



TECHNICAL AND ECONOMIC CLUSTERING OF ENERGY COMMUNITIES FOR CENTRALIZED BATTERY STORAGE IN MEDIUM-VOLTAGE NETWORKS

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ABSTRACT

In medium-voltage electrical networks with a high presence of photovoltaic generation, energy communities often produce large surpluses during periods of high solar irradiance, creating technical challenges such as voltage regulation issues, reverse power flows, and the need for curtailment of renewable generation, as well as economic challenges due to reduced return on investment of these systems. A standard solution to address these challenges is the installation of battery storage systems at each transformer; however, this approach results in high initial costs, increased dependence on government incentives, and greater operational complexity due to the large number of units required. This paper presents a novel methodology for the technical and economic clustering of neighboring communities, enabling the use of centralized storage at strategic points in the network. A case study in a Brazilian neighborhood shows that the proposed solution can reduce investment costs, enhance network performance, and improve the economic viability of renewable energy utilization.

Keywords: Energy communities; BESS; ROI

1 INTRODUCTION

The accelerated growth of renewable energy, especially solar photovoltaic, has transformed consumers into prosumers, paving the way for collective generation models. In this context, Neves, Baptista and Rosa (2023), notes that energy communities (ECs) are consolidating as a collective model that promotes broader and more equitable access to distributed generation, while improving the efficiency of local resource use. Likewise, studies such as Palacios et al. (2023) explain that the formation of ECs not only facilitates the collective use of solar generation in dense urban environments but also contributes to reducing technical losses in distribution networks and enhancing urban sustainability.

As a consequence of EC formation, the high penetration of photovoltaic generation in distribution networks often leads, during periods of high irradiance, to production exceeding local demand, generating energy surpluses that translate into reverse power flows toward substations and, (Chinh; Tung; Ha, 2024). Furthermore, the proper utilization of these surpluses faces both technical and economic barriers. The literature indicates that the incorporation of battery energy storage systems (BESS) appears as an alternative when integrated with photovoltaic generation under tariff schemes where BESS can be charged during low-price hours and discharged during peak demand, mitigating adverse technical effects (Zhou et al., 2018) and reducing total electricity costs (Guedes et al., 2024). Proper coordination with PV systems increases operational flexibility and enables modes such as energy autonomy (Hemmati; Saboori, 2017).

Despite the technical benefits offered by BESS, their implementation faces significant economic challenges, being highly dependent on the cost per kWh of batteries. Studies show that the investment becomes attractive only when this value falls below



365 USD/kWh (Pinto; Naspolini; Rüther, 2024). Complementary simulations with optimal buy–sell energy configurations show that, under current prices, the Net Present Value (NPV) remains negative, indicating a lack of profitability (Alexandre, 2024). One of the strongest factors conditioning the economic feasibility of BESS in Brazil is the high tax burden applied to these systems, which significantly increases project costs (Pinto; Naspolini; Rüther, 2024). As studies indicate, taxation can represent up to an additional 65% for national equipment and nearly 80% for imported equipment, creating a significant obstacle to expansion. In this regard, authors highlight that a specific tax exemption would decisively accelerate adoption and improve the economic return on storage investments (Campos de Sousa; Belati; Pereira de Godoy, 2025). Thus, the financial viability of BESS largely depends on the existence of government subsidies (Cristea et al., 2022).

