	6.78 (97.5%)	8.88 (97.5%)	10.74 (97.7%)
4	Total Cost (CAPEX & OPEX) (M NRs.)	273	344	413
5	LCOS (NRs./kWh)	13.05	12.86	12.76

The above analysis evaluates three BESS configurations sized for 7.2%, 8.0%, and 8.8% annual load growth. Larger systems support higher power and energy needs, with optimized capacities ranging from 7.1 MWh to 11.0 MWh. While upfront costs increase with size, LCOS slightly decreases, indicating better long-term economics for larger installations. All systems maintain high capacity retention in Year 2 (~97.5–97.7%), supporting reliable long-term operation. The results suggest that scaling BESS size with load growth improves cost efficiency and system viability over time.

4.4. Financial and economic analysis

The optimal BESS size of 1.9 MW and 9.1 MWh, derived from MATLAB simulations, was reconfigured to 2 MW and 10 MWh based on market availability for the purpose of economic evaluation. A multiyear cash flow model over a 15 years project lifecycle was developed for this BESS configuration and compared with a diesel generator of equivalent power and energy capacity. The financial evaluation framework was established using cost and performance inputs from ADB reports, manufacturer and supplier data, NEA tariff data as well as published studies from EMBER and IRENA etc.

4.4.1. Cost assumptions and input parameters

The table 4.4 presents the key cost, revenue, and financial parameters used for the comparative techno-economic evaluation of the Battery Energy Storage System (BESS) and the diesel generator (DG) alternative. The capital expenditure (CAPEX) components capture major equipment, installation, land, and miscellaneous costs based on NEA practice, supplier data, and international reference reports. Operational expenditure (OPEX) assumptions include routine operation and maintenance, insurance, fuel consumption and escalation rates to reflect long-term cost behavior. Revenue parameters are derived from prevailing NEA electricity tariffs for energy charging and selling. Common financial assumptions such as discount rate, project life, and exchange rate, ensure a consistent basis for comparing the economic performance of BESS and DG options.

Table 4-4: Financial input parameters

Parameter	**BESS**	**DG**	**Unit**	**Source**
CAPEX				
Battery Pack (10 MWh)	84	-	USD/kWh	ADB Hand Book Report and EMBER Report and Supplier Data
PCS & Inverter (2 MW)	31	-	USD/kW	
MV Transformer 3 MVA (0.4/33 kV)	65625		Set (USD)	NEA Practice
Storage Container for Battery (2 MWh per Container) with PCS	21000		Per Container (USD)	ADB Hand Book Report and EMBER Report and Supplier Data
Generator Set	-	125	USD/kVA	Supplier/ Manufacturer Data
Transportation, Construction & Installation	10726	39750	Lump sum (USD)	NEA Practice
Land Cost for BESS Container	17143		Lump sum (USD)	NEA Practice
Miscellaneous Cost	38705	3975	Lump sum (USD)	NEA Practice
OPEX				
Operation & Maintenance costs	.10% of CAPEX	.10% of CAPEX	%	Maintenance contracts
Increment in O/M cost	2.00% per annum	2.00% per annum	%	NEA Practice

Parameter	**BESS**	**DG**	**Unit**	**Source**
	in O & M cost	in O & M cost		
Insurance	0.1% of CAPEX	0.1% of CAPEX	%	NEA Practice
Periodic Maintenance Cost		1% of CAPEX every five years	%	NEA Practice
Increment in Fuel Cost		1% per annum in Fuel Cost	%	NEA Practice
Fuel Cost	-	146	NRs./Ltr.	NOC price
Fuel Consumption		0.195	Ltr/kWh	Supplier/Manufacturer Data
Revenue Parameters				
Selling Rate	13.5	13.5	NRs./kWh	NEA Tariff
Charging Rate	7.15		NRs./kWh	NEA Tariff for Off Peak
Financial Parameters				
Discount Rate	10	10	%	
Economic Year	15	15	years	Analysis period
Exchange Rate	140	140	NRs./USD	NRB Rate

4.4.2. Capital and operational cost comparison

The following table 4.5 compares the capital (CAPEX) and operational (OPEX) costs of a BESS and a diesel generator.

