Jurnal Teknologi Elekterika, 2025, Volume 22 (1): 19-26 e- ISSN 2656-0143

Optimizing Energy Efficiency in Commercial and Industrial Sectors Through Battery Energy Storage Systems (BESS) for Peak Shaving Applications

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Abstract*— Battery Energy Storage Systems (BESS) have emerged as an innovative solution to enhance energy efficiency in commercial and industrial sectors, particularly through the implementation of peak shaving methods. This technology enables energy storage during periods of low demand and its utilization during peak demand, thereby reducing the load on the power grid. This study explores the integration of BESS in managing electrical loads to lower peak energy consumption while improving operational efficiency and power system stability. By utilizing daily load profile data and BESS parameters, a system is developed to regulate charging and discharging processes to achieve optimal energy balance. Simulation results indicate that BESS implementation can reduce peak loads by up to 20%, distribute energy more evenly throughout the day, and enhance the reliability and efficiency of the power grid. This technology also offers environmental benefits by reducing dependence on fossil fuel-based power plants and supporting the transition toward a more sustainable energy system.

***Keywords*— Battery Energy Storage System (BESS), peak shaving, energy efficiency, load management, industrial sector, sustainable energy**

I. Introduction

Battery Energy Storage Systems (BESS) have emerged as an important technology in the quest for energy efficiency and sustainability. These systems store energy during periods of low demand and release it during peak consumption times, thereby reducing the load on the power grid [1]. Peak shaving methods are particularly beneficial for commercial and industrial users, in reducing peak load energy demand [2]. By implementing BESS, these sectors can achieve significant cost savings and improve their operational efficiency [3].

In the industrialized world, operating machines often cause large fluctuations in power demand. These surges can result in greater electrical energy usage and costs [2]. BESS can solve this problem by providing a stable energy supply during peak periods, ensuring that machines operate smoothly without causing sudden load spikes. In addition, this not only reduces energy costs but also extends equipment life by preventing overloads [1].

The integration of BESS with peak shaving methods also has significant environmental benefits. By reducing reliance on fossil fuel-based power generation during peak demand periods [4], BESS can help reduce greenhouse gas emissions [1, 5]. In addition, the integration of renewable energy sources, such as solar and wind power, with BESS can further improve the sustainability of the energy system [6]. As the world moves towards a greener future, the role of BESS in achieving energy efficiency and environmental sustainability cannot be underestimated.

As such, the implementation of BESS in the commercial and industrial sectors not only offers a solution for managing peak energy demand but also contributes to environmental sustainability. By reducing dependence on conventional energy sources and utilizing renewable energy, BESS can help reduce greenhouse gas emissions and support the transition to a greener and more efficient energy system. Therefore, further research and investment in BESS technology is essential to achieve global energy efficiency and sustainability goals.

II. Literature Review

A. Energy Storage Systems

The application of energy storage systems (ESSs) has been identified as a possible solution to compensate for the challenges faced by the modern electric power system. ESSs are in urgent demand by the conventional power generation industry, DERs, and intermittent renewable energy supply systems as they can offer required ancillary support and flexibility to them. Energy storage does not mean just the energy sources but they also provide the added benefits of improving reliability, stability, and also the quality of the power supply[7].

They are suitable for large (GW), medium (MW), or micro (kW) scale applications of the electric power system, depending on the task and requirement. They can be utilized for power demand balance, energy arbitrage, and reserve at the generation side; for investment deferral and frequency regulation at transmission level; for grid capacity support and voltage control at the distribution side; and for cost management and for peak shaving, etc., at the customer-side. Thus, ESS is a necessary component and plays a key role in mitigating a wide range of operational challenges faced by the modern electric power system.

