TOWARD NET-ZERO INTERCONNECTED MICROGRIDS: COORDINATED USE OF MOBILE BATTERY ENERGY STORAGE TO BALANCE SURPLUS ENERGY AND CARBON EMISSIONS

Mohammadreza Gholami[1], Yao Gao[2], Guo Chen[3*], S M Muyyen[1]*

[1] *Department of Electrical Engineering, Qatar University, Doha 2713, Qatar*
[2] *Department of Electrical Automation, Shanghai Maritime University, Shanghai, China*
[3] *School of Electrical Engineering and Telecommunications, the University of New South Wales, Sydney, Australia.*
**mohammadreza.gholami@qu.edu.qa*

Keywords: INTERCONNECTED MICROGRIDS, BATTERY ENERGY STORAGE SYSTEM (BESS), MOBILE BESS, SURPLUS ENERGY, CARBON EMISSION

Abstract

The growing penetration of renewable energy in distributed systems demands smarter energy management strategies, especially in sectors like agriculture where supply and demand vary both spatially and temporally. While BESS are highly beneficial in enhancing energy reliability and reducing emissions, their stationary nature limits flexibility, often leading to the loss of surplus energy. This study proposes a novel optimization framework for the coordinated deployment of Mobile Battery Energy Storage Systems (MBESS) across two connected MGs (commercial and residential), aimed at reducing renewable energy curtailment, grid import dependency, and associated CO2 emissions. An optimized operational framework for a MBESS integrated with interconnected microgrids using a shared BESS is proposed. The proposed system enables flexible energy transfer, surplus management, and reduced reliance on the main grid through a Mixed-Integer Linear Programming (MILP) approach. The model considers spatio-temporal constraints, and transportation energy costs, ensuring realistic and applicable results. Simulation outcomes indicate that while the addition of MBESS introduces a modest increase in operational cost (approximately 2.7%), it significantly reduces grid energy imports by 22%, surplus energy wastage by 65%, and CO2 emissions by 13%. These results underscore the effectiveness of mobile storage in enhancing energy autonomy and environmental sustainability in decentralized renewable systems.

1 Introduction

The global energy sector is undergoing a rapid and profound transformation driven by the urgent need to reduce greenhouse gas emissions, decentralize energy production, and enhance the resilience of power systems [1]. Renewable energy sources (RES), particularly solar photovoltaic (PV) and wind turbines (WT), have emerged as the cornerstones of this transition [2]. However, the intrinsic intermittency and variability of these sources pose significant operational challenges, especially in isolated or weakly connected systems such as microgrids (MGs) [3]. The imbalance between generation and demand leads to two primary concerns: energy curtailment due to surplus generation during low-demand periods, and dependency on grid imports or fossil-based backup systems during renewable shortfalls [4]. despite their benefits, MGs alone may not always achieve optimal energy independence or economic performance, especially when operated in isolation or without sufficient flexibility [5]. One major obstacle is the lack of storage capacity that can smooth out temporal fluctuations and support demand-side management [6].

To address this, Battery Energy Storage Systems (BESS) have increasingly been integrated into MGs, providing the means to store excess renewable energy and redistribute it during peak demand [7]. BESS have emerged as critical enablers of renewable energy integration within modern power systems [8] [9]. This capability significantly reduces the mismatch between renewable supply and load demand, thereby decreasing reliance on fossil-based grid imports and improving the overall efficiency and sustainability of energy systems [10]. BESS also supports ancillary services such as peak shaving, reliability improvement, frequency regulation, and voltage support, making it a versatile asset for both grid-connected and islanded MG operations [11] [12]. In the context of MGs, especially those operating with high renewable penetration and limited grid interconnection, shared BESS plays a particularly strategic role. It facilitates cooperative energy management across multiple MGs, enabling distributed generation to be pooled and excess energy to be stored centrally for mutual benefit [13]. However, the fixed location of BESS may constrain its flexibility in geographically dispersed systems or where renewable generation and consumption are unevenly distributed.

This limitation sets the stage for the complementary use of Mobile BESS (MBESS), which introduces the spatial flexibility that fixed BESS lacks. [14] MBESS can physically relocate stored energy across MGs, bridging supply-demand gaps not only across time but also across space. This mobility dimension introduces a new layer of optimization and coordination, enabling energy to be dispatched where it is most needed, thereby maximizing renewable utilization and minimizing waste or costly grid dependence [15].

1.1 Related works

Various studies, have considered utilizing MBESS and its technical impact in grid operation. A study in [16] introduces an innovative approach to enhance electric vehicle (EV) charging infrastructure through the optimal deployment of a MBESS, conceptualized as a self-powered, self-driving mobile charging station (MCS). Simulation results validate the benefits of this mobile strategy, showing a 3.46% reduction in daily operating costs and a dramatic 94% drop in EV charging queue lengths at fixed stations. A study in [17] provides a comprehensive review of the application of MESS in enhancing the resilience of power distribution networks, especially in the face of natural disasters. The review emphasizes that this operational flexibility is particularly valuable during emergencies when fast response and adaptability are essential. The study explores the need to simultaneously consider both power system constraints and transportation logistics when planning for the allocation of mobile energy resources.

A study in [18] introduces a novel and efficient spatio-temporal model for MBESS in distribution networks, highlighting their advantages over traditional stationary counterparts. The proposed approach accounts for the dual flexibility of MBESS—both in time and space—by enabling optimal deployment across various network locations as needs change. The model simplifies operational complexity by using only the transportation time between network buses to represent mobility, avoiding the intricacies of full transportation network modeling. Linear and computationally efficient equations are employed to capture transportation costs and constraints, making the method scalable and suitable for real-world distribution networks. A study referenced in [19] explores the development and control of a standalone high-capacity MBESS designed to meet the energy demands of a typical Malaysian household. In this work, a programmable logic controller is proposed as the main control mechanism, addressing common shortcomings of traditional control units such as limited interface options, low resilience to electrical noise, and inadequate performance in high-power applications.

A study in [20] introduces a method for the optimal integration and sizing of MBESS within renewable-rich distribution networks. The proposed framework approaches the integration as a bi-objective optimization problem, aiming to enhance system reliability while minimizing energy transaction costs. The authors also perform a cost–benefit analysis to determine optimal MBESS capacities under practical constraints. A study in [21] investigates the combined use of fixed and mobile battery energy storage systems (BESS) to enhance the flexibility and operational robustness of a two-way active distribution network. The network is modeled as bidirectional—capable of being fed from both ends—which allows for improved load balancing, reduced losses, and lower operating costs.

