



OPTIMIZATION MODEL FOR SITING AND SIZING MOBILE BATTERY ENERGY STORAGE SYSTEMS FOR SERVICE RESTORATION IN MEDIUM-VOLTAGE DISTRIBUTION NETWORKS UNDER EXTREME EVENTS

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ABSTRACT

The growing frequency and intensity of extreme weather events, such as torrential rainfall, present critical challenges to medium-voltage distribution networks, particularly in ensuring supply continuity. In this context, mobile energy storage systems have emerged as a promising solution to enhance resilience by enabling islanded operation during power outages or other contingencies. Despite their potential, the optimal sizing and allocation of these systems remain underexplored in the literature. To address this gap, this paper presents an optimization model for the strategic allocation and dimensioning of mobile battery storage systems to support service restoration. The model, applied to the IEEE 33-bus distribution network, shows its effectiveness in minimizing unserved energy, reducing power losses, and controlling operational costs, ultimately contributing to improved continuity and reliability under adverse weather conditions.

1 INTRODUCTION

Global climate change has driven significant variations in weather patterns, intensifying the frequency and severity of extreme events such as torrential rainfall and wind gusts (BERK SAHIN et al., 2025). In recent years, such events have led to failures in electricity supply, resulting in prolonged outages, substantial economic losses, and risks to human life (STANKOVIĆ et al., 2023). These impacts underscore the urgent need to strengthen the resilience of power networks, understood as the capacity to withstand and rapidly recover from severe weather events (MOHANTY et al., 2024).

In distribution systems, approximately 70% of power supply interruptions are attributed to damage caused by extreme weather events (KEBEDE et al., 2021). These events often result in isolated regions subjected to extended periods without electricity supply (STONE JR et al., 2021). Although conventional restoration methods, such as network reconfiguration and the dispatch of repair crews, are employed, these mechanisms have proven insufficient to ensure rapid service recovery in densely populated urban areas.

In the process of service restoration following power outages, solutions based on Mobile Power Sources (MPSs) have been proposed to enhance system flexibility and response speed (SZOTT et al., 2021). MPSs include electric vehicles, Mobile Energy Storage Systems (MESSs), and Mobile Emergency Generators (MEGs), which are capable of relocating resources according to system needs and enabling the islanded operation, comprising residents, businesses, or institutions that collectively produce, share, and consume clean energy (ZHU et al., 2025). In particular, these devices can serve as backup energy sources for priority loads, ensuring minimum supply to hospitals, urban service operation centers, and other critical facilities (KHALEDI et al., 2023).

Although several studies have explored the role of Battery Energy Storage Systems (BESSs) in enabling and strengthening power grids, significant gaps remain in the literature. There is a noticeable scarcity of methodologies that integrate,



in a coordinated manner, the sizing and allocation of Mobile Energy Storage Systems (MESSs), particularly when considering the potential need for islanded operation to supply critical loads during periods of unavailability of the utility power grid. In the literature, examples can be found of: joint recovery of MESSs with network reconfiguration and microgrids after disasters (YAO et al., 2020); proposals for separable MESSs that independently address the transporter and the storage module (WANG et al., 2022); and two-stage scheduling strategies for MPSs before and after disasters (LEI et al., 2018).

Considering the increasing frequency and intensity of extreme weather events, it is essential to develop operational planning tools that proactively strengthen the resilience of distribution networks. In this context, this work addresses relevant gaps in the literature by proposing a joint methodology for the sizing and allocation of mobile energy storage systems, capable of operating in islanded mode and assessing the effectiveness of the proposal in an IEEE 33-bus distribution network to demonstrate improvements in unserved energy reduction, electrical loss mitigation, and operational cost containment.

In summary, an optimization model is developed for the sizing and allocation of mobile electrical energy storage systems, with the purpose of supporting supply restoration and reducing reliance on diesel-powered emergency generators. Thus, this research not only addresses an urgent need to enhance the resilience of power systems against extreme events but also contributes with solutions for energy security and the sustainability of distribution networks in a future increasingly adverse to historical patterns.

2 METHODOLOGY

In this work, the mathematical formulation of the sizing and allocation problem for energy storage systems within medium-voltage distribution networks is developed. The objective is to minimize the operational costs of MPSs, specifically MESSs and MEGs, as well as the unserved energy resulting from power grid failures caused by extreme weather events. Additionally, the formulation aims to minimize energy losses throughout the network, taking into account the specific characteristics of Brazilian power distribution systems.

