Technical and economic analysis for integrating consumer-centric markets with batteries into distribution networks

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***Abstract*—Widespread adoption of distributed energy resources led to changes in low-voltage power grids, turning prosumers into active members of distribution networks. This incentivized the development of consumer-centric energy markets. These markets enable trades between peers without third-party involvement. However, violations in network technical constraints during trades challenges integration of market and grid. The methodology used in this work employs batteries to prevent network violations and improve social welfare in communities. The method uses sequential simulations of market optimization and distribution network power flows, installing batteries if violations are identified. Simulation solves nonlinear deterministic optimization for market trades and results are used in power flow analysis. The main contribution is assessing battery participation in energy markets to solve distribution network violations. Case studies use realistic data from distribution grids in Costa Rica neighborhoods. Results indicate potential gains in social welfare when using batteries, and case-by-case analysis for prevention of network violations.**

***Index Terms*—Batteries, Consumer-Centric Energy Markets, Distributed Energy Resources, Distribution, Optimization.**

I. INTRODUCTION

The Sustainable Development Goals have driven a massive insertion of renewable energy in electricity grids. This, coupled with compelling investment costs, has led to an increase in solar and wind energy producers in recent years. While it diversifies electricity networks, concerns arise.

One concern is small-scale energy production in medium and low voltage distribution networks [1], that promotes decentralization and alters traditional energy markets [2].

In this context, consumers that usually rely on local Distribution System Operators (DSOs) may now invest in local energy generation. They can also become suppliers in energy markets by selling excess energy [3]. This shift creates a category of small energy producers and consumers known as "prosumers" [4].

As the prosumers' influence grows, new opportunities arise for the formation of consumer-centric energy markets. The idea of these markets is to enable prosumers to trade energy among themselves. However, there is a concern related to incorporation of batteries into models of these market structures. Uncommon in traditional networks, energy storage devices in the electricity sector are growing due to potential economic and energetic benefits. Such potential can translate into individual or collective economic gains, as well as supplementary measures to address problems in distribution networks.

A final concern is the integration of consumer-centric markets into existing distribution networks. Specifically, how energy transactions conducted in market impact the operating constraints of the distribution network.

A. Literature Review

Consumer-centric energy market models are, fundamentally, based on the concept of coordinated multilateral trades [5]. As renewable resources increasingly participate in energy matrices, new electricity market designs have incorporated this concept, with Parag *et al.* [6] proposing organizational models, that focus on prosumers' needs and preferences, for their participation in the market. This idea gained momentum over the years, with a variety of works exploring the subject.

By using nonlinear energy costs to model market agent's flexibility, studies began exploring how to best employ distributed energy management to coordinate generation, loads and storage devices in the grid [7]. To measure benefits related to evolving market models, several studies have also used optimization in their analysis. Optimizing individual or collective energy resources became highly relevant to the success of such energy markets.

Consequently, consumer-centric market optimization has started incorporating individual or collective preferences, introducing "product differentiation" to each model. However, concerns about fairness, as addressed by [8], have emerged. This shifted attention to how these markets would integrate with the network. [9] explored methods to ensure energy exchange in the market without violating network constraints through sensitivity analysis.

In [10] classified consumer-centric market models into Full Peer-to-Peer (P2P), Community-Oriented Market (CM), and Hybrid Market. They discussed the strengths and weaknesses of each model, mathematical optimization, and potential future developments.

23rd Power Systems Computation Conference Paris-Saclay, France — June 4th to 7th, 2024
PSCC 2024

Studies continued addressing market and network integration, including line congestion and voltage constraints. [11] proposed coordination between DSO and P2P to apply additional tariffs on prosumers causing grid limit violations. [12] evaluated technical gains of P2P trading versus other models for transactive energy.

Various techniques emerged, such as estimating prosumers' allowed power injection for P2P trading best engagement [13]. This strategy focuses network usage cost for each prosumer and promotion of local transactions. Another method introduces mathematical models for P2P flexibility trading at the distribution system to address congestion, voltage, and frequency issues [14].

Tang *et al.* [15] proposed a stochastic model to use energy storage in reserve markets to provide valuable grid services. The proposition is based on day-ahead joint energy and reserve market operation while ensuring use of battery systems as a storage technology. Other studies have also assessed integration of batteries into community market optimization, providing sets of equations to emulate the behavior of batteries as market agents [16].

Case studies about specific scenarios have also been published, such as optimizing markets using data of energy consumers and producers in Brazil [17]. Other studies penalize prosumers' transactions that cause violations in the network [18]. Some works provided supplementary results to this study. One of them on technical-economical analysis of residential solar PV systems' battery storage in Brazilian regulatory context [19].

