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Energy community markets under network constraints considering battery units integration

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RESUMO

A penetração crescente de Recursos Energéticos Distribuídos (REDs) atualmente, trouxe desafios para as redes de baixa tensão tradicionais. Como consequência, o rápido avanço dessa tecnologia consolidou a posição dos prosumidores, entidades que produzem e consomem eletricidade, como membros ativos de muitas redes de distribuição. Dentre as mudanças causadas por tais avanços, as demandas dos prosumidores levaram à proliferação dos mercados de energia locais baseados em modelos centrados nos consumidores. Esses modelos de mercado permitem contratos entre as partes (*peers*) sem a intervenção de terceiros nas transações. Isso, entretanto, implica em possíveis violações de restrições operativas da rede elétrica onde os *peers* se encontram. Esse estudo, almeja abordar o tema de integração dos mercados centrados nos consumidores à rede elétrica de distribuição existente através de uma série de simulações computacionais. Para tanto, uma metodologia foi implementada no sentido de empregar baterias nos mercados centrados nos consumidores como uma maneira de agregar *social welfare* para uma comunidade e garantir que as restrições de rede não sejam violadas durante transações energéticas. O método descrito foca em simulações sequenciais de otimização do mercado e análise do fluxo de potência da rede de distribuição, instalando baterias nas barras e linhas que sofrem violações durante operação. As simulações sequenciais tem inicio com a solução de um problema de otimização de um mercado de energia, determinístico e não-linear, estruturado usando a ferramenta de otimização `Pyomo`. Em seguida, a simulação sequencial continua e usa os resultados obtidos na otimização do mercado como entrada para o problema de fluxo de potência, usando a ferramenta de simulação de sistemas de distribuição `OpenDSS`. Todos os estágios da metodologia proposta nesse trabalho foram simulados por um programa em `Python`, que encadeia os resultados de cada etapa de simulação com o início da etapa seguinte. Para validar essa estratégia, sete estudos de caso foram simulados e discutidos usando dados reais do consumo e produção de energia de prosumidores enquanto conectados a uma rede de distribuição típica da Costa Rica. Os resultados obtidos indicam potenciais ganhos para o *social welfare* quando instaladas baterias e uma análise caso a caso para prevenção de violações na rede.

Palavras-chave: Mercados de Energia Elétrica, Otimização, Recursos Energéticos Distribuídos, Mercados Centrados no Consumidor.

ABSTRACT

The greater penetration of Distributed Energy Resources (DERs) in recent years has led to many changes in traditional low-voltage networks. As a consequence, the rapid advance of this technology has consolidated the position of prosumers, an entity that produces and consumes electricity, as an active member of many distribution networks. Among the changes that this entails, prosumers' demands have led to the proliferation of local energy markets based on existing consumer-centric models. These market models allow trade between peers without intervention of conventional parties in transactions. This, however, implies possible violations to the technical constraints of the electricity network where such peers are located. This study aims to address, as its main objective, the subject of integrating consumer-centric markets to the existing distribution network through a series of computational simulations. To do so, a methodology was implemented in order to employ batteries in consumer-centric markets as a way to aggregate social welfare to a community and ensure that network constraints are not violated during the energy exchange. The method described focuses in sequential simulations of market optimization and distribution network power flow analysis, installing batteries in buses and lines that directly experience any constraint violation during operation. The sequential simulation starts by solving an energy market non-linear deterministic optimization problem structured using the `Pyomo` optimization tool. Afterwards, the sequential simulation continues with market results being used as input for the power flow using the `OpenDSS` distribution system simulation tool. All stages of the methodology proposed in this work were simulated in a `Python` based program that binds each step's results with start of the following step. To verify this strategy, seven case studies were simulated and discussed using realistic data of prosumers energy consumption and generation while connected to a typical distribution network in Costa Rica. The results obtained point towards potential social welfare gains from installing batteries and a case-by-case analysis to preventing network violations.

Keywords: Electricity Markets, Optimization, Distributed Energy Resources, Consumer-Centric Markets.