However, effectively coordinating shared and mobile storage assets within a network of interconnected MGs requires sophisticated energy management strategies. Traditional rule-based or heuristic methods are often insufficient for such tasks. This necessitates the application of optimization-based methods, particularly those capable of handling mixed logical and continuous decisions—such as Mixed-Integer Linear Programming (MILP) [22] [23]. MILP provides a powerful framework to model operational decisions involving binary variables (e.g., whether to deploy MBESS to a certain location) and continuous variables (e.g., power levels of generation or charging).

1.2 Objective and contribution of the study

The increasing complexity of modern energy systems, calls for advanced strategies to manage energy efficiently, reduce environmental impact, and ensure supply reliability. This study is centered around exploring the potential of MBESS as a flexible and dynamic solution in such networks. This work aims to address several key questions related to the deployment and operation of MBESS in interconnected MG environments: What is the impact of integrating MBESS on greenhouse gas (CO_2) emissions and total operational costs? A comprehensive analysis is performed to quantify the environmental and economic benefits associated with optimized MBESS operation compared to static storage or no-storage scenarios.

To address these questions, this study provides the following novel contributions:

- Development of an optimized energy management model for MBESS operation in a system of interconnected greenhouse MGs with a shared stationary BESS: A spatio-temporal optimization framework is proposed based on MILP.
- Quantitative evaluation of MBESS impact on surplus energy utilization and CO_2 emission reduction: By simulating various operating scenarios, the study demonstrates how MBESS contributes to lowering CO_2 emissions through reduced fossil fuel reliance and better renewable energy usage. These contributions provide valuable insights into the practical application of MBESS technology in sustainable energy systems, supporting both operational resilience and environmental sustainability (Fig. 1).

The remainder of this paper is organized as follows: Section 2 outlines the methodology, covering system configuration, modeling assumptions, and the energy management framework. Section 3 details the MILP-based mathematical formulation, including the objective function and key operational constraints such as power balance, battery dynamics, mobility, and emissions. Section 4 presents simulation results across multiple scenarios, offering quantitative insights into MBESS performance. A discussion follows on its impact in reducing surplus energy, CO_2 emissions, and enhancing system flexibility. Section 5 concludes the study, summarizing key findings and proposing directions for future research.

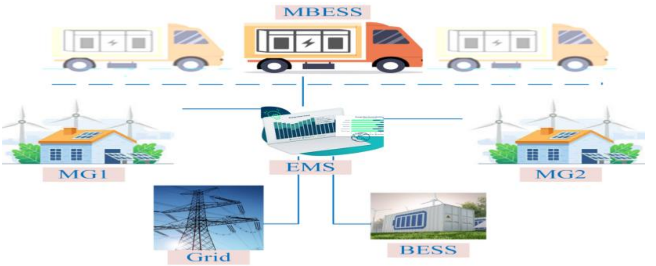

Fig. 1 The schematic diagram of EMS utilizing MBESS in interconnected MG

2 Methodology

This section presents a MILP-based methodology for optimizing the operation of a MBESS within a network of interconnected greenhouse MGs. The approach targets cost reduction, surplus energy management, CO_2 emission mitigation, and enhanced operational flexibility. The methodology unfolds in five key stages:

Stage 1: The system comprises multiple greenhouse MGs, each with local renewable sources (e.g., PV), controllable loads, and access to a mobile, truck-mounted MBESS. MGs operate independently but coordinate through a centralized energy management system. The MBESS facilitates energy transfer between MGs, enabling surplus redistribution and system-wide optimization.

Stage 2: MBESS Modeling: The MBESS is modeled as a mobile energy carrier with constraints on capacity, charge/discharge power, and efficiency. Its mobility is constrained by travel time and energy consumed during transportation. The model incorporates, state of charge (SOC) dynamics over time, spatio-temporal scheduling, energy transfer constraints, and transportation energy cost, accounted for by subtracting the required driving energy from the MBESS storage.

Stage 3: Operational Constraints: Several operational constraints are included in the model to ensure technical feasibility and alignment with practical system behavior: Power balance constraints for each MG, ensuring supply meets demand at all times, battery operational limits, mobility constraints, and grid interaction constraints are considered in the model.

Stage 4: Objective Function: The core of the methodology is the objective function, formulated to minimize the total operational cost of the system while considering environmental impact. The function includes cost of electricity purchased from the grid, operational cost of the MBESS, and environmental cost in terms of CO_2 emissions based on the carbon intensity of imported electricity.

Stage 5: Scenarios and Simulation Setup: Constraints ensure practical feasibility, including power balance for each MG, storage operation limits, mobility scheduling, and grid import/export limits. The optimization framework is illustrated in Fig. 2, detailing the process flow from system configuration to scenario simulation.