Moreover, Liu *et al.* [20] shows that optimization models can be expanded to include other types of energy storage, such as hydrogen-based storage, in P2P trading optimizations of net-zero energy communities. Others are concerned with Key Performance Indicators (KPI) for market services [21]. Optimal sizing of PV and battery storage and their distribution grid impacts is addressed in [22].

Finally, the integration of BESS into distribution networks with the intent of voltage regulation remains a topic of interest for some works. [23] proposes the creation of a transactive platform for community batteries to trade voltage regulation services with the system operator. Meanwhile [24] focuses on technical aspects of integrating batteries for voltage regulation, giving insights into net-billing profitability for prosumers.

B. Main Contributions

Many studies proposed creating additional tariffs to solve problems caused by integrating the market and network. Other studies proposed coordination techniques between energy communities and DSO by using batteries to improve voltage profiles in the distribution grid, discussing governance issues and operational aspects [25].

The main contribution of this study is to employ a different approach capable of highlighting consequences to social welfare in energy market optimization when integrating batteries into the distribution system. These batteries aim to mitigate complications caused by integrating market trades and the distribution network. However, results will show that batteries installation are not always beneficial to system operation. To assess the efficacy of the proposed strategy, this study aims to answer the following research questions:

> RQ1: Is there any economic benefit to incorporating battery agents into realistic consumer-centric market model?
> RQ2: What are the implications of creating consumer-centric market models in existing distribution networks?
> RQ3: What are the electrical and energetic consequences of adding batteries in such situations? Can batteries solve network violations while participating in energy market?
> RQ4: Is the strategy proposed effective? What are key requirements, and can it be applied to large-scale systems?

C. Paper Structure

This paper is organized as follows. Introduction brings the state of the art. Section II establishes theoretical basis of CM models and integration of battery resources. Also, electricity grid constraints are added to the model. Section III presents the proposed methodology and offers a brief description of the Case Studies simulated. Section IV presents an analysis and discussion of results of each Case Study. The last section summarizes the conclusions and indicates possible future works.

II. CONSUMER-CENTRIC MARKETS FUNDAMENTALS

In the context of energy production by prosumers in medium and low voltage distribution networks, consumer-centric market models have emerged as viable options. Notably, P2P and CM models received attention on how to be best integrated into existing electricity networks.

However, there are concerns regarding energy trades violating grid operating constraints. This work proposes addressing these issues by installing batteries in the network and making them active market agents, capable of draining or injecting energy into the system like other market participants.

To achieve this, consumer-centric market optimization models were adapted to simulate multiple communities with battery agents. Additionally, it outlines an approach for translating battery resources into market agents and mathematical constraints in the optimization model. The study also explains how distribution network operating constraints are incorporated in the mathematical model.

A. Community-oriented market framework

In a community oriented market, prosumers are able to trade energy with others of the same community. Each community has its own manager, who is mainly responsible for inter community trades and ensuring that prosumers energy demands are satisfied. To illustrate how a simplified CM could operate, Figure 1 shows a small-scale system composed of two communities, their managers and their peers.

In the figure, gray arrows represent transactions between potential trade partners. This representation enables the development of a mathematical model capable of optimizing negotiations considering each peers costs and energy prices.

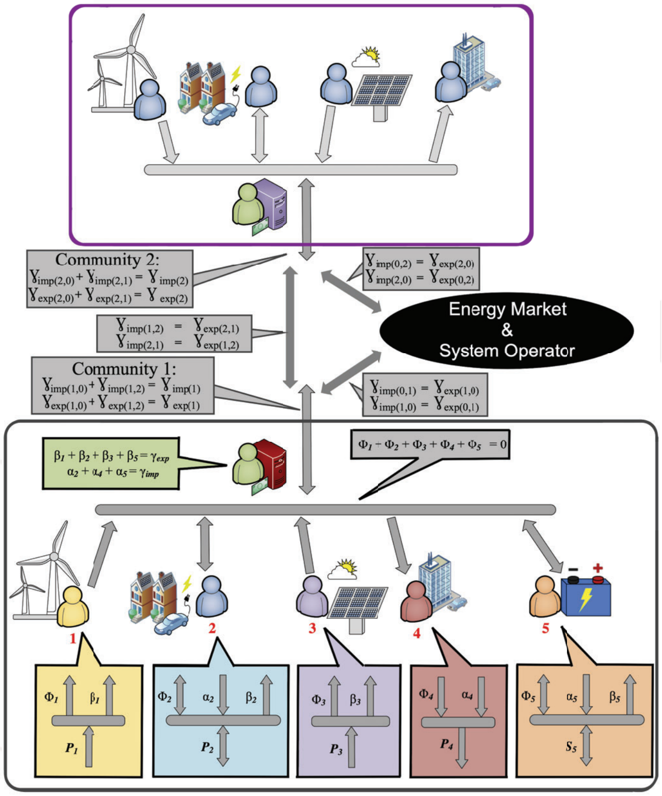


Fig. 1. Representation of transactions and optimization variables in CM.