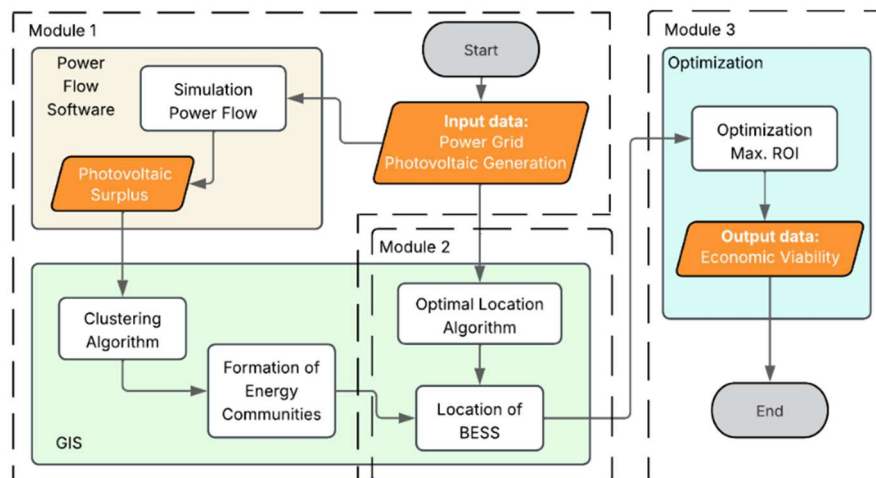
The feasibility of such subsidies is supported by the formation of larger communities, where the installed capacity of BESS becomes more economically viable. In Campos de Sousa, Belati and Pereira de Godoy (2025), it is explained that BESSs are financially feasible for large consumers, as they enable reducing financial costs, improving investment returns, and enhancing supply reliability.

This work presents a novel methodology for the technical and economic clustering of neighboring communities, enabling the use of centralized storage at strategic points in the network. Likewise, a case study is applied in the Santo André neighborhood, SP, to show the potential benefits compared to decentralized strategies. The results demonstrate higher economic viability, reduced payback periods, and superior technical performance, aligning with evidence that BESS can be economically viable for large consumers. In this way, the work contributes not only to urban energy planning and the integration of renewable energy but also to the design of public policies focused on centralized storage in energy communities.

2 METHODOLOGY

The methodology consists of three modules, as illustrated in Figure 1. These modules aim to evaluate the technical and economic feasibility of centralized storage in energy communities. Input data were obtained from the ANEEL database, from which the distribution network was modeled, providing load curves and photovoltaic surpluses for each transformer. These results constitute the basis for the clustering process.

Figure 1 - Flowchart of the Proposed Methodology





2.1 Module 1

In Module 1, network transformers were organized into energy communities through a spatial–electrical clustering algorithm with photovoltaic surplus constraints. The medium-voltage network was represented as a graph in QGIS, where vertices corresponded to nodes of the network geometry and edges to conductor segments weighted by length (in meters). The distance between two transformers i and j was defined as the shortest path in the network, calculated using Dijkstra's algorithm:

$$d(i, j) = \min_{C \in \mathcal{C}(i, j)} \sum_{(u, v) \in C} l(u, v) \quad (1)$$

Where $\mathcal{C}(i, j)$ is the set of possible paths between transformers and $l(u, v)$ is the length of segment (u, v) .

The clustering process was agglomerative, starting with each transformer as an independent group and merging neighboring communities whenever three conditions were simultaneously satisfied: (i) the electrical distance did not exceed a maximum threshold; (ii) the sum of the peak surpluses of the transformers involved did not exceed the limit; and (iii) the sum of daily surpluses remained below a maximum value:

$$d(i, j) \leq D_{NET}, \quad FR_i^P + FR_j^P \leq P_{CAP}, \quad FR_i^T + FR_j^T \leq T_{CAP} \quad (2)$$

Where:

- D_{NET} , Minimum electrical distance between transformer i and transformer j
- FR_i^P , Photovoltaic peak surplus in [kW] of transformer i
- FR_j^P , Photovoltaic peak surplus in [kW] of transformer j
- FR_i^T , Photovoltaic total daily surplus in [kWh/day] of transformer i
- FR_j^T , Photovoltaic total daily surplus in [kWh/day] of transformer j
- P_{CAP} , Maximum limit for the sum of peak surpluses allowed within a community in [kW]
- T_{CAP} , Maximum limit for the sum of daily surpluses within a community in [kWh/day]

2.2 Module 2

In Module 2, the optimal location of storage systems was determined through a location algorithm on the electrical graph. Candidate sites corresponded to medium-voltage poles, filtered under two criteria: (i) exclusion of poles too close to transformers for safety and operational reasons; (ii) location within the MV network, ensured by snapping to the nearest node with maximum tolerance. Two classical objective functions were evaluated.

