

Optimization of Battery Energy Storage Systems for Peak Shaving: Implications for Sustainable Energy Management and Policy

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Abstract

Battery Energy Storage Systems (BESS) are increasingly important for organizations and industries seeking to enhance sustainability, improve energy efficiency, and strengthen operational reliability. As global energy demand continues to rise, adopting storage technologies is not only a technical solution but also a strategic approach that supports corporate sustainability agendas and environmental, social, and governance (ESG) commitments. This study explores the optimal deployment of BESS using an optimization-based approach under a 24-hour demand profile. Two scenarios are analyzed: the use of a single storage unit and the use of multiple units. The results show that integrating BESS improves system stability and reduces energy losses compared to operating without storage. Moreover, the multiple-unit configuration provides more effective peak shaving and load balancing than the single-unit case, emphasizing the importance of appropriate capacity planning. Beyond the technical results, the findings highlight practical implications for managers and policymakers in improving operational efficiency, reducing energy risks, and aligning with national energy transition goals.

Keywords: Battery Energy Storage System, Energy Management, Energy Efficiency, Peak Shaving, Sustainability

Introduction

The increasing demand for electricity driven by rapid urbanization and population growth has placed significant stress on power distribution networks. These challenges are further compounded by concerns over CO₂ emissions and climate change. To address such issues, the integration of advanced energy storage technologies has become a critical solution for enhancing grid reliability, flexibility, and efficiency (Olabi et al., 2023).

Battery Energy Storage Systems (BESS) have emerged as one of the most promising options for modern power systems due to their ability to store energy during low-demand periods and discharge during peak hours (Chatzigeorgiou et al., 2024a). This capability not only mitigates peak demand but also improves voltage stability, reduces power losses, and enhances overall system performance (Okafor et al., 2025). However, the benefits of BESS strongly depend on appropriate sizing and placement within the network. Oversized units increase investment costs, while undersized units limit performance.

High penetration of renewable energy resources (RERs), particularly above 20%, such as wind turbines, can significantly contribute to network instability (Hassanzadeh et al., 2023). This challenge can be mitigated through the optimal sizing and placement of Battery Energy Storage Systems (BESS). While previous studies have extensively investigated the optimal size of a single BESS, many have overlooked the importance of location. Neglecting placement can negatively impact power losses and voltage stability. Therefore, it is essential to determine both the optimal size and location of BESS units, enabling multiple batteries to operate in coordination to minimize grid losses and enhance system stability (Glücker et al., 2024; Hassanzadeh et al., 2023; Momani et al., 2025; Okafor & Folly, 2023; Z. Zhao et al., 2025).

To achieve optimal performance, metaheuristic optimization techniques have gained attention for solving the complex, nonlinear nature of BESS sizing and operation problems. Among them, the Grasshopper Optimization Algorithm (GOA), inspired by the swarming behavior of grasshoppers, offers efficient exploration and exploitation of the solution space, making it a promising approach for energy storage applications (Ahmadipour et al., 2023; Elsayed et al., 2025; Saremi et al., 2017). This paper applies to GOA to determine the optimal sizing of BESS in a distribution network, with the objective of minimizing power losses and enhancing peak shaving performance. The proposed method is validated using the IEEE 69-bus system under different operational scenarios, providing insights into the impact of BESS deployment strategies on system performance.

Beyond their technical benefits, the adoption of BESS has significant managerial and policy implications. For corporations, BESS deployment contributes to sustainability goals by reducing carbon footprints and supporting compliance with environmental, social, and governance (ESG) reporting (Feng & Lazkano, 2025). From an operational perspective, BESS enables cost efficiency in energy-intensive industries by lowering peak demand charges and improving energy utilization (Qin et al., 2025). At the national level, large-scale integration of BESS supports energy transition policies aimed at increasing renewable energy penetration and enhancing grid stability (Jafari et al., 2022). Therefore, studies on optimal BESS sizing and operation are not only technically relevant but also strategically important for organizational competitiveness and national energy sustainability agendas.

Battery Energy Storage System (BESS)

A BESS stores electrical energy for later use, enabling grid operators to balance supply and demand effectively. During periods of low demand, the system charges, while during peak hours it discharges stored energy to reduce stress on the grid (Chatzigeorgiou et al., 2024b; C. Zhao et al., 2023). This dual operation helps to stabilize the network, minimize operational costs, and improve power quality. Compared to other storage technologies, BESS offers advantages such as high efficiency, rapid response, and flexible deployment.