Table 4-5 : Cost structure comparison

Cost Component	**BESS**	**DG**	**Remarks**
CAPEX (MUSD)			
Battery Pack (10 MWh)	0.84		
PCS & Inverter (2 MW)	0.06		
MV Transformer 3 MVA (0.4/33 kV)	0.07		
Storage Container for Battery (2 MWh per Container) with PCS	0.11		
Generator Set		0.31	
Transportation, Construction & Installation	0.01	0.01	
Land Cost for BESS Container	0.02		
Miscellaneous Cost	0.04	0.001	
Total CAPEX (M USD)	**1.14**	**0.32**	
Total CAPEX (M NRs.)	**159.49**	**44.71**	
OPEX (M NRs.)			
Battery Charging Cost	210.29		
Operation & Maintenance costs (including Periodic Maintenance)	2.76	2.11	
Insurance	2.39	0.67	
Fuel Cost (including Increment in Fuel Cost)		7627.59	
Total OPEX (M NRs.)	**215.44**	**7630.37**	

The cost comparison shows that the BESS requires a more upfront capital investment than the diesel generator, with a CAPEX of NRs. 159.49 million compared to NRs. 44.71 million. The most significant difference arises in operating costs, where the BESS incurs a total OPEX of only NRs. 215.44 million, while the diesel generator's OPEX escalates to NRs. 7,630.37 million, mainly due to high and increasing fuel costs. In addition, operation and maintenance expenses for the BESS are considerably lower, while insurance costs remain comparable for both options. When lifecycle costs are considered, diesel generation becomes economically unsustainable for frequent or long-term operation. Overall, the mobile BESS emerges as a far more cost-effective, reliable, and flexible solution for temporary grid support at overloaded substations.

4.4.3. Financial results parameter

The following table 4.6 presents a financial evaluation of a BESS and a diesel generator under different energy selling rates. Key metrics include simple payback period, net present value (NPV) of benefits and costs, benefit-cost ratio, internal rate of return (IRR), and levelized cost of storage/energy (LCOS/LCOE). This comparison illustrates how varying the energy selling price impacts the economic viability of each technology, highlighting trade-offs between upfront investment, long-term returns and cost-effectiveness.

Table 4-6: Financial performance parameter

Parameter	BESS @ Energy Selling Rate (NRs./kWh)		Diesel Generator @ Energy Selling Rate (NRs./kWh)		
	13.5	18.0	13.5	18.0	30.5
Simple Payback Period (Years)	13.06	7.05	-	-	4.37
NPV Benefits (M NRs.)	183.03	244.04	1,553.67	2,071.56	3,510.15
NPV Cost (M NRs.)	244.26	244.26	3,497.95	3,497.95	3,497.95

Parameter	BESS @ Energy Selling Rate (NRs./kWh)		Diesel Generator @ Energy Selling Rate (NRs./kWh)		
	13.5	18.0	13.5	18.0	30.5
NPV Benefits-Cost (M NRs.)	(61.23)	(0.22)	(1,944.27)	(1,426.38)	12.20
Benefit cost ratio	0.75	1.00	0.44	0.59	1.00
IRR	1.67%	9.97%	-	-	6.4%
(LCOS/LCOE) (NRs./kWh)	12.75	12.75	30.74	30.74	30.74

The financial evaluation compares BESS and diesel generation under different energy selling rates and shows that BESS performance improves as the selling tariff increases. At an energy selling rate of NRs. 13.5/kWh, the BESS project is not financially viable, with a negative NPV and IRR of 1.67%. For the viability of BESS with benefit cost ratio to be 1, the energy selling rate to be increased to NRs. 18/kWh, the BESS achieves a positive IRR of 9.97% with a simple payback period of about 7 years, although the NPV remains slightly negative. In contrast, diesel generation shows very high NPV benefits due to higher energy revenues but also extremely high costs, resulting in strongly negative net NPVs at lower tariffs. Even at a high tariff of NRs. 30.5/kWh, the diesel generator only approaches breakeven, with a benefit–cost ratio close to unity and a marginal IRR of about 6.4. The benefit–cost ratio of BESS remains higher than that of diesel at comparable tariffs, indicating better relative efficiency. The LCOS of BESS is around NRs. 12.75/kWh, which is less than half of the diesel LCOE of about NRs. 30.74/kWh. Overall, while both options struggle to achieve strong financial returns at NEA present tariffs, BESS demonstrates lower lifecycle cost, better economic resilience, and superior long-term viability compared to diesel generation.

4.5. Tonne of Oil Equivalent of BESS

Tonne of Oil Equivalent (toe) of BESS is a way to express the energy delivered or displaced by a Battery Energy Storage System in terms of equivalent fossil fuel energy, specifically oil.

The toe associated with a BESS is usually calculated based on the net electrical energy supplied or diesel generation displaced:

$$toe = \frac{\text{Annual energy discharged by BESS (kWh)}}{11630}$$

=1.96*1000000/11630

=168.6

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

This study evaluated the techno-economic feasibility a BESS placement at the NEA, Chanauli 33/11 kV Substation to mitigate transmission/distribution line congestion. Based on detailed analysis of substation load data, seasonal load variation and projected demand growth of 8% increment in load, the existing 33 kV transmission line operates near its thermal limit during summer peak periods and will frequently violate the 16 MVA line limit constraint within the next two years challenging reliability and energy security if NEA does not take any corrective measures immediately.