B. Mathematical formulation

Considering a consumer-centric market system comprised of multiple communities, there are several variables to optimize during simulations. Single community mathematical optimization models have been described in detail by [10] and further expanded to include batteries in [16]. However, to conduct a systemic analysis of how multiple community-oriented markets affect local distribution networks, this study proposes the mathematical model represented by Equations (1) to (18).

$$\max_{D} \sum_{c=1}^{N_c} \sum_{n \in \Omega} f_n(P_n,\ S_n,\ \Phi_n,\ \alpha_n,\ \beta_n) + g(\gamma_{(exp,c)}, \gamma_{(imp,c)}) \tag{1}$$

s.t

$$P_n + S_n + \Phi n - \alpha_n + \beta_n = 0 \qquad \forall\ n \in \Omega \tag{2}$$

$$\sum_{n \in \Omega} \Phi_{(n,c)} = 0 \qquad \forall\ c \in \{1, \ldots, N_c\} \tag{3}$$

$$\sum_{n \in \Omega_c} \alpha_{(n,c)} = \gamma_{(imp,c)} \qquad \forall\ c \in \{1, \ldots, N_c\} \tag{4}$$

$$\sum_{n \in \Omega_p} \beta_{(n,c)} = \gamma_{(exp,c)} \qquad \forall\ c \in \{1, \ldots, N_c\} \tag{5}$$

$$\gamma_{(imp,c)} = \sum_{j \in \omega_c} \gamma_{[imp|(c,j)]} \qquad \forall\ c \in \{1, \ldots, N_c\} \tag{6}$$

$$\gamma_{(exp,c)} = \sum_{j \in \omega_c} \gamma_{[exp|(c,j)]} \qquad \forall\ c \in \{1, \ldots, N_c\} \tag{7}$$

$$\gamma_{[imp|(c,j)]} = \gamma_{[exp|(j,c)]} \qquad \forall\ c \in \{1, \ldots, N_c\},\ j \in \omega_c \tag{8}$$

$$\mathrm{SoC}_n^t = \mathrm{SoC}_n^{(t-1)} \cdot (1 - \lambda_{sd}) + \frac{S_n}{cap_n} \qquad \forall\ n \in \Omega_b \tag{9}$$

$$S_n \cdot \eta_{cha} \leq (\overline{\mathrm{SoC}_n} - \mathrm{SoC}_n) \cdot cap_n \qquad \forall\ n \in \Omega_b \tag{10}$$

$$-S_n \cdot \eta_{dis} \geq (\mathrm{SoC}_n - \underline{\mathrm{SoC}_n}) \cdot cap_n \qquad \forall\ n \in \Omega_b \tag{11}$$

$$S_n \leq \lambda_{cha} \cdot cap_n \qquad \forall\ n \in \Omega_b \tag{12}$$

$$-S_n \geq \lambda_{dis} \cdot cap_n \qquad \forall\ n \in \Omega_b \tag{13}$$

$$\underline{P_n} \leq P_n \leq \overline{P_n} \qquad \forall\ n \in \Omega \tag{14}$$

$$P_n \geq 0 \qquad \forall\ n \in \Omega_c \tag{15}$$

$$P_n \leq 0 \qquad \forall\ n \in \Omega_p \tag{16}$$

$$\alpha_n, \quad \beta_n \geq 0 \qquad \forall\ n \in \Omega \tag{17}$$

$$P_n, \quad S_n, \quad \Phi_n \quad free \qquad \forall\ n \in \Omega \tag{18}$$

where n represents an individual market agent and N_c represents the total number of communities in a system. P_n is energy produced or consumed by a market peer, Φ_n is energy traded by a peer within the community, α_n is energy imported by a peer from another community, β_n is energy exported by a peer to another community. Variables γ_{imp} and γ_{exp} are the sum of all energy imports or exports by a community. Meanwhile S_n is energy injected or drained by a peer representing a battery, SoC_n^t is the state of charge of battery agents at the end of simulation for time t, $\underline{\mathrm{SoC}_n}$ and $\overline{\mathrm{SoC}_n}$ are maximum and minimum acceptable SoC values, cap_n is the battery total energy capacity. Battery performance can be modelled by η_{cha} and η_{dis} that are battery charge and discharge efficiencies, while λ_{cha}, λ_{dis} and λ_{sd} are battery's rate of charge, discharge and self-discharge. Finally, Ω represents all market peers, Ω_c represents all consumer peers, Ω_p represents all producer peers, Ω_b represents all battery peers and ω_n represents all possible trade partners of market peer n.