Peak Shaving Problem

In peak shaving applications, the goal is to reduce system power losses while maintaining stable voltage profiles. This requires determining the optimal size and placement of BESS units within the distribution system. Improper sizing may either result in excessive costs or insufficient peak reduction. The objective of the optimization in this study is to minimize system real power loss. Constraints such as bus voltage limits, charging/discharging power limits, and BESS capacity are incorporated to ensure feasible and reliable operation.

Grasshopper Optimization Algorithm (GOA)

The Grasshopper Optimization Algorithm (GOA) is a swarm-based metaheuristic inspired by the natural foraging and social behavior of grasshoppers. In this study, GOA is employed to determine the optimal size and placement of BESS units in a distribution system. The algorithm operates by initializing a population of candidate solutions, each representing a possible BESS configuration. Through iterative updates guided by attraction and repulsion forces, solutions converge toward the optimal objective value. The objective function is defined as the minimization of total system power loss. The GOA flowchart is presented in Fig. 1. The optimization process consists of the following steps:

1. **Initialization:** Define the search agents, maximum iterations, and design variables (location, size, and power rating of BESS).
2. **Fitness Evaluation:** Calculate the fitness function based on system power losses and operational constraints.
3. **Position Update:** Update each solution using GOA equations that balance local exploitation and global exploration.
4. **Constraint Handling:** Ensure voltage, capacity, and charging/discharging rate limits are satisfied.
5. **Termination:** Stop when the maximum number of iterations is reached or the optimal solution is achieved.