Using MATLAB based iterative optimization an optimal BESS size of 1.9 MW / 9.1 MWh was determined which also satisfies battery's maximum depth of discharge constraints and minimum state of charge requirements considering battery degradation over the design period of 2 years. The optimized BESS effectively shaves peak demand during critical summer hours by charging during off-peak periods and discharging during peak demand and preventing line overloading without any curtailment of load.

From an economic point of view, the BESS placement demonstrates a clear lifecycle cost advantage over the diesel generator alternative. Even though both options require high capital investment, the diesel generator incurs extremely high operating costs due to fuel consumption and fuel price escalation. However, the BESS exhibits significantly lower and more predictable operating costs. The LCOS of the BESS is approximately NRs. 12.75/kWh which is less than half of the diesel generator’s LCOE i.e NRs. 30.74/ kWh. Financial analysis further indicates that while BESS profitability is sensitive to energy selling tariffs, it performs better than diesel generation under all comparable tariff scenarios.

Moreover, the BESS also contributes to fuel displacement equivalent to approximately 168.6 tonnes of oil equivalent (toe) annually emphasizing its role in reducing fossil fuel dependence, emissions and fuel import.

Overall, the results confirm that mobile BESS provides a technically effective, economically robust and environmentally sustainable temporary solution for transmission line congestion management at the Chanauli Substation until permanent network reinforcement measures are implemented.

5.2. Recommendations

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

1. Nepal Electricity Authority may implement the proposed 2 MW / 10 MWh mobile BESS as per the market availability at Chanauli Substation as an immediate mitigation measure to address summer peak congestion and avoid forced load shedding.
2. BESS should be treated as a means that can be implemented and relocated to other substations facing similar transmission constraints once permanent line upgrades or new transmission lines are commissioned.
3. Diesel generators should be avoided for daily or long duration grid support due to their high operating cost, fuel price escalation and environmental impact. BESS offers superior long term economic and operational performance.
4. For the financial viability of BESS, NEA should consider suitable tariff mechanisms, peak-shaving incentives or ancillary service compensation for BESS placement.
5. Additional analysis on network losses reduction, voltage regulation benefits and ancillary services such as frequency support may further strengthen the case for BESS placement at distribution substations.
6. The methodology adopted in this study can be replicated for other constrained substations within the NEA network to systematically identify locations where mobile BESS as an immediate solution to mitigate the line overloading constructing new line is not feasible.
7. Future studies should assess the integration of BESS with local renewable energy sources such as solar PV to further reduce charging costs and enhance system sustainability.

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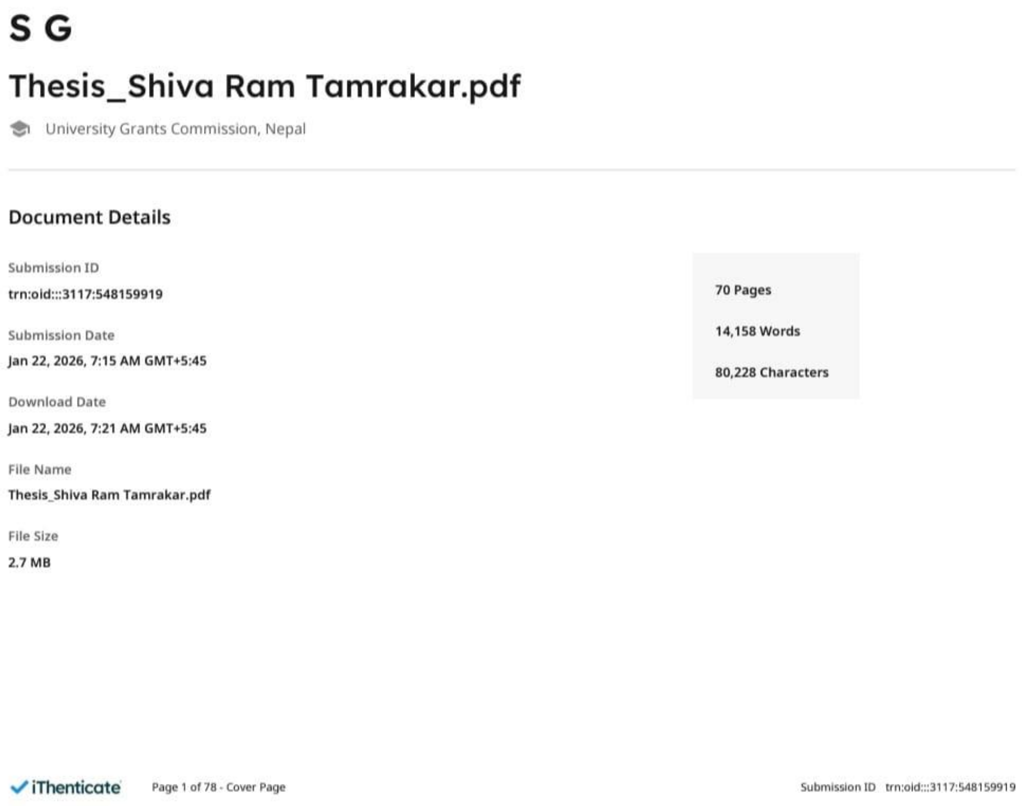
APPENDICES