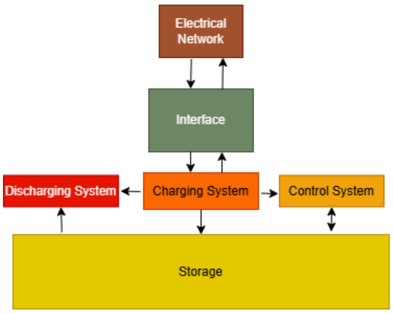


Figure 1 Main components of an ESS

Figure 1 Energy Storage Opportunities and Challenges as follows : *Storage Medium*, This provides the means to store energy for later use; such as the battery, PHES, flywheel energy storage system (FESS), capacitive/super-capacitive energy storage (CES/SCES), thermal energy storage (TES), compressed air energy storage (CAES), and superconducting magnetic energy storage (SMES), *Control*, It manages the functioning of the entire energy storage system and acts as a brain of the ESS, *Charging*, The charging unit facilitates the flow of energy from the electrical system to the energy storage medium, *Discharging*, It allows the flow of stored energy from the storage medium to the load when required.

ESS are the methods and technologies used to store electrical energy. ESS helps in maintaining power quality, load demand, grid stability, loss reduction, voltage and frequency regulation, energy efficiency improvement, reduction in fossil fuel usage, and protecting the environment from greenhouse gas emission and global warming[8, 9].

B. Storage Technology Perspective in Modern Power System

the development of renewable energies such as solar, wind, and batteries has been identified as a solution. However, this solution cannot be applied globally, as not all places in the world have enough sunlight for a time and intensity enough to meet the needs of a home, an industry, or a city. The energy produced by these renewable and non-polluting sources is distributed by the network in real time[10].

It is important to have storage as generating energy as solar and wind energy are intermittent. For years, industries have been using storage technologies in electronic equipment, vehicles, and turbines. Some alternatives have already been developed which include lead-acid batteries and lithium-ion batteries and contribute to the stabilization of energy supply systems[11].

Electric energy storage systems provide greater flexibility, especially for industries, but they are also very desired by non-industrial consumers, because through storage it is possible to reduce the final cost of the service. In other words, for storage to become viable in applications in homes, companies, and industries, it is necessary to include policies aimed at reducing the costs of storage systems and the correct selection of tariff values [12, 13].

In addition, it can also level the daily load curve, reduce peak shaving demands, among others. All these characteristics make the combination of clean and renewable energies with energy storage techniques the most competitive in terms of sales and implementation[14].

C. Battery Energy Storage System (BESS)

Batteries are energy storage devices which are used for inertia emulation to offer inertia in power systems with a large share of RES. A coordinated control mechanism with BESS improves the frequency stability of the system network. A lithium-ion battery is commonly used in a low-inertia power system which helps in improving frequency stability. The frequency and voltage regulation control methods in a PV system with lithium-ion batteries is presented in [15].

A battery suffers from the problems of large charging time and requirement of one extra source for charging, increasing its complexity and cost. This combination of wind/solar-based power plant with BESS can be replaced with fuel cell because this single device is renewable, requires no additional infrastructure for charging and has the ability to store [16]. It converts the chemical energy into surplus electrical energy to fulfill the demand of power supply. Additionally, it has no rotating part, resulting in less maintenance and nearly zero noise in comparison to the wind energy–based power plants, particularly[17, 18].

Apart from the above-mentioned advantages, fuel cells are sustainable, fuel flexible, low carbon emissive, and inexpensive. As a result they are gradually coming up as an excellent alternative in power systems as well as in other domestic and industrial applications [19, 20]. Lithium-ion (Li-ion) and redox flow batteries (RFBs) are available in the market as rival technologies to be utilized as back-up storage in the modern power system. the state of charge of the battery at any time of the year should meet the following requirements:

$$p_{Es,t} \geq Max\left|p_{L,t} - (p_{WG,t}, p_{PV,t})\right. \quad (1)$$

The power rating of the battery can be calculated using the following equation:

$$P_{bat}^{max} = \frac{N_{bat}V_{bat}I_{bat}}{1000} \quad (2)$$

D. Peak Load Shaving

Shaving peak load demand is the most important application of BESS. BESS is charged during low power consumption, lower electricity price and excess renewable power generation. The energy stored in BESS is dispatched to meet peak load demands to relieve congestion in the network. The energy demand and peak load demand is growing rapidly, and integration of renewables is also increasing accordingly.