A. Objective Functions

The objective function (1) represents the amount to be paid by the electric utility, considering the need to mitigate the effects of extreme weather events. This value comprises the operating cost of the Mobile Power Sources (MPSs) to be deployed in response to failures in the power grid; the penalty cost imposed by ANEEL (Brazilian Electricity Regulatory Agency) for non-compliance with regulations, such as prolonged power supply interruptions; and the revenue loss resulting from electrical energy losses. To execute the algorithm that solves the mathematical model, the utility must have as input data the forecast of loads, renewable generation, and market prices. Thus, the objective function $\min Z$ is calculated as follows:

$$\min_{A_i^{MESS}, A_i^{MEG}, P_{i,t}^{ns}, P_{ij,t}^{loss}} Z = \sum_{i \in \Omega_N} C^{MESS} \cdot A_i^{MESS} + \sum_{i \in \Omega_N} C^{MEG} \cdot A_i^{MEG} + \sum_{t \in \Omega_t} \sum_{i \in \Omega_N} \rho_t^M \cdot \Delta t \cdot P_{i,t}^{ns} + \sum_{t \in \Omega_t} \sum_{ij \in \Omega_C} \rho_t^e \cdot \Delta t \cdot P_{ij,t}^{loss} \quad (1)$$

Where t refers to the index of the hour under analysis; i is the node index, Ω_t is the set of time intervals under analysis, Ω_N is the set of nodes connected to the main medium-voltage distribution network; Ω_C is the set of circuits; C^{MESS} is the cost of the



MESS modules in R\$; A_i^{MESS} is an integer variable indicating in which node i the MESS units will be installed and their quantity; C^{MEG} is the total cost of each MEG in R\$; A_i^{MEG} is a binary variable indicating in which node i the MEGs will be installed; ρ_t^M is the penalty value for unserved energy in period t (R\$/kWh); Δt is the duration of a time interval in hours; $P_{i,t}^{ns}$ is the amount of active power not supplied by the utility at node i during interval t (kW); ρ_t^e is the medium-voltage energy price in period t (R\$/kWh); $P_{ij,t}^{loss}$ is the amount of active power lost in branch ij (kW). Furthermore, since (1) is a convex objective function with quadratic constraints, it is solved using a Mixed-Integer Second-Order Cone Programming (MISOCP) solver.

B. Constraints

1) Network modeling: To model the power flow relationships in a radial network, equations (2)–(5) are employed.

$$\sum_{ki \in \Omega_C} P_{ki,t} - \sum_{ij \in \Omega_C} (P_{ij,t} + R_{ij} \cdot I_{ij,t}^{sqr}) + P_{i,t}^S + P_{i,t}^{PV} + P_{i,t}^{dis} + P_{i,t}^{MEG} + P_{i,t}^{ns} - P_{i,t}^{ch} - P_{i,t}^{EV} - P_{i,t}^{load} = 0 \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (2)$$

$$\sum_{ki \in \Omega_C} Q_{ki,t} - \sum_{ij \in \Omega_C} (Q_{ij,t} + X_{ij} \cdot I_{ij,t}^{sqr}) + Q_{i,t}^S + Q_{i,t}^{dis} + Q_{i,t}^{MEG} + Q_{i,t}^{ns} - Q_{i,t}^{load} - Q_{i,t}^{ch} = 0 \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (3)$$

$$V_{i,t}^{sqr} - 2 \cdot (R_{ij} \cdot P_{ij,t} + X_{ij} \cdot Q_{ij,t}) - Z_{ij}^2 \cdot I_{ij,t}^{sqr} - V_{j,t}^{sqr} = 0 \quad \forall i \in \Omega_N, \forall ij \in \Omega_C, \forall t \in \Omega_t \quad (4)$$

$$P_{ij,t}^2 + Q_{ij,t}^2 \leq V_{j,t}^{sqr} \cdot I_{ij,t}^{sqr} \quad \forall i \in \Omega_N, \forall ij \in \Omega_C, \forall t \in \Omega_t \quad (5)$$

