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DESIGN AND SIMULATION OF A BATTERY ENERGY STORAGE SYSTEM FOR PEAK LOAD SHAVING IN MONGOLIA

Bachelor Thesis

by

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I did not use any sources other than those stated. In case that the work is additionally submitted on a data medium, I declare that the written and the electronic form are completely identical. The work was not submitted in the same or similar form to any examination authority.

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Abstract

Mongolia’s power system faces increasing challenges due to rapid growth in electricity demand and pronounced daily and seasonal peak loads, particularly during evening hours and winter periods. The limited flexibility of existing generation, combined with reliance on electricity imports during peak demand, places significant operational stress on the system and raises concerns regarding reliability. Addressing peak demand has therefore become a critical priority for improving overall system stability and efficiency.

This study investigates the application of a Battery Energy Storage System (BESS) for peak load shaving at the Nalaikh substation, part of the Central Energy System (CES), which supplies the majority of Mongolia’s electricity demand. The Nalaikh substation is selected as a representative case study due to its role as an urban load center and the availability of real operational data.

A simulation-based approach is developed using load data collected over four consecutive days (March 1–4). The model is implemented in Python using the pandapower framework to perform time-series analysis over a 24-hour period. A threshold-based control strategy is applied, where the BESS charges during low-demand periods and discharges during peak demand.

Based on the load analysis, the BESS is designed with a power rating of 6 MW and an energy capacity of 30 MWh, operating within State of Charge (SOC) limits of 15% to 95%. Simulation results show that the system reduces peak load from 60.56 MW to 55 MW, corresponding to a reduction of 5.56 MW (9.2%). The load profile becomes smoother, and the load factor increases from 88.42% to 96.84%, indicating improved system utilization.

The results confirm that BESS is a practical and effective solution for peak load management at the substation level. The proposed system enhances grid flexibility, reduces operational stress, and improves the efficiency of the power system.

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Abbreviation

AC	Alternating Current
ADB	Asian Development Bank
AUES	Altai-Uliastai Energy System
BESS	Battery Energy Storage System
BMS	Battery Management System
CES	Central Energy System
CHP	Combined Heat and Power Plant
DC	Direct Current
DSM	Demand-Side Management
EES	Eastern Energy System
IPG	Interconnected Power Grid
kV	Kilovolt
kWh	Kilowatt-hour
MW	Megawatt
MWh	Megawatt-hour
PCS	Power Conversion System
SOC	State of Charge
WES	Western Energy System

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1. Introduction

The electricity demand in Mongolia has increased steadily over the past decade due to population growth, urbanization, and the expansion of industrial activities. The majority of the country's electricity demand is supplied by the Central Energy System (CES), which covers the main load centers, including Ulaanbaatar and surrounding regions. In 2024, the CES accounted for 88.8% of the total electricity demand in Mongolia, making it the most important power system in the country [1].

One of the major operational challenges faced by the Mongolian power system is the significant variation between peak and off-peak electricity demand. Peak load occurs when electricity consumption reaches its maximum level within a given period, typically during the evening hours. In Mongolia, peak demand is especially pronounced during winter due to extremely low temperatures and increased electricity usage for heating and residential consumption.

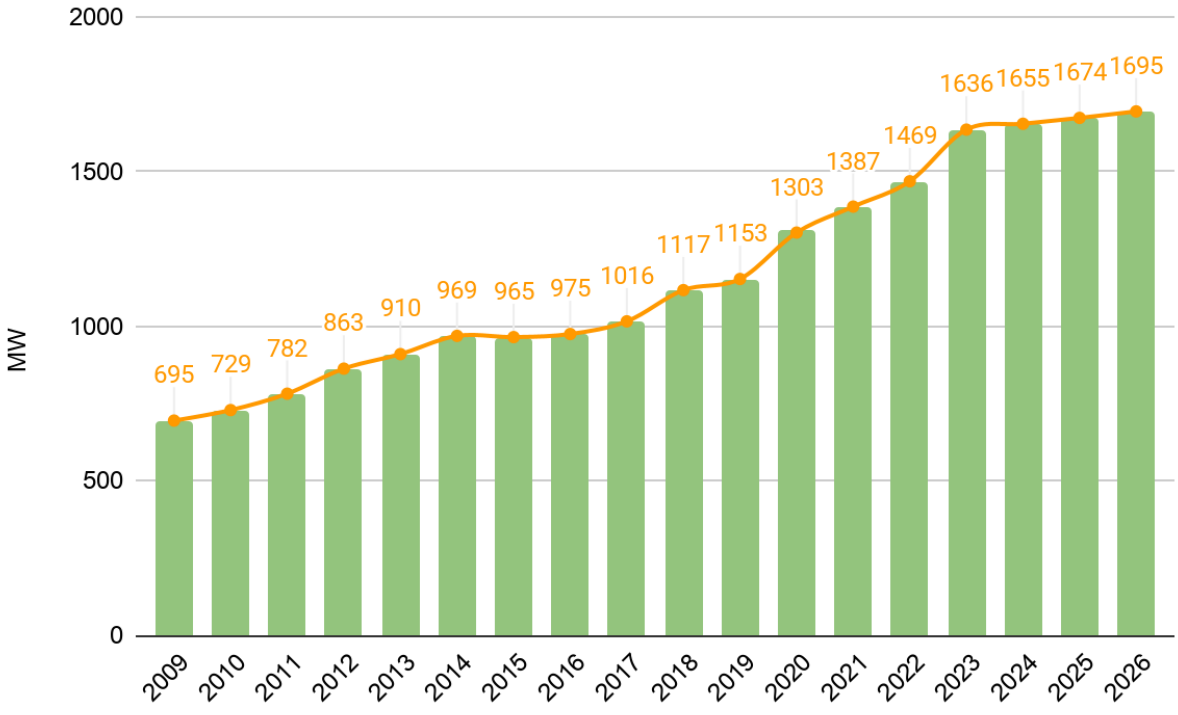


Figure 1: Historical CES Peak Load

Source: Ministry of Energy and [2]

Figure 1 illustrates the historical growth of peak load in the Central Energy System (CES), showing a significant and consistent upward trend over the past decade and beyond. The peak demand increased from approximately 695 MW in 2009 to about 1,695 MW in 2026, representing more than a twofold increase. This corresponds to an average annual growth rate of roughly 5–6%, highlighting the rapid expansion of electricity demand in Mongolia. This continuous increase in electricity demand places additional pressure on the existing power generation infrastructure.

Table 1: Historical CES Peak load [2]

Year:	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
P_{max}, MW	695	729	782	863	910	969	965	975	1016
Growth, %	3.3	4.9	7.3	10.3	5.4	6.5	-0.4	1.0	4.2
Year:	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
P_{max}, MW	1117	1153	1309	1387	1469	1636	1655	1674	1695
Growth, %	9.9	3.2	13.5	6.0	5.9	11.4	1.2	1.2	1.3

Table 1 presents the annual peak load of the CES together with the corresponding yearly growth rates. While Figure 1 illustrates the overall upward trend, the table shows that growth is not uniform across years. For example, notable increases appear in 2012 (10.3%), 2020 (13.5%), and 2023 (11.4%), whereas some years reflect slower growth or even a slight decrease, such as 2015 (-0.4%).

It is important to note that the value reported for 2026 (1,695 MW) does not represent a full-year peak, but rather a recorded value as of January 26, 2026.[3] The final annual peak for 2026 is therefore expected to be higher.

Another important characteristic of Mongolia's electricity demand is the large difference between daily minimum and maximum load levels. During winter peak periods, the daily electricity consumption in the CES ranges from 18 to 23 million kWh, while the difference between minimum and maximum load can reach 280–350 MW.[2] Such large fluctuations create operational challenges for power plants and grid operators, who must ensure that sufficient generation capacity is available to meet peak demand.

1.1 Importance of Battery Energy Storage Systems (BESS)

Battery Energy Storage Systems (BESS) have become an important technology for improving the flexibility and reliability of modern power systems. By storing energy during low-demand periods and supplying it during peak demand, BESS helps balance electricity supply and demand.

One of the key applications of BESS is peak load shaving, where stored energy is discharged during peak hours to reduce the maximum load on the power grid. This reduces stress on power plants and enhances overall system stability.

This is particularly relevant for Mongolia's power system, where electricity demand exhibits strong daily and seasonal variations. During high-demand periods, especially in winter, power plants often operate near their capacity limits. In such conditions, BESS can provide additional support by reducing peak demand and improving system reliability.[2,4]

Recent developments in Mongolia further highlight the growing importance of BESS in real-world applications. Several large-scale projects have been implemented, including the Tsenggleg BESS (0.6 MW / 3.6 MWh), Songino BESS (80 MW / 200 MWh), Baganuur BESS (50 MW / 200 MWh), and Erdene BESS (20 MW / 80 MWh). These systems actively support grid operation by contributing to peak load management, frequency and voltage regulation, and overall system stability.[4]

In 2024, the operation of BESS in Mongolia reduced peak electricity imports by approximately 31.46 MW, resulting in significant economic benefits, including savings of around 16.4 billion MNT.[4] These results demonstrate that BESS is already being successfully applied in Mongolia and is an effective solution for managing peak demand and improving grid performance.

1.2 Objective of the study

The objective of this study is to design and evaluate a Battery Energy Storage System (BESS) for peak load shaving at the Nalaikh substation. The Nalaikh area was selected as the case study due to the availability of real operational data and its relatively manageable system scale, which enables a more accurate and practical analysis.

The study aims to identify peak demand characteristics and determine an appropriate BESS configuration, including power rating and energy capacity. A simulation model is developed using the pandapower framework in Python to analyze the operation of the BESS under realistic load conditions.

The effectiveness of the BESS is evaluated in terms of its ability to reduce peak demand, smooth the load profile, and improve overall system performance.

1.3 Scope and limitations

This study focuses on the application of BESS for peak load shaving at the Nalaikh substation within the Mongolian power system. The research includes analysis of real operational load data, development of load profiles, and simulation-based evaluation of BESS performance using the pandapower framework.

A case study approach is adopted using measured data from the Nalaikh substation to investigate daily load variations and identify peak demand periods. Based on this analysis, a BESS is designed and its operation is simulated to assess its ability to reduce peak load, smooth the load curve, and improve system performance. The study aims to provide practical insights into the use of energy storage systems for load management in distribution-level networks in Mongolia.

Despite the structured approach taken in this research, several limitations should be noted:

- Data availability: The analysis is based on load data collected over a limited period of four consecutive days. Due to data access restrictions and the confidentiality of operational information, extended datasets were not available. While the selected data captures typical daily load patterns, it may not fully represent long-term seasonal or operational variations.
- Simplified modeling: The simulation is performed at a substation level using a simplified representation of the system. Detailed network characteristics such as line constraints, voltage variations, and protection systems are not explicitly modeled.
- Assumptions in system parameters: Certain parameters, including power factor, battery efficiency, SOC operating range and operational constraints, are assumed to be constant, which may differ from real-world operating conditions.