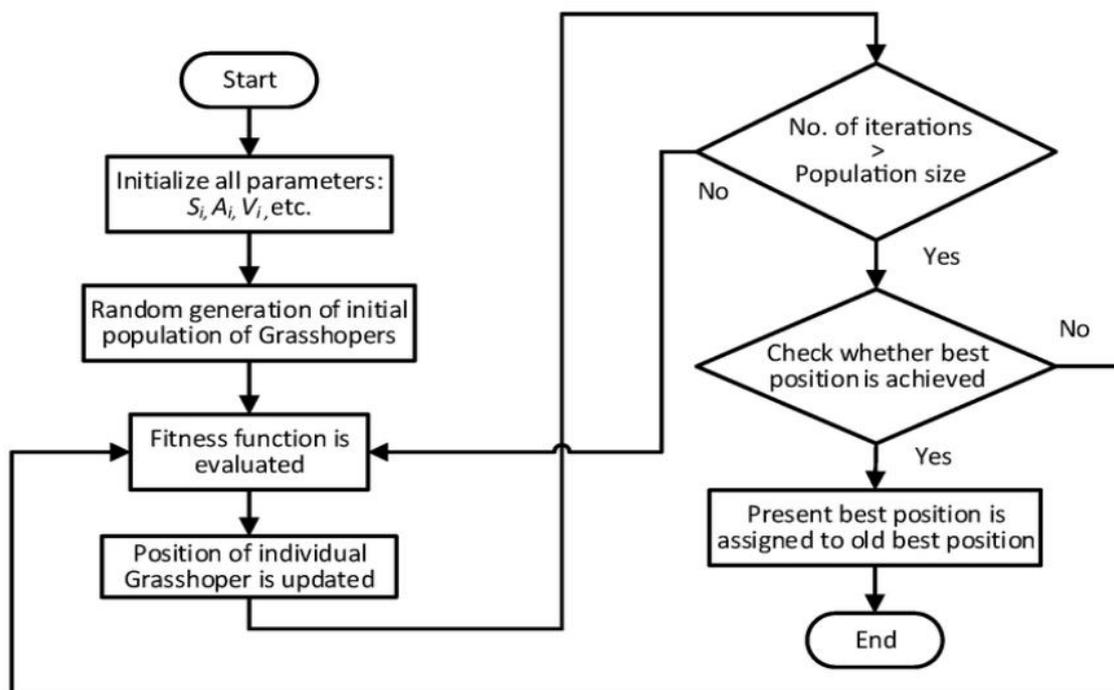


Fig.1. Flowchart of Grasshopper Optimization Algorithm

Load Profile and BESS Operation Strategy

Fig. 2 presents the 24-hour demand profile of the IEEE 69-bus system used in this study. The profile shows low demand during the early morning hours, a sharp increase beginning around 8:00 with a peak of approximately 1.8 kW at 9:00, and a gradual decline after 16:00. To evaluate peak shaving performance, the Battery Energy Storage System (BESS) operates under three modes: charging, discharging, and idle. From 1:00 to 9:00, the BESS charges during off-peak periods when demand is below 1.1 kW. Between 9:00 and 16:00, the BESS discharges stored energy to support the grid during peak demand, thereby reducing system stress and minimizing power losses. From 16:00 to midnight, the BESS remains idle since the demand decreases progressively, and cycling the battery would yield little benefit while accelerating degradation. This operating schedule ensures efficient energy utilization, effective peak shaving, and preservation of battery lifespan.

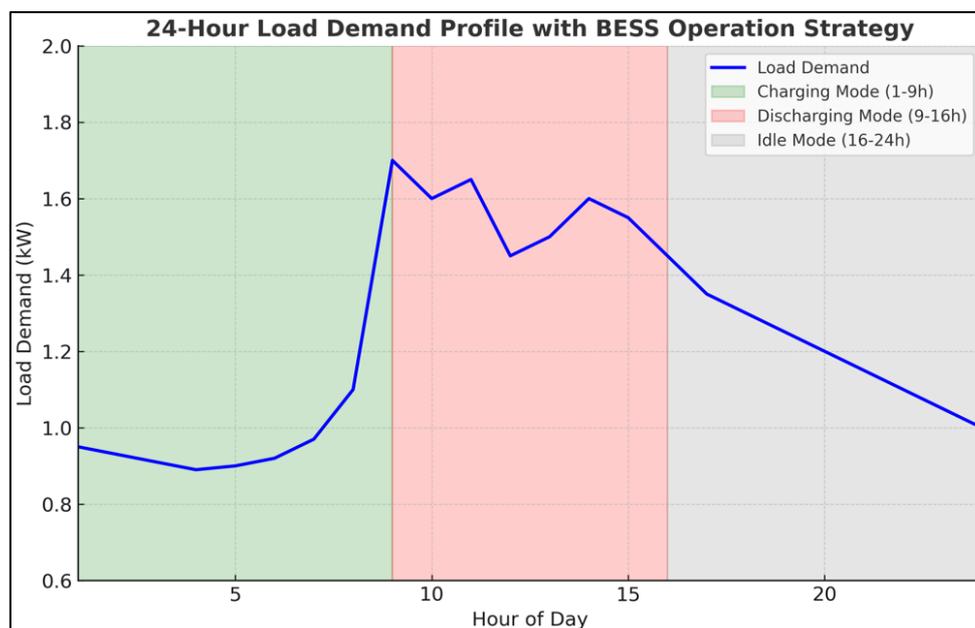


Fig. 2: Load profile

Results and Discussion

The load demand profile and BESS operating strategy described in Fig. 2 form the basis for the performance evaluation presented here. The system operates under three distinct modes: charging during off-peak hours (1:00–9:00), discharging during peak hours (9:00–16:00), and idle during moderate demand periods (16:00–24:00). This operational framework ensures that the BESS utilizes low-demand periods for charging and supports the grid during high-demand periods, while avoiding unnecessary cycling in the evening. The results discussed in the following subsections evaluate system performance under three scenarios: without BESS, with one BESS unit, and with five BESS units.

Without BESS

The system performance without BESS is illustrated in Fig. 3 and Fig. 4, which present the hourly variations of bus voltage and power loss, respectively. As shown in Fig. 3, the minimum voltage drops to 0.826 pu during peak demand hours, indicating significant voltage instability. Meanwhile, Fig. 4 shows that the maximum power loss reaches 0.8146 MW, with high losses concentrated during peak load periods. These results confirm that, without energy storage

support, the system is unable to maintain stable operation under varying demand conditions. This case establishes the baseline for evaluating the improvements achieved with BESS integration.