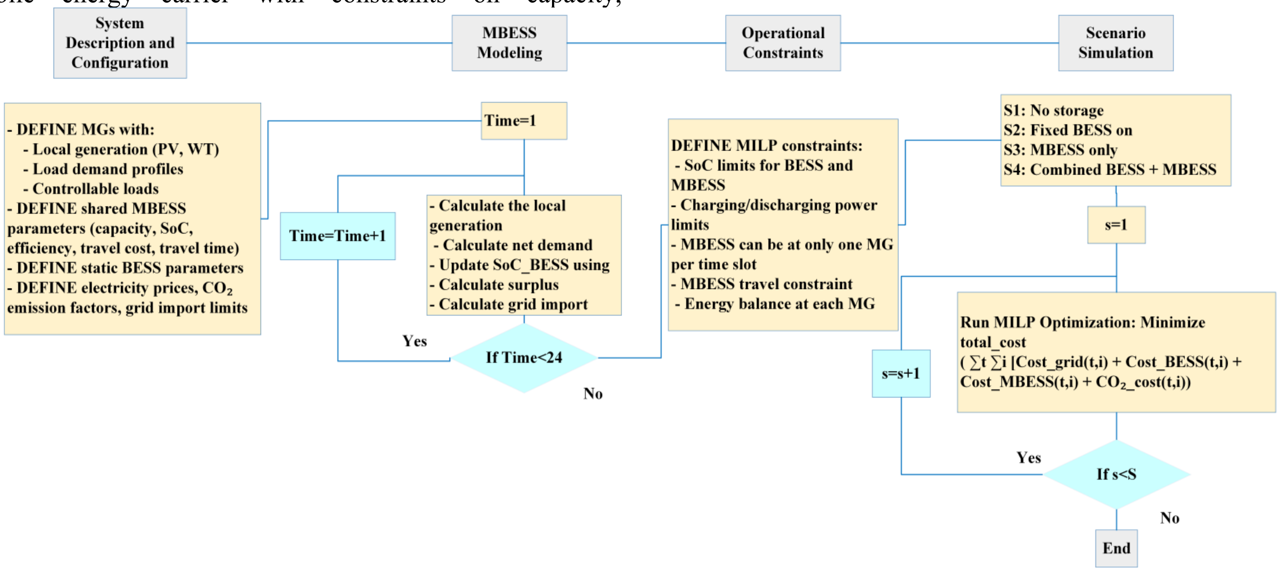

Fig. 2 Flowchart of the optimization framework

3. Mathematical Modelling

In this section, we present the mathematical framework used to model the operation of the MBESS integrated into interconnected MGs.

3.1. *Objective formulation*

The objective of the optimization problem is to minimize the total cost including the cost of MGs, grid, BESS and MBESS.

Equation (1) represents the sum of costs over each time step t, for both MGs $i = 1,2$.

$$Min\ Cost_{total} = \sum_{t=1}^{24}\sum_{i=1}^{2} Cost_{grid,t} + Cost_{MGi,t} + Cost_{BESS,t} + Cost_{MBESS,t} \quad (1)$$

$$Cost_{grid,t} = E_{grid,t} \times p_t \quad (2)$$

$$Cost_{MGi,t} = Cost_{WT,t} + Cost_{PV,t} \tag{3}$$

$$Cost_{BESS,t} = C_{BESS,t} \times p_{BESS} \tag{4}$$

$$Cost_{MBESS,t} = C_{MBESS,t} \times p_{MBESS} + p_{traveling} \tag{5}$$

where, $E_{grid,t}$ is the amount of energy imported from the main grid, and p_t is the unit price of grid electricity at time t. Cost of generating energy for each MG ($Cost_{MGi,t}$) includes cost of WT ($Cost_{WT,t}$) and PV ($Cost_{PV,t}$)in MG i at time t. Also, cost of BESS ($Cost_{BESS,t}$) depends on the energy of BESS at time t ($E_{BESS,t}$) and the cost coefficient for the BESS (p_{BESS}) in \$/kWh. $p_{traveling}$ is the cost associated with moving the MBESS from one location to another.

In addition, regarding the energy balance and CO_2 we have:

$$P_{surplus,t} = P_{surplus,t,MG1} + P_{surplus,t,MG2} \tag{6}$$

$$P_{surplus,t,i} = P_{WT,t,i} + P_{PV,t,i} + P_{BESS,t,i} + P_{MBESS,t,i} - P_{load,t,i} \tag{7}$$

$$P_{grid,t,i} = P_{load,t,i} - P_{WT,t,i} - P_{PV,t,i} - P_{BESS,t,i} - P_{MBESS,t,i} \tag{8}$$

$$CO_{2,t,i} = P_{grid,t,i} \times 0.6 \tag{9}$$

where, surplus power ($P_{surplus,t}$) for MG i at time t, is defined as the total generation ($P_{WT,t,i} + P_{PV,t,i}$) and discharge ($P_{BESS,t,i} + P_{MBESS,t,i}$) from storage systems minus the local load demand in each MG ($P_{load,t,i}$). If local supply and storage are insufficient, the equation (8) determines how much power needs to be drawn from the grid ($P_{grid,t,i}$). Moreover, the linear relationship in equation (9) estimates CO_2 emissions assuming 0.6 kg CO2 per kWh of grid energy.

3.2. *Constraint of the problem*

Equation (10) shows energy dynamics of BESS/MBESS ($E_{BESS/MBESS,t}$), based on the maximum charging and discharging capabilities of both BESS and MBESS ($P^{C}_{BESS/MBESS}$ *and* $P^{D}_{BESS/MBESS}$).

$$E_{BESS/MBESS,t} = E_{BESS/MBESS,t-1} + (P^{C}_{BESS/MBESS} \times \eta_C - \frac{P^{D}_{BESS/MBESS}}{\eta_D}) \times \Delta t \tag{10}$$

$$SoC_{BESS,min} \leq SoC_{BESS,t} \leq SoC_{BESS,max} \tag{11}$$

$$0 \leq P^{C}_{BESS/MBESS}(t) \leq P^{max,C}_{BESS/MBESS} \tag{12}$$

$$P^{D}_{BESS/MBESS}(t) \leq P^{max,D}_{BESS/MBESS} \tag{13}$$

where, η_C *and* $\eta_D$represent the efficiency of battery in charging and discharging. Equation (11) ensures the battery's State of Charge ($SoC_{BESS,t}$), charging capacity ($P^{C}_{BESS/MBESS}$) and discharging capacity ($P^{D}_{BESS/MBESS}$) remains within safe operational limits.

Equation (14) limits the power imported from the grid based on physical or contractual limits.

$$P_{grid,t} \leq P^{max}_{grid} \tag{14}$$

Finally, equation (15), restricts how far or frequently the MBESS can move between network locations over each time interval ($\boldsymbol{\alpha_t}$).

$$T_{MBESS}(t) - T_{MBESS}(t-1) \leq \alpha_t \tag{15}$$

4. Numerical Study

The primary inputs include hourly load demand profiles for both MGs, generation from WT and PV, and the parameters of BESS and MBESS systems. Carbon emissions are calculated using a factor of 0.6 kg CO_2 per kWh of imported energy.

Fig. 3 illustrates the load demand versus the renewable energy generation (PV and WT) for both MGs. MG1, being commercial, shows a pronounced peak during working hours, while MG2 exhibits more spread residential demand. Load profiles are stylized based on typical commercial (MG1) and residential (MG2) patterns from references [24] [25]. Renewable generation contributes significantly during daylight hours, particularly from PV.