- Economic considerations: This study does not include a detailed cost-benefit or financial analysis of BESS implementation. Therefore, it cannot provide a comprehensive economic evaluation of the proposed solution, which is an important factor in real-world decision-making.
- Environmental factors: The study does not consider the environmental impacts associated with BESS implementation, including material sourcing, recycling, and end-of-life disposal. These aspects may be important for a comprehensive assessment of sustainability.

2. Literature Review

2.1 Peak Load in Power Systems

Peak load refers to short periods when electricity demand rises sharply above normal operating levels, placing stress on generation, transmission, and distribution assets.[5] Because these peaks are usually brief, building new capacity only to cover them can be economically inefficient, since equipment remains underutilized for most of the day.[6] For that reason, peak shaving is widely treated as a way to defer network expansion and reduce reliance on expensive peaking generators.[5]

2.2 Methods for Peak Load Reduction

Several strategies have been developed to reduce peak electricity demand and improve system efficiency. One widely adopted approach is Demand-Side Management (DSM), which encourages consumers to shift or reduce electricity usage during peak periods through mechanisms such as time-of-use pricing and demand response programs [5,6].

Load shifting techniques also play an important role by transferring energy consumption from peak periods to off-peak periods. This can be achieved through technologies such as thermal storage systems, smart grid control, and electric vehicle charging management [5].

Among the available solutions, Battery Energy Storage Systems (BESS) have emerged as one of the most effective technologies for peak load reduction. BESS can store energy during periods of low demand or excess generation and discharge it during peak periods, thereby reducing the maximum load on the grid. Their fast response time and operational

flexibility make them particularly suitable for peak shaving and integration with renewable energy sources.

In addition to these methods, improvements in grid infrastructure and the deployment of distributed energy resources further enhance system flexibility. However, compared to other approaches, BESS provides a direct and controllable solution for managing peak demand, making it a key focus of this study.

2.3 BESS Technology

A Battery Energy Storage System (BESS) is a technology that converts and stores energy in chemical form and later releases it as electrical energy. Several types of batteries are commonly used in power systems, including Lead-acid, Lithium-ion (Li-ion), Nickel-Cadmium (Ni-Cd), Nickel-Metal Hydride (NiMH), and Sodium-Sulfur (NaS) batteries [7]. Table 2 presents a comparison of the main performance characteristics of these battery technologies.

Table 2: Performance of the different types of batteries [7]

Type of battery	Ni-Cd	Lead acid	Li-ion	NiMH	NaS
Cell Voltage (V)	1.0-1.3	2.0	3.7	1.0-1.3	2.08
Life cycle	2000-2500	500-1000	1000-10000	300-500	2500
Energy density (Wh/L)	60-150	50-80	200-500	~170-420	150-250
Efficiency (%)	~ 72-78	85	~ 97	~ 85	85
Self-Discharge/Daily (%)	~ 20-60	~ 10-20	~ 10-30	~ 5-20	~ 0

From this comparison, Lithium-ion batteries are widely considered the most suitable option for modern energy storage applications. They offer several advantages, including a long life cycle (up to 10,000 cycles), high energy density (200–500 Wh/L), relatively low self-discharge rates, and high efficiency (up to approximately 97%) [7]. These

characteristics make Li-ion batteries particularly appropriate for large-scale grid applications.

Figure 2 presents the typical applications of BESS based on their operational duration. The figure shows that different grid services require different discharge time ranges, highlighting the versatility of BESS in power system applications.

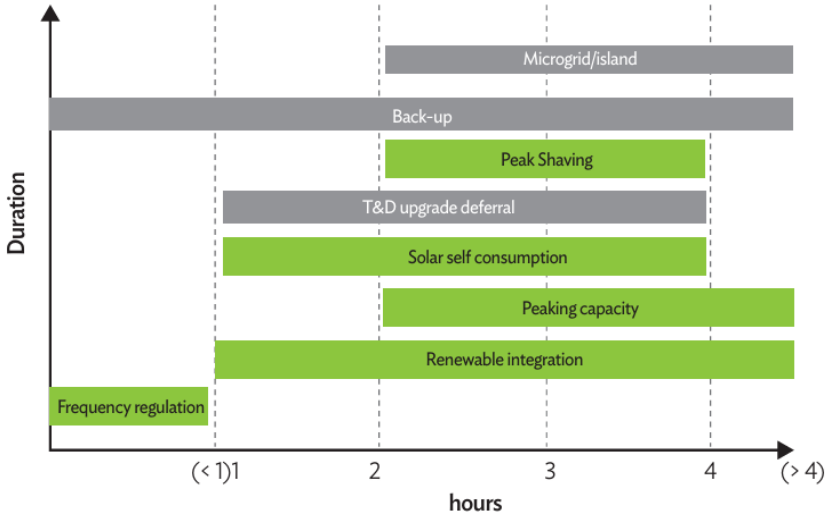


Figure 2: Stackable Value Streams for BESS projects

Source: Korea Battery Industry Association 2017 "Energy storage system technology and business model."

Short-duration applications, typically less than one hour, include frequency regulation, where fast response is required to maintain system stability. Medium-duration applications, ranging from approximately 1 to 4 hours, include peak load shaving, renewable energy integration, and solar self-consumption. Among these, peak shaving is one of the most practical applications, as it directly reduces the maximum load on the power grid during high-demand periods.

Longer-duration applications, exceeding four hours, include backup power supply and microgrid or islanded operation, which require sustained energy delivery over extended periods. This classification demonstrates that BESS can support a wide range of power system functions depending on its design and operational strategy.

2.4 Control Strategies for Peak Shaving

Effective peak shaving depends not only on the size of the BESS but also on the control strategy used during operation. Control strategies determine how and when the battery charges and discharges in response to system load conditions.

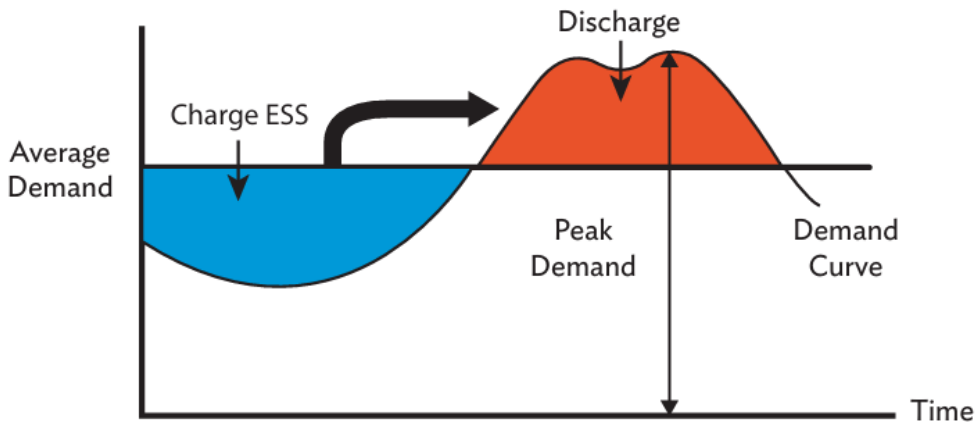


Figure 3: Use of Energy Storage Systems for Peak Shaving

Source: Korea Battery Industry Association 2017 "Energy storage system technology and business model."

Figure 3 illustrates the basic principle of peak load shaving using an energy storage system. During periods of low demand, the battery charges by storing excess energy. During peak demand periods, the stored energy is discharged to reduce the maximum load on the power grid [5]. This process effectively shifts energy from off-peak to peak periods, resulting in a smoother load profile.

Various control methods have been proposed in the literature. Advanced approaches include load forecasting-based control, where system demand is predicted using real-time or historical data to optimize battery operation [6]. Other strategies aim to minimize load variance or reduce the peak-to-valley difference, improving overall load smoothing performance.[6]

In this study, a threshold-based control strategy is adopted due to its simplicity and practical applicability. In this approach, a predefined load limit is set, and the battery discharges when demand exceeds the threshold, while charging when demand falls

below it [7,8]. This method enables efficient energy shifting from off-peak to peak periods, directly reducing peak demand and improving system performance [5].

In addition, peak shaving reduces the need to operate expensive peaking generators and can delay investments in new generation capacity [5]. Therefore, an appropriate control strategy plays a critical role in maximizing the effectiveness of BESS in power system applications.

2.5 Black start Capability of BESS

Battery Energy Storage Systems (BESS) can also provide *black start capability,* which refers to the ability to restore power to a portion of the electrical grid without relying on an external power source. In the event of a total system blackout, conventional power plants require external electricity to start auxiliary equipment such as pumps, fans, and control systems. However, when the grid is completely de-energized, this external supply is unavailable. Black start resources are therefore required to initiate the restoration process [9].

Traditionally, black start capability has been provided by hydroelectric plants, diesel generators, or gas turbines. In recent years, BESS has emerged as a viable alternative due to its fast response time, high reliability, and ability to operate independently of fuel supply. Unlike conventional generators, BESS can deliver power almost instantaneously and establish voltage and frequency in an islanded system, making it suitable for initiating system restoration [10].

In a typical black start sequence using BESS, the battery first energizes a local section of the grid and establishes stable voltage and frequency conditions. It then supplies the necessary auxiliary power required to start larger generation units. Once these generators are operational, the system is gradually reconnected, and normal grid operation is restored [11].

The importance of BESS in black start applications has increased with the growing penetration of renewable energy sources. Since renewable generation is intermittent and may not be available during system restoration, energy storage provides a controllable and reliable source of power for initiating the recovery process. Furthermore, studies have shown that BESS can improve system recovery speed and reduce voltage and frequency fluctuations during restoration [12].

2.6 Previous Simulation Studies

Recent simulation studies show that Battery Energy Storage Systems (BESS) can significantly reduce peak load demand by charging during off-peak periods and discharging during peak hours, thereby flattening the load curve and improving system reliability. In several studies, peak load reductions of up to approximately 30% have been reported, depending on system configuration and control strategy.

Simulation-based analyses typically evaluate key parameters such as battery capacity, charge–discharge scheduling, and state-of-charge (SOC) limits, using platforms such as MATLAB/Simulink, PSCAD, and DIgSILENT PowerFactory. Advanced approaches combine optimization techniques, such as mixed-integer programming, with rolling load forecasting methods, improving peak shaving performance.

Results from various case studies indicate that relatively moderate battery capacities, typically in the range of 8–16 MWh for a 4 MW system, can achieve substantial peak reduction while limiting battery degradation to approximately 1.2 full-equivalent cycles.



