

MAXIMIZING RENEWABLE ENERGY UTILIZATION THROUGH BATTERY ENERGY STORAGE SYSTEMS (BESS) FOR PEAK SHAVING IN SOLAR POWER INTEGRATION

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Abstract— *The integration of solar energy into sustainable energy systems faces the challenge of intermittency, where peak generation occurs during the day, while peak demand occurs in the evening. Battery Energy Storage Systems (BESS) enable peak shaving by storing excess energy generated during the day and discharging it during peak demand periods, thereby enhancing grid stability. In addition to reducing operational costs and optimizing energy infrastructure, BESS also contributes to lowering greenhouse gas emissions and decreasing reliance on fossil fuels. In this study, a simulation was conducted using MATLAB R2021A to model the load profile before and after BESS integration, as well as solar energy utilization. The simulation results indicate that the load profile decreased from 400 kW to 300 kW however the second load from 800 kW to 694.74 kW, leading to an overall reduction of 100 kW and 105.26 respectively. These findings confirm that BESS implementation is effective in supporting peak shaving and enhancing the efficiency of renewable energy utilization in solar power systems.*

Keywords—Renewable energy, solar power, BESS, peak shaving, load profile

I. Introduction

The integration of renewable energy sources like solar power is essential for transitioning towards sustainable energy systems. Solar energy is abundant and clean, but its intermittent nature poses a challenge, as peak generation occurs during the day while peak demand happens in the evening. Effective energy storage solutions are needed to address this mismatch [1]

Battery Energy Storage Systems (BESS) are crucial in this regard. BESS stores excess solar energy generated during the day and releases it during evening peak demand hours, a process known as peak shaving [2]. This helps balance

energy supply and demand, ensuring a stable and reliable power grid. BESS enhances the efficiency of renewable energy systems and reduces the need for additional generation capacity from conventional power plants [3]

Economically, integrating BESS with solar power for peak shaving lowers operational costs and energy prices by reducing reliance on fossil fuel-based power plants during peak demand periods [4]. It also defers the need for costly infrastructure upgrades by optimizing existing energy infrastructure [5].

Environmentally, adopting BESS for peak shaving reduces greenhouse gas emissions and pollutants from conventional power generation. It allows higher penetration of renewable energy sources into the grid, contributing to a cleaner and more sustainable energy future [6]. It also enhances energy security by reducing dependence on imported fuels and promoting energy independence [7].

Therefore, maximizing renewable energy utilization through BESS for peak shaving in solar power integration is vital for addressing the intermittency of solar power and achieving a sustainable energy future.

II. Literature Review

A. Energy Storage Systems

Energy storage systems are the methods and technologies used to store electrical energy. These systems are needed mainly by populations living in remote regions, and therefore they do not have access to electricity. This reality is very common in underdeveloped and developing

countries, since this equal distribution of resources often depends on governmental interest [8, 9].

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 [10]. 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 [11].

The issues and opportunities related to the RES encourage the researchers to provide reliable and efficient solutions in the form of ESS that have the capability to store and deliver energy when required. In addition to this, 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 [12, 13]. Electrical energy is not stored in its original form, but it can be converted to other forms of energy like chemical, mechanical, electrochemical, or thermal energy and can be stored (except electrostatic and electromagnetic storage, which are considered as electrical ESS) [14].

B. PV systems with Battery Energy Storage system (BESS)

Integrating renewable energy into the smart grid is essential to meet these targets. Solar energy is harnessed using Photovoltaic (PV) panels or solar thermal systems[15]. PV panels convert sunlight directly into electricity, while solar thermal systems use sunlight to generate heat, which can then be used to generate

electricity. Solar energy is abundant, renewable, and emits no pollutants during operation, but it is unreliable as it depends on the variability of weather conditions[16].

To manage this, energy storage systems, such as batteries, are used to store excess solar energy for use during periods of low sunlight, while advanced forecasting and grid management tools help integrate intermittent energy sources such as solar power into the grid[17].

generator as well as contribute in providing reserve power. The incorporation of BESS allows PV units with the ability to control frequency and voltage regulation when it is connected to the grid as shown in Figure 1 PV integration with BESS.