Table 1. Summary of Input Parameters [26] [10]

Parameter	Value	Parameter	Value
CO_2 Emission Factor	0.6 (kg CO_2/kWh)	Cost of WT	0.033(\$/kWh)
Shared BESS Capacity	80 (kWh)	Cost BESS	0.37 (\$/kWh)
MBESS Capacity	55 (kWh)	Cost MBESS	0.5 (\$/kWh)
Time of Use Tariff : Peak, Off-Peak, Intermediate	0.43,0.3, and 0.12 for (\$/kWh)	Efficiency of BESS/MBESS	Charging / discharging : 0.8-0.8
Cost of PV	0.048 (\$/kWh)	SoC of battery	20-80

Fig. 4 compares surplus energy levels and renewable energy utilization efficiency across three operational scenarios. In Scenario 1 (S1), the absence of storage results in a high surplus (1029 kWh, 20.26%) due to the inherent temporal mismatch between renewable generation and demand. This demonstrates the system's inability to absorb peak generation periods—particularly midday PV output—highlighting the need for flexibility mechanisms. Scenario 2 (S2) introduces a shared BESS, which significantly reduces surplus to 381 kWh (7.05%). This improvement stems from the BESS's ability to store mid-peak solar and early-morning wind generation for use during later demand peaks. However, since the BESS is stationary, it may not be optimally located at all times to absorb localized excess energy in both MGs. Scenario 3 (S3) includes both shared BESS and MBESS, further reducing surplus to 190 kWh (3.74%). The MBESS enhances spatial flexibility, dynamically relocating to areas of highest surplus or deficit. This mobility allows real-time alignment of storage resources with localized generation/demand variations—something the fixed BESS cannot achieve. This results in the lowest curtailment and the most efficient use of renewable resources among all scenarios. The comparative results across the three scenarios reveal the incremental value of coordinated and mobile storage deployment, not just in reducing surplus but in providing adaptive, location-aware energy balancing.

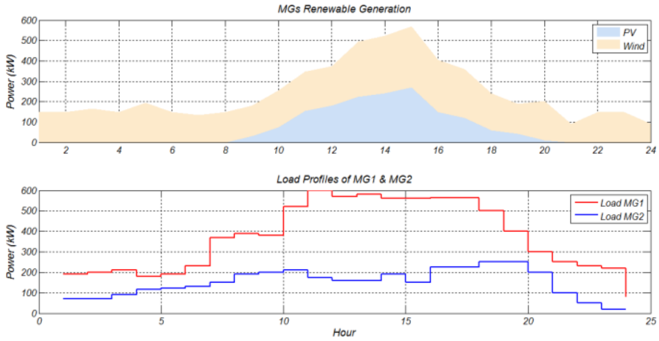

Fig. 3 Load Demand vs Renewable Generation for MG1 and MG2

Fig. 5 illustrates the hourly imported power profiles across the three scenarios, highlighting the role of energy storage in reducing reliance on external grid electricity. In Scenario 1 (S1)—without energy storage—grid dependency is highest, with a peak import of 360 kW at Hour 10 and consistently elevated imports from Hours 6 to 18. Sharp spikes (e.g., 280 kW at Hour 7, 310 kW at Hour 9) reflect the absence of internal balancing. Minimal import occurs only during low-load nighttime hours (e.g., Hours 4, 5, 22, 23). Scenario 2 (S2), incorporating a shared BESS, flattens the import curve modestly. While peak imports remain (e.g., 360 kW at Hour 10), noticeable reductions occur during key periods—170 kW at Hour 6 (vs. 250 kW in S1) and 155 kW at Hour 8 (vs. 235 kW in S1)—indicating effective BESS discharge during high demand. However, the stationary nature of the storage limits flexibility. Scenario 3 (S3), combining shared and mobile BESS, achieves the most significant improvement. No imported power is required during Hours 0–5, and major reductions are observed during peak times—165 kW at Hour 17 (vs. 300 kW in S1) and 0 kW at Hours 19 and 20, compared to 287 kW and 99 kW in S1. The MBESS enhances both temporal and spatial balancing, greatly reducing grid dependence.