Figure 4: Songino BESS



Figure 5: Baganuur BESS

Real-world projects further support these findings. In Mongolia, the Baganuur (50 MW / 200 MWh) and Songino (80 MW / 200 MWh) BESS installations have demonstrated effective peak demand support [1,2,4]. The Songino system, connected to the 220/110/35 kV substation in Ulaanbaatar and commissioned in December 2023 with support from the Asian Development Bank ADB), is capable of supplying electricity to approximately 25,000 households and plays a key role in improving grid flexibility and reliability in the Central Energy System (CES) [2].

Internationally, large-scale systems such as the Hornsdale Power Reserve (150 MW / 194 MWh) [13] and the Moss Landing facility (400 MW / 1600 MWh) [14] confirm the role of BESS in enhancing grid flexibility and renewable energy integration. These international projects demonstrate that battery energy storage systems play a crucial role in modern power systems by reducing peak demand, supporting renewable energy integration, and improving grid stability.

Table 3: BESS projects

Project	Country	Power (MW)	Energy Capacity (MWh)	Year
Tsenggleg BESS	Mongolia	0.6	3.6	~
Baganuur BESS	Mongolia	50	200	2024
Songino BESS	Mongolia	80	200	2023
Erdenenar BESS	Dornogovi, Mongolia	20	80	2025
Hornsdale Power Reverse	Australia	150	194	2017
Moss Landing BESS	USA	400	1600	2020

However, despite the growing implementation of BESS projects in Mongolia, there is still limited academic research focusing on detailed simulation and analysis of battery energy storage applications for peak load shaving in the Mongolian power system. Therefore, further simulation-based research is necessary to evaluate the optimal design and operational strategies of BESS for supporting the CES and reducing peak demand under local conditions.

3. Power System Overview of Mongolia

The Mongolian power system is heavily dependent on coal-fired combined heat and power (CHP) plants, which account for a large share of electricity generation. These thermal power plants generally operate under relatively stable load conditions and have limited flexibility to rapidly adjust their output in response to sudden changes in demand. As electricity demand continues to grow and new generation capacity has been delayed, the existing CHP plants often operate at capacity factors above 90% during winter peak periods, leaving limited reserve capacity for the system.[2]

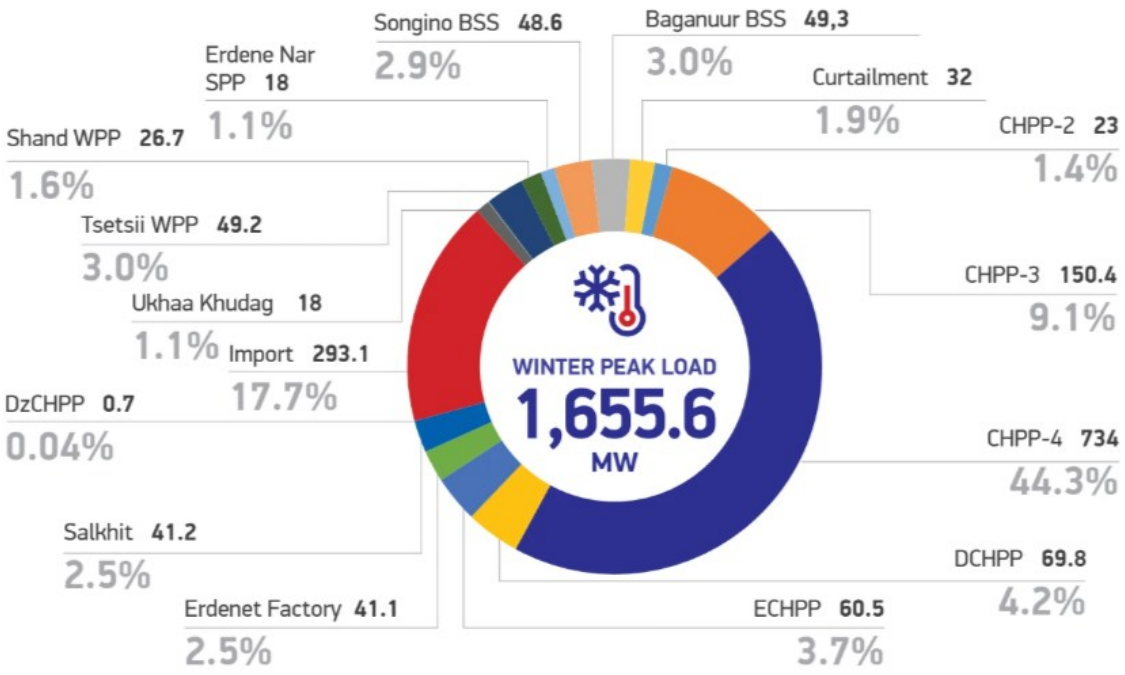


Figure 6: Contribution of Power Plants to the Peak Load of the IPG

Source: [1]

This situation is clearly reflected in Figure 6, which shows the winter peak load distribution of approximately 1,655.6 MW. A large portion of the demand is supplied by major CHP plants, particularly CHP-4, which alone contributes over 44% of the total load. At the same time, a considerable portion is covered by electricity imports from neighboring countries, particularly from the Russian power grid, highlighting the system's dependence on external support during peak conditions. This dependence reflects the limited reserve capacity and flexibility of the domestic power system.

The Mongolian power system is divided into several regional power grids that operate semi-independently:

- Central Energy System (CES)
- Western Energy System (WES)
- Altai-Uliastai Energy System (AUES
- Eastern Energy System (EES)
- Southern Region Power Supply System

These systems are only weakly interconnected, which limits the ability to transfer electricity between regions and reduces overall system flexibility [15,16].

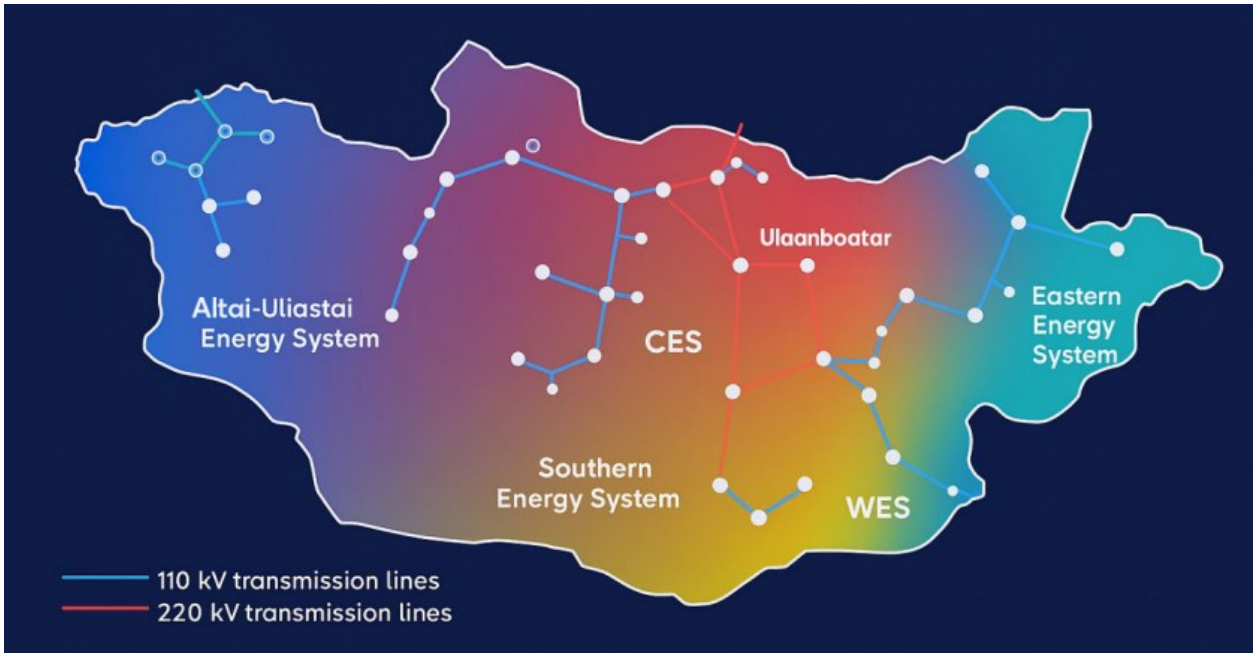


Figure 7: Mongolian Power System Grid Connection

Source: Energy Regulatory Commission, 2023 [16]

Figure 7 illustrates the national transmission network and major generation sources. The Central Energy System is clearly the dominant grid, supplying the largest share of electricity demand, particularly in Ulaanbaatar.

3.1 Power Generation and Transmission Infrastructure

Mongolia's electricity generation mix consists of thermal power plants, hydropower plants, renewable energy sources, and diesel generators. Among these, CHP plants play the most important role, as they simultaneously generate electricity and heat for urban areas [1,2,4].

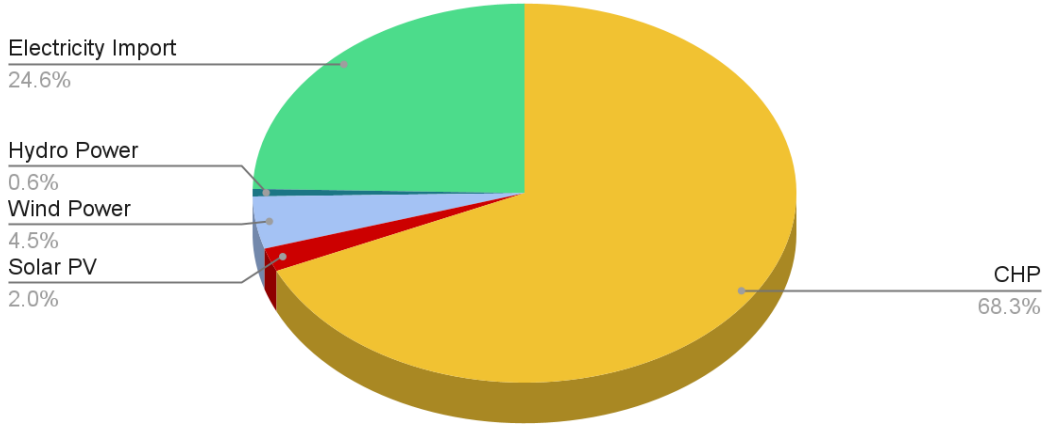


Figure 8: Mongolia's Power Supply Mix, 2024

Source: Energy Statistics 2024 Report [1]

Figure 8 shows that CHP plants dominate electricity generation, accounting for the largest share, while renewable energy sources such as wind and solar contribute a smaller portion. Imports also represent a significant share of supply, highlighting the system's dependence on external energy sources.

The largest generation facilities are located in the Central Energy System, including major CHP plants such as CHP-3 and CHP-4. CHP-4, with a capacity of over 600 MW, is the largest power plant in Mongolia and supplies a major portion of Ulaanbaatar's electricity demand [1,2].