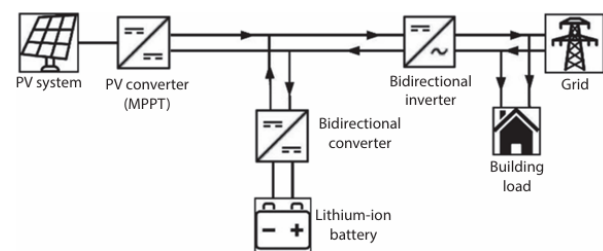


Figure 1 PV integration with BESS

Li Xin and Wang Ning in [18] suggested a concept of virtual synchronous machine with ESS and its control mechanism for frequency control and regulation. In this technique, the power inverter has the ability of power control and frequency regulation that provides system stability when connected to the power grid.

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 [19]. In [20], Manohar Chamana et al. proposed a control methodology where a PV source is connected with BESS at the DC link bus. This provides an advantage in that it can emulate the behaviour of synchronous.

By relying on storage devices, consumption can be reduced. During peak load times, energy storage devices are discharged to serve the priority load. During off-peak hours, these devices are recharged and excess power is stored[21].

C. Modelling of Battery Energy Storage System

The operational constraints and state-of-charge dynamics of the Battery Energy Storage System (BESS) are governed by Equations (1) - (5). Equation (1) defines the permissible range of the SOC, ensuring it remains within predefined limits. Equation (2) represents the SOC evolution over time, considering charge and discharge power. Equation (3) provides a discrete formulation of the SOC update, incorporating charging and discharging efficiency. Equation (4) establishes the constraints on BESS power during charging and discharging, while Equation (5) specifies the allowable rated capacity of the battery.

$$SoC_{min} \leq SoC(t) \leq SoC_{max} \quad (1)$$

$$SoC(t) = SoC_0 + \frac{1}{3600 \eta S C_{REF}} \int_{t_0}^t (p_{sc} - p_{sd}(t)) dt \quad (2)$$

$$SOC_i^t = SOC_i^{t-1} + \left(\frac{\sqrt{\eta} P_{ch,i}^{BESS,t}}{B_i^{rated}} - \frac{P_{dis,i}^{BESS,t}}{\sqrt{\eta} B_i^{rated}} \right) \quad (3)$$

$$P_{min}^{BESS} \leq P_{ch/dis,i}^{BESS,t} \leq P_{max}^{BESS} \quad (4)$$

$$0 \leq B_i^{rated} \leq B^{max} \quad (5)$$

D. Peak Load Shaving

A Peak shaving is an energy management strategy designed to reduce electricity consumption from the grid at times of peak demand. The strategy aims to create greater energy efficiency, reduce electricity costs and support the sustainability of the electricity system. The concept is increasingly relevant amidst growing global energy needs and the challenges faced by modern energy systems, including demand fluctuations, grid capacity limitations, and demands to reduce carbon emissions[3, 22].

Controllable loads in the micro-grid can participate in demand response, which can contribute to peak shaving during times of 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 [23, 24]. The calculation of the value of peak shaving ($p_{shaving}$) uses equation (6), The operational efficiency ($\eta_{operasional}$) of the system can be calculated using Equation (7)

$$p_{shaving} = p_{peak,before} - p_{peak,after} \quad (6)$$

$$\eta_{operasional} = \frac{P_{avg}}{P_{peak}} \times 100\% \quad (7)$$

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[25].

III. Research Methods

The process of conducting research begins with the collection of data, which includes the gathering of information on solar photovoltaic (PV) capacity, solar PV output power in terms of surplus or deficit energy, user demand profiles, and key BESS parameters such as capacity and minimum state of charge (SoC). After the data has been received, it is processed in order to establish the most effective way to regulate the flow of energy. This includes determining when excess energy should be stored in the BESS and when energy should be discharged in order to maintain the system during times of high demand.

The system will analyze the amount of energy that is available from solar photovoltaics once the initial data has been processed. In the event that there is a surplus, which occurs when the amount of power generated by solar photovoltaic panels is greater than the amount of electricity required by the load at the moment, the surplus energy is used to charge the battery energy storage system (BESS). Alternatively, in the event that there is no extra energy available, the system will determine whether or not the load profile of the user exceeds the maximum threshold that has been specified. It is possible for the stored energy to be discharged in order to assist in stabilizing the demand in the event that the load is excessive and the SoC of the BESS is adequate.