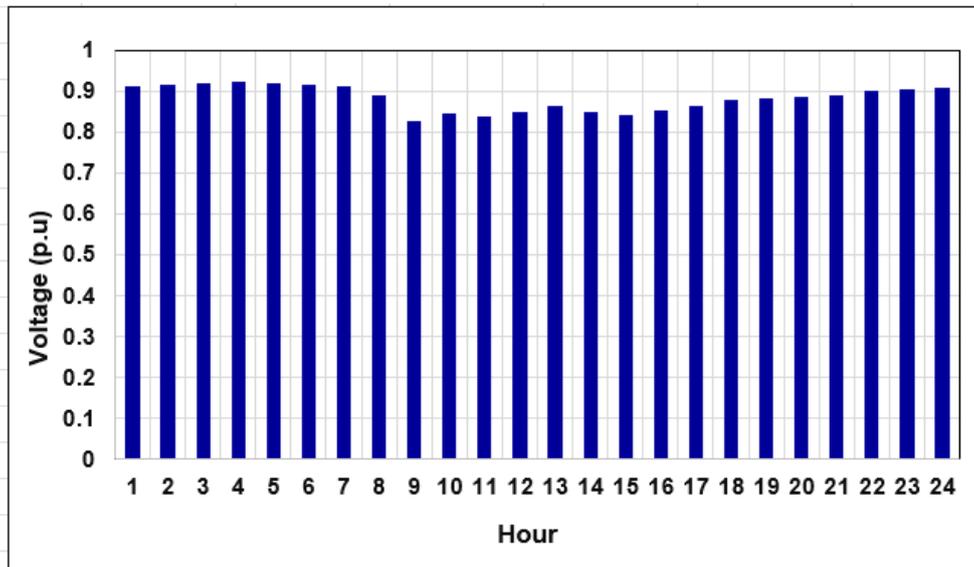


Fig. 3: Voltage Profile (Without BESS)

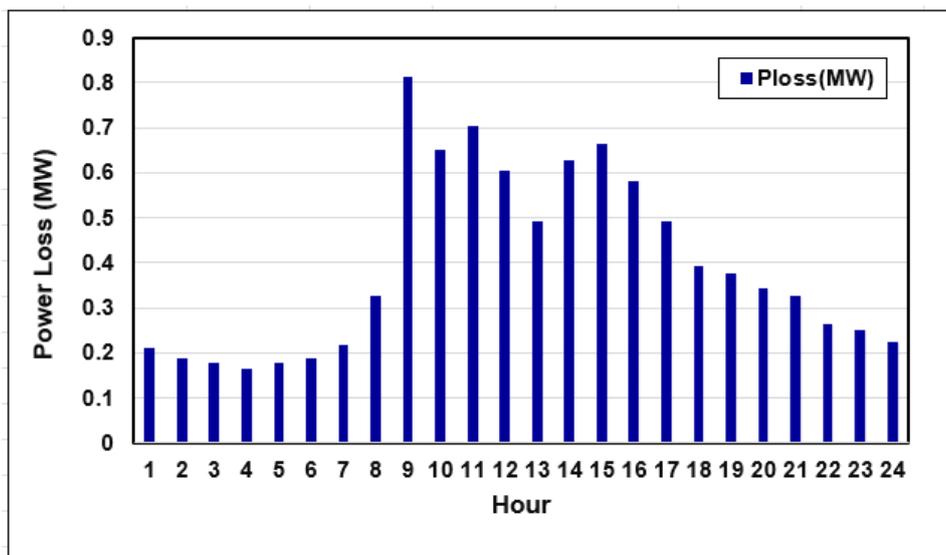


Fig. 4: Power Loss (Without BESS)

Case with Single BESS Unit

When a single BESS unit is integrated into the system, significant improvements in performance are observed., compared to the substantial voltage drop seen in the base case. Similarly, Fig. 5 shows that power losses are substantially reduced, particularly during peak demand hours, indicating the effectiveness of BESS in supporting the grid. the system voltage profile remains stable with minimum voltages consistently above the 0.90 pu threshold.

The results demonstrate that the optimally sized single BESS unit is able to absorb excess energy during off-peak hours and discharge it during high-demand periods, effectively shaving the peak load. This not only reduces stress on network components but also improves

overall system efficiency. Compared to the base case, the system with one BESS unit achieves higher voltage stability and lower losses, confirming that proper sizing of a single storage unit can deliver considerable operational benefits.