To ensure optimal energy trades, it is possible to determine maximum economic returns – or *social welfare* – as an objective for the optimization. Equation (1) shows that energy importation and exportation must be accounted for in the CM model in addition to terms used for social welfare calculations in a local energy market. To accomplish this, energy cost functions for each agent were created based on second-order equations, as described in [7].

The first constraint, equation (2), known as balance constraint, binds variables to ensure that the sum of trades made by a peer is zero. This ensures the amount each peer bought or sold is delivered in its entirety.

Equation (3) determines energetic balance of a community, meaning the amount of energy sold in a community is equal to the amount bought. Meanwhile, equations (5) and (6) ensure the sum of all individual energy importation or exportation equals the amount imported or exported by the community.

Furthermore, equations (6), (7) and (8) ensure energy balance during transactions between communities. These constraints guarantee the amount of energy exported by a community is equal to the amount of energy imported by its trade partners, and vice-versa.

Equations (9) to (13) are specifically adopted to simulate battery agents' behaviour during market optimization. The calculation of an agent's State of Charge (SoC) at the end of an optimization run is determined by equation (9). This constraint relies on values of an initial SoC and binds results to a specific time-step during sequential simulation. Additional constraints for the maximum and minimum amounts of energy a battery peer can trade during a single run, shown in equations (10) and (11), respectively, must consider SoC, efficiencies and capacity limitations. The last battery constraints, shown in equations (12) and (13) insert boundaries to the amount of energy an agent may inject into or drain from the system.

Following this, equation (14) enables prosumers to adjust their demand or supply due to energy prices and availability. Finally, for mathematical precision, equation (15) determines all consumer trades as positive and equation (16) determines all producer trades as negative. It is important for the reader to bear in mind this convention for the following sections.

III. METHODOLOGY

The optimization models presented in the previous sections demonstrate the integration of market and network operation. Furthermore, when these processes negatively impact each other, batteries can be utilized to mitigate the situation.

As previously described, a consumer-centric market can operate within a distribution network by obeying a set of rules and ensuring certain standards. In instances where violations occur, this study proposes that the community can adjust the number of battery modules available to battery agents. By doing so, the community can determine if increasing peer energy capacity is sufficient to rectify network violations. To ensure operational standards, this work uses equation (19) to constrain bus voltages and equation (20) to constrain line currents in the distribution network.

$$V_k^{min} \leq V_k \leq V_k^{max} \quad \forall \quad k \in \Omega_k \tag{19}$$

$$I_j \leq I_j^{max} \quad \forall \quad j \in \Omega_L \tag{20}$$

where V_k is the voltage at bus k; V_k^{min} and V_k^{max} are voltage limits, Ω_k is the set of system buses; I_j is the current of line j, I_j^{max} is the maximum current capacity of line j, and, finally, Ω_L is the set of lines in the system.

This investigation applied the framework shown by the flowchart illustrated in Figure 2 to determine potential advantages of installing battery agents in a system. The entire process can be described as a sequence of stages that must be simulated for every time step.

Stage I, involves initializing the simulation by importing market agents and distribution network data sets. After proper processing, data is sent to the market optimization problem.