When it comes to managing peak loads, peak shaving is a significant approach that is

implemented at this point. This method leverages the energy that is stored in the BESS. Both the total energy that is discharged to support the load and the total energy that is stored from solar photovoltaics during a period of twenty-four hours are computed by the system. The system also provides key data outputs, such as the total quantity of energy generated by solar photovoltaics (PV), the amount of energy that was effectively stored in the battery energy storage system (BESS), and peak load values both before and after the integration of the BESS.

When this procedure is complete, the findings are shown graphically, and a comparison is made between the load profile before and after the integration of the BESS. These graphics illustrate how the integration of BESS components contributes to the reduction of peak loads, the maximization of the exploitation of renewable energy sources, and the overall improvement of system efficiency. Furthermore, in order to provide a

comprehensive overview of the process of energy management, the system displays key indicators. These indicators include the extent to which solar photovoltaic energy is utilized, the amount of battery capacity that is utilized, and the charging status of the battery energy storage system (SoC).

Finally, all of the data that has been collected and processed is examined in order to evaluate the performance of the system as a whole. This analysis leads to conclusions that can be used to optimize future energy management strategies. By integrating Solar PV and BESS, the system not only reduces dependence on the main power grid but also enhances energy sustainability through the efficient utilization of renewable energy sources. MATLAB is used throughout the process to facilitate simulations, perform technical calculations, and visualize results. The overall process is illustrated in Figure 2 Flowchart of Research Procedures