Where $P_{ki,t}$ is the active power flow through circuit ki during period t (kW); $P_{ij,t}$ is the active power flow supplied through circuit ij during period t (kW); R_{ij} is the resistance of circuit ij ($m\Omega$); $I_{ij,t}^{sqr}$ is the squared current through circuit ij (A^2); $P_{i,t}^S$ is the active power supplied by the substation at node i during interval t (kW); $P_{i,t}^{PV}$ is the active power generated by the photovoltaic system at node i during interval t (kW); $P_{i,t}^{dis}$ is the active power discharged by the MESS at node i during interval t (kW); $P_{i,t}^{MEG}$ is the active power of the MEGs (kW); $P_{i,t}^{ch}$ is the active power charged by the MESS at node i during interval t (kW); $P_{i,t}^{EV}$ is the active power demanded by electric vehicles at node i during interval t (kW); $P_{i,t}^{load}$ is the active power demanded by loads at node i during interval t (kW); $Q_{ki,t}$ is the reactive power flow demanded through circuit ki during period t (kVar); $Q_{ij,t}$ is the reactive power flow supplied through circuit ij during period t (kVar); X_{ij} is the reactance of circuit ij ($m\Omega$); $Q_{i,t}^S$ is the reactive power supplied by the substation at node i during interval t (kVar); $Q_{i,t}^{dis}$ is the reactive power discharged by the MESS at node i during interval t (kVar); $Q_{i,t}^{MEG}$ is the reactive power of the MEGs (kVar); $Q_{i,t}^{ns}$ is the reactive power not supplied by the utility at node i during interval t (kVar); $Q_{i,t}^{ch}$ is the reactive power charged by the MESS at node i during interval t (kVar); $Q_{i,t}^{load}$ is the reactive power demanded by loads at node i during interval t (kVar); $V_{i,t}^{sqr}$ is the squared voltage at node i during period t (kV^2) and Z_{ij} is the impedance of circuit ij ($m\Omega$).

With respect to the physical and operational limits of the system, the following constraints (6)–(7) must be satisfied:

$$0 \leq I_{ij,t}^{sqr} \leq \overline{I_{ij}^{sqr}} \quad \forall ij \in \Omega_C, \forall t \in \Omega_t \quad (6)$$

$$\underline{V_{i,t}^{sqr}} \leq V_{i,t}^{sqr} \leq \overline{V_{i,t}^{sqr}} \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (7)$$



Where $\overline{I_{ij}^{sqr}}$ is the squared current limit through circuit ij (A^2); $\underline{V^{sqr}}$ is the minimum squared voltage limit (kV^2); $\overline{V^{sqr}}$ is the maximum squared voltage limit (kV^2).

2) Mobile Energy Storage Systems modeling: The operation of the MESS is subject to the constraints defined in equations (8)–(15).

$$E_{i,t}^{str} = E_{i,t-1}^{str} + (n^{ch} \cdot \Delta t \cdot P_{i,t}^{ch}) - \left(\Delta t \cdot \frac{P_{i,t}^{dis}}{n^{dis}} \right) - \beta^{str} \Delta t E_{i,t}^{str} \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (8)$$

$$\underline{E}^{str} \leq E_{i,t}^{str} \leq \overline{E}^{str} \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (9)$$

$$E_{i,t}^{str} = E_0^{str} \quad \forall i \in \Omega_N, t = 1 \quad (10)$$

$$Q_{i,t}^{ch} = P_{i,t}^{ch} \cdot \tan(\arccos(fp^{ch})) \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (11)$$

$$Q_{i,t}^{dis} = P_{i,t}^{dis} \cdot \tan(\arccos(fp^{dis})) \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (12)$$

$$\underline{P}^{str} \cdot u_{i,t}^{str} \cdot A_i^{MESS} \leq P_{i,t}^{ch} \leq \overline{P}^{str} \cdot u_{i,t}^{str} \cdot A_i^{MESS} \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (13)$$

$$\underline{P}^{str} \cdot (1 - u_{i,t}^{str}) \cdot A_i^{MESS} \leq P_{i,t}^{dis} \leq \overline{P}^{str} \cdot (1 - u_{i,t}^{str}) \cdot A_i^{MESS} \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (14)$$

$$C_{i,t}^{MESS,O\&M} = C_{O\&M}^{MESS} \cdot P_{i,t}^{dis} \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (15)$$