Appendix 1: Plagiarism



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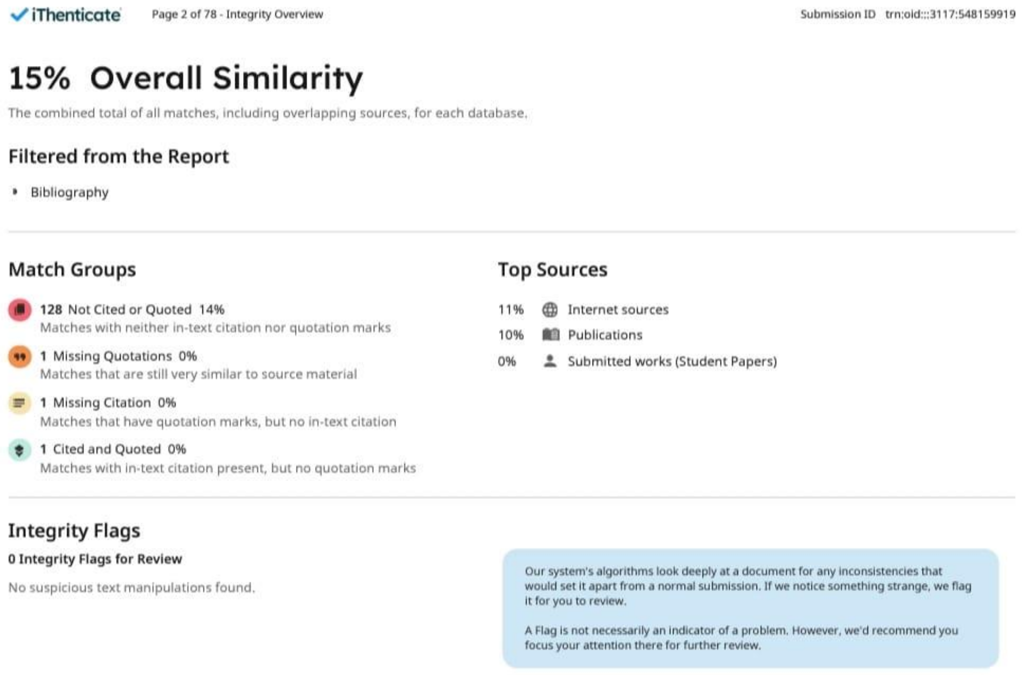

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Appendix 2: Acceptance letter for journal publication

Journal of Science and Engineering (JScE)

ACCEPTANCE LETTER

From:
Chief Editor
Journal of Science and Engineering (JScE)

January 05, 2025

To:
Authors: Shiva Ram Tamrakar, Ajay Kumar Jha and Jeetendra Chaudhary

Dear Authors,

We are pleased to inform you that your manuscript titled "**Feasibility Analysis of Battery Energy Storage Systems in Nepal: A Techno-Economic Case Study of Chanauli 33 kV Substation**" has been accepted for publication in the 13th Volume of the *Journal of Science and Engineering*. This is a UGC-recognized, double-blind, peer-reviewed open-access journal published by Khwopa Engineering College and Khwopa College of Engineering. Once published, your paper will be available on the journal's official website (https://jsce.com.np) and also on Nepal Journal Online (https://www.nepjol.info/index.php/jsce).

Thanking you.

With regards

……………………………
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Appendix 3: Research paper (page1)

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

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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 management—are critical for safe and reliable operation (Nehrir, 2022). Despite growing global adoption, studies on BESS

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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 oper-ational manuals. Key parameters include:

- Conductor type: ACSR DOG (6/1/3.35 mm)
- Maximum current rating: 280 A
- Line Lingth: 21 km
- Resistance: 0.2732 Ohm/km at 20 degree Celcius
- 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 Phosphate) 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

Appendix 5: Research paper (page 3)

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 (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

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

which represents the minimum theoretical energy capacity neglecting lifetime degradation.

Appendix 6: Research paper (page 4)

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:

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

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

If the lifetime constraint in (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.

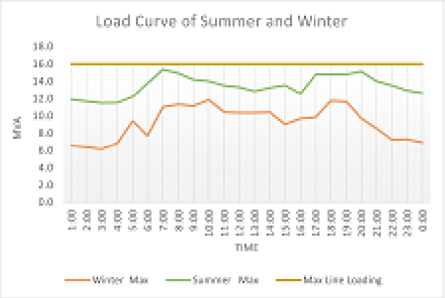

Figure 1. Representative daily load profile of the Chanauli 33/11 kV substation.