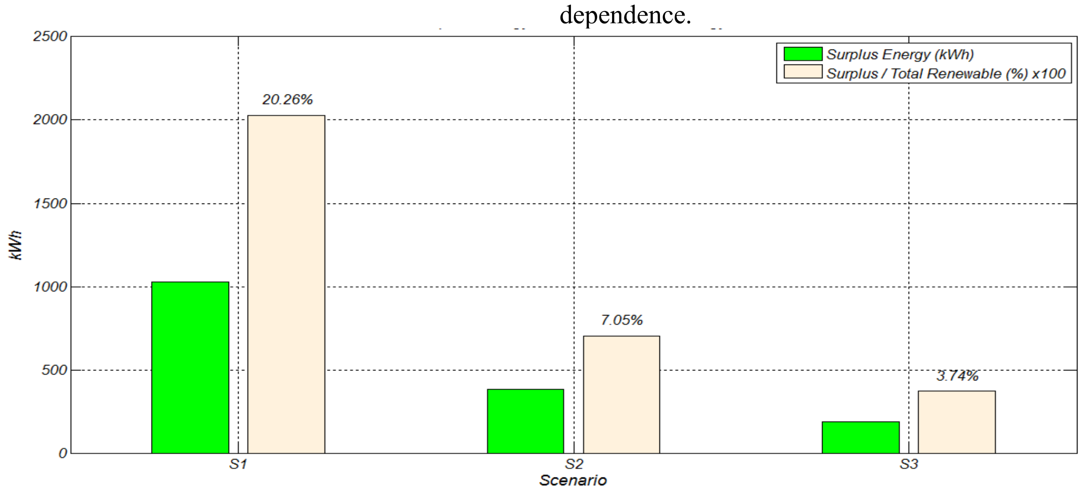

Fig. 4 Surplus Energy across Scenarios

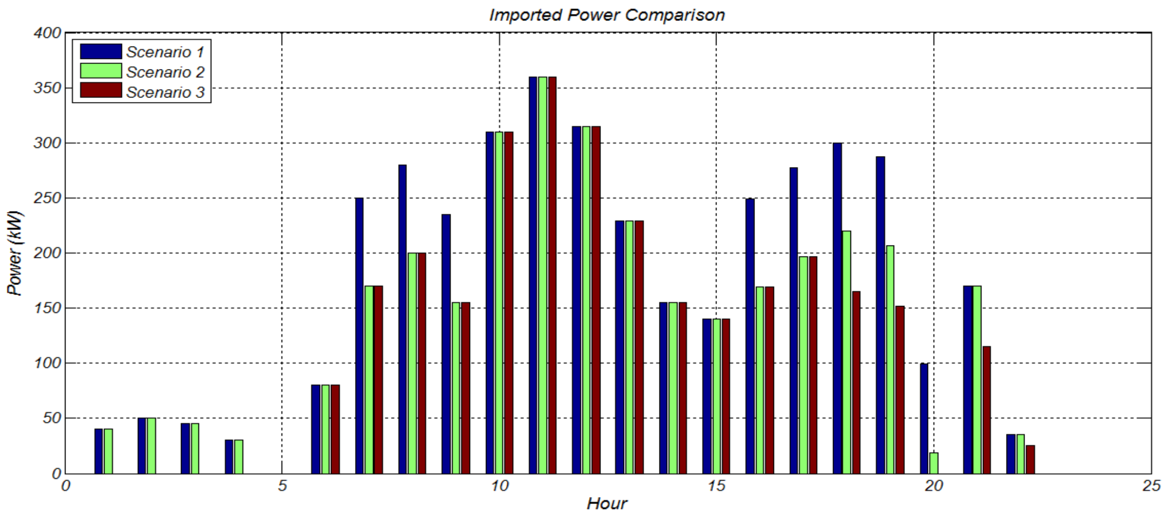

Fig. 5 Imported Power Comparison across Scenarios

Fig. 6 presents the percentage breakdown of energy sources—imported power, PV, WT, and BESS/MBESS—for each scenario, highlighting how storage integration reshapes the energy mix in the MGs. In S1, the system relies heavily on imported power (40.1%), with wind (44%) and PV (15.8%) making up the remainder. The absence of storage leads to curtailed renewable energy and increased grid dependence. S2introduces a shared BESS, reducing imported power to 33.6%—a 16% relative drop—with 6.5% of energy now supplied by the BESS. PV and wind contributions remain unchanged, implying better utilization of existing generation rather than added capacity. In S3, the addition of MBESS further cuts grid imports to 29.9%, with a combined 10.2% from both storage systems (6.5% BESS + 3.7% MBESS). Despite no change in renewable generation levels, enhanced storage flexibility enables real-time load matching and deeper renewable integration. By Scenario 3, nearly 70% of total demand is met by local resources, demonstrating the pivotal role of storage—particularly mobile systems—in improving energy independence and grid resilience.

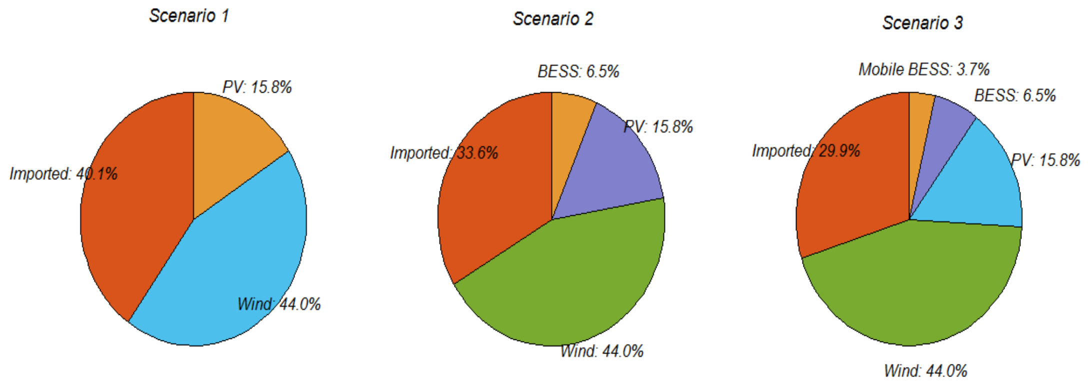

Fig. 6 Energy Source Contribution by Scenario

Table 2. Total Cost and CO2 Emissions

Scenario	Total Cost ($)	CO_2 Emissions (ton)
Baseline	2045.50	2.935
S1	1764.40	2.362
S2	1537.20	1.978
S3	1554.00	1.762

Table 2 presents a comparative overview of total operational costs and associated carbon dioxide (CO_2) emissions across the three examined scenarios. This analysis highlights the economic and environmental benefits realized through progressive integration of energy storage systems. In this baseline, the system incurs the highest operational cost of $2045.50 and emits approximately 2.935 tons of CO_2, reflecting the heavy dependence on carbon-intensive grid imports. In S1, where the MGs operate without any form of energy storage, the total cost amounts to $1764.40, and the system emits approximately 2.362 tons of CO_2 over the evaluation period. This scenario reflects the highest reliance on imported grid electricity—known to be both costly and carbon-intensive—due to limited utilization of surplus renewable energy. With the deployment of a shared BESS in S2, a significant cost reduction of $227.20 is observed, lowering the total expenditure to $1537.20. This equates to a 12.9% cost saving compared to Scenario 1. Correspondingly, CO_2 emissions drop to 1.978 tons, indicating a 16.2% reduction in environmental impact. These improvements stem from enhanced utilization of on-site renewable resources, where excess energy is stored instead of curtailed, and then used to offset grid imports. In S3, which builds upon S2 by integrating a MBESS in addition to the shared system, the total cost slightly increases to $1554.00—just 1.1% higher than S2. However, this slight economic trade-off brings about a further drop in emissions to 1.762 tons, which is the lowest among all scenarios and represents a 25.4% reduction from Scenario 1. This highlights the effectiveness of mobile storage in peak shaving and real-time load balancing, allowing more renewable energy to displace grid consumption during carbon-intensive periods.

Fig. 7 illustrates the charging and discharging patterns of the Shared BESS and Mobile BESS over a 24-hour period, highlighting their roles in energy balancing. In Scenario 2, the Shared BESS (BESS_SHARE) undergoes distinct charge/discharge cycles. In Scenario 3, the Mobile BESS (MBESS_SHARE) adds spatio-temporal flexibility, with a more distributed operational profile. It charges during early hours (–55 kW at Hours 5–7) in sync with the shared BESS, then discharges later (+55 kW at Hours 17–18, 20), extending support when the shared BESS is potentially constrained. Figure 8 shows the Shared BESS charging activity in Scenario 2, disaggregated by microgrids MG1 and MG2 over 24 hours. MG1 dominates early charging efforts, with notable inputs of 40–65 kW between Hours 7–9 and peaking at 80 kW during Hours 15–19. Figure 9 presents MBESS charging behavior in Scenario 3, again split by MG1 and MG2. Unlike the Shared BESS, usage here is more dynamic and asymmetrical. MG1 consistently charges the MBESS in the early morning (40–50 kW from Hours 1–4), likely storing overnight surplus or off-peak energy. A second charging wave appears in Hours 17–21 (10–45 kW), prepping for evening demand. MG2's activity is more intermittent, with selective bursts of 10–55 kW during Hours 17–20, suggesting opportunistic charging based on local conditions.