The integration of a single BESS unit shows noticeable improvements compared to the base case but with limited effectiveness. As illustrated in Fig. 5, the minimum voltage profile improves relative to the case without BESS, remaining above 0.909 pu for most of the load cycle. Similarly, Fig. 6 shows a reduction in power losses; however, the improvement is modest and concentrated during specific peak periods.

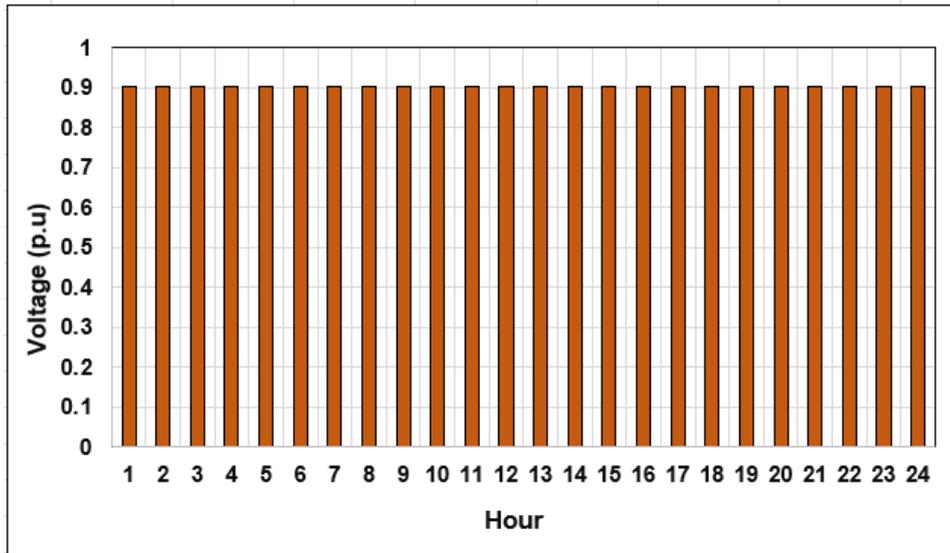


Fig. 5: Voltage Profile (Single BESS)

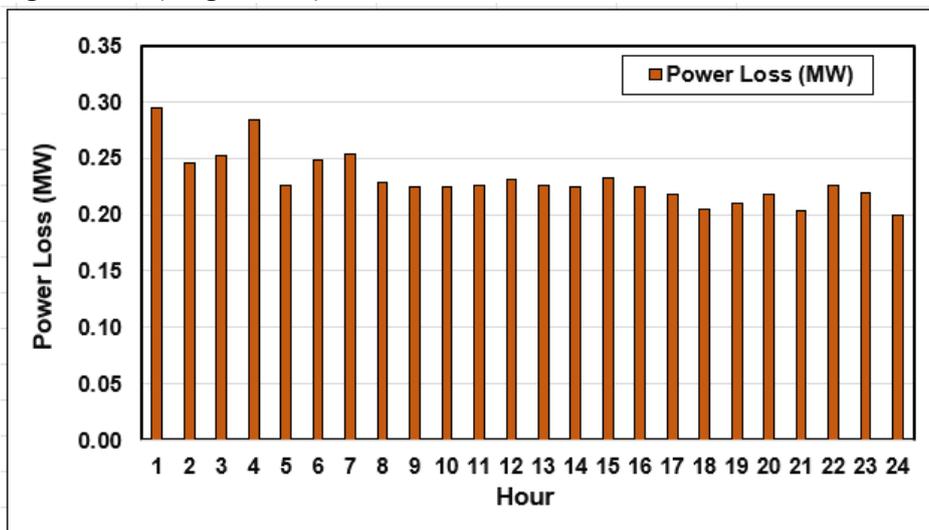


Fig. 6: Power Loss (Single BESS)

Case with Five BESS Units

The installation of five BESS units was also evaluated to examine the impact of distributing storage capacity across multiple locations. As shown in Fig. 7, the minimum voltage consistently maintained above 0.909 pu, even during the highest demand hours. In addition, Fig. 8 demonstrates a greater reduction in power losses across the 24-hour period. The distributed nature of the multiple units allows for more effective load balancing, as the

combined storage capacity is able to absorb surplus energy during off-peak hours and discharge it efficiently during peak demand. These results highlight that multiple BESS units provide superior peak shaving capability and enhanced system stability.