- **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 Fig. 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

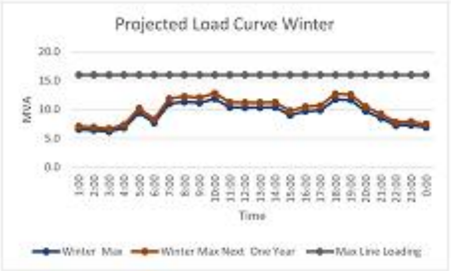

Figure 2. Projected summer peak load under 8% annual demand growth.

satisfy winter peak demand over the next two years, summer peak demand increasingly violates the 16 MVA line limit. As illustrated in Fig. 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 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 9.11 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.

The operational behavior of the optimized BESS is illustrated through simulated charge–discharge profiles and state-of-charge (SOC) trajectories for different time windows. Fig. 3 presents the BESS operation over 31 days in the design year, while Fig. 4 and Fig. 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 Fig. 6, confirming that degradation remains within acceptable limits.

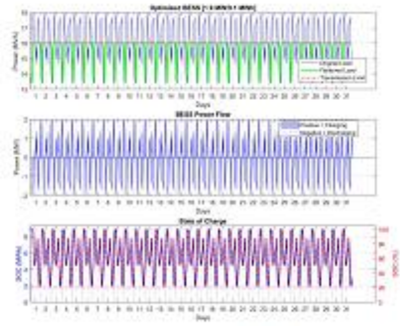

Figure 3. BESS optimization curve for 31 days in designed year

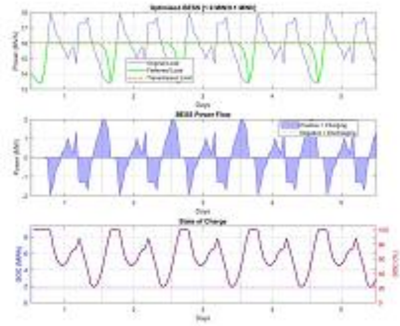

Figure 4. BESS optimization curve for 5 days in designed year

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.

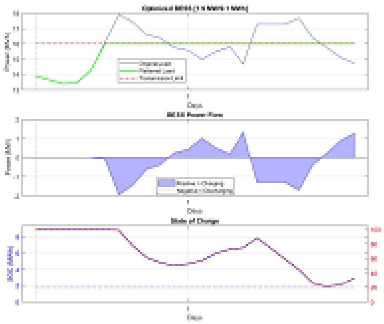

Figure 5. BESS optimization curve for 1 days in designed year

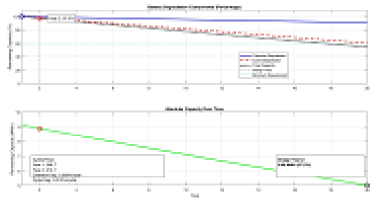

Figure 6. Battery degradation and absolute capacity for designed year

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 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 higher upfront investment (NRs. 159.49 million) compared to the diesel generator (NRs. 44.71 million), the most significant difference arises 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 9.97% 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.