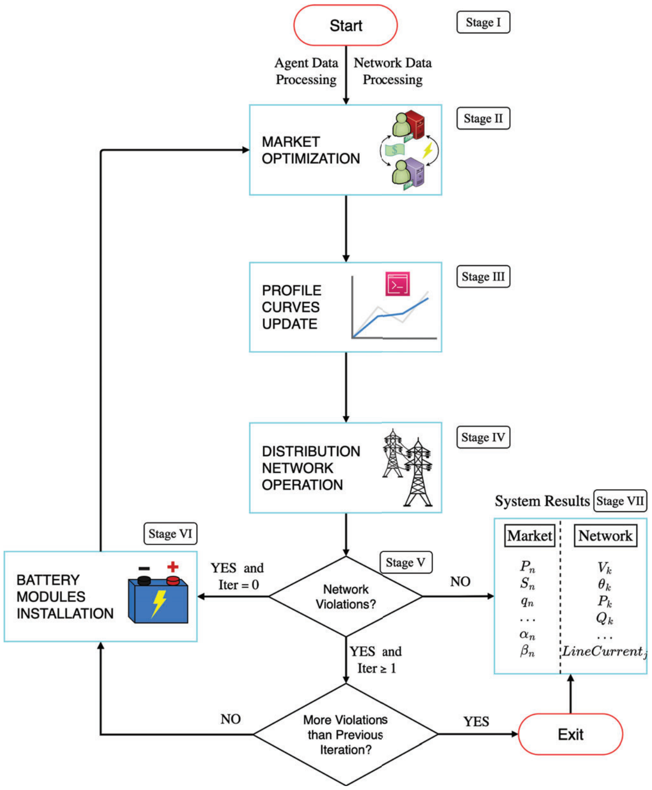


Fig. 2. Flowchart of the iterative simulation process.

Stage II focuses on hourly simulations of market optimization based on resources available at each time step. The mathematical model used for each hourly run of the optimization process is described in Section II. Note that modifications may be required in the model, depending on the number of communities simulated or the time step.

Stage III involves updating each agent's profile curves based on hourly market optimization results. It is noteworthy that although hourly simulations were used, the model is capable of handling smaller or larger time steps.

Afterwards, Stage IV imports data into power flow simulation, where these curves are used to determine energy intake of each load and energy output of each generator over the entire simulation time. In this research, Stage IV simulates three-phase power flows using the software OpenDSS, which is suitable for analyzing both balanced and unbalanced systems, regardless of network structure, existing controls, or distributed generation. It has been proven to be efficient and robust in large-scale systems simulations [26].

Upon completion of Stage IV, Stage V analyzes if any bus or line experienced violations during simulation time. For this particular distribution network, operational constraints are determined by Equations (19) and (20).

If violations are detected, Stage VI adds battery modules to the buses or lines where operational bounds are violated, and the iterative process restarts. Otherwise, market optimization and power flow results are reported in Stage VII. The following

TABLE I
AGENTS SIMULATED BY CASE STUDY.

Case Study	N° of Communities	Consumer Agents	Producer Agents
1	1	Load053 through Load136	PV053 through PV136
2	5	Load001 through Load136	PV001 through PV136

section provides details on this framework implementation in Case Study simulations.

IV. CASE STUDIES AND RESULTS

To validate the proposed methodology described in the previous section, this research reproduces a realistic distribution system network through hourly simulations of energy market negotiations and grid dispatch. Two Case Studies, briefly described below, are analyzed in this research.

- Case Study 1: simulates a single disperse community, where the consumer-centric market consists of prosumers scattered in the distribution network. Market agents are not situated in immediately adjacent buses or lines.
- Case Study 2: simulates the system with 5 communities. The entire process optimized energy transactions between these communities, reaching a total of 272 prosumers trading energy during the simulation period.

Each Case Study presented in this section simulates the entire iterative process of Figure 2. To achieve this, Case Study simulations first import relevant information about market agents and the distribution network related to the energy community, or communities, of interest. The agent's data shown in Table I illustrates which agents are observed during Case Study simulations. This means that each Case Study has its own sets of agents and focuses on optimizing data given to the mathematical model. In Table I, column two shows the number of communities simulated in each Case Study. Additionally, column three shows consumer agent names, while column four shows producer agent names of each Case Study simulation.

Table II provides an overview of each Case Study discussed. The table shows the number of network violations observed in each simulation, as well as the number of standard battery units connected to each bus that experienced violations, at the final iteration of the process shown in Figure 2. Note that Case Studies 1 and 2 used different amounts of battery modules in the last iteration of the simulation process. This happens due to recurring violations in some of the network's buses or lines. The different amounts of battery modules used in each Case Study results are discussed further on.

TABLE II
CASE STUDIES OVERVIEW.

Case Study	Number of Communities	Base Scenario Violations	Amount of SBUs at Last Iteration
1	1	61	1 *and* 5
2	5	61	1 *and* 3

* SBUs - Standard Battery Units.

All case studies were simulated in a laptop with 3 GHz Intel Core i7 processor and 8 Gb of RAM memory. Regarding simulation times, although varying depending on the specific Case Study, the shortest run took approximately 1 minute while the longest took no more than 3 minutes.

A. Standard Battery Unit

The Standard Battery Unit (SBU) used in this study refers to electrical specifications of a single battery component connected to the distribution network's buses during simulations. The unit's data can be found in Table III. Battery behaviour is simulated by the model according to these parameters.

Values used in the SBU are a representation of parameters commonly found in commercial batteries available in the market. Parameter values do not related to a specific commercial battery model; they only represent a simplified unit.