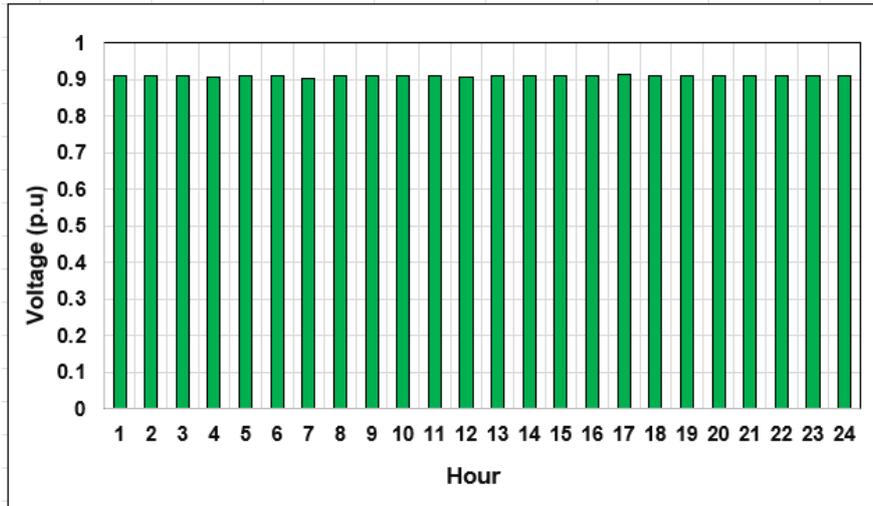


Fig. 7: Voltage Profile (Multiple BESS)

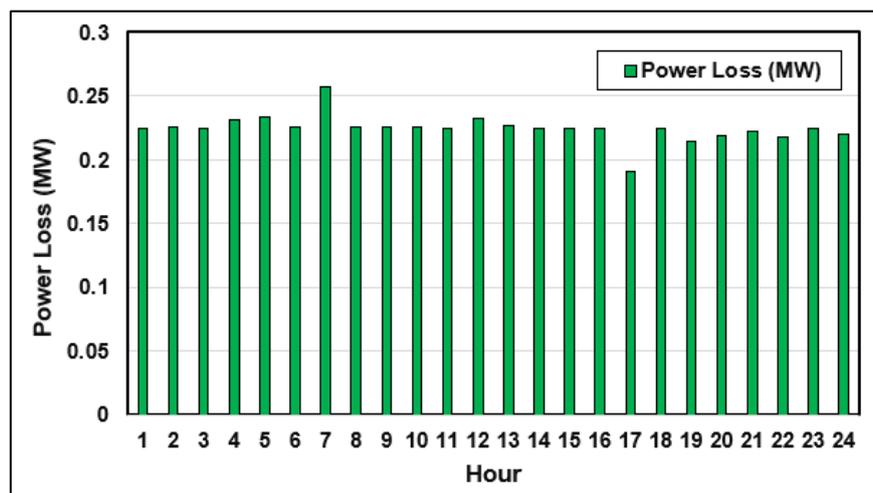


Fig. 8: Power Loss (Multiple BESS)

Comparative Analysis

A comparison of the three scenarios; without BESS, with one BESS, and with five BESS units, highlights the effectiveness of energy storage in enhancing system performance. In the base case, the system suffers from significant power losses (up to 0.8146 MW) and a minimum voltage of only 0.826 pu, underscoring its vulnerability during peak demand periods. The integration of multiple BESS unit leads to the most substantial improvement, with minimum voltage levels maintained above 0.909 pu and noticeable reductions in power loss across the daily load cycle. Conversely, while the deployment of a single BESS units also improves performance relative to the base case, the results are less favorable than the multiple-unit configuration due to small capacity and operational inefficiencies. This indicates that while one BESS unit can partially support grid performance, its limited capacity restricts its ability to fully mitigate peak demand and power losses. These findings confirm that the optimal sizing and placement of a multiple BESS unit is more beneficial than increasing the number of smaller units, both in terms of power loss reduction and voltage stability. The results also

emphasize the importance of intelligent optimization methods such as GOA, which can identify the best configuration to maximize system benefits.