Controllable loads in the micro-grid can participate in demand response, which can contribute to peak shaving during peak demand by reducing their own consumption via shedding of non-critical loads and delivering more power to the main grid utility. Micro-grids can lower overall distribution system losses and voltage management by implementing distributed generation located at the demand site, eliminating the need for transmission lines and deferring the construction of new transmission lines to a later time. Therefore, considerable revenue can be generated to MG network operator with RES and BESS [21, 22].

III. Research Methods

The peak shaving method with Battery Energy Storage System (BESS) aims to reduce peak power consumption in the power grid. The BESS stores energy when demand is low and uses it when demand increases, thereby reducing grid load. This power management starts with data collection, including daily load profiles and BESS parameters such as storage capacity and minimum State of Charge (SoC) limits. This data is used to time the storage and release of power to optimize energy consumption.

After the data is collected, the system receives an input in the form of a peak load threshold. If the load exceeds the threshold and the SoC of the BESS is sufficient, the BESS will be discharged to reduce the peak load. If the load is still within safe limits or the SoC is insufficient, the system continues to run without intervention. In addition, the system also calculates the operating time of the BESS and adjusts the peak load after the discharge is performed.

After discharge, the system re-evaluates the load and SoC of the BESS. If the load is below the threshold and the BESS capacity allows, the system activates the charging mode using energy from renewable sources or the grid. The system also adjusts the peak load value after the charging process.

The system calculates efficiency by comparing the peak load before and after the use of BESS. In addition, the total energy stored and released is calculated to evaluate the effectiveness of BESS in reducing peak load.

After all calculations are complete, the results are visualized in the form of graphs to provide a clearer picture of BESS performance in the system. The graphs displayed include daily load curves before and after the use of BESS, graphs showing the charging and discharging process of BESS, and SoC BESS graphs showing changes in power storage capacity during the process.