Although all battery units are considered identical, battery banks are constructed through integration of multiple SBU. Consequently, battery agents represented in simulations may have different sizes and energy storage capacities, depending on the number of stackable modules each agent chooses to deploy. All agents share the same battery data shown in Table III, except for "Power [kW]" and "Capacity [kWh]" fields, which are determined by the number of modules employed.

B. Distribution Network

Case Studies results were obtained from simulations using distribution network data from Costa Rica [27]. The network was chosen because it represents a real world infrastructure, which serves to enhance and validate the proposed strategy.

The network operates based on three line-neutral base voltages: 138 kV for high voltage system; 19.9 kV for medium voltage system; and 120 V for low voltage system.

To illustrate relevant systems operating according to base voltages mentioned, Figure 3 shows a graphical representation of distribution network employed in simulations [27].

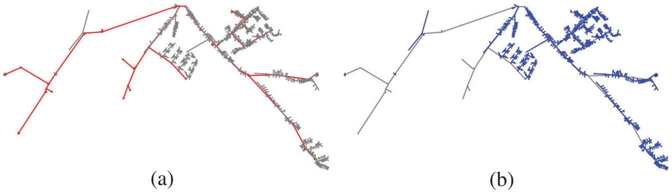

(a) (b)

Fig. 3. General depiction of distribution network used during simulations. Highlights for: (a) medium voltage buses and lines (red); (b) low voltage buses and lines (blue).

Figure 3a identifies medium voltage buses and lines in red. Similarly, Figure 3b highlights low voltage buses and lines in blue. This colour scheme will be employed throughout this study to facilitate visual identification.

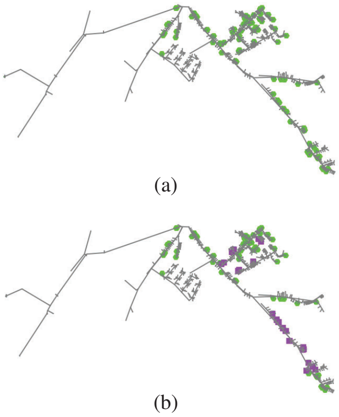
This study aims to evaluate benefits and consequences of an energy community located within a distribution network, especially in its low voltage buses and lines, since locations primarily accommodate small loads and generators.

TABLE III
STANDARD BATTERY UNIT PARAMETERS.

Units	**Power** [kW]	**Capacity** [kWh]	**SoC**$_{Max}$ [%]	**SoC**$_{Min}$ [%]	**SoC**$_{Init}$ [%]	**Eff**$_{Ch}$ [%]	**Eff**$_{Dis}$ [%]	**Rate**$_{Ch}$ [%]	**Rate**$_{Dis}$ [%]	**Rate**$_{AutoDis}$ [%]
1	2.56	10.24	0.8	0.2	0.5	0.96	0.96	0.25	0.9375	1.72e-05
3	7.68	30.72	0.8	0.2	0.5	0.96	0.96	0.25	0.9375	1.72e-05
5	12.8	51.20	0.8	0.2	0.5	0.96	0.96	0.25	0.9375	1.72e-05

C. Case Study 1 Results

The geographical location of agents is illustrated in Figure 4 where prosumers and storage units are represented in green and purple, respectively. This particular Case Study was selected to demonstrate that it is not necessary for all prosumers to be located in close proximity when establishing an energy CM. All market agents are connected to low voltage buses. Here it is possible to verify the effectiveness of larger consumer-centric markets with similar configurations while determining if they are prone to experience more violations due to activity of loads and generators outside the community market.


(a)

(b)

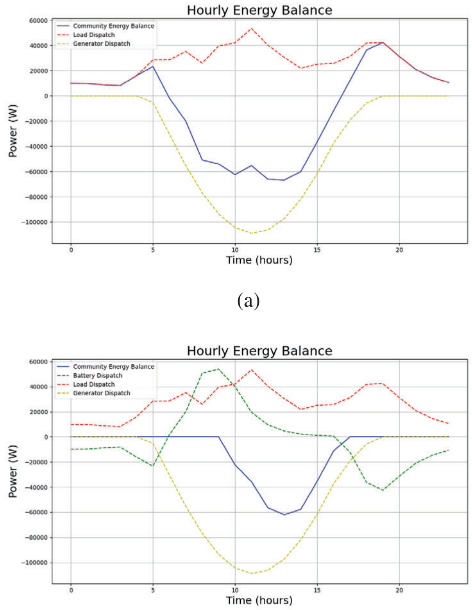
Fig. 4. Case Study 1 agents locations in distribution network. Highlights for: (a) market without batteries - agents in green; (b) market with batteries - batteries in purple.