Weighted 1-median, minimizing total distance between candidate site and community transformers, weighted by surplus magnitude:

$$f_{med}(p) = \sum_{i \in T} \omega_i * d(p, i) \quad (3)$$

Where ω_i represents the peak or total surplus of transformer i and $d(p, i)$ the distance.

1-center, minimizing the worst-case distance within the group:

$$f_{ctr}(p) = \max_{i \in T} d(p, i) \quad (4)$$



2.3 Module 3

With communities defined and BESS located, OpenDSS simulations integrated with Python were run to estimate technical losses, voltage profiles, and reverse power flow reductions. These results fed into an economic–operational optimization model in Pyomo that sizes and operates the BESS to maximize ROI under time-of-use tariffs and operational constraints (charging/discharging windows, power/energy limits, initial/final state of charge, and self-discharge).

CAPEX was modeled by disaggregating BESS components into battery modules (USD/kWh), inverters (USD/kW), and other costs (USD/kWh) (Zhou et al., 2018). These values were then converted into BRL using the exchange rate and adjusted for taxation (Campos; Belati; Pereira, 2025) and, where applicable, subsidies. Part of the tax burden was modeled as fixed parameters, while another fraction was treated as variable, allowing the model to select the most advantageous regime within plausible ranges. From a public policy perspective, an eligibility criterion was considered that favors aggregated communities, where the incentive becomes applicable; in smaller-scale configurations, the subsidy component remains inactive. In this way, the model consistently compares scenarios with and without targeted support.

The objective function maximizes the annual ROI by considering the net yearly benefit, i.e., revenues from time-shifting arbitrage minus O&M costs, and the annualized CAPEX through the capital recovery factor (CRF):

$$Max\ ROI = \frac{\sum_t (L_t - U_{oper}(t) * om_{rate} * Cap) - CAPEX_{(T_{imp}, T_{sub})} * CRF}{CAPEX_{(T_{imp}, T_{sub})}} \quad (5)$$

Where:

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (6)$$

and CAPEX (including taxes and, where applicable, subsidies) is given by:

$$CAPEX_{(T_{imp}, T_{sub})} = (1 + T_{imp})[(1 - T_{sub})(C_b * Cap + C_i * Cap * P_{max} + C_o * Cap)] \quad (7)$$

Here C_b (USD/kWh), C_i (USD/kW) and C_o (USD/kWh) represent the unit costs of the battery, inverter, and other BESS components; $T_{imp} \in [0.55, 0.80]$, accounts for taxes (import duties, IPI, PIS, COFINS, ICMS [9]); and $T_{sub} \in [0, 0.60]$ represents the subsidy applied in eligible large-scale scenarios. Additionally, a minimum CAPEX constraint of $CAPEX \geq 1000 * Cap$ was imposed to ensure that subsidies are only activated until reaching the threshold at which the investment yields a positive return (Alexandre, 2024).