5. Discussion

The integration of energy storage systems, both stationary (BESS) and mobile (MBESS), within distributed MG environments presents significant opportunities for enhancing energy autonomy, reducing dependency on external grid sources, minimizing carbon emissions, and improving overall economic efficiency. These performance gains are not only evident in quantitative reductions in surplus and imported energy but also in operational behavior such as load shifting, peak shaving, and inter-microgrid collaboration. It should be noted that, this study focuses on short-term operational optimization and does not include battery degradation costs in the economic analysis. In long-term applications, degradation due to cycling and depth-of-discharge can significantly influence total cost and optimal usage strategies. Future work could extend the current model by incorporating battery aging mechanisms and cost penalties for cycling, enabling a more accurate assessment of storage system sustainability and lifecycle economics. The following achievements summarize the key benefits realized from the scenario evolution.

a) Achievements

- Enhanced Renewable Utilization and Surplus Reduction: The adoption of storage systems significantly minimized renewable energy waste. In Scenario 1 (no storage), surplus energy totaled 1029 kWh, representing 20.26% of total renewable output. With shared BESS in Scenario 2, surplus dropped to 381 kWh (a 62.9% reduction), and further declined to 190 kWh in Scenario 3 with the inclusion of MBESS—an 81.5% improvement over the baseline. This demonstrates the pivotal role of storage in converting intermittent renewable output into usable energy.

- Substantial Reduction in Grid Dependency: Imported power reliance was noticeably curtailed through energy storage integration. Scenario 1 saw high import peaks of 360 kW and consistent midday draw from the grid. By Scenario 3, MBESS enabled total elimination of imports during multiple hours (e.g., 0 kW at Hours 0–5 and 19–20), while reducing import at Hour 17 from 300 kW in S1 to just 165 kW. This flexibility directly reduces stress on external grids and improves energy autonomy.

- Optimized Energy Mix and Improved Self-Sufficiency: Energy source contributions across scenarios reveal improved self-reliance. Imported power accounted for 40.1% in S1 but dropped to 33.6% in S2 and just 29.9% in S3. The addition of MBESS brought a 3.7% contribution, complementing the 6.5% from BESS, resulting in over 10% energy being delivered from storage. This allowed over 70% of energy in S3 to be locally sourced, compared to just under 60% in the base case.