Additionally, stressing the distribution network wasn't necessary to detect system operation violations. The number and diversity of prosumer profile curves as well as their various locations, naturally lead to network violations (Table II).

Results initially focus on the optimal energy market coupled to three-phase power flow of system without batteries (Figure 4a). Subsequent results include additional agents representing battery banks (Figure 4b). Notably, agent transactions and distribution network violations are influenced by energy generation and consumption of other agents at adjacent buses, which are outside of the community. This Case Study illustrates a network where violations occur naturally.

During hourly market optimization simulations, the community's social welfare heavily relies on its energy generation. Negative social welfare occurs during hours of low sunlight irradiance when the community imports energy from external grid market players to meet its demands. Conversely, social welfare peaks during high irradiance hours due to surplus energy generation exported to the external grid.

The impact of battery agents becomes more apparent when analyzing the community's energy balance in Figure 5 (a and b). Both figures show: total load dispatch (in red), total generator dispatch (in yellow), and the community's energy balance (in blue). Figure 5b introduces an additional curve representing the energy balance of battery agents (in green). The community's energy balance is calculated by summing all available dispatch curves.



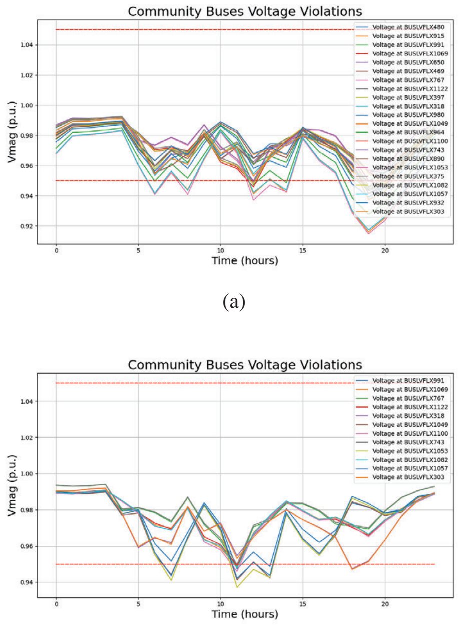
(a)

(b)

Fig. 5. Case Study 1 hourly energy balance optimization results. Results for: (a) system without batteries; (b) system with batteries.

Finally, given the amount of buses and lines that had to be supervised, buses with undervoltage violations became more noticeable during hours of peak energy consumption and intense trade. These buses and their respective voltages are shown in Figure 6a. After successive additions of battery modules to the buses with violations, the final iteration of the simulation process resulted in fewer bus voltage violations shown by Figure 6b.

These violations can be summarized in a report, exemplified by Table IV. The violation summary focuses on buses directly relevant to the community, as previously mentioned.



(a)

(b)

Fig. 6. Case Study 1 hourly bus voltages violations. Results for: (a) bus voltage violations in system without batteries; (b) bus voltage violations in system with batteries.

TABLE IV
CASE STUDY 1 RESULTS OVERVIEW.

Storage	Social Welfare (R$)	Violations
No (Size = 0)	83.314 (Reference Value)	61
Yes (Size = 1)	109.170 (↑ 31.034%)	21
Yes (Size = 1 and 3)	119.195 (↑ 43.067%)	20
Yes (Size = 1 and 5)	124.172 (↑ 49.040%)	23

During the iterative process, battery modules were added only at buses with persistent voltage violations. Some buses received smaller-capacity battery agents, while others, particularly problematic ones, got larger-capacity ones. Results from battery simulations were obtained from agents of sizes 1 and 3.

Additionally, a key observation in this Case Study is that some buses faced multiple voltage violations, indicating high energy demand and potential network infrastructure weaknesses. This suggests the need for network renovations or adaptations rather than prioritizing battery bank installations. This recurring voltage issue is further highlighted by 22 buses experiencing 61 undervoltage episodes during the simulation period, which battery banks aim to mitigate.

The strategy employed in this Case Study has demonstrated notable progress in solving the issue of recurring voltage violations. It not only suggests improvements in social welfare but also proves effective under specific circumstances.

Although combining battery agents with sizes 1 and 5 may be more beneficial to the overall social welfare of the community, it leads to a higher number of voltage violations compared to simulations involving smaller battery size combinations. Hence, the results related to simulations of battery agents with sizes 1 and 3 were presented, as they are advantageous from both the social welfare perspective and the network's operational standpoint.

D. Case Study 2 Results

Prosumers are connected to low voltage buses and their placement is arranged according to the graphical representation of Figure 7. The figure shows a similar map to the one presented in Case Study 1. However, there are also differences related to agents from communities 1 to 4.