3 RESULTS AND DISCUSSION

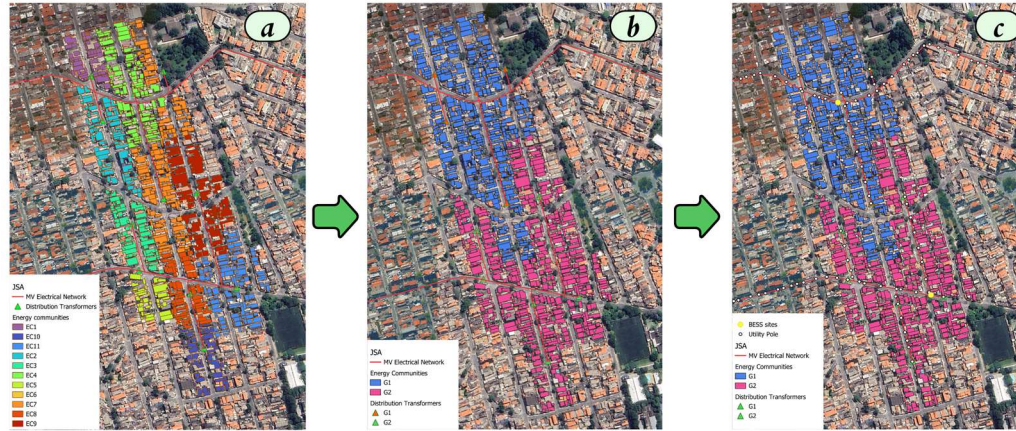
In the initial analysis of the neighborhood located in Santo André, 11 energy communities were identified (EC1, EC2, EC3... EC11), as shown in Figure 2a. The application of the spatial–electrical clustering algorithm from Module 1 organized these communities into two groups (G1 and G2), as illustrated in Figure 2b. G1 comprises EC1, EC2, EC4, EC6, and EC7, while G2 includes EC3, EC5, EC8, EC9, EC10, and EC11. Subsequently, Module 2 evaluated candidate medium-voltage poles, applying the 1-median (Eq.3) and 1-center (Eq.4) functions to ensure efficient coverage of the transformers, determining the optimal BESS locations, represented by yellow points in Figure 2c.



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Figure 2 – Formation of Energy Communities

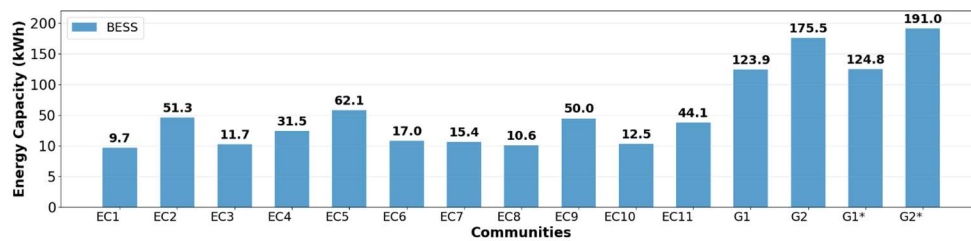


These results enable a comparison of the economic and technical performance of the eleven individual communities versus the two aggregated groups, providing the basis for assessing the benefits of integration.

3.1 Storage Capacity

Figure 3 presents the storage capacities of each community and the aggregated groups. The comparative analysis shows that G1 achieves a total capacity of 123.9 kWh, slightly lower than the sum of its individual communities G1 (124.8 kWh), with a difference of -0.9 kWh. For G2, the total capacity is 175.5 kWh, lower than the sum of its six communities G2 (191.0 kWh), resulting in a difference of -15.5 kWh.

Figure 3 – Energy Capacity by Community



This slight discrepancy suggests that aggregating communities allows for some optimization in capacity allocation, covering total demand without exactly replicating the capacity of each individual community.

3.2 Economic Analysis

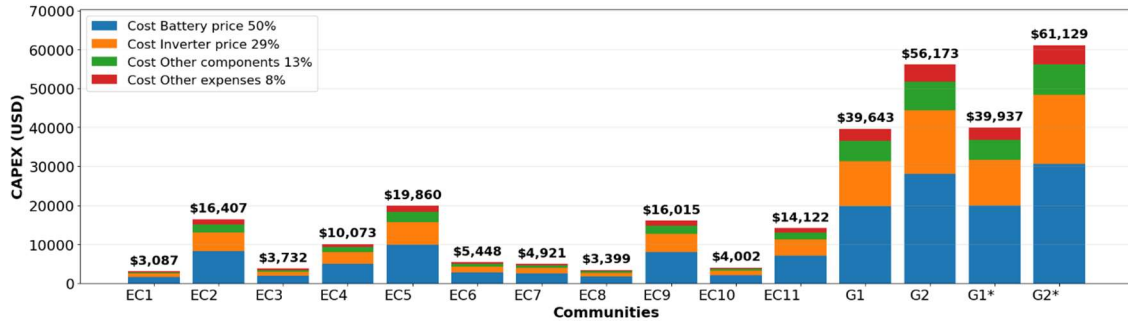
As a first step in the economic analysis, CAPEX was compared without considering taxes or subsidies to evaluate the effect of operating communities individually versus in aggregated groups (Figure 4). For Group 1 (G1), CAPEX was USD 9,643 compared to USD 39,937 for the individual communities (G1*), resulting in savings of USD 293 (0.7%). In G2, CAPEX decreased from USD 61,129 to USD 56,173, achieving savings of USD 4,956 (8.1%). Overall, aggregation reduced total CAPEX from USD 101,066 to USD 95,817, generating global savings of USD 5,249 (5.2%), demonstrating that integration improves economic efficiency without compromising technical feasibility. The resulting unit costs were approximately USD 496.01/kWh and USD 708.58/kWh; however, when including an 80% fiscal tax, these values make CAPEX unfeasible for implementing BESS in energy communities. The analysis was conducted under the “tarifa branca”