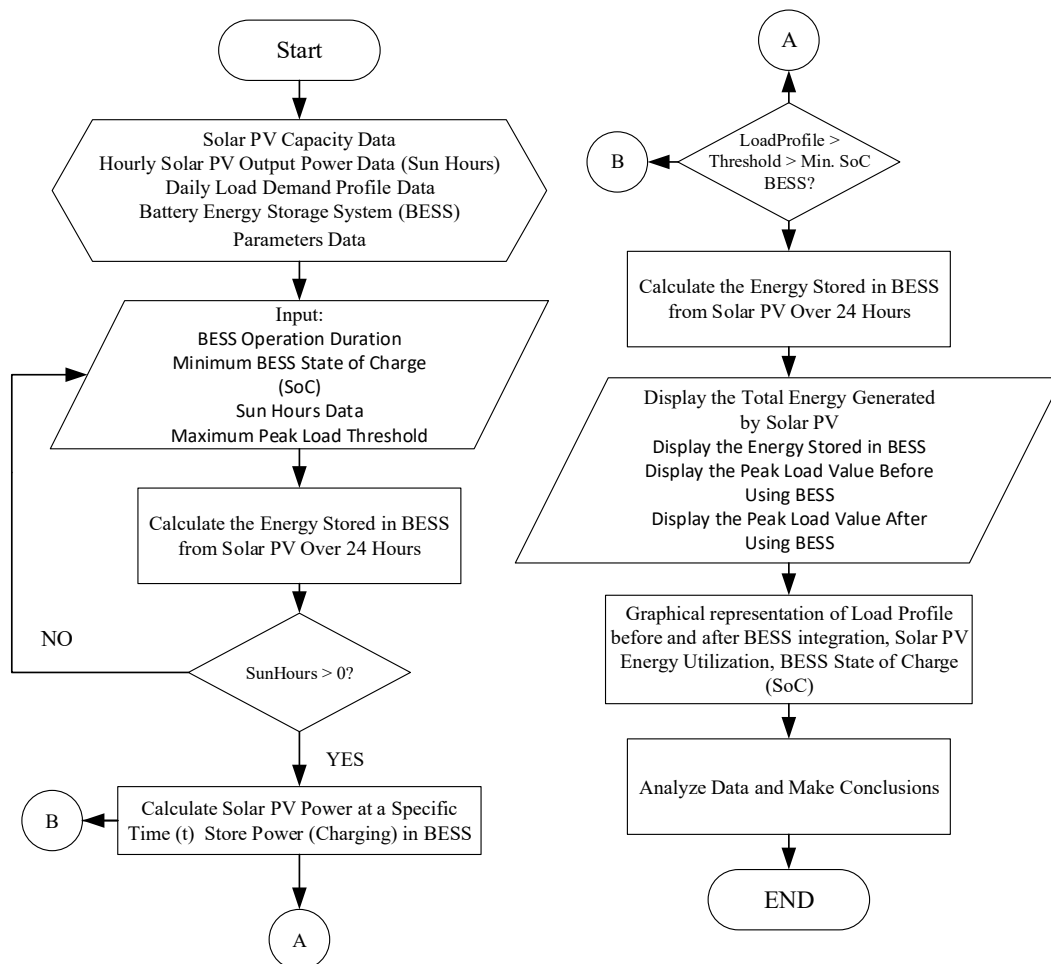


Figure 2 Flowchart of Research Procedures

iv. Result and Discussion

In applying the peak shaving method, there are three main stages reflected in the curve. In the first stage, charging, which occurs from midnight to noon, the BESS charges while the electrical load is still low and stable as shown at Figure 3.

Table 1 illustrates the daily energy generation of a solar power plant (PLTS) with a total installed capacity of 2250 kW. However, the total power demand over the same period reaches 3290 kW for Load I and 6580 kW for Load II, as presented in Table 1.

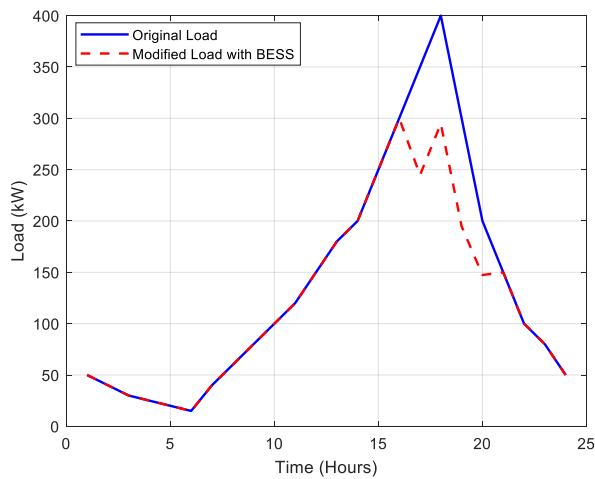
Table 1. 24-hour load profile and sunhours data

Time [Hour]	PV Power [kW]	Load I [kW]	Load II [kW]
1	0	50	100
2	0	40	80
3	0	30	60
4	0	25	50
5	0	20	40
6	0	15	30
7	100	40	80
8	200	60	120
9	300	80	160
10	400	100	200
11	500	120	240

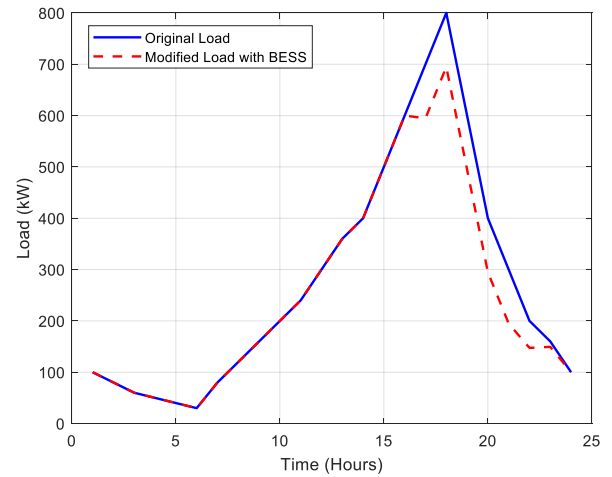
Time [Hour]	PV Power [kW]	Load I [kW]	Load II [kW]
12	400	150	300
13	300	180	360
14	200	200	400
15	100	250	500
16	50	300	600
17	0	350	700
18	0	400	800
19	0	300	600
20	0	200	400
21	0	150	300
22	0	100	200
23	0	80	160
24	0	50	100

A. Load Profile before and after BESS integration

During this period, there was no significant difference between the blue and red curves on Load I and Load II. In the second stage, which was discharge from afternoon to evening, BESS began to distribute the energy that had been stored earlier when the load approached its peak, thereby reducing the surge in power drawn from the power grid. As seen in Figure 3



(a)



(b)

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

This is evident from the difference between the blue and red curves in Load I and Load II at around 17-18 h. After the peak load has passed, the system enters the third stage, known as the recovery phase, where electricity consumption decreases again and the BESS starts recharging for use in the next cycle.