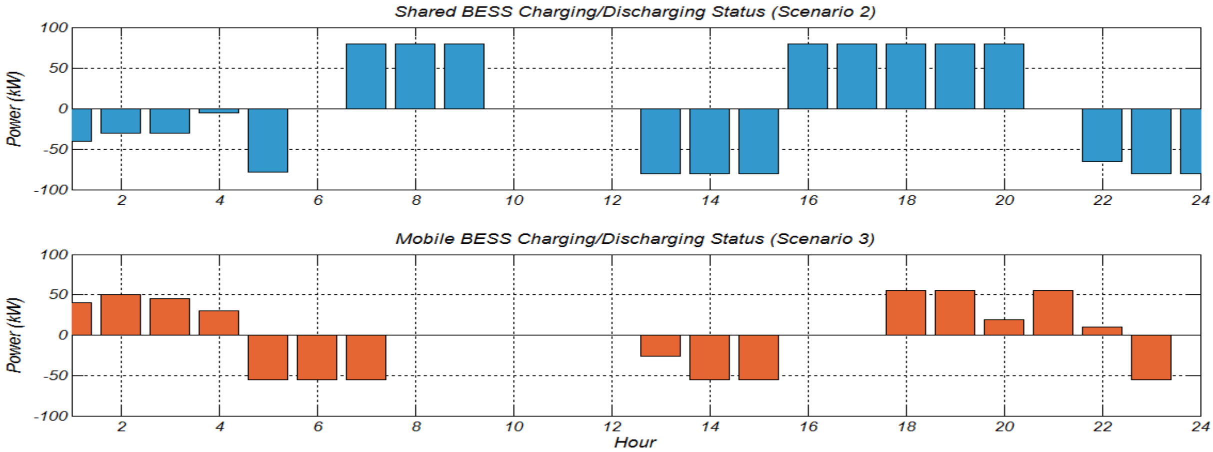

Fig. 7 BESS / MBESS distribution

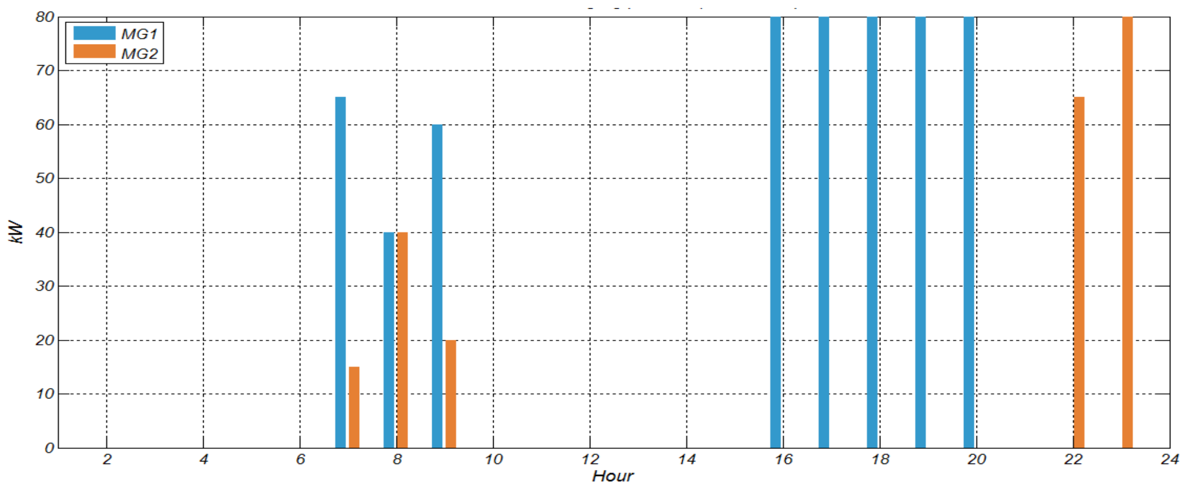

Fig. 8 Shared BESS Utilization in Scenario 2

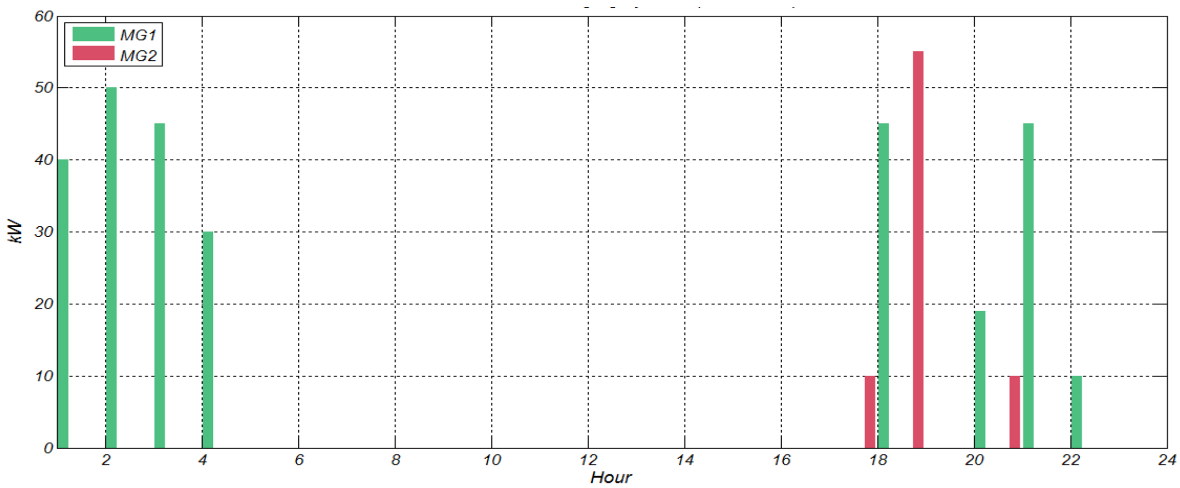

Fig. 9 MBESS Utilization in Scenario 2

b) Limitations

While the proposed hybrid storage strategy shows notable improvements in operational efficiency, energy independence, and environmental impact, several limitations must be acknowledged that may affect the generalizability or scalability of these results in real-world applications. First, both BESS and MBESS systems demonstrated discharge plateaus at +80 kW, suggesting potential saturation. Moreover, the current optimization framework operates under a perfect-forecast assumption for renewable energy availability. While this simplifies the analysis and isolates the benefits of MBESS coordination, it does not capture uncertainties inherent in real-world PV and wind power generation. In practical scenarios, prediction errors could lead to suboptimal dispatch decisions, such as overcharging or underutilization of storage resources. To address this, future extensions of the model could adopt robust optimization or stochastic programming techniques that explicitly account for forecast uncertainty. Such approaches would improve the practical applicability and reliability of MBESS scheduling in dynamic and uncertain environments.

6. Conclusion

This study demonstrates the substantial benefits of integrating both shared and MBESS within interconnected MGs through an MILP-based optimized energy management framework. By comparing three operational scenarios, we quantified how flexible storage improves renewable energy utilization, reduces grid dependency, lowers operational costs, and cuts CO_2 emissions. The proposed MILP model enables cost-optimal coordination of generation, storage, and grid import, capturing both binary and continuous decision variables to ensure feasible and scalable solutions. Without storage, the results showed high renewable energy curtailment (1029 kWh) and peak grid imports (360 kW). Scenario's inclusion of a shared BESS reduced surplus energy by 62.9% and smoothed peak demand. With the addition of a mobile BESS, further lowered surplus energy by 81.5%, decreased grid imports by 25.4%, and cut CO_2 emissions by the same margin relative to the baseline. Notably, nearly 70% of energy demand in Scenario 3 was met by local renewables, highlighting the effectiveness of coordinated storage systems. The shared BESS provided centralized stability, while the mobile BESS added geographic flexibility, addressing temporal and spatial mismatches between generation and load. Overall, this work advances decentralized energy planning by demonstrating how mobile storage complements traditional solutions to enhance renewable integration and sustainable MG operation. Future research should explore renewable generation uncertainties, vehicle-to-grid technologies, and real-time control to further improve system resilience and adaptability.

7. Conflict of interest

The authors state that there is no conflict of interest.

8. Data availability

Data will be made available on request.

9. Acknowledgment

This research was supported by the Australian Research Council (ARC) Linkage Pro-ject LP200100056 and the 4th Cycle of MME Grant No. MME04-0607-230060, from the Qatar Research, Development and Innovation (QRDI) Council, in collaboration with the Ministry of Municipality, Qatar. The authors would like to thank Dr. G. Yao for his contribution and support.

10. References

[1] A. F. Güven and E. Yücel, "Sustainable energy integration and optimization in microgrids: enhancing efficiency with electric vehicle charging solutions," Electr. Eng., 2024, doi: 10.1007/s00202-024-02619-x.

[2] S. Dixit, P. Singh, J. Ogale, P. Bansal, and Y. Sawle, "Energy Management in Microgrids with Renewable Energy Sources and Demand Response," Comput. Electr. Eng., vol. 110, p. 108848, 2023, doi: https://doi.org/10.1016/j.compeleceng.2023.108848.

[3] L.-Y. Lung, T.-Y. Chou, W.-C. Chang, and C.-C. Kuo, "Development of Energy Storage Systems for High Penetration of Renewable Energy Grids," Appl. Sci., vol. 13, no. 21, p. 11978, 2023, doi: 10.3390/app132111978.

[4] A. F. Güven, N. Yörükeren, and O. Ö. Mengi, Multi-objective optimization and sustainable design: a performance comparison of metaheuristic algorithms used for on-grid and off-grid hybrid energy systems, vol. 36, no. 13. 2024. doi: 10.1007/s00521-024-09585-2.

[5] R. Madhana and G. Mani, "Power enhancement methods of renewable energy resources using multiport DC-DC converter: A technical review," Sustain. Comput. Informatics Syst., vol. 35, no. January, p. 100689, 2022, doi: 10.1016/j.suscom.2022.100689.