Where $E_{i,t}^{str}$ is the state of charge of the storage device at node i during period t (kWh); n^{ch} is the charging efficiency of the MESS; n^{dis} is the discharging efficiency of the MESS; β^{str} is the self-discharge rate of the MESS; $\underline{E}^{str}$ is the minimum stored energy limit of the MESS (kWh); $\overline{E}^{str}$ is the maximum stored energy limit of the MESS (kWh); E_0^{str} is the initial state of charge of the MESS (kWh); fp^{ch} is the charging power factor; fp^{dis} is the discharging power factor; $u_{i,t}^{str}$ is the binary variable representing whether the MESS is charging or discharging; $\underline{P}^{str}$ is the minimum charging/discharging limit of the MESS (kW); $\overline{P}^{str}$ is the maximum charging/discharging limit of the MESS (kW); $C_{i,t}^{MESS,O\&M}$ is the O&M cost of each MESS (R\$); $C_{O\&M}^{MESS}$ is the O&M cost per kW (R\$/kW).

3) Mobile Emergency Generators modeling: The operation of the MEG is subject to the constraints defined in equations (16)–(22).

$$\underline{P}_i^{MEG} \cdot A_i^{MEG} \cdot u_{i,t}^{MEG} \leq P_{i,t}^{MEG} \leq \overline{P}_i^{MEG} \cdot A_i^{MEG} \cdot u_{i,t}^{MEG} \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (16)$$

$$Q_{i,t}^{MEG} = P_{i,t}^{MEG} \cdot \tan(\arccos(fp^{MEG})) \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (17)$$

$$F_{i,t}^{MEG} = \alpha \cdot P_{i,t}^{MEG} + \beta \cdot P^{MEG,rated} \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (18)$$

$$C_{i,t}^{fuel} = C_f \cdot F_{i,t}^{MEG} \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (19)$$

$$CO2_{i,t} = NCV \cdot EF \cdot F_{i,t}^{MEG} \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (20)$$

$$C_{i,t}^{CO2} = C_{CO2} \cdot CO2_{i,t} \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (21)$$

$$C_{i,t}^{MEG,O\&M} = C_{O\&M}^{MEG} \cdot P_{i,t}^{MEG} \quad \forall i \in \Omega_N, \forall t \in \Omega_t \quad (22)$$

Where $\underline{P}_i^{MEG}$ is the minimum active power limit of the MEGs (kW); $\overline{P}_i^{MEG}$ is the maximum active power limit of the MEGs (kW); $u_{i,t}^{MEG}$ is the binary variable representing the on/off status of the MEGs; $F_{i,t}^{MEG}$ is the fuel consumption of each generator (liters); α is slope coefficient of the fuel curve; β is Fuel intercept coefficient; $P^{MEG,rated}$ is the rated capacity of the MEG; $C_{i,t}^{fuel}$ is the fuel cost of each generator (R\$); C_f is the fuel price (R\$/liter); $CO2_{i,t}$ is the CO₂ emission (t CO₂); NCV is the net calorific



value of the fuel (TJ/ton); EF is the emission factor (kg CO₂ per TJ of fuel); $C_{i,t}^{CO_2}$ is the cost of CO₂ emissions (R\$); C_{CO_2} is the CO₂ emission penalty (R\$/kg); $C_{i,t}^{MEG_O\&M}$ is the O&M cost of each MEG (R\$) and $C_{O\&M}^{MEG}$ is the O&M cost per kW (R\$/kW)

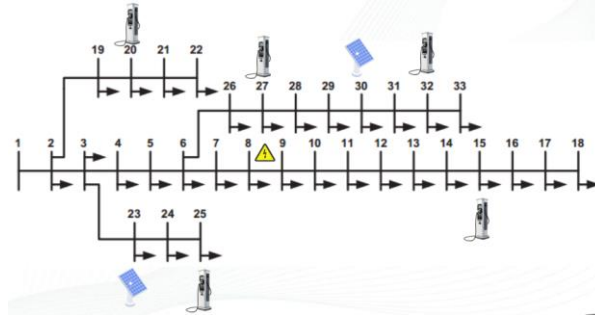
3 RESULTS E DISCUSSION

The optimization problem was implemented in Pyomo and solved using the IBM ILOG CPLEX Optimization Studio solver on a computer equipped with an Intel Core i9-14900F CPU running at 2.0 GHz.