Fig. 9 compares the load demand curves under the three cases: without BESS, with one BESS, and with five BESS units. In the base case, the system experiences a sharp peak of 1.76 kW at 9:00, stressing the network. With one BESS unit, the peak is reduced to approximately 1.64 kW, showing partial improvement. The most significant reduction occurs with five BESS units, where the peak is lowered to around 1.58 kW, demonstrating effective load shifting from peak to off-peak hours. These results confirm that multiple BESS units provide superior peak shaving capability, resulting in a smoother load profile and improved system reliability. By flattening the demand curve, the network benefits from reduced stress on infrastructure, lower power losses, and enhanced operational efficiency.

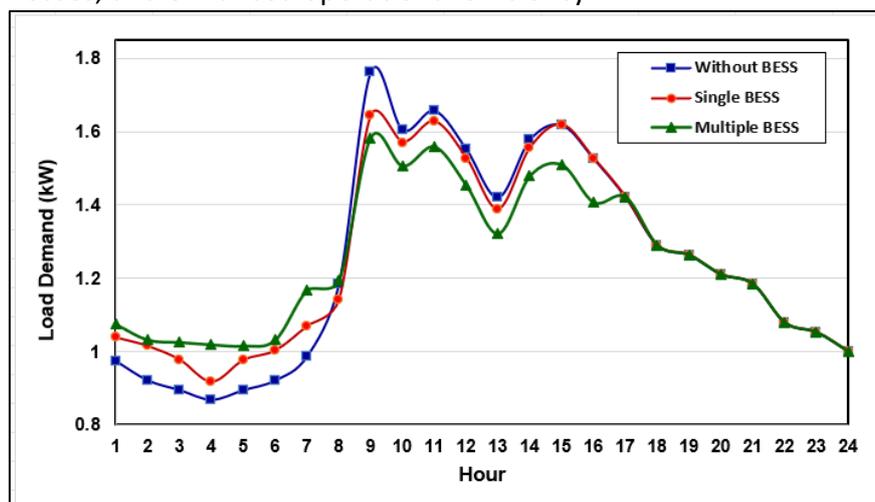


Fig. 9: Peak Shaving

Conclusion

This study applied the Grasshopper Optimization Algorithm (GOA) to determine the optimal sizing of Battery Energy Storage Systems (BESS) for peak shaving in a distribution system. The results confirmed that BESS integration improves voltage stability and reduces power losses compared to the base case without storage. Notably, the multiple-unit configuration outperformed the single-unit case, providing more effective peak shaving and greater reductions in system losses.

From a broader perspective, these outcomes highlight the managerial and policy relevance of adopting BESS in energy-intensive sectors. Improved reliability and efficiency can support organizational sustainability agendas, reduce operational risks, and contribute to national energy transition strategies. For managers and policymakers, the study provides evidence that optimization-based approaches can inform investment and planning decisions in renewable energy infrastructure. Future work may extend this study by incorporating cost-benefit analysis, human resource development for smart energy systems, and policy frameworks to accelerate adoption.

Theoretically, this study contributes to the growing body of research on metaheuristic optimization by demonstrating the effectiveness of GOA in solving complex BESS sizing and placement problems. By contrasting single-unit and multi-unit configurations, it advances the

literature with new evidence that distributed storage deployment enhances voltage stability and peak shaving more effectively than centralized solutions. Contextually, the study provides valuable insights for industries and policymakers by underscoring the role of BESS in supporting national energy transition goals, reducing operational risks, and aligning with sustainability agendas. These contributions bridge the gap between technical modeling and practical decision-making, offering both scholarly advancement and actionable guidance for energy management practices.