[6] D. Aguilar, J. J. Quinones, L. R. Pineda, J. Ostanek, and L. Castillo, "Optimal scheduling of renewable energy microgrids: A robust multi-objective approach with machine learning-based probabilistic forecasting," Appl. Energy, vol. 369, p. 123548, 2024, doi: https://doi.org/10.1016/j.apenergy.2024.123548.

[7] M. R. Chakraborty, S. Dawn, P. K. Saha, J. B. Basu, and T. S. Ustun, "A Comparative Review on Energy Storage Systems and Their Application in Deregulated Systems," Batteries, vol. 8, no. 9, 2022, doi: 10.3390/batteries8090124.

[8] J. Wong and Y. S. Lim, "Experimental validation for dynamic fuzzy-controlled energy storage system to maximize renewable energy integration," Int. J. Electr. Electron. Eng. Telecommun., vol. 7, no. 3, pp. 83–89, 2018, doi: 10.18178/ijeetc.7.3.83-89.

[9] H. Takano, R. Hayashi, H. Asano, and T. Goda, "Optimal Sizing of Battery Energy Storage Systems Considering Cooperative Operation with Microgrid Components," pp. 1–13, 2021.

[10] P. Wongdet, T. Boonraksa, P. Boonraksa, W. Pinthurat, B. Marungsri, and B. Hredzak, "Optimal Capacity and Cost Analysis of Battery Energy Storage System in Standalone Microgrid Considering Battery Lifetime," Batteries, vol. 9, no. 2, pp. 1–16, 2023, doi: 10.3390/batteries9020076.

[11] A. Abdukhakimov, S. Bhardwaj, G. Gashema, and D. S. Kim, "Reliability analysis in smart grid networks considering distributed energy resources and storage devices," Int. J. Electr. Electron. Eng. Telecommun., vol. 8, no. 5, pp. 233–237, 2019, doi: 10.18178/ijeetc.8.5.233-237.

[12] N. K. Noyanbayev, A. J. Forsyth, and T. Feehally, "Efficiency analysis for a grid-connected battery energy storage system," Mater. Today Proc., vol. 5, no. 11, pp. 22811–22818, 2018, doi: 10.1016/j.matpr.2018.07.095.

[13] M. Gholami, S. M. Muyeen, and S. Lin, "Optimizing microgrid efficiency: Coordinating commercial and residential demand patterns with shared battery energy storage," J. Energy Storage, vol. 88, p. 111485, 2024, doi: https://doi.org/10.1016/j.est.2024.111485.

[14] T. Dodge, O. Long, A. Alnahwi, R. Horton, and H. Nazaripouya, "Mobile Battery Energy Storage System for On/Off Grid Applications," IEEE Glob. Energy Conf. GEC 2022, pp. 324–328, 2022, doi: 10.1109/GEC55014.2022.9987233.

[15] E. Zarate-perez, E. Rosales-asensio, and A. González-martínez, "Battery energy storage performance in microgrids : A scientific mapping perspective," Energy Reports, vol. 8, no. May, pp. 259–268, 2022, doi: 10.1016/j.egyr.2022.06.116.

[16] H. Saboori, S. Jadid, and M. Savaghebi, "Optimal management of mobile battery energy storage as a self-driving, self-powered and movable charging station to promote electric vehicle adoption," Energies, vol. 14, no. 3, 2021, doi: 10.3390/en14030736.

[17] J. Dugan, S. Mohagheghi, and B. Kroposki, "Application of mobile energy storage for enhancing power grid resilience: a review," Energies, vol. 14, no. 20, pp. 1–19, 2021, doi: 10.3390/en14206476.

[18] H. Saboori and S. Jadid, "Mobile and self-powered battery energy storage system in distribution networks–Modeling, operation optimization, and comparison with stationary counterpart," J. Energy Storage, vol. 42, p. 103068, 2021, doi: https://doi.org/10.1016/j.est.2021.103068.

[19] N. Mohammed, K. A. Danapalasingam, and A. Majed, "Design, control and monitoring of an offline mobile battery energy storage system for a typical malaysian household load using PLC," Int. J. Power Electron. Drive Syst., vol. 9, no. 1, pp. 180–188, 2018, doi: 10.11591/ijpeds.v9.i1.pp180-188.

[20] Y. Zheng et al., "Optimal integration of mobile battery energy storage in distribution system with renewables," J. Mod. Power Syst. Clean Energy, vol. 3, no. 4, pp. 589–596, 2015, doi: 10.1007/s40565-015-0134-y.

[21] M. Zhu et al., "Application of fixed and mobile battery energy storage flexibilities in robust operation of two-way active distribution network," Electr. Power Syst. Res., vol. 244, p. 111556, 2025, doi: https://doi.org/10.1016/j.epsr.2025.111556.

[22] F. Boutros, M. Doumiati, J. C. Olivier, I. Mougharbel, and H. Kanaan, "New modelling approach for the optimal sizing of an islanded microgrid considering economic and environmental challenges," Energy Convers. Manag., vol. 277, no. September 2022, p. 116636, 2023, doi: 10.1016/j.enconman.2022.116636.

[23] R. Asri, H. Aki, and D. Kodaira, "Optimal operation of shared energy storage on islanded microgrid for remote

communities," Sustain. Energy, Grids Networks, vol. 35, p. 101104, 2023, doi: 10.1016/j.segan.2023.101104.

[24] L. He and N. Liu, "Load profile analysis for commercial buildings microgrids under demand response," Proc. 2017 12th IEEE Conf. Ind. Electron. Appl. ICIEA 2017, vol. 2018-Febru, pp. 461–465, 2018, doi: 10.1109/ICIEA.2017.8282889.

[25] T. Nguyen-Duc, L. Hoang-Tuan, H. Ta-Xuan, L. Do-Van, and H. Takano, "A Mixed-Integer Programming Approach for Unit Commitment in Micro-Grid with Incentive-Based Demand Response and Battery Energy Storage System," Energies, vol. 15, no. 19, 2022, doi: 10.3390/en15197192.

[26] M. Gholami, S. A. Mousavi, and S. M. Muyeen, "Enhanced Microgrid Reliability Through Optimal Battery Energy Storage System Type and Sizing," IEEE Access, vol. 11, no. June, pp. 62733–62743, 2023, doi: 10.1109/ACCESS.2023.3288427.