Electricity generated by these plants is transmitted through high-voltage transmission networks, primarily at 220 kV and 110 kV levels. The National Power Transmission Grid operates these transmission lines and substations across the country. Power is then distributed to consumers through medium- and low-voltage networks [2].

However, the transmission system faces several challenges, including aging infrastructure, high transmission losses (over 13%), and limited interconnection between regional grids [16]. These factors reduce system efficiency and increase the risk of supply shortages during peak demand periods.

3.2 CES Operation and Load Characteristics

The Central Energy System (CES) is selected as the focus of this study due to its high load concentration and critical role in Mongolia's power system. In particular, the Nalaikh substation, which is part of the CES, is a typical urban load center where peak-demand issues are prominent.

At the operational level, the CES exhibits clear daily load variations. Electricity demand remains relatively stable during nighttime and early daytime, then increases significantly during evening hours. Peak demand typically occurs between 18:00 and 21:00, mainly driven by residential consumption, including heating, lighting, and appliance usage. Similar daily load patterns have been observed in urban power systems where residential demand dominates peak behavior [17].

Seasonally, the CES experiences even more extreme variations. During winter, electricity demand increases significantly due to heating requirements, as Mongolia experiences very low temperatures that can fall below −30 °C. This leads to a sharp increase in electricity consumption and causes peak loads to approach or exceed

available generation capacity, requiring electricity imports to maintain system stability [18]. In contrast, summer demand is relatively stable and lower, allowing generation units to operate with greater flexibility and reduced operational stress.

4. Methodology

This thesis aims to investigate the application of a Battery Energy Storage System (BESS) for peak load shaving at the Nalaikh substation. To achieve this objective, a methodology was developed that combines real data acquisition, load profile modeling, BESS sizing, and performance simulation using the *pandapower* framework in Python. Figure 9 illustrates the overall methodology adopted in this study.

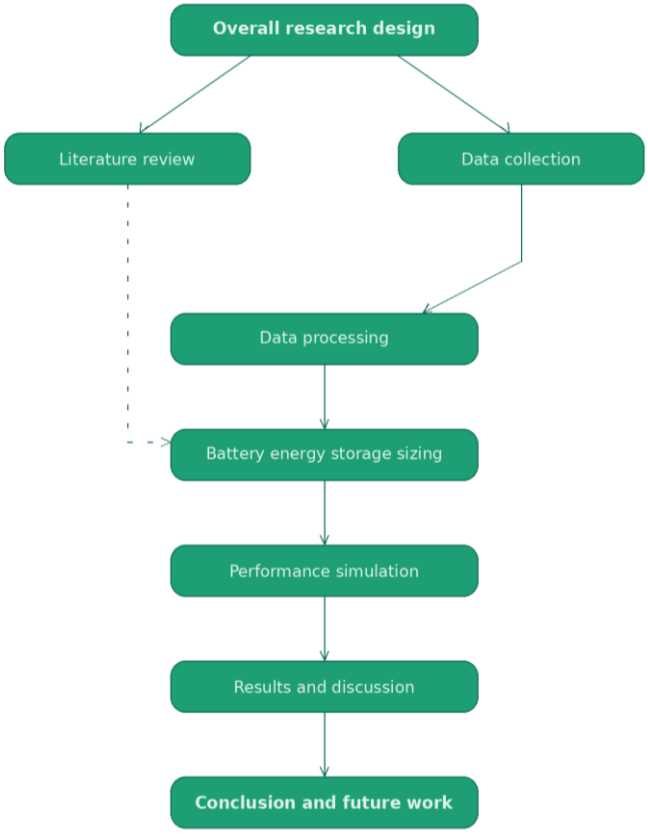


Figure 9: Research methodology

4.1 Data collection and processing

The load data used in this study was obtained from the Nalaikh substation operational records. Due to data availability constraints, a dataset covering four consecutive days was collected.

The original data was recorded in terms of electrical current (A). To obtain the total load profile, the following processing steps were applied:

- Extraction of hourly total load values

- ❖ Conversion of current (A) into active power (MW) using the three-phase power equation
- ❖ A power factor of 0.9 is assumed as a typical value for distribution-level systems based on standard operational conditions
- ❖ Construction of hourly load profiles for each day

The processed data were used to develop representative daily load profiles for simulation.

4.2 Load Profile Modeling

Load profile modeling is essential for evaluating the performance of the Battery Energy Storage System (BESS) in peak load shaving applications. In this study, the load profile is developed based on real measured data obtained from the Nalaikh substation, rather than using a purely theoretical or simplified demand curve.

The processed dataset consists of hourly load values over four consecutive days. These measurements are converted into power (MW) and used to construct daily load profiles representing the variation of electricity demand over a 24-hour period.

The developed load profiles exhibit consistent daily patterns, characterized by:

- relatively stable demand during early hours,
- a slight reduction in load during midday periods,
- a significant increase in demand during evening hours,
- peak load typically occurring between 18:00 and 22:00.

By analyzing multiple days of data, the consistency and repeatability of the load pattern are verified. This ensures that the modeled load profile accurately represents typical operating conditions of the Nalaikh substation. The resulting load profiles are directly used as input for the simulation model.

4.3 BESS System Design Method

The Battery Energy Storage System (BESS) is designed to support the power system by reducing peak electricity demand. In this study, the BESS operates by storing electrical energy during periods of low demand and supplying that energy back to the

grid during peak demand periods. This operation helps reduce the maximum load on the power system and improves system flexibility.

The design of the BESS includes several important technical parameters, including battery capacity, power rating, charging and discharging strategy, and the state-of-charge (SOC) operating limits. These parameters are defined in order to simulate the behavior of the battery system within the electricity demand model.

4.3.1 Battery Energy Capacity

Battery capacity represents the total amount of electrical energy that the battery can store. It is typically expressed in megawatt-hours (MWh). The battery capacity determines how much energy can be stored during off-peak periods and how long the battery can supply electricity during peak demand.

The required battery energy capacity can be estimated using the following equation:

$$E_{BESS} = P_{peak} * t \qquad (1)$$

where:

- E_{BESS}= Battery energy capacity (MWh)
- P_{peak}= Power supplied by the battery during peak demand (MW)
- t = Duration of battery discharge (hours)

For peak load shaving applications, the battery is typically designed to supply energy for 2–4 hours during peak demand periods.

4.3.2 Battery Power Rating

The power rating of the battery system determines the maximum power that the battery can deliver to the grid or absorb from the grid. It is expressed in megawatts (MW). The power rating is important because it defines how much the battery can reduce the system's peak load.

In this study, the required power rating is determined based on the difference between the observed peak demand and the selected threshold value:

$$P_{BESS} = P_{peak} - P_{th} \qquad (2)$$

where:

- P_{BESS} = Battery power rating (MW)
- P_{peak}= maximum system load (MW)
- P_{th} = desired peak load threshold (MW)

4.3.3 Charging and Discharging Strategy

The operation of the battery system is controlled through a charging and discharging strategy. The BESS operates according to the electricity demand profile modeled in the previous section.

During low-demand periods, typically during nighttime hours, the battery charges by storing energy from the grid. During peak demand periods, particularly during the evening peak, the battery discharges and supplies energy to the system.

This strategy allows the battery to shift energy from periods of low demand to periods of high demand, effectively reducing the peak load experienced by the power system.

4.3.4 State of Charge (SOC) Limits

The State of Charge (SOC) represents the percentage of energy stored in the battery relative to its maximum capacity. Maintaining appropriate SOC limits is important for protecting the battery and ensuring stable operation.

The SOC can be expressed as:

$$SOC = \frac{E_{stored}}{E_{max}} * 100 \qquad (3)$$

where:

- SOC = State of Charge (%)
- E_{stored} = Energy currently stored in the battery (MWh)
- E_{max}= Maximum battery capacity (MWh)

To maintain safe operation and extend battery lifetime, the battery is typically operated within SOC limits of:

- Minimum SOC: 15%
- Maximum SOC: 95%

These limits prevent deep discharge and overcharging of the battery system.

4.4 Simulation Platform

To evaluate the effectiveness of the Battery Energy Storage System (BESS) for peak load reduction, a simulation model is developed using Python with the pandapower framework. Pandapower is an open-source Python-based tool designed for power system analysis, particularly for distribution and transmission network modeling. It provides functions for power flow calculation, network element modeling, and time-series simulation, making it suitable for studying the interaction between load demand and energy storage systems [19]

Pandapower was selected due to its capability for efficient power flow analysis and flexibility in modeling distribution-level systems. The framework allows easy integration of custom control strategies, such as the threshold-based peak shaving method used in this study.

The model is designed to analyze battery behavior under varying load conditions, including charging during low-demand periods and discharging during peak demand. By comparing system load before and after BESS integration, the model enables evaluation of peak load reduction and overall system performance.

5. Case Study: Nalaikh Substation Load and BESS Application

5.1 Overview of Nalaikh Power System

The Nalaikh district is supplied by a 110/35/10 kV substation equipped with two 25 MVA transformers, which are connected to the Central Energy System (CES) through a 110 kV transmission network. The substation plays a critical role in supplying electricity to residential, industrial, and commercial consumers within the district.

In recent years, electricity demand in Nalaikh has increased significantly due to urban development and industrial growth. According to available data, the district load has grown from approximately 14.5 MW in 2020 to around 32 MW in 2023, while total electricity consumption has also increased substantially [20].

The distribution of electricity consumption by sector shows that 49% is used for industrial purposes, 15% for residential apartments, and 36% for households in ger (traditional housing) areas. This distribution highlights the mixed nature of the load, combining industrial and residential demand, which contributes to the variability of the load profile. In terms of electricity supply, approximately 98.4% of consumers are connected to the centralized power system, while 0.7% use renewable energy systems, and the remaining 0.9% rely on small-scale generators [20].

This rapid increase in demand highlights the importance of efficient load management strategies to ensure reliable and stable operation of the power system.

5.2 Load Characteristics of Nalaikh Substation

The load characteristics of the Nalaikh substation are analyzed using measured hourly data collected over four consecutive days (March 1–4, 2026). The data is processed and converted into power values (MW) to construct representative 24-hour load profiles for each day.