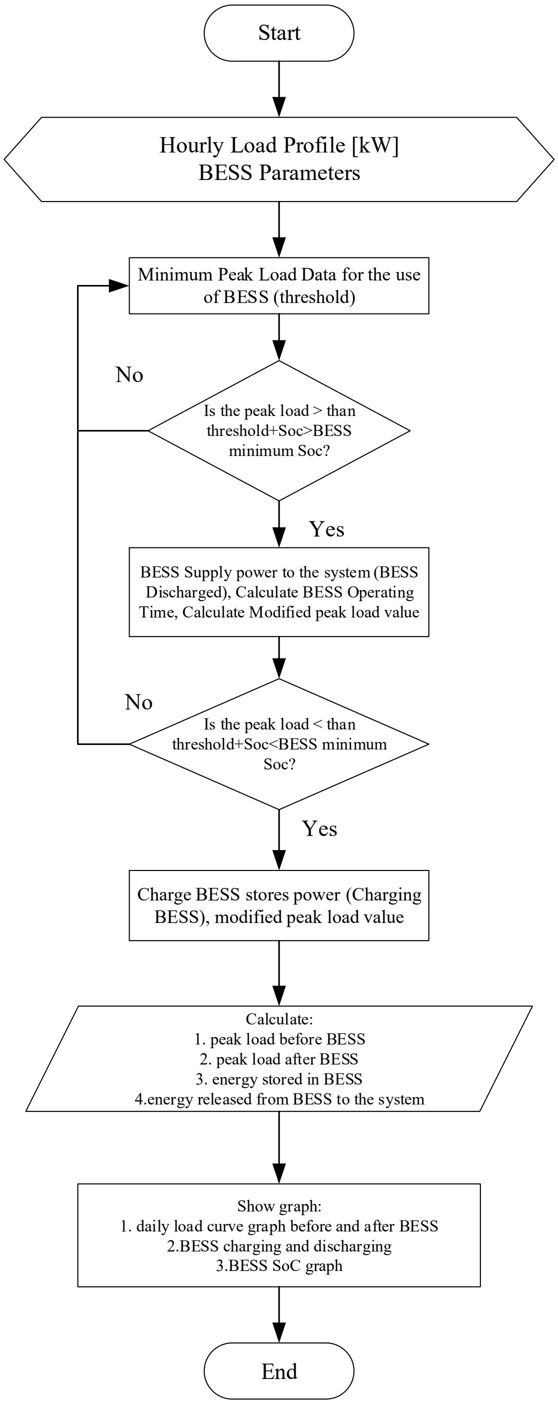


Figure 2 Flowchart of Research Procedures

Data processing with Peak Threshold variables in the BESS system aims at energy optimization and peak shaving. The process begins with the analysis of daily load profile data to determine consumption patterns and set peak threshold values according to load management objectives. Next, a simulation of the use of BESS to reduce peak load and calculate the energy stored and released is conducted. The simulation results are then evaluated by comparing the load before and after BESS to assess the effectiveness of peak load reduction and improve energy system efficiency.

IV. Result and Discussion

A. Load Profile before and after BESS integration

The data in Table 1 shows electricity consumption patterns throughout the day, with loads varying depending on the time of day and the activities taking place.

Table 1 Data Loadprofile

time [hours]	Load I [kW]	Load II [kW]
1	80	85
2	100	110
3	120	125
4	140	150
5	160	165
6	180	190
7	500	505
8	600	610
9	700	705
10	750	760
11	800	805
12	700	710
13	600	605
14	400	410
15	300	305
16	200	210
17	180	185
18	160	170
19	140	145
20	120	130
21	100	105
22	90	100

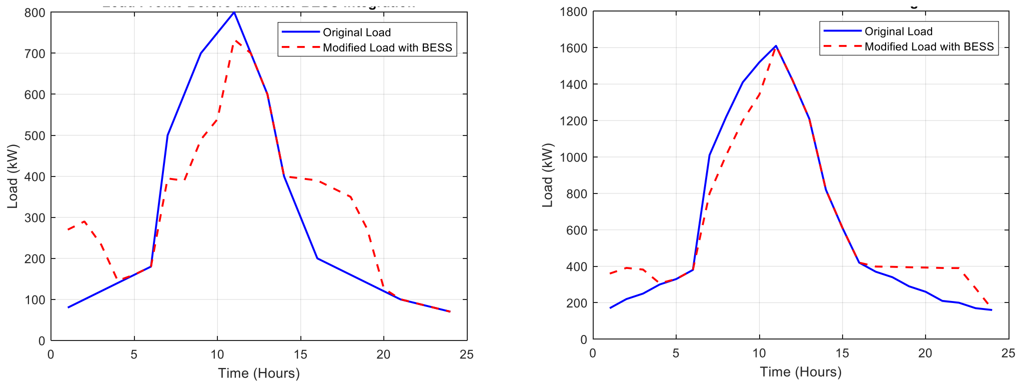
time [hours]	Load I [kW]	Load II [kW]
23	80	85
24	70	80

Figure *3* illustrates the load profile curves before and after the integration of the Battery Energy Storage System (BESS), where Figure 3(a) represents Load Profile I and Figure 3(b) represents Load Profile II. The horizontal axis indicates the time over a 24-hour period, while the vertical axis represents the load in kilowatts (kW). Each figure consists of two curves: the blue solid line shows the original load without BESS, and the red dashed line indicates the modified load after BESS integration.

In Figure 3(a), the total energy consumption within 24 hours reaches 7270 kW, with the highest peak load occurring at 11:00, reaching 800 kW. To reduce system stress and improve operational efficiency, a 20% reduction in peak load was implemented, decreasing the load at 11:00 to approximately 400 kW. The integration of BESS allows for energy to be stored during periods of low demand (off-peak hours) and discharged during peak demand periods. As a result, the load curve becomes more balanced throughout the day, minimizing power fluctuations. This demonstrates that BESS effectively performs peak shaving and valley filling, leading to a more stable and efficient energy distribution.