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Figure 4 – Composition of CAPEX by cost categories



The analysis of tax and subsidy rates shows that if all 11 communities were under the REIDI regime, a fixed rate of 55% would apply to all BESS. Despite the reduction from 80% to 55%, this scenario remains unfeasible, with ROI values around -0.7% and payback close to 9 years, as shown in Table 1. In contrast, when aggregating the communities into G1 and G2 and evaluating CAPEX adjusted with optimal taxes and subsidies according to Equation 7, it was determined that both groups maintain the 80% tax rate and require a 68.94% subsidy to achieve viability, as proposed by (Alexandre, 2024). This configuration considerably improves system feasibility, achieving a positive annual ROI of 16.1% and reducing payback to 3 years and 7 months.

Table 1 - Economic performance indicators of individual and aggregated energy communities

Community	Base CAPEX (USD)	Taxes (USD)	CAPEX with Taxes (USD)	Subsidies (USD)	Final CAPEX (USD)	Payback (Time)	Annual ROI (%)
EC1	3,086.67	1,697.67	4,784.34	N/A	4,784.34	9 years and 0,5 months	-0,72
EC2	16,407.25	9,023.99	25,431.24	N/A	25,431.24	9 years and 0,7 months	-0,74
EC3	3,731.83	2,052.51	5,784.34	N/A	5,784.34	9 years and 0,5 months	-0,72
EC4	10,073.07	5,540.19	15,613.26	N/A	15,613.26	9 years and 0,5 months	-0,72
EC5	19,860.28	10,923.15	30,783.43	N/A	30,783.43	9 years and 1 month	-0,77
EC6	5,448.43	2,996.64	8,445.07	N/A	8,445.07	9 years and 0,5 months	-0,72
EC7	4,921.34	2,706.74	7,628.08	N/A	7,628.08	9 years and 0,5 months	-0,72
EC8	3,399.09	1,869.50	5,268.59	N/A	5,268.59	9 years and 0,5 months	-0,72
EC9	16,014.86	8,808.17	24,823.03	N/A	24,823.03	9 years and 0,5 months	-0,72
EC10	4,001.70	2,200.93	6,202.64	N/A	6,202.64	9 years and 0,5 months	-0,72
EC11	14,121.54	7,766.85	21,888.39	N/A	21,888.39	9 years and 0,5 months	-0,72
Total EC	101,066.06	55,586.33	156,652.39	N/A	156,652.39	N/A	N/A
G1	39,643.27	21,803.80	61,447.07	-36,868.24	24,578.83	3 years and 7 months	16,1
G2	56,173.35	30,895.34	87,068.68	-52,241.21	34,827.47	3 years and 7 months	16,1
Total Group	95,816.62	52,699.14	148,515.75	-89,109.45	59,406.30	N/A	N/A