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 addition to direct financial metrics, the BESS provides substantial energy displacement benefits. The annual energy delivered by the BESS corresponds to approximately 168.6 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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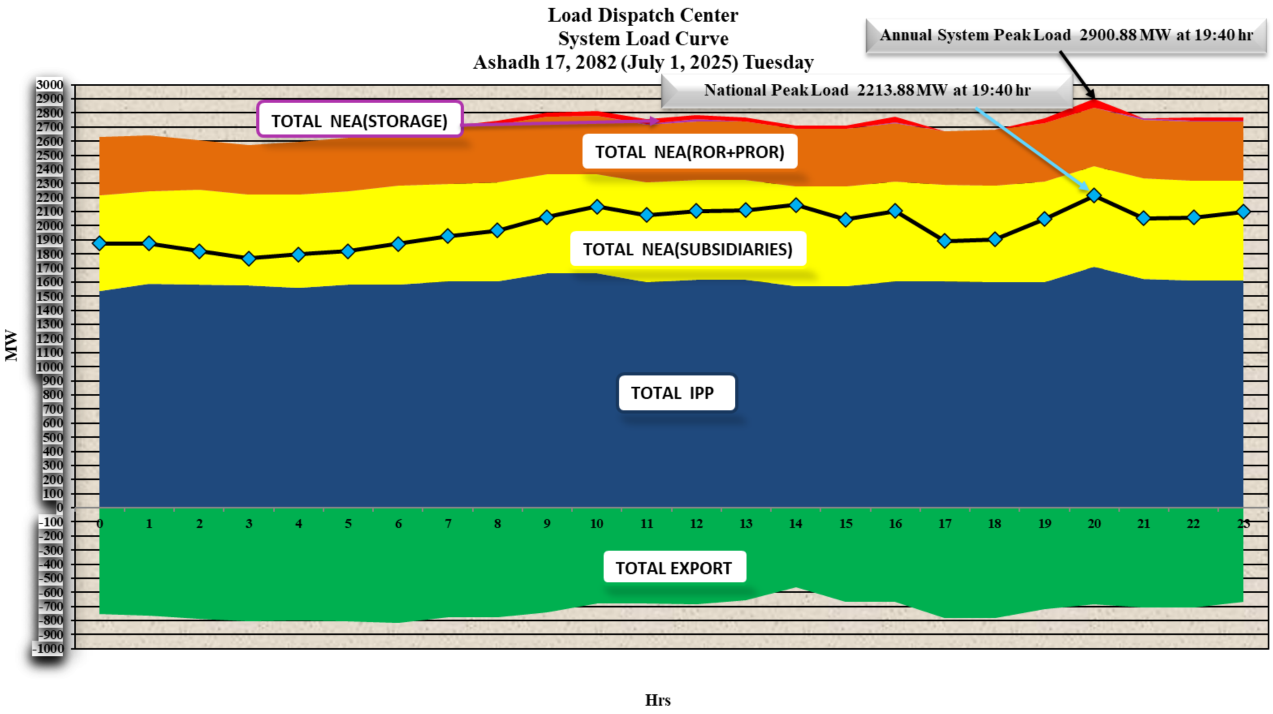
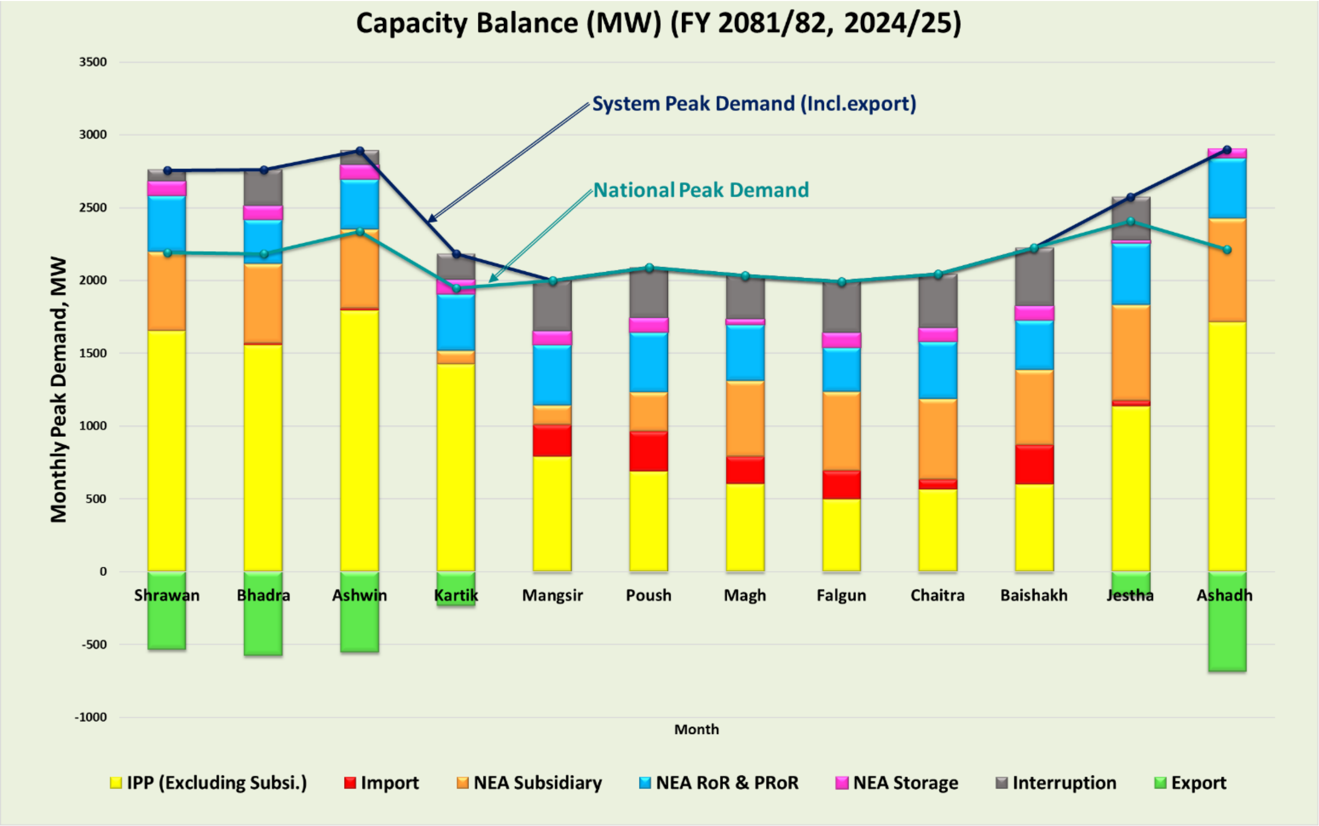
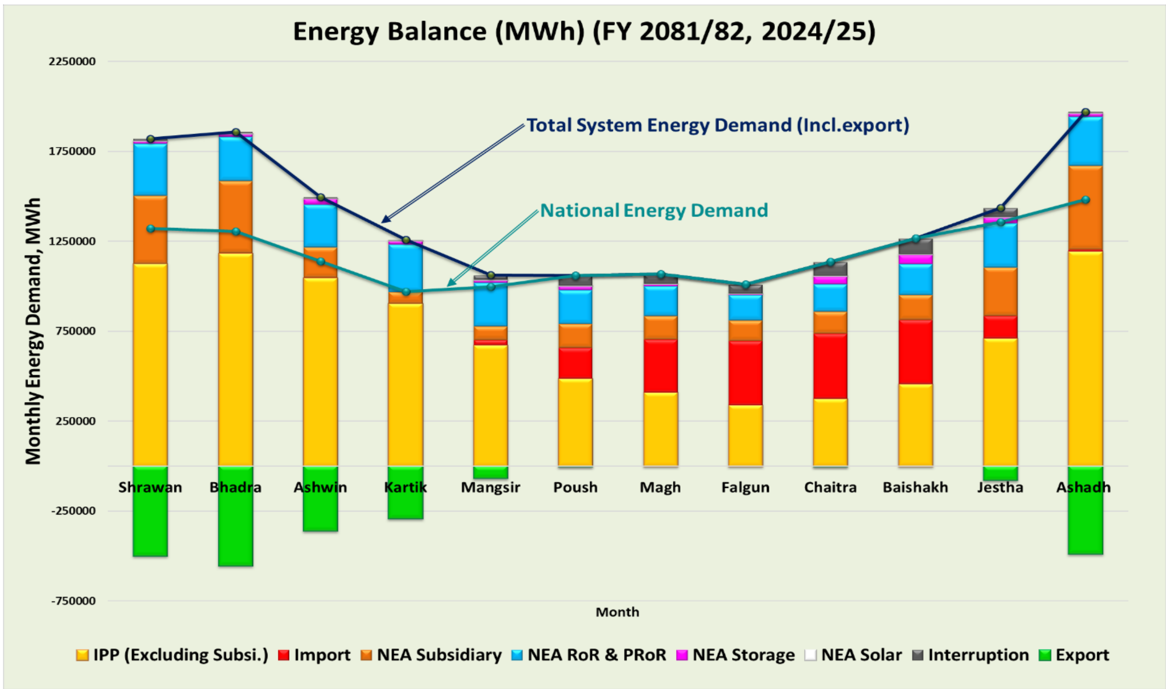
Appendix 11: System load curve (maximum demand)