The amount of power reduction achieved through the peak shaving process can be calculated using Equation (6).

$$P_{shaving} = P_{peak,before} - P_{peak,after}$$

The following results show the reduction obtained for both Load I and Load Profile II:

For Peak Load I:

$$P_{shaving,1} = 400 \text{ kW} - 300 \text{ kW} = 100 \text{ kW}$$

For Peak Load II:

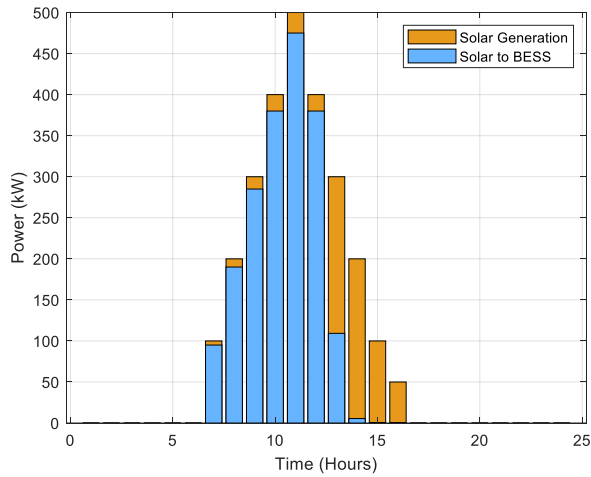
$$\begin{aligned} P_{shaving,2} &= 800 \text{ kW} - 694.74 \text{ kW} \\ &= 105.26 \text{ kW} \end{aligned}$$

Thus, the peak shaving achieved after the integration of BESS was 100 kW for Load I and 105.26 kW for Load II. The blue curve in Figure 3 represents the original load before the

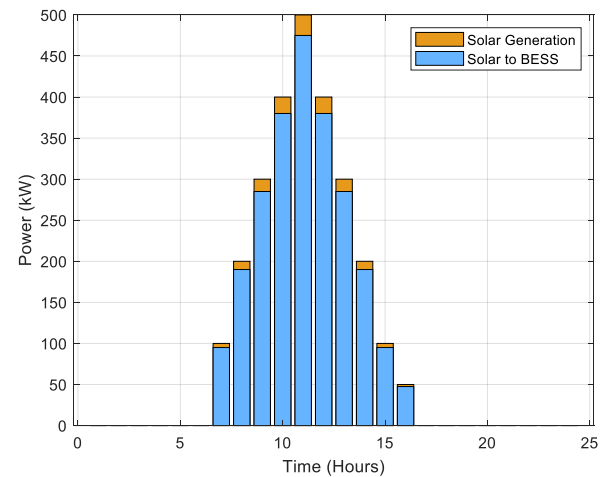
integration of BESS, where the electrical demand gradually increases and reaches its peak at around 17:00–18:00 hours, with values of approximately 400 kW for Load I and 800 kW for Load II based *Table I*, then decreases again in the evening. Meanwhile, the dashed red curve shows the load profile after the implementation of BESS, which appears lower at peak load than the blue curve. This is because the BESS stores energy when the load is low and releases it when the load is near peak, thereby reducing spikes in power demand from the grid.

B. Solar Energy Utilization

In the morning, solar power generation remains relatively low; therefore, most of the produced energy is directed to charge the battery. As solar irradiance increases throughout the day, energy production rises and reaches its maximum value of approximately 600 kW for both Load I and Load II, as shown in Figure 4.



(a)

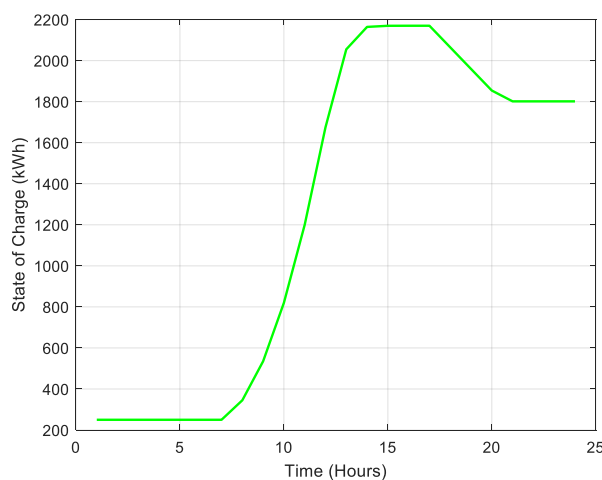


(b)