Meanwhile, Figure 3(b) shows the load profile for a system with a larger capacity. The original peak load reaches approximately 1600 kW, which occurs around midday. After BESS integration, the peak load decreases to around 1400–1500 kW, while the load during off-peak periods slightly increases. This pattern confirms that BESS operates consistently across different system scales—charging during low-load periods and discharging during high-load periods. Consequently, the overall load profile becomes smoother, the peak demand is reduced, and the system's operational reliability is improved.

In summary, the implementation of BESS in both load profiles (a and b) successfully achieves load leveling by reducing peak loads and filling valleys during low demand. This not only stabilizes the electrical system but also enhances its efficiency, reliability, and flexibility, while minimizing dependence on conventional generation and reducing operational costs. The results indicate that BESS plays a vital role in achieving a more balanced and sustainable energy management system.



(a) (b)

Figure 3 The load profile curve before and after BESS integration, (a) for load I and (b) for load II

B. Profile Charging and Discharging BESS

Table 2 Parameters BESS

Parameters BESS	Load Profile I	Load Profile II
Peak Load	800 kW	1610 kW
BESS Capacity	1000 kW	9040 kW
BESS Max charge	200 kW	200 kW
BESS Max Discharge	200 kW	200 kW
BESS Efficiency	0.95 kW	0.95 kW
BESS State of Charge	500 kW	500 kW
BESS Min SoC	200 kW	200 kW
BESS Max SoC	1000 kW	1000 kW

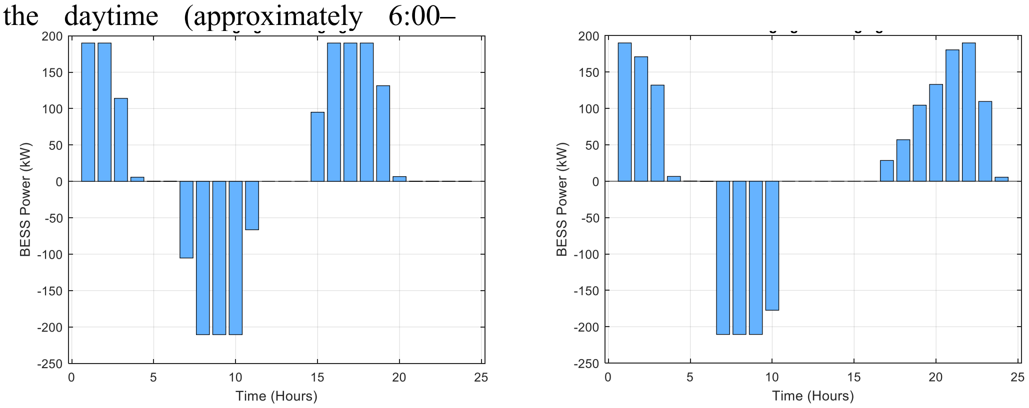
The graphs illustrate the charging and discharging profiles of the Battery Energy Storage System (BESS) over a 24-hour period for two different load conditions, namely Load I and Load II. The x-axis represents time in hours, while the y-axis shows BESS power in kilowatts (kW). Positive values indicate charging periods, where the BESS stores energy, while negative values represent discharging periods, where the BESS supplies power to the grid.

From Figure *4*, it can be observed that under both Load I and Load II conditions, the BESS performs charging mainly during the early hours (around 1:00–3:00) and nighttime (around 17:00–21:00), when energy demand is relatively low. During these periods, the BESS absorbs excess energy from the system, reaching a maximum charging power of approximately 200 kW, according to the system's design parameters.

Conversely, discharging occurs primarily during the daytime (approximately 6:00–11:00), when the system experiences its peak load condition. During this period, the BESS releases stored energy back into the grid with power levels ranging from -200 kW to -220 kW, thereby reducing the peak demand and maintaining system stability.

By comparing the two load conditions, it is evident that both Load I and Load II follow a similar charge–discharge pattern, although Load II exhibits slightly higher discharging intensity, indicating greater variability in load demand. Despite these differences, the BESS successfully performs its role in load leveling, ensuring that energy is stored during off-peak periods and discharged during high-demand hours.