Appendix 12: Capacity balance (MW) in FY 2081/82 (2024/25)



Appendix 13: Energy balance in GWh of 2081/82 (2024/25)



Appendix 14: Current and projected load profile of summer Season

Time/ Day	Current Summer Max (MVA)	Summer Max Next One Year (MVA)	Summer Max Next Two Year (MVA)
1:00	11.9	12.87	13.90
2:00	11.7	12.63	13.64
3:00	11.5	12.41	13.40
4:00	11.5	12.46	13.46
5:00	12.2	13.22	14.28
6:00	13.8	14.89	16.08
7:00	15.4	16.61	17.94
8:00	14.9	16.13	17.42
9:00	14.2	15.37	16.60
10:00	14.0	15.16	16.37
11:00	13.5	14.59	15.76
12:00	13.3	14.41	15.57
13:00	12.8	13.88	14.99
14:00	13.3	14.34	15.49
15:00	13.5	14.62	15.79
16:00	12.6	13.58	14.67
17:00	14.8	16.00	17.28
18:00	14.8	16.00	17.28
19:00	14.8	16.00	17.28
20:00	15.2	16.38	17.69
21:00	14.0	15.15	16.36
22:00	13.5	14.61	15.78
23:00	13.0	14.00	15.12
0:00	12.6	13.64	14.73

Appendix 15: Current and projected load profile of winter season

Time/ Day	Winter Max (MVA)	Winter Max Next One Year (MVA)	Winter Max Next Two Year (MVA)
1:00	6.6	7.10	7.67
2:00	6.4	6.91	7.47
3:00	6.2	6.67	7.20
4:00	6.8	7.36	7.95
5:00	9.4	10.19	11.00
6:00	7.7	8.32	8.99
7:00	11.0	11.90	12.85
8:00	11.3	12.23	13.21
9:00	11.2	12.06	13.03
10:00	11.9	12.81	13.83
11:00	10.4	11.25	12.15
12:00	10.4	11.19	12.09
13:00	10.4	11.19	12.09
14:00	10.4	11.25	12.15
15:00	9.0	9.76	10.55
16:00	9.7	10.49	11.33
17:00	9.9	10.66	11.52
18:00	11.7	12.69	13.71
19:00	11.7	12.59	13.59
20:00	9.7	10.50	11.34
21:00	8.5	9.22	9.96
22:00	7.2	7.82	8.45
23:00	7.3	7.90	8.53
0:00	6.9	7.48	8.08