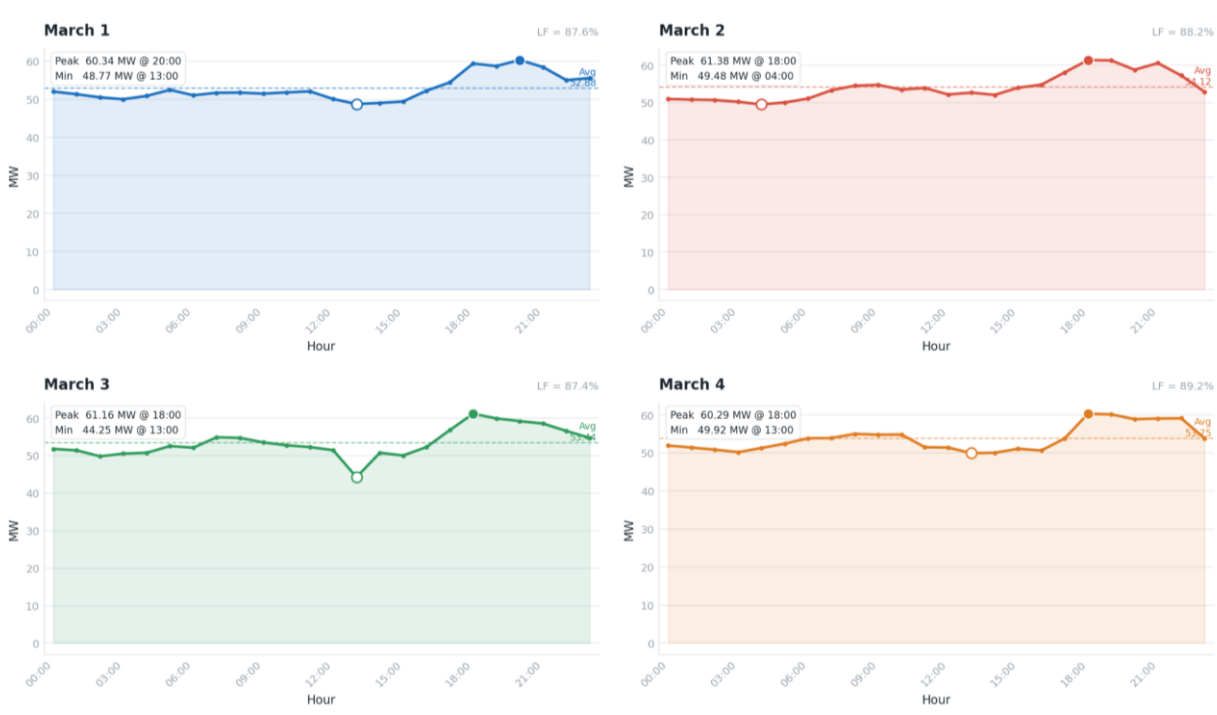


Figure 10: Individual daily load profiles (March 1-4, 2026)

Figure 10 illustrates the individual daily load profiles. Although slight variations exist between the days, the overall pattern remains consistent. The peak load ranges between

approximately 60 MW and 61 MW, occurring during the evening period, typically between 18:00 and 20:00. The minimum load values are observed during midday or early afternoon, with the lowest value reaching approximately 44.25 MW on March 3. This variation indicates a daily load fluctuation of around 15–17 MW, which is significant for system operation.

The comparison of the four days shows that March 2 has the highest recorded peak, while March 3 exhibits the largest load variation due to a noticeable midday drop. Despite these differences, the general shape of the load curve is similar across all days, confirming the repeatability and reliability of the measured data.

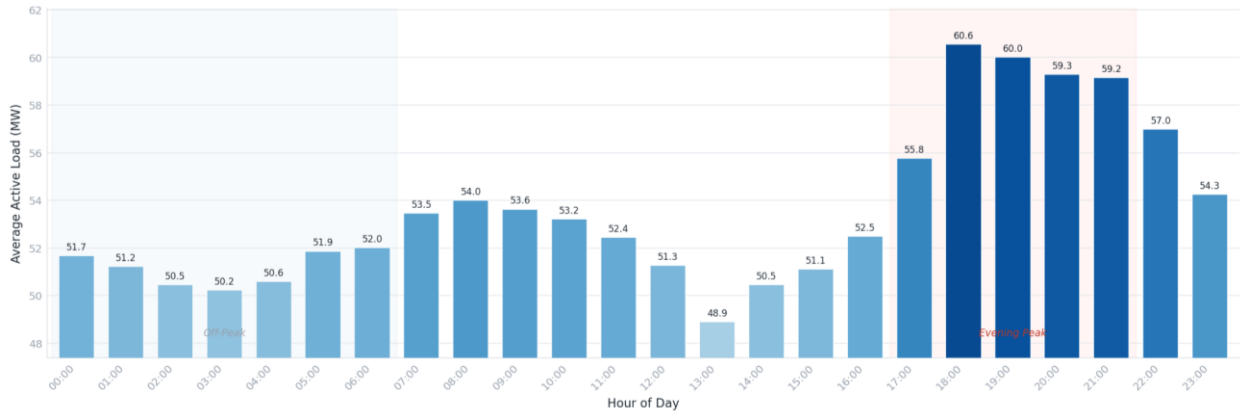


Figure 11: System Average Load per hour (March 1-4)

Figure 11 presents the average hourly load profile calculated from the four-day dataset. The averaged curve clearly highlights the typical daily demand behavior of the Nalaikh substation. During the early hours (00:00–06:00), the load remains relatively stable at around 50–52 MW, indicating low system activity. As the day progresses, the demand gradually increases, reaching moderate levels during the morning and early afternoon.

A slight reduction in load is observed around midday (12:00–14:00), which may be associated with lower industrial or residential activity during this period. However, the most prominent feature of the load profile is the sharp increase in demand during the evening hours (18:00–22:00), where the load reaches its daily maximum. This peak is primarily driven by residential electricity usage, including lighting, heating, and appliance operation.

Table 4: Load statistics summary

Bus	Peak (MW)	Peak hour	Min (MW)	Min hour	Avg (MW)	Load factor	Daily total (MWh)
March 1	60.341	20:00	48.775	13:00	52.876	87.63%	1269.0
March 2	61.378	18:00	49.484	04:00	54.117	88.17%	1298.8
March 3	61.160	18:00	44.247	13:00	53.444	87.38%	1282.7
March 4	60.287	18:00	49.921	13:00	53.751	89.16%	1290.0

Table 4 summarizes the key load statistics for the analyzed period (March 1–4, 2026), based on measured data from the Nalaikh substation.

The results indicate that the system operates within a relatively narrow load range, with peak values slightly above 60 MW and minimum values generally remaining above 45 MW. The average load remains stable across all days, resulting in a consistently high load factor of approximately 87–89%. This suggests that the system is operating close to its average capacity for most of the day.

Overall, the analysis shows that the Nalaikh substation follows a typical daily load pattern, characterized by a pronounced evening peak and moderate variation during daytime hours. This behavior indicates that the system is well-suited for peak load shaving using BESS.

5.3 BESS Requirement Estimation

Based on the load characteristics presented in the previous section, the Battery Energy Storage System (BESS) requirements are estimated to support peak load reduction at the Nalaikh substation.

The load analysis shows that the system experiences peak demand values slightly above 60 MW, while the average load remains around 53 MW. To reduce the impact of peak demand on the system, a target peak threshold is defined. In this study, a threshold of:

$$P_{th} = 55MW$$

is selected as a practical level to limit the maximum load.

5.3.1 Required Battery Power Rating

The required BESS power rating is determined based on the difference between the observed peak load and the selected threshold:

$$P_{BESS} = P_{peak} - P_{th}$$

Using the maximum observed value:

$$P_{BESS} = 60.56 - 55 = 5.56\,MW$$

To ensure reliable operation and account for variations in load, the power rating is rounded and selected as:

$$P_{BESS} = 6\,MW$$

This allows the system to effectively reduce peak demand during all observed conditions.

5.3.2 Required Battery Energy Capacity

The energy capacity of the BESS is determined based on the duration of peak demand and the required discharge time. From the simulation results, the BESS operates in:

Discharge mode: approximately 6 hours

Charge mode: approximately 5 hours

The required energy capacity is calculated as:

$$E_{BESS} = P_{BESS} * t$$

$$E_{BESS} = 6 * 5 = 30\,MWh$$

Thus, the selected battery capacity is:

$$E_{BESS} = 30MWh$$

5.3.3 Battery Storage System Configuration

The Battery Energy Storage System (BESS) used in the simulation is configured based on the design parameters obtained in Section 5.3.1 and Section 5.3.2 . A lithium-ion battery is selected due to its high efficiency, long cycle life, and widespread application in grid-scale energy storage systems.

The main parameters of the BESS are defined as follows:

- Power rating: 6 MW
- Energy capacity: 30 MWh
- State of Charge (SOC) limits: 15% – 95%

- Round-trip efficiency: 95%
- Control strategy: threshold-based peak shaving

The BESS is connected to the system at the load bus and operates according to the defined control strategy. During periods of low demand, the battery charges by storing energy from the grid. During peak demand periods, it discharges to supply power and reduce the net system load.

The operation of the BESS is constrained by its power rating and SOC limits to ensure realistic and stable performance. The SOC is updated at each simulation time step based on the charging and discharging power.

This configuration allows the BESS to effectively shift energy from off-peak to peak periods, enabling evaluation of its performance in reducing peak load and improving overall system behavior.

5.4 Performance Simulation

5.4.1 Model setup

The simulation model is developed using the pandapower framework in Python. First, the pandapower library is installed and configured in the Python environment to enable power system modeling and analysis.

The simulation is performed using hourly time steps. At each time step, the system load is updated, and the BESS operation is determined based on the defined control strategy. Power flow calculations are carried out using pandapower to evaluate the system behavior under different load conditions.

5.4.2 Simulation Workflow

To clearly illustrate the implementation of the simulation model, a flowchart of the overall process is presented in Figure 12. The diagram summarizes the key steps of the BESS modeling and simulation procedure, including data processing, system design, control logic, and time-series simulation.