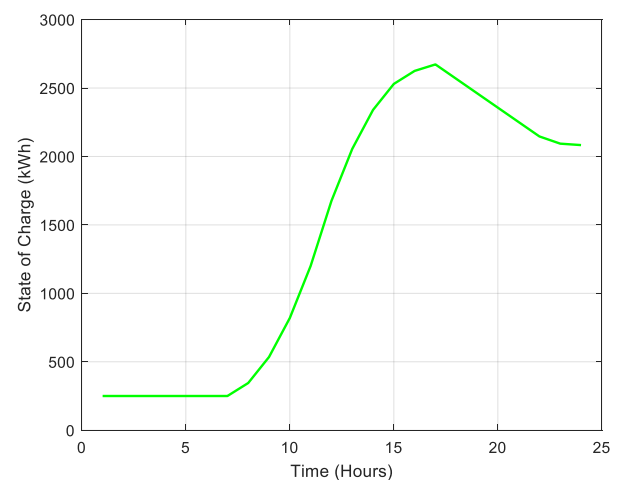
Figure 4 Graph solar energy utilization, (a) for load I and (b) for load II

During this period, most of the power is still stored in the battery as the direct consumption from the solar panel is not yet maximized. The difference between Load I and Load II can be observed in the battery charging duration. Since the BESS capacity in Load II is larger and has been adjusted to accommodate the higher load demand, the battery charging process can be carried out for a longer period compared to Load I, as seen in Figure 4. After passing the peak point, solar power production begins to decrease in the afternoon, while the proportion of directly used power increases, causing the

amount of power delivered to the battery to decrease. Towards evening, solar power production continues to decline until it finally stops after sunset. At this time, no more power is generated directly, so the system relies on the energy that has been stored in the battery beforehand. With the BESS in place, excess energy generated during the day can be used to meet electricity demand at night, thereby increasing the efficiency of renewable energy utilization and reducing dependence on the conventional power grid.



(a)



(b)

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

In the Load I and Load II systems, the energy change pattern shows a dynamic cycle of battery charging and

discharging that lasts for 24 hours of operation. At the start of the day until around 6 h, the battery remains in a

stable condition with a low energy storage level of around 250–400 kWh, indicating that the charging process has not yet occurred because electricity production from the solar power plant is still limited. From 7 h to around 14 h, the energy capacity increases sharply as solar radiation intensity rises and solar power production becomes high. In Load I, the energy storage level reaches approximately 2170 kWh at 15–16 h, while in Load II, the increase continues until it reaches approximately 2670 kWh at 17 h, or about 61% of the total battery capacity of 4340 kWh. After reaching this maximum point, the energy capacity gradually decreases until 24 h, indicating the release of stored energy to supply the load when solar production decrease.

This operational trend indicates that the battery system functions effectively in balancing energy production and consumption, with energy storage occurring during the daytime and discharge taking place at night. In Load I, the charging process reaches its maximum point as the battery becomes fully charged, reflecting optimal utilization of solar power during peak radiation periods. Conversely, Load II only reaches approximately 61% of the total BESS capacity, which may be caused by limited solar energy availability or higher load demand. As electricity demand rises in the late afternoon and evening, the battery begins discharging energy into the grid to mitigate peak loads (peak shaving). This pattern demonstrates the system's capability to maintain energy supply reliability through adaptive control of the charging and discharging cycles in response to generation and load conditions.

v. Conclusion

Based on the results of the simulations that have been carried out, it can be concluded that:

The integration of the Battery Energy Storage System (BESS) effectively reduces peak load through optimized charging and discharging operations. For Load I, the peak demand decreased from 400 kW to 300 kW, resulting in a reduction of 100 kW, while for Load II, the peak load decreased from 800 kW to 694.74 kW, with a reduction of 105.26 kW. This outcome demonstrates the capability of BESS to perform efficient peak shaving by storing

excess solar energy during high-generation periods and releasing it during peak demand hours, thereby enhancing system reliability and ensuring a more balanced and stable power supply.

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