Appendix 16: BESS cost estimate

S.N.	Item Description	Unit	Qty.	Unit Cost (USD)	Total Cost (USD)
1	Battery (1.2 kV)	MWh	10	84,000	840,000.00
2	Power Control System (PCS)	MW	2	31,000	62,000.00
3	MV Transformer 3 MVA (0.4/33 kV)	Set	1	65,625	65,625.00
4	Storage Container for Battery (2 MWh per Container) with PCS	No.	5	21,000	105,000.00
5	Transportation, Construction & Installation	LS	1	10,726	10,726.25
6	Land Cost for BESS Container	LS	1	17,143	17,142.86
7	Miscellaneous Cost	LS	1	38,705	38,705.00
Total Cost (USD)					1,139,199.1
Total Cost (NRS)					159,487,875.00

Appendix 17: BESS financial parameter

BESS Size		2	MW
BESS Capacity		10	MWh
Economic Year (Balance of Plant)		15	Years
Daily Battery Cycling		0.57	Cycles
Depth of Discharge (DOD)		0.8	%
Round Trip Efficiency		0.85	%
Useful Life (Battery Cells)		15000	Cycle
Annual calendar degradation rate		0.5	%
Cycle degradation rate		0.01	%
ENERGY PRODUCTION			
Annual Energy Production		1.96	GWh
Annual Energy Discharge		1.96	GWh
ENERGY SALES			
Energy Selling Rate	=	18	NRs/kWh
Battery Charging Rate	=	7.15	NRs/kWh
Discount rate	=	10.00%	
CONSTRUCTION SCHEDULE			
Construction start year	=	2025	Year
Operating start year	=	2026	Year
CAPITAL COST			
Cost in NPR	=	159,487,875.00	NRs.
ANNUAL COST			
Operation & Maintenance costs	=	0.10%	of total cost, annually
Increment in O/M cost	=	2.00%	per annum in O & M cost
Insurance cost	=	0.10%	of total cost, annually
OUTPUT FOR ECONOMIC INDICATORS			
Simple Payback Period	=	7.05	Year
NPV benefits	=	244,043,962.80	NRs.
NPV cost	=	244,259,897.09	NRs.
NPV benefits-cost	=	(215,934.30)	NRs.
Benefit cost ratio	=	1.00	
IRR on the project	=	9.97%	
Levelised Cost of Storage (LCOS)	=	12.75	NRs./kWh

Appendix 18: DG cost estimate

S.N.	**Item Description**	**Unit**	**Qty.**	**Unit Cost (USD)**	**Total Cost (USD)**
1	Diesel Generator	MVA	2.5	125,000	312,500.00
2	Transportation, Construction & Installation	LS	1	6,250	6,250.00
3	Miscellaneous Cost	LS	1	625	625.00
Total Cost (USD)					319,375.00
Total Cost (NRS)					44,712,500.00

Appendix 19: DG financial parameter

DG Size		1.9	MW
DG Capacity		2.5	MVA (Pf is 0.8)
Economic Year (Balance of Plant)		15	Year
Annual Operating Hour		8760	Hr
Fuel Consumption		0.195	Ltr/kWh
Fuel Price		146	NRs./Ltr
ENERGY PRODUCTION			
Annual Energy Production		16.64	GWh
ENERGY SALES			
Energy Selling Rate	=	30.5	NRs/kWh
Discount rate	=	10.00%	
CONSTRUCTION SCHEDULE			
Construction start year	=	2025	Year
Operating start year	=	2026	Year
CAPITAL COST			
Cost in NPR	=	284,371,500.00	NRs.
ANNUAL COST			
Operation & Maintenance costs	=	0.10%	of total cost, annually
Increment in O/M cost	=	2.00%	per annum in O & M cost
Insurance cost	=	0.10%	of total cost, annually
Periodic Maintenace Cost	=	1.00%	of total cost, every five years
Increment in Fuel Cost	=	1.00%	per annum in Fuel Cost
OUTPUT FOR ECONOMIC INDICATORS			
Simple Payback Period	=	4.37	Year
NPV benefits	=	3,510,150,375.22	NRs.
NPV cost	=	3,497,947,043.28	NRs.
NPV benefits-cost	=	12,203,331.94	NRs.
Benefit cost ratio	=	1.00	
IRR on the project	=	6.40%	
Levelised Cost of Energy (LCOA)	=	30.74	NRs./kWh