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References

- Ahmadipour, M., Murtadha Othman, M., Salam, Z., Alrifayy, M., Mohammed Ridha, H., & Veerasamy, V. (2023). Optimal load shedding scheme using grasshopper optimization algorithm for islanded power system with distributed energy resources. *Ain Shams Engineering Journal*, 14(1), 101835. <https://doi.org/10.1016/J.ASEJ.2022.101835>
- Chatzigeorgiou, N. G., Theocharides, S., Makrides, G., & Georghiou, G. E. (2024a). A review on battery energy storage systems: Applications, developments, and research trends of hybrid installations in the end-user sector. *Journal of Energy Storage*, 86, 111192. <https://doi.org/10.1016/J.EST.2024.111192>
- Chatzigeorgiou, N. G., Theocharides, S., Makrides, G., & Georghiou, G. E. (2024b). A review on battery energy storage systems: Applications, developments, and research trends of hybrid installations in the end-user sector. *Journal of Energy Storage*, 86, 111192. <https://doi.org/10.1016/J.EST.2024.111192>
- Elsayed, A. M., El-Rifaie, A. M., Areed, M. F., Shaheen, A. M., & Atallah, M. O. (2025). Allocation and control of multi-devices voltage regulation in distribution systems via rough set theory and grasshopper algorithm: A practical study. *Results in Engineering*, 25, 103860. <https://doi.org/10.1016/J.RINENG.2024.103860>
- Feng, S., & Lazkano, I. (2025). Energy storage and clean energy transitions. *Energy Policy*, 198, 114447. <https://doi.org/10.1016/J.ENPOL.2024.114447>
- Glücker, P., Pesch, T., & Benigni, A. (2024). Optimal sizing of battery energy storage system for local multi-energy systems: The impact of the thermal vector. *Applied Energy*, 372, 123732. <https://doi.org/10.1016/J.APENERGY.2024.123732>
- Hassanzadeh, M. E., Nayeripour, M., Hasanvand, S., & Sepehrzad, R. (2023). Hierarchical optimal allocation of BESS using APT-FPSO based on stochastic programming model considering voltage sensitivity and eigenvalues analyses. *International Journal of Electrical Power & Energy Systems*, 153, 109291. <https://doi.org/10.1016/J.IJEPES.2023.109291>
- Jafari, M., Botterud, A., & Sakti, A. (2022). Decarbonizing power systems: A critical review of the role of energy storage. *Renewable and Sustainable Energy Reviews*, 158, 112077. <https://doi.org/10.1016/J.RSER.2022.112077>
- Momani, R. Q., Abuelrub, A., Al-Masri, H. M. K., & Al-Shetwi, A. Q. (2025). Cost-optimal sizing of battery energy storage systems in microgrids using artificial Rabbits optimization. *Energy Nexus*, 19, 100486. <https://doi.org/10.1016/J.NEXUS.2025.100486>

- Okafor, C. E., & Folly, K. A. (2023). Optimal placement of BESS in a power system network for frequency support during contingency. *Energy Reports*, 10, 3681–3695. <https://doi.org/10.1016/J.EGYR.2023.10.017>
- Okafor, C. E., Gbadamosi, S. L., Krishnamurthy, S., Ratshitanga, M., & Moodley, P. (2025). Techno-economic analysis of battery storage technologies in distribution networks with integrated electric vehicles and solar PV systems. *Energy Reports*, 14, 579–599. <https://doi.org/10.1016/J.EGYR.2025.06.008>
- Olabi, A. G., Elsaid, K., Obaideen, K., Abdelkareem, M. A., Rezk, H., Wilberforce, T., Maghrabie, H. M., & Sayed, E. T. (2023). Renewable energy systems: Comparisons, challenges and barriers, sustainability indicators, and the contribution to UN sustainable development goals. *International Journal of Thermofluids*, 20, 100498. <https://doi.org/10.1016/J.IJFT.2023.100498>
- Qin, Z., Ma, J., Zhu, M., & Khan, T. (2025). Advancements in energy storage technologies: Implications for sustainable energy strategy and electricity supply towards sustainable development goals. *Energy Strategy Reviews*, 59, 101710. <https://doi.org/10.1016/J.ESR.2025.101710>
- Saremi, S., Mirjalili, S., & Lewis, A. (2017). Grasshopper Optimisation Algorithm: Theory and application. *Advances in Engineering Software*, 105, 30–47. <https://doi.org/10.1016/J.ADVENGSOFT.2017.01.004>
- Zhao, C., Andersen, P. B., Træholt, C., & Hashemi, S. (2023). Grid-connected battery energy storage system: a review on application and integration. *Renewable and Sustainable Energy Reviews*, 182, 113400. <https://doi.org/10.1016/J.RSER.2023.113400>
- Zhao, Z., Shang, Y., Qi, B., Wang, Y., & Zhang, Q. (2025). Optimal sizing and siting of energy storage systems based on power grid vulnerability analysis: a trilevel optimization model. *Energy Strategy Reviews*, 59, 101720. <https://doi.org/10.1016/J.ESR.2025.101720>