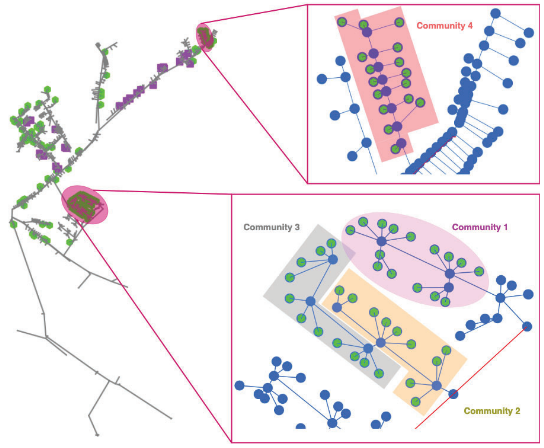


Fig. 7. Case Study 2 agents locations in distribution network.

Before installing battery banks in the network it was necessary to determine which buses or lines experienced violations during the simulation period. Such violations were mainly expected from energy transactions in community 5 (disperse and encompassing all peers not contained in communities 1 through 4), considering that communities 1 to 4 are located in isolated and, most importantly, oversized areas of the network. In light of the voltage violations that Community 5 experiences during its normal operation, the report obtained at the end of the base case was identical to the one of Case Study 1.

Consequently, due to identical violations reported in Case Studies 1 and 2, the same buses were chosen for the installation of battery banks. The graphical representation showing a detailed view of the network, highlighting prosumers and battery agents can be seen in Figure 7.

In that regard, following the same process of Case Study 1, the simulated battery agents had their energy capacity updated with additional modules at the end of each iteration. This means that the amount of units in the battery bank grows if the voltage violations persist in the buses to which they are connected. As a result, the system's simulations start with single battery units in the violated buses and afterwards starts to mix battery agents of different sizes in the network. However, differently from Case Study 1, the iterative procedure reaches an earlier exit. That occurs due to the growing number of violations that take place on the distribution network once some of the battery agents sizes start to be updated.

Considering that graphs with hourly results and most of the conclusions have already been drawn from previous reports in this section, results shown here focus on presenting observations made after analyzing the system. Therefore, simulation results were summarized in Table V.

Regardless of choice on the matter of battery sizes, after the reported values were thoroughly inspected, it is possible to verify the effectiveness of the strategy proposed. It becomes clear that a systemic approach to the consumer-centric market organization is not only more profitable, but also lessens investments in batteries necessary to prevent network violations.

TABLE V
CASE STUDY 2 RESULTS OVERVIEW.

Storage	**Social Welfare** (R$)	**Violations**
No (Size = 0)	136.408 (Reference Value)	61
Yes (Size = 1)	160.865 (↑ 17.929%)	14
Yes (Size = 1 and 3)	168.730 (↑ 23.695%)	16

Also, both Case Study results showed an increase of network violations once more battery modules are installed in a system. This could be explained by conclusions shown in [25] that a battery's degradation models affects its operation during simulation. Consequently, this reduces the number of observed distribution network violations.

V. CONCLUSIONS

This study focused on simulating a mathematical model to optimize energy transactions of consumer-centric markets embedded in distribution networks. Simulation results show energy transactions between prosumers can impact power flows, causing operational violations. The model used identifies these issues and determines if including battery units as market agents in specific buses can mitigate network violations.

Results show the effectiveness of the model, considering that operational violations caused by integration of consumer-centric markets to distribution network are generally related to voltage levels in buses. Consequently, the strategy of connecting batteries to communities will increase overall social welfare, while ensuring adequate voltage levels for operation. Overall it was observed that large scale systems tend to perform better, reducing the number of violations, when applying the proposed method.

Currently, the responsibility for resolving operating problems in the distribution network lies with the DSO. Consequently, future works should address issues of capital costs for batteries and governance of energy resources. Possible solutions from the DSO standpoint could be fining prosumers that cause violations, grants for investments in batteries and cost-sharing with prosumers for special administrative rights.

Benefits of installing batteries are amplified when the community market is less dependent on external energy sources. Technical and economic feasibility studies are necessary to determine whether a community should prioritize expanding its energy generation capacity or investing in batteries.

ACKNOWLEDGMENT

This research was supported in part by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) under Grant 001, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) under grant 404068/2020-0, Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) under grant APQ-03609-17, and Instituto Nacional de Energia Elétrica (INERGE). It is also supported by the Scientific Employment Stimulus Programme from the Fundação para a Ciência e a Tecnologia (FCT) under the agreement 2021.01353.CEECIND.

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