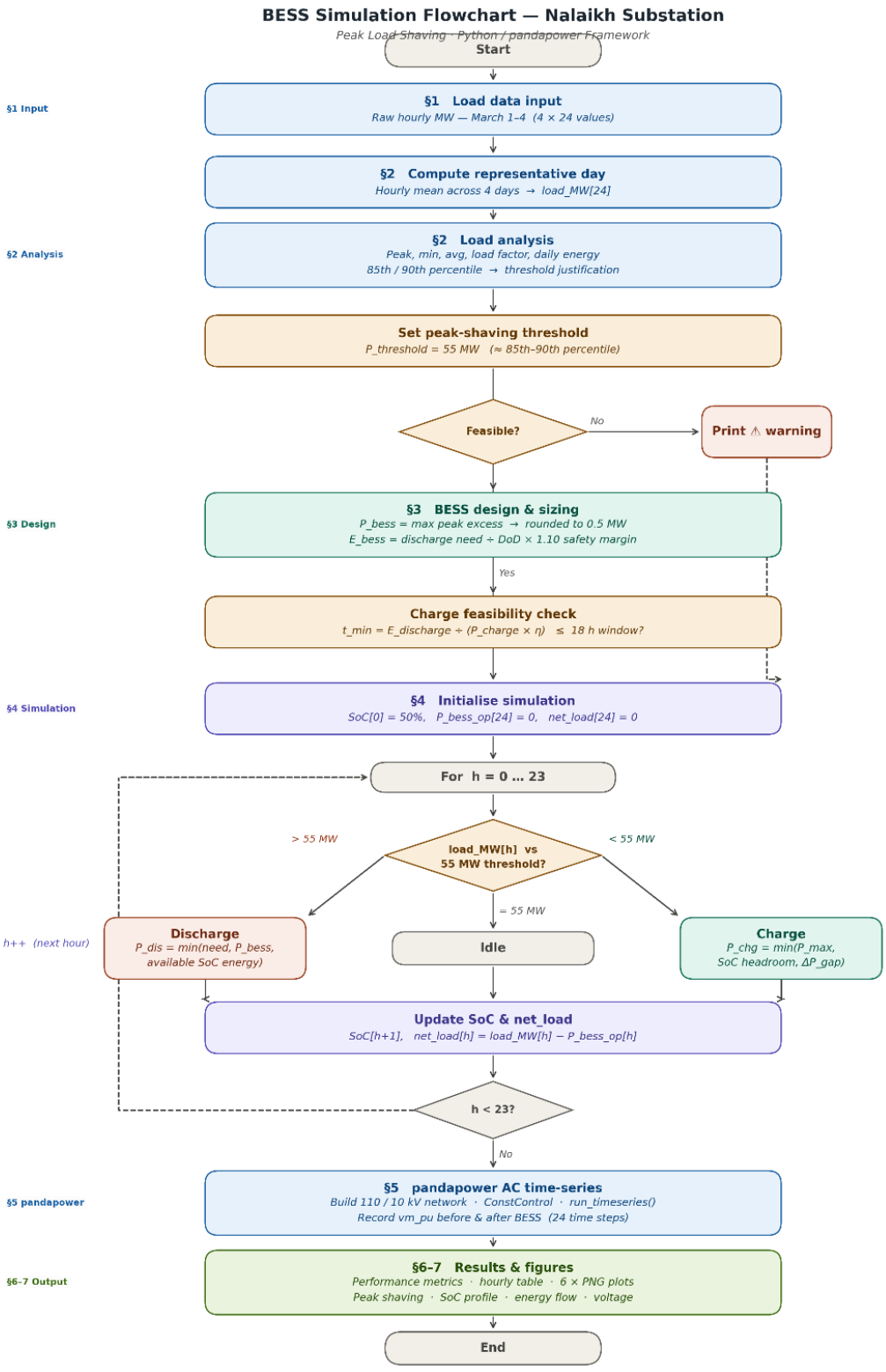


Figure 12: Flowchart of the BESS simulation process implemented in Python using the pandapower framework

The workflow begins with the input of raw load data, followed by preprocessing to generate a representative daily load profile. Based on this data, the peak-shaving threshold is defined and the BESS is sized according to the required power and energy capacity.

The simulation then proceeds through a time-series loop, where at each time step the system load is compared with the threshold value. Depending on the load condition, the BESS operates in charging, discharging, or idle mode. The state of charge (SOC) and net load are updated accordingly.

Finally, power flow calculations are performed using the pandapower framework, and the simulation results are recorded for analysis, including peak load reduction, SOC behavior, energy flow, and voltage profile.

6. Results and Discussion

6.1 Peak Load Reduction

The simulation results demonstrate that the BESS effectively reduces peak electricity demand in the modeled system. Figure 13 shows the comparison between the original load profile and the load profile after BESS integration. The results clearly indicate that the BESS effectively reduces the peak demand during evening hours.

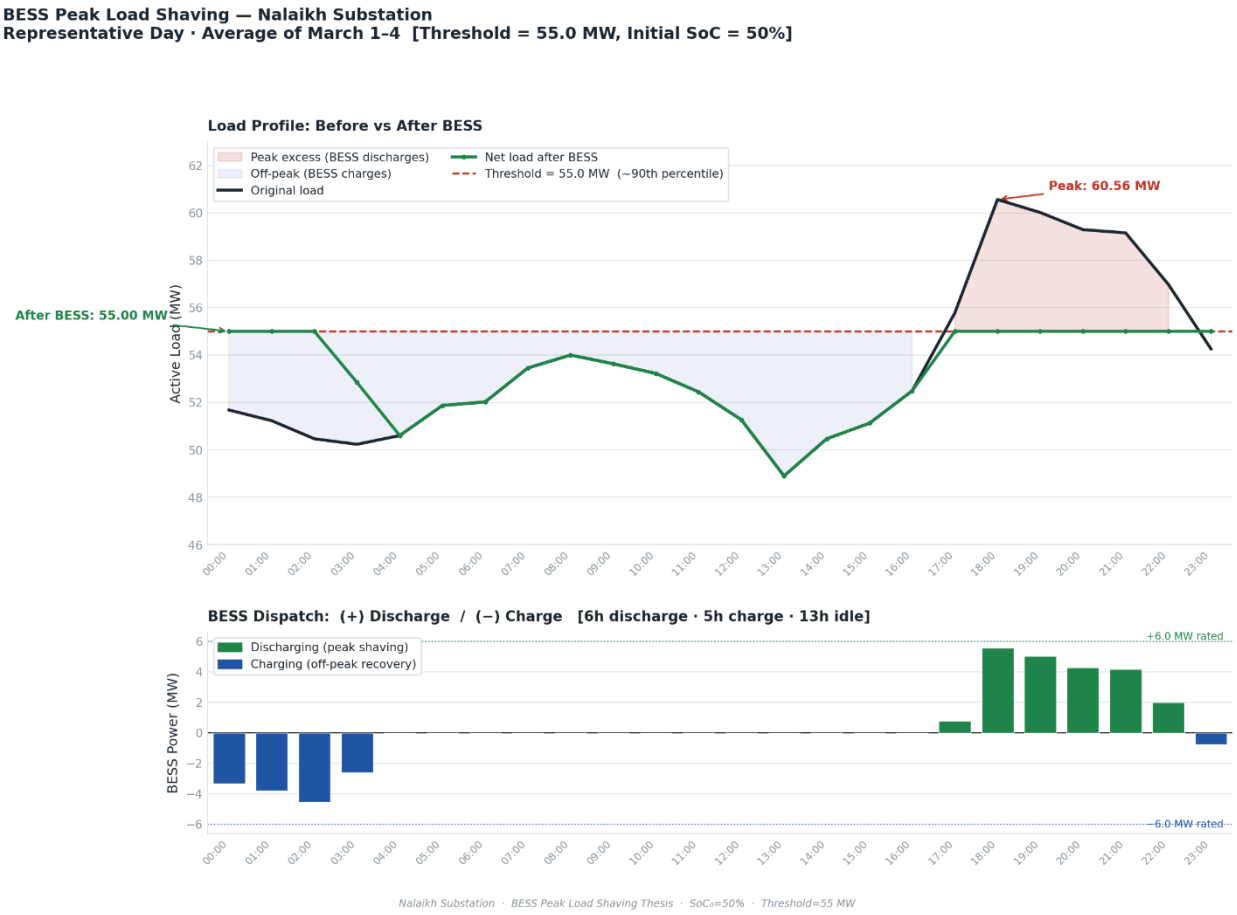


Figure 13: Load profile before and after BESS and BESS dispatch

The original peak load reaches approximately 60.56 MW, while after applying the BESS, the peak is reduced to the defined threshold of 55 MW. This corresponds to a peak reduction of approximately:

$$\Delta P = 60.56 - 55 = 5.56 \text{ MW}$$

or about 9.2% reduction.

The load curve after BESS operation becomes smoother, with a noticeable flattening during peak hours. This demonstrates the effectiveness of the threshold-based control strategy in limiting maximum demand.

6.2 Battery Utilization Performance

The SOC profile (Fig. 14) illustrates the charging and discharging behavior of the battery over the 24-hour simulation period.

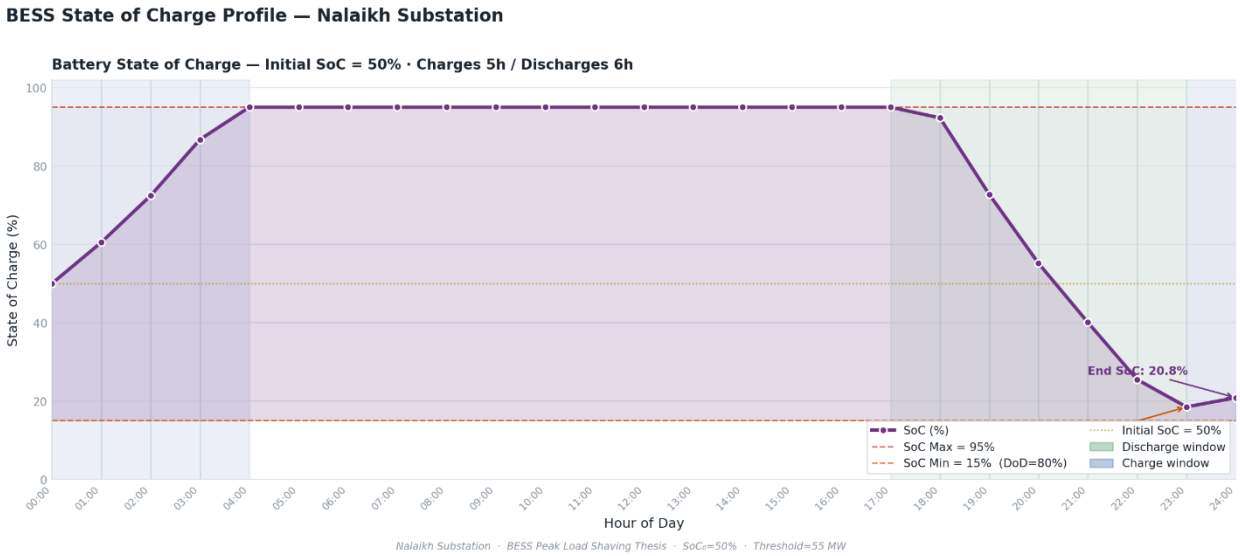


Figure 14: Battery State of Charge (SOC) over 24-hour operation

At the beginning of the simulation, the battery is initialized at 50% SOC. During the early hours of the day (00:00–04:00), the system load remains below the defined threshold of 55 MW, allowing the BESS to operate in charging mode. As a result, the SOC steadily increases and reaches approximately 95%, which corresponds to the upper SOC limit.

From approximately 04:00 to 17:00, the battery remains nearly fully charged and operates in an idle state, as the system load stays close to or below the threshold level. This indicates that sufficient energy is stored in advance to support the upcoming peak demand period. During the evening peak hours (18:00–23:00), the system load exceeds the threshold, triggering the BESS to discharge. Consequently, the SOC decreases progressively as the battery supplies power to the grid. By the end of the simulation period, the SOC drops to approximately 20.8%, remaining safely above the minimum limit of 15%.

The SOC profile confirms that the battery operates within the defined limits of 15%–95% throughout the simulation. The charging occurs during low-demand periods, while discharging is concentrated during peak hours, demonstrating effective energy shifting. This behavior validates that the selected battery capacity and control strategy are appropriate for peak load shaving at the Nalaikh substation.

6.3 Energy flow and BESS Dispatch analysis

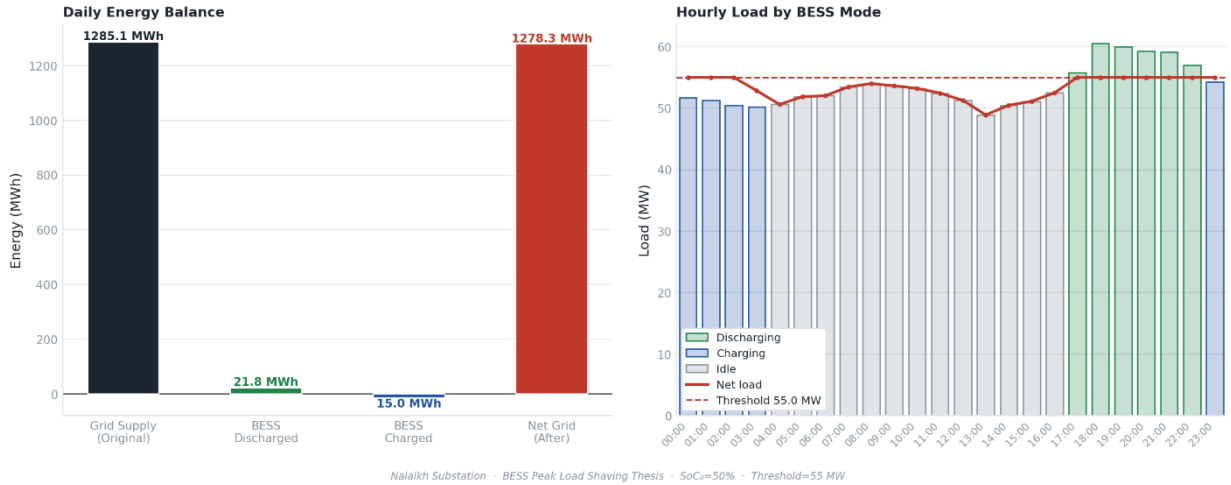


Figure 15: BESS Energy flow and Hourly dispatch analysis

Figure 15 presents the energy flow and hourly dispatch behavior of the BESS during a 24-hour operation period. The analysis includes both the total daily energy balance and the hourly charging and discharging patterns.

From the energy balance results, the total energy supplied by the grid without BESS is approximately 1285.1 MWh, while the net grid supply after BESS operation is reduced to about 1278.3 MWh. This indicates that part of the energy demand is effectively supported by the BESS. The battery discharges a total of approximately 21.8 MWh during peak demand periods, while it charges about 15.0 MWh during low-demand periods. The difference between charged and discharged energy is mainly due to system losses and the operational constraints of the battery, including efficiency and SOC limits.

The hourly dispatch profile further illustrates the operational behavior of the BESS. During early hours (00:00–04:00), the battery operates in charging mode, as indicated by negative power values. During most of the daytime, the battery remains idle since the system load stays below the threshold level. In the evening period (18:00–22:00), the BESS operates in discharge mode, supplying power to reduce the system load and maintain it near the defined threshold of 55 MW. After the peak period, the battery gradually returns to charging mode or remains idle depending on the load condition.

Overall, the results confirm that the BESS effectively shifts energy from off-peak to peak periods. The charging and discharging behavior aligns with the control strategy,

demonstrating that the system operates efficiently and supports peak load reduction without violating operational limits.

6.4 Bus voltage profile analysis

Figure 16 shows the bus voltage profile at the 10 kV level of the Nalaikh substation before and after the integration of the BESS. The results are obtained from the AC power flow simulation using the pandapower framework.

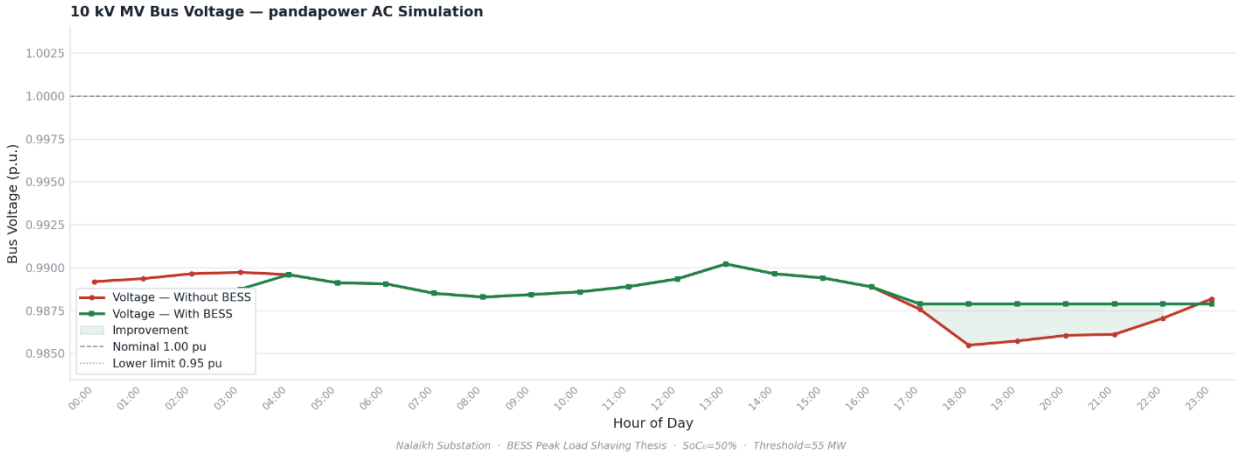


Figure 16: Load bus voltage profile with operational limits

The voltage profile without BESS remains relatively stable throughout the day but shows a noticeable voltage drop during the evening peak period, particularly between 18:00 and 21:00. During this time, the voltage decreases to approximately 0.985–0.986 p.u., indicating increased system stress due to high load demand. After integrating the BESS, the voltage profile shows a slight improvement during the peak hours. The battery discharges during this period, supplying additional power to the system and reducing the load on the grid. As a result, the voltage is maintained at a slightly higher level, around 0.988 p.u., compared to the case without BESS.

Although the overall voltage improvement is relatively small, the results demonstrate that BESS contributes positively to voltage stability. The voltage remains within acceptable operational limits throughout the entire day, staying above the lower limit of 0.95 p.u.

6.5 Load duration curve

The load duration curve provides a comprehensive view of how often different load levels occur throughout the day and is useful for evaluating the overall impact of BESS on system demand.

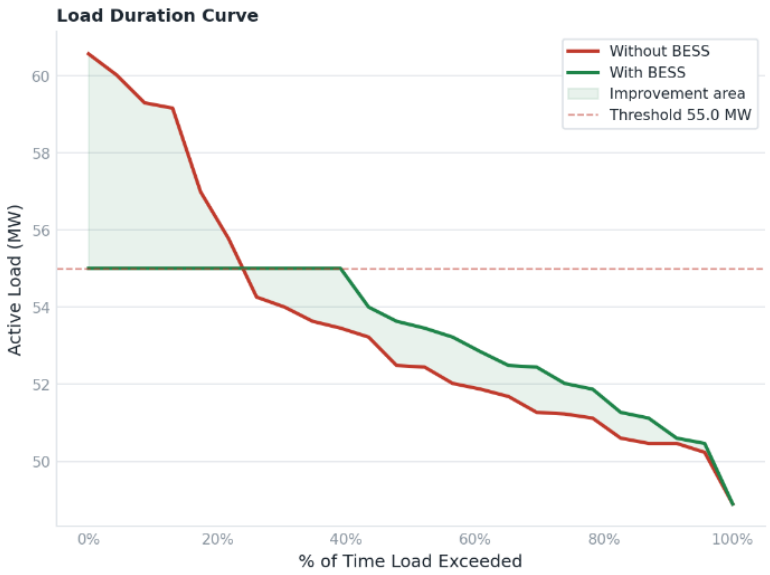


Figure 17: Load duration curve

As shown in Figure 17, the original load duration curve exhibits a clear high-load region, with peak values exceeding 60 MW. After integrating the BESS, the upper portion of the curve is significantly flattened, with the maximum load effectively limited to the threshold value of 55 MW.

The shaded area between the two curves represents the portion of load that is supplied by the BESS during peak periods. This demonstrates that the battery successfully shifts energy from low-demand periods to high-demand periods, reducing stress on the power system. In addition to peak reduction, the curve becomes more uniform after BESS operation, indicating improved load distribution and reduced variability. This contributes to more stable and efficient system operation.

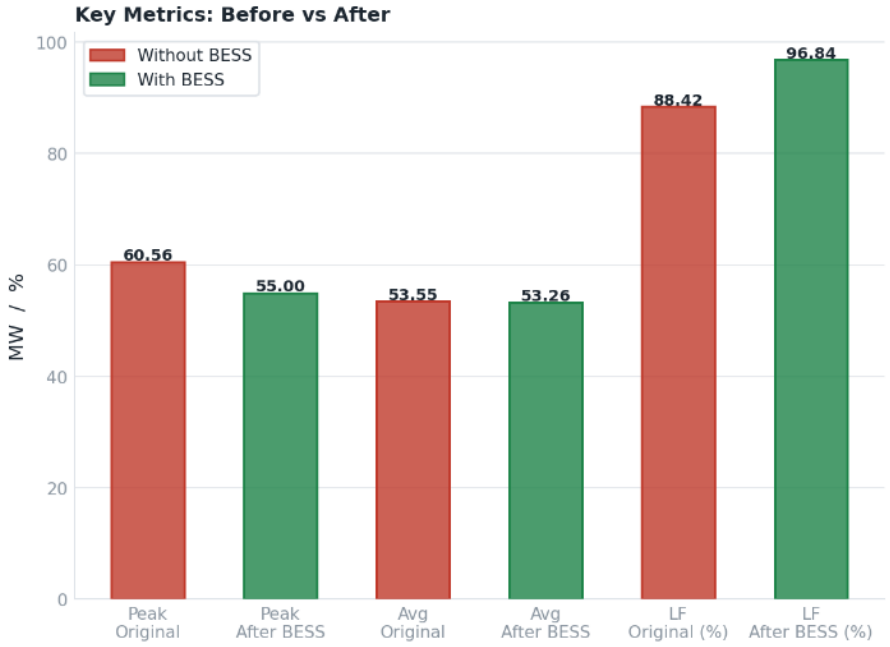


Figure 18: Key metrics: Before vs After

The comparison further highlights the improvement in system performance after BESS integration. One important indicator is the load factor (LF), which increases from 88.42% to 96.84% after applying peak shaving.

The load factor represents the ratio of average load to peak load and is used to evaluate how efficiently the power system is utilized. The observed increase in LF indicates that the difference between peak demand and average demand has been reduced. This is mainly due to the BESS limiting the peak load while maintaining a similar average load level.

As a result, the system operates in a more balanced manner, with less extreme demand fluctuations. A higher load factor is desirable because it reflects improved utilization of generation and network capacity, reduced stress on system components, and more stable operating conditions.

Therefore, the increase in load factor confirms that the BESS not only reduces peak demand but also enhances the overall efficiency and reliability of the power system.

7. Conclusion and Future Recommendation

In conclusion, this study has provided valuable insights into the application of Battery Energy Storage Systems (BESS) for peak load shaving at the substation level. The results demonstrate that BESS can effectively reduce peak demand, improve load profile characteristics, and enhance the overall performance of the power system. The study highlights the importance of energy storage technologies in addressing operational challenges associated with increasing electricity demand and load variability in Mongolia.

A detailed analysis of the results reveals several key findings that contribute to a deeper understanding of the relationship between BESS configuration and system performance:

1. Impact on peak load reduction:
   The simulation results show that the implementation of BESS significantly reduces peak demand. In this study, the peak load was reduced by approximately 5.56 MW (9.2%), demonstrating that even a moderately sized BESS can effectively alleviate system stress during high-demand periods.
2. Energy shifting capability:
   The results confirm that BESS enables efficient energy shifting from off-peak to peak periods. The system successfully charges during low-demand hours and discharges during peak demand, reducing the load imbalance and improving system operation.
3. Balance between power and energy capacity:
   The analysis indicates that an appropriate balance between battery power rating and energy capacity is essential for effective peak shaving. The selected configuration (**6 MW / 30 MWh**) provides sufficient discharge duration while avoiding unnecessary oversizing of the system.
4. Improvement in system utilization:
   The load factor increased from **88.42% to 96.84%,** indicating a reduction in demand variability and improved utilization of system capacity. This demonstrates that BESS contributes not only to peak reduction but also to more efficient operation of the power system.
5. Operational performance and efficiency**:**
   The battery operated effectively within the defined SOC limits (15%–95%) and achieved a utilization rate of approximately **72.6%**, confirming efficient use of

available capacity. The estimated battery lifetime of **9.6 years (3500 cycles)** indicates that the system can provide reliable long-term operation under the given conditions.

6. Additional system benefits:
   In addition to peak load reduction, the results show a slight improvement in voltage stability during peak hours. This highlights the capability of BESS to provide auxiliary support to the power system, contributing to improved reliability and stability.

Considering these findings, it is evident that a well-designed BESS can provide an effective solution for managing peak demand at the substation level. The results suggest that a moderate BESS size with sufficient discharge duration can achieve meaningful performance improvements without excessive system cost or complexity.

However, it is important to recognize that this study is based on a simplified model and a limited dataset. Factors such as long-term seasonal variations, economic feasibility, battery degradation, and detailed network constraints were not fully considered. Therefore, further analysis is required to determine the optimal BESS configuration for practical implementation.

Future Work

An important direction for future work is the integration of BESS with renewable energy sources such as wind and solar power. Mongolia has significant renewable energy potential, particularly in wind energy.

BESS can support renewable integration by storing excess energy during periods of high generation and supplying it during periods of low generation or high demand. This helps address the variability and intermittency of renewable energy sources.

Future studies could investigate integrated systems combining BESS, renewable generation, and substation load. Such systems would enable both peak load shaving and renewable energy smoothing, improving grid flexibility, reducing dependence on fossil-fuel-based generation, and supporting the transition toward a more sustainable and resilient energy system in Mongolia.

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Appendix

Annex A: Nalaikh substation data

Hour	March 1	March 2	March 3	March 4
1	52.05	50.96	51.78	51.94
2	51.34	50.79	51.39	51.39
3	50.52	50.68	49.81	50.85
4	50.03	50.19	50.52	50.19
5	50.9	49.48	50.74	51.28
6	52.48	50.03	52.54	52.43
7	51.07	51.07	52.1	53.85
8	51.72	53.3	54.89	53.9
9	51.78	54.5	54.72	54.99
10	51.5	54.72	53.52	54.78
11	51.83	53.47	52.76	54.83
12	52.1	53.9	52.27	51.5
13	50.08	52.16	51.45	51.39
14	48.77	52.65	44.25	49.92
15	49.05	52.05	50.74	50.03
16	49.43	53.96	50.03	51.07
17	52.27	54.78	52.27	50.63
18	54.45	58.05	56.79	53.79
19	59.41	61.38	61.16	60.29
20	58.76	61.27	59.9	60.12
21	60.34	58.76	59.2	58.87
22	58.49	60.56	58.54	59.03
23	55.05	57.23	56.58	59.09
24	55.59	52.87	54.72	53.85

Annex B : Simulation code (Excerpt)

```
import numpy as np
import matplotlib.pyplot as plt
import matplotlib.gridspec as gridspec
import matplotlib.ticker as ticker
import matplotlib.patches as mpatches
from matplotlib.lines import Line2D
import pandas as pd
import warnings
warnings.filterwarnings("ignore")

import os
OUT = os.path.join(os.path.dirname(os.path.abspath(__file__)), "bess_output")
os.makedirs(OUT, exist_ok=True)

try:
    import pandapower as pp
    import pandapower.timeseries as ts
    import pandapower.control as control
    from pandapower.control import ConstControl
    from pandapower.timeseries import run_timeseries, OutputWriter
    from pandapower.timeseries.data_sources.frame_data import DFData
    HAS_PP = True
except ImportError:
    HAS_PP = False

raw_data = {
    "March 1":
[52.048332,51.339078,50.520708,50.029686,50.902614,52.484796,
            51.066288,51.720984,51.775542,51.502752,51.8301,52.10289,
            50.084244,48.774852,49.047642,49.429548,52.266564,54.448884,
```

```
            59.413662,58.758966,60.341148,58.486176,55.049022,55.594602],
    "March 2": [50.957172,50.793498,50.684382,50.19336,49.484106,50.029686,
            51.066288,53.303166,54.503442,54.721674,53.46684,53.903304,
            52.157448,52.64847,52.048332,53.957862,54.776232,58.049712,
            61.37775,61.268634,58.758966,60.55938,57.231342,52.866702],
    "March 3": [51.775542,51.393636,49.811454,50.520708,50.73894,52.539354,
            52.10289,54.885348,54.721674,53.521398,52.757586,52.266564,
            51.448194,44.246538,50.73894,50.029686,52.266564,56.794878,
            61.159518,59.904684,59.19543,58.540734,56.576646,54.721674],
    "March 4": [51.939216,51.393636,50.848056,50.19336,51.28452,52.430238,
            53.848746,53.903304,54.994464,54.776232,54.83079,51.502752,
            51.393636,49.92057,50.029686,51.066288,50.629824,53.794188,
            60.28659,60.122916,58.868082,59.031756,59.086314,53.848746],
}

hours = list(range(24))
hour_labels = [f"{h:02d}:00" for h in hours]

load_MW = np.array([
    np.mean([raw_data[d][h] for d in raw_data]) for h in hours
])

P_peak = load_MW.max()
P_min = load_MW.min()
P_avg = load_MW.mean()
peak_hour = int(load_MW.argmax())
min_hour = int(load_MW.argmin())
load_factor = P_avg / P_peak * 100
daily_energy = load_MW.sum()
```

```
p85 = np.percentile(load_MW, 85)
p90 = np.percentile(load_MW, 90)

P_threshold = 55.0

peak_excess = np.maximum(load_MW - P_threshold, 0)
valley_avail = np.maximum(P_threshold - load_MW, 0)
E_discharge_req = peak_excess.sum()
E_charge_avail = valley_avail.sum()

eta_rt = 0.90
eta_charge = np.sqrt(eta_rt)
eta_discharge = np.sqrt(eta_rt)
DoD = 0.80
SoC_max = 0.95
SoC_min = SoC_max - DoD
SoC_init = 0.50
safety_margin = 1.10

P_bess_raw = peak_excess.max()
P_bess = np.ceil(P_bess_raw / 0.5) * 0.5

E_bess_raw = E_discharge_req / DoD
E_bess = np.ceil(E_bess_raw * safety_margin / 0.5) * 0.5

C_rate_dis = P_bess / E_bess
C_rate_chg = P_bess / E_bess
P_charge_max = min(P_bess, E_bess * eta_charge)

E_to_recover = E_discharge_req
t_charge_min = E_to_recover / (P_charge_max * eta_charge)
charge_win_hrs = sum(1 for h in hours if load_MW[h] < P_threshold)
```

```
cycle_life = 3500
calendar_years = cycle_life / 365

SoC = np.zeros(25)
SoC[0] = SoC_init
P_bess_op = np.zeros(24)
net_load = np.zeros(24)

for h in range(24):
    load = load_MW[h]
    if load > P_threshold:
        need = load - P_threshold
        avail = (SoC[h] - SoC_min) * E_bess * eta_discharge
        P_dis = min(need, P_bess, avail)
        P_dis = max(P_dis, 0.0)
        SoC[h+1] = SoC[h] - P_dis / (E_bess * eta_discharge)
        P_bess_op[h] = P_dis

    elif load < P_threshold:
        headroom = (SoC_max - SoC[h]) * E_bess / eta_charge
        max_no_peak = P_threshold - load
        P_chg = min(P_charge_max, headroom, max_no_peak)
        P_chg = max(P_chg, 0.0)
        SoC[h+1] = SoC[h] + P_chg * eta_charge / E_bess
        P_bess_op[h] = -P_chg

    else:
        SoC[h+1] = SoC[h]
        P_bess_op[h] = 0.0

    net_load[h] = load - P_bess_op[h]
```

```
SoC = np.clip(SoC, SoC_min, SoC_max)

P_net_peak = net_load.max()
peak_reduction = P_peak - P_net_peak
peak_red_pct = peak_reduction / P_peak * 100

E_delivered = float(P_bess_op[P_bess_op > 0].sum())
E_absorbed = float(abs(P_bess_op[P_bess_op < 0].sum()))
battery_util = E_delivered / E_bess * 100
rt_eff_actual = E_delivered / (E_absorbed + 1e-9) * 100

discharge_hours = int(np.sum(P_bess_op > 0.01))
charge_hours = int(np.sum(P_bess_op < -0.01))
idle_hours = 24 - discharge_hours - charge_hours

net_lf = net_load.mean() / net_load.max() * 100
SoC_end = SoC[24]
SoC_recovery = (SoC_end - SoC_init) * 100
```