The IEEE 33-bus test system is a simplified model used to study power distribution networks. The nominal substation voltage is 12.66 kV. The network topology used is shown in Figure 1. Two photovoltaic (PV) systems of 75 kW each are implemented, allocated at buses 23 and 30. Five electric vehicle (EV) charging systems with a storage capacity of 27.2 kWh are considered, allocated at buses 17, 20, 25, 27, and 32. The MEGs have a rated capacity of $P^{MEG\ rated} = 75\text{ kVA}$, $f_p^{MEG} = 0.85$. Additionally, each MESS has a capacity of 100 kWh and operates with the following parameters: $\underline{p}^{str} = 0$, $\overline{p}^{str} = 50\text{ kW}$, $n^{ch} = n^{dis} = 0.95$, $\underline{E}^{str} = 10\%$ of the MESS nominal capacity, $\overline{E}^{str} = 90\%$ of the MESS nominal capacity. The initial state of charge was considered as $E_{i,0}^{str} = 90\%$, since at the time of module installation they are already at near maximum capacity. Additionally, the voltage limits for the MV network are $\underline{V}^{sqr} = 0.93\text{ pu}$ e $\overline{V}^{sqr} = 1.05\text{ pu}$, with a time step of $\Delta t = 1h$. For the penalty paid by the utility to ANEEL for inadequate power supply, a factor of 1000 times the hourly energy tariff was considered.

Figure 1 shows the modified IEEE 33-bus test network, indicating the connection locations of the PV systems and EVs within the distribution network. As a case study, a power supply interruption between buses 8 and 9 was considered, starting at 12:00 and lasting for 10 hours, with power restoration occurring at 21:00.

Figure 1 - Modified IEEE 33-bus test network



In this case study, the energy price (ρ_t^e) corresponds to the Conventional Tariff established by Enel SP for subgroup A4 (2.3 to 25 kV) under the Blue modality, considering both the Distribution System Usage Tariff (TUSD) and the Energy Tariff (TE). On weekdays, the tariff varies across two time-of-use periods within the concession area: Peak hours (17:30 to 20:30), which correspond to the period of highest energy demand, with a rate of \$0.062 per kWh; and off-peak hours (20:30 to 17:30), corresponding to the period of lowest energy demand, with a rate of \$0.22 per kWh.

The optimal location of the MESSs for the case study is shown in Figure 2. A total of eighteen modules were allocated as follows: two at bus 9, two at bus 10, one at bus 11, two at bus 12, three at bus 13, three at bus 14, one at bus 15, one at bus 16, one at bus 17, and two at bus 18. It should be noted that the allocation was carried out to fully meet the specific demand



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at each point in the network, avoiding oversizing and ensuring efficient use of resources. Therefore, only the modules strictly necessary to satisfy demand in this section of the radial network were installed.

Figure 2 - Modified IEEE 33-bus test network with MESSs

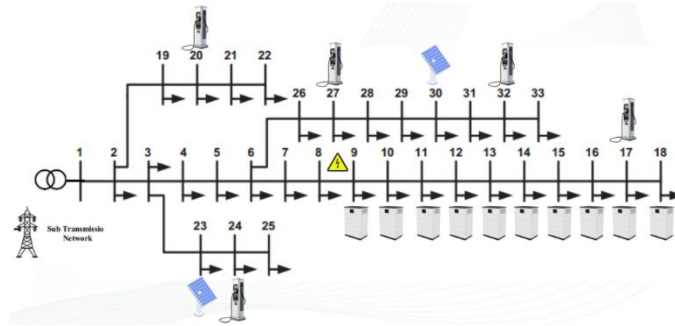


Figure 3 illustrates the optimal allocation of the MEGs in the analyzed system, with a total of six units individually positioned at buses 9, 10, 11, 12, 14, and 15. The distribution was carried out based on the local demand at each bus, ensuring precise supply without unnecessary excess. This strategy guarantees rational utilization of the generators, installing only the number necessary to meet the load of the isolated segment of the radial network.