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LIST OF ABBREVIATIONS AND ACRONYMS

CM	Community-Oriented Markets
DER	Distributed Energy Resources
DSO	Distribution System Operator
EV	Electric Vehicles
KPI	Key Performance Indicators
P2P	Full Peer-to-Peer
PV	Photovoltaic Systems
SoC	State of Charge

LIST OF SYMBOLS

C_{exp}	Community cost of exporting energy to the grid
C_{imp}	Community cost of importing energy from the grid
CB_n	Energy cost of battery peer n
P_n	Total energy traded by peer n
$\overline{P_n}$	Maximum tradable energy by peer n
$\underline{P_n}$	Minimum tradable energy by peer n
P_{nm}	Energy traded between peer n e o peer m
S_n	Energy traded by battery peer n
SoC_n^t	State of Charge of battery peer n at time t
SoC_n^0	Initial State of Charge of battery peer n — (SoC_{Init})
$\overline{\mathrm{SoC}_n}$	Maximum State of Charge of battery peer n — (SoC_{Max})
$\underline{\mathrm{SoC}_n}$	Minimum State of Charge of battery peer n — (SoC_{Min})
a_n	Quadratic coefficient to the peers energy cost function
b_n	Linear coefficient to the peers energy cost function
cap_n	Battery peer n energy capacity
α_n	Energy imported by peer n
β_n	Energy exported by peer n
γ_{imp}	Energy imported by community
γ_{exp}	Energy exported by community
λ_{cha}	Battery peer rate of charge — (RATE_{Ch})
λ_{dis}	Battery peer rate of discharge — (RATE_{Dis})
λ_{sd}	Battery peer rate of self-discharge or auto-discharge — ($\mathrm{RATE}_{Autodis}$)
η_{cha}	Battery peer charge efficiency — (EFF_{Ch})
η_{dis}	Battery peer discharge efficiency — (EFF_{Dis})
Φ_n	Energy traded by peer n within community
Ω	Set of peers that are market members
Ω_c	Set of consumer peers that are market members
Ω_p	Set of producer peers that are market members
Ω_n	Set of trade partners of peer n
Ω_k	Set of network buses hosting market peers
Ω_l	Set of network lines connecting market peers

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1 INTRODUCTION

The current trend for sustainable development of the energy sector has pushed for massive insertion of renewable energies in electricity network. Coupled with compelling investment costs, this trend has favored a considerable rise on the number of solar and wind based energy producers in recent years. That being the case, although this constant growth in renewable generation contributes to the diversification of several electricity networks, it also raises many concerns and debates.

One such concern, for example, is related to energy production by small scale entities connected to the medium and low voltage distribution networks (DRANKA; FERREIRA, 2020). Despite the fact this behavior favors the physical decentralization of traditional energy sector structures, such Distributed Energy Resources (DER) can also be a catalyst for changes in traditional energy markets (ABRISHAMBAF *et al.*, 2019).

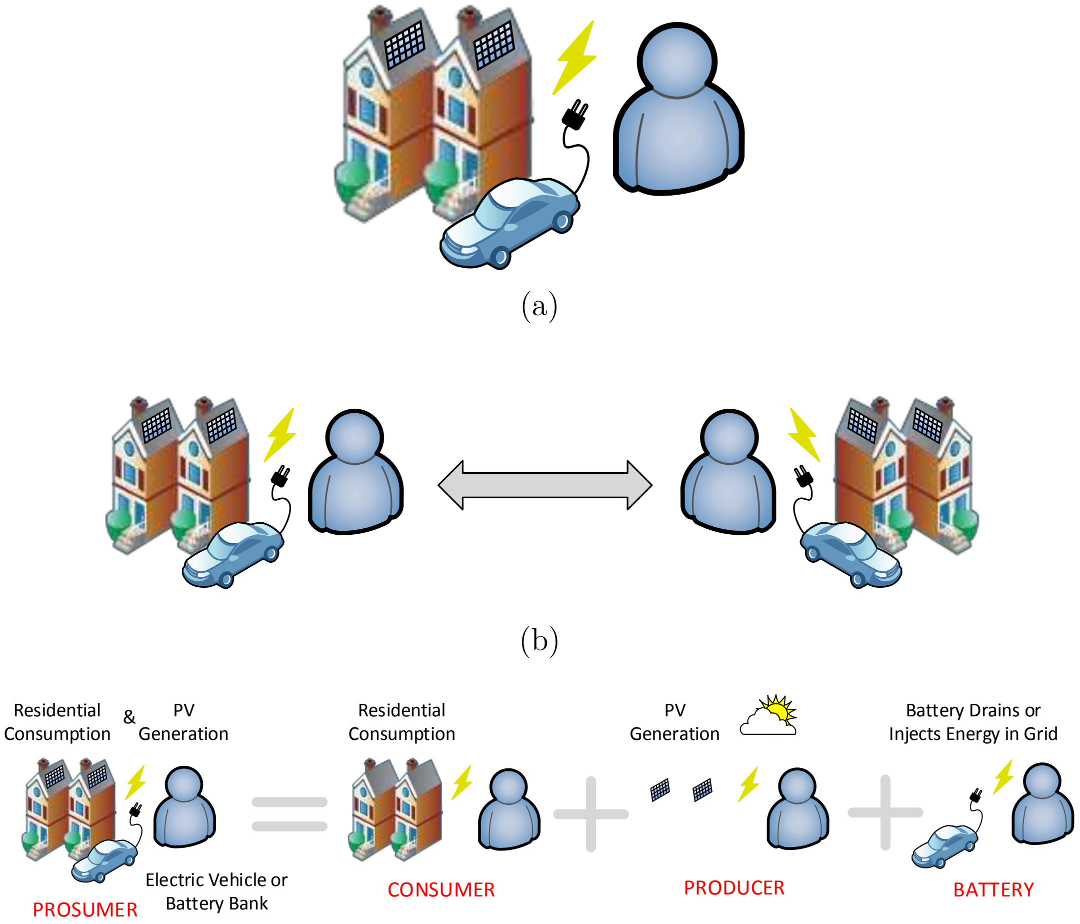
Under these conditions, loads that would have to satisfy their electricity demand by signing on the services of a local Distribution System Operator (DSO) can, otherwise, start to dabble in energy generation. For all intents and purposes, if fully engrossed in locally producing energy, these same loads could also behave as suppliers for the energy market by selling their surplus generation (MENGELKAMP *et al.*, 2018). In any case, this paradigm shift gives rise to a new category of small energy producer and consumer, namely the prosumers (MEEUS, 2020).