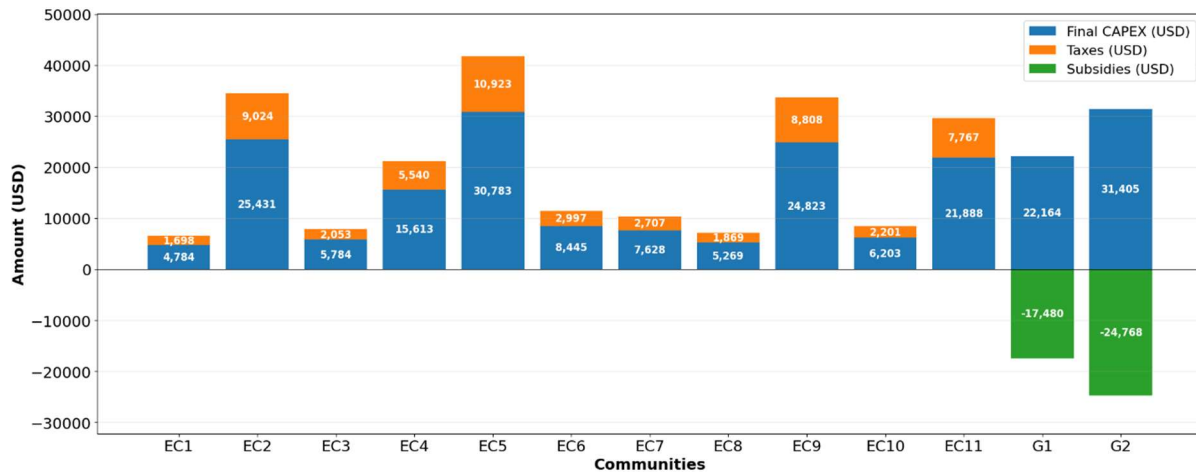
The total CAPEX of the 11 individual communities was USD 101,066 (USD 156,652 including taxes), while aggregating them into two groups reduced combined CAPEX to USD 95,817, and after taxes and subsidies, it decreased to USD 59,406. This demonstrates that integrating communities along with optimizing rates significantly reduces costs and enhances the economic viability of BESS. Figure 4 illustrates the final CAPEX considering taxes and subsidies: the orange bar represents the tax cost applied to each BESS, the green bar shows the difference between subsidies and tax costs, and the blue bar indicates the final CAPEX of each BESS. The aggregated approach reduced unit costs to USD 178.89/kWh and USD 255.56/kW, reinforcing evidence that economies of scale are decisive in the economic feasibility of community energy storage systems.



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Figure 4 – CAPEX taxes and subsidies



3.3 Discussion

The results indicate that aggregating energy communities into groups G1 and G2 not only optimizes storage capacity but also significantly improves the economic performance of BESS. While individual communities show negative ROI of -0.7% and payback near 9 years, the aggregated groups achieve ROI of 16.1% and payback of 3 years and 7 months, demonstrating a transition from unfeasible to profitable scenarios. Moreover, aggregation maintains almost the same overall capacity as individual communities, ensuring energy coverage while distributing resources more efficiently. Concentrating subsidies on fewer consolidated projects further enhances their effectiveness compared to dispersing them across multiple isolated communities, confirming that aggregation is both technically and economically advantageous.

4 CONCLUSIONS

The results highlight that the installation of battery storage at the level of individual energy communities presents persistent economic limitations. Payback periods remain around 9 years, the annual ROI stays slightly negative -0.7% , and unit costs are above USD 483.01/kWh and USD 697.67/kW. These indicators reveal that isolated projects struggle to reach financial viability due to their reduced scale and the high relative investment required.

By contrast, the aggregation of communities leads to decisive improvements. The combined scenarios (G1 and G2) show payback reduced to 3 years and 7 months, annual ROI above 16% , and unit costs around USD 178.89/kWh and USD 250.45/kW. Furthermore, CAPEX reductions of more than 40% were achieved through economies of scale and optimized distribution of component costs. In this new scenario, aggregated communities not only move closer to viability but already demonstrate profitable performance under the assumed subsidy and tax configurations.

These findings suggest that collective approaches should be prioritized in urban planning and policy design. Future regulatory frameworks and incentive mechanisms must be tailored to recognize the benefits of community-scale storage, ensuring fair distribution of costs and rewards, and fostering sustainable energy transitions in metropolitan areas.



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