Figure 3 - Modified IEEE 33-bus test network with MEGs

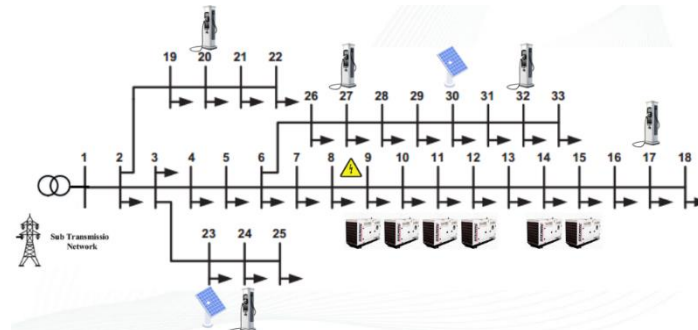


Table 1 presents a comparison of the operational and economic performance of solutions based on MESS and MEGs, applied to energy supply under contingency conditions. It can be observed that, although the MEGs supplied a slightly higher amount of energy (1430.62 kW compared to 1297.73 kW from the MESS), this result is directly associated with higher losses during the outage period. Specifically, the MEGs experienced losses of 186.68 kW, corresponding to 13.05% of the energy supplied, whereas the MESS registered losses of only 53.79 kW, or 4.14%. This contrast highlights the significantly higher efficiency in the utilization of stored energy by the MESS.

From an economic perspective, the MESS demonstrated clear superiority. The total cost associated with their operation was only \$15.99, whereas the MEGs reached \$731.67, a difference of over 4500%, even considering that the MESS must be pre-charged with energy from the grid. The operation and maintenance (O&M) cost of the MEGs (\$72.69) was more than four times higher than that of the MESS (\$15.99), an impact further amplified by the high fuel cost (\$604.56) and associated emissions (1777.69 tCO₂). These emissions generated an additional estimated environmental cost of \$54.42, which does not exist in the case of the MESS, as they operate with zero direct emissions.



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The analysis of the ratio between total cost and energy supplied reinforces the advantage of the MESS. While the MEGs incurred a cost of \$0.51 per kW delivered, the MESS operated at only \$0.013 per kW, representing a reduction of more than 97% in the specific energy cost. Furthermore, the battery-based solution demonstrated greater adaptability, with 18 units allocated compared to only 6 MEGs, allowing for more distributed coverage that aligns with the local needs of the network.

Between 18:00 and 21:00, the highest levels of energy supply were recorded for both the MESS and the MEGs. This behavior is explained by the increased load demand during this period, intensified by electric vehicle charging and the higher electricity tariff. The discharging strategy adopted during this interval proved effective in reducing network losses, improving voltage levels, and ensuring continuity of power supply to consumers, even in the event of interruptions from the conventional distribution network.

Based on the results, it can be concluded that from the perspectives of energy, economic, and environmental efficiency, the MESS represents a highly competitive alternative for resilience strategies in distribution networks.

Table 1 - Comparison between MESS and MEG

Indicators	MESS	MEG
CO ₂ Emissions [tCO ₂]	0	1777.69
Emission Cost [\$]	0	54.42
O&M Cost [\$]	15.99	72.69
Fuel Cost [\$]	0	604.56
Total Cost [\$]	15.99	731.67
Energy Supplied [kW]	1297.73	1430.62
Cost-to-Energy Ratio [\$/ kW]	0.013	0.51
Island Losses [kW]	53.79	186.68
Losses Relative to Energy Supplied [%]	4.14	13.05
Allocated Equipment	18	6

4 CONCLUSION

The proposed MISOPCP programming model for the sizing and allocation of mobile power sources proved effective in reducing costs, losses, and emissions, while ensuring islanded operation during contingencies. In the IEEE 33-bus test system, the MESSs presented a total cost 45.7 times lower and losses 68% lower than the MEGs, in addition to eliminating direct CO₂ emissions. The cost-to-energy ratio (\$0.013/kW for MESSs versus \$0.51/kW for MEGs) highlights the economic superiority of the solution. These results indicate that the optimized use of MESSs simultaneously contributes to the resilience, sustainability, and operational efficiency of distribution networks.

As future work, it is proposed to apply the model to real Brazilian networks, incorporating uncertainties in demand and generation within a stochastic programming framework, thereby extending its practical applicability and robustness.

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