As the prosumers influence in the energy sector grows, opportunities also arise for the formation of consumer-centric markets. According to the premise upon which they are established, these markets may enable prosumers to trade energy among themselves. To illustrate this reality, Figure 1 shows three representations of prosumers as they can be conceived nowadays.

The first, shown in Figure 1a, is a standard representation of a energy consumer and producer commonly found in distribution networks. The second, shown in Figure 1b exemplifies how prosumers can be represented as market agents and how the trades between two prosumers can be conducted. These trades would involve an agreed payment upon signing of a energy transaction contract. The last representation, shown in Figure 1c is a description of the different market entities that can be established pertaining a prosumer.

Another concern regarding consumer-centric market that is very important to the development of this work has to do with the insertion of batteries in the models that organize each market structure. Despite being uncommon in traditional networks, the growing participation of energy storage technologies in the electricity sector is worthy of mention, given their potential economical and energetic benefits. Such potential, when properly analyzed and explored, can be translated into individual or collective economical gains, as well as supplementary measures to address problems that may be caused in local distribution networks.

Figure 1 – Graphical representation of prosumers.



(a)

(b)

(c)

Caption: (a) Typical residential prosumer ; (b) Energy trade between prosumers; (c) Different market entities representing a prosumer.

Source: Adapted from (BARBOSA, 2021).

A final concern related to consumer-centric markets has to do with their insertion into existing distribution networks. That is to say, how transactions made in these market models respect the operational constraints and limitations that are observed in existing distribution network. This concern has been amply discussed in literature, as the next section will show.

1.1 LITERATURE REVIEW

As a structure, the consumer-centric energy market models are, fundamentally, based on the concept of coordinated multilateral trades. This idea has been published and discussed in literature since Wu e Varaiya (1999) first proposed it. From then on, the concept has been continuously discussed and explored in literature.

Once the penetration of renewable resources in the energy matrices of different countries started to rise over the years, the idea of new electricity market designs also followed suit. In that regard, Parag e Sovacool (2016) focus on prosumer's needs and preferences while proposing organization models for their participation in the market. Naturally, after being brought into the limelight, the idea gradually gains momentum.

Consequently, in ensuing years the scientific community witnessed a variety of works on the subject. By using nonlinear energy costs to model a market agent's flexibility, studies began exploring how to best employ distributed energy management to coordinate generation, loads and storage devices in the grid (HUG; KAR; WU, 2015).

In hopes of measuring benefits related to the constantly evolving market models, a growing number of studies started to incorporate optimization in their analysis. As it happens, optimizing individual or collective particularities of each system became highly relevant to the success of such energy markets.

Along these lines, the optimization models of consumer-centric markets started to incorporate individual or collective preferences under the guise of "product differentiation" (MORET; PINSON, 2018). This, however, adds concerns regarding the fairness of the referred market models that Moret e Pinson (2018) addressed in their work.

As a result of the popularity involving more complex models, concerns started to shift towards how these consumer-centric markets would be integrated into the network. In that regard, Guerrero, Chapman e Verbič (2018) explores how to guarantee the exchange of energy in a market while ensuring that no network constraints are violated. Their proposition is grounded on a sensitivity analysis that assesses the impact of transactions on the network.

Succeeding this initial enthusiasm of the scientific