This operational behavior, as depicted in Figure *4*, demonstrates the effectiveness of BESS in improving overall grid efficiency, minimizing peak demand stress, and optimizing energy utilization within the system.



(a)

(b)

Figure 4 BESS profile charging/discharging curve, (a) for load I and (b) for load II

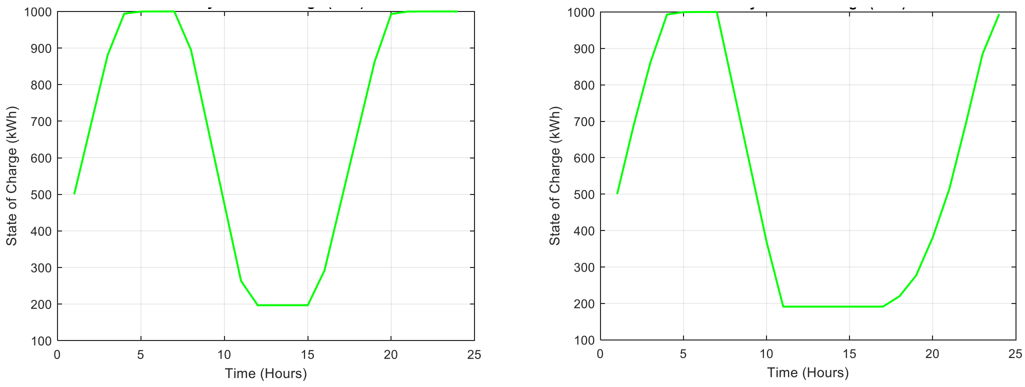
The graphs illustrate the State of Charge (SoC) of the Battery Energy Storage System (BESS) over a 24-hour operating period for both Load I and Load II conditions. The x-axis represents time in hours, while the y-axis indicates the stored energy capacity within the battery in kilowatt-hours (kWh).

From Figure 5, it can be observed that the battery initially starts with a moderate charge level of approximately 500 kWh. During the early hours, the SoC increases steadily until it reaches the maximum capacity of around 1000 kWh, indicating that the BESS is in the charging phase. This charging process occurs during periods of low energy demand, when excess power from the grid is stored in the battery.

Subsequently, as the system enters the midday period (around 6:00–12:00), the SoC decreases significantly, reaching a minimum level of approximately 200 kWh. This sharp decline corresponds to the discharging phase, when the BESS releases stored energy to support the grid during peak load conditions, thereby helping to maintain power balance and reduce demand stress on the system.

In the afternoon to evening hours (approximately 16:00–22:00), the SoC begins to rise again as the BESS recharges, ultimately returning to its full capacity of 1000 kWh. This repeating charge–discharge pattern indicates that both Load I and Load II follow a similar operational cycle, although Load II shows a slightly smoother charging recovery, suggesting a more gradual increase in available surplus energy during evening hours.

Overall, the State of Charge profiles in Figure 5(a) and Figure 5(b) demonstrate the effectiveness of the BESS in performing load leveling by storing energy during off-peak periods and discharging during peak demand. This operation enhances overall system efficiency, stabilizes grid performance, and optimizes energy utilization throughout the 24-hour cycle.



(a) (b)

Figure 5 State of Charge (SoC) Curve (a) for load I and (b) for load II

V. Conclusion

Given the outcomes of the simulations that have been conducted, it is possible to infer that:

1. The implementation of the Battery Energy Storage System (BESS) effectively reduces peak load by distributing energy more evenly throughout the day, resulting in improved stability and efficiency of the power system.
2. The operation of BESS allows charging during low-demand periods and discharging during high-demand periods, which optimizes energy utilization, enhances grid performance, and reduces dependency on conventional power generation sources.
3. Overall, BESS plays a significant role in supporting load leveling, improving system reliability, and contributing to a more sustainable and efficient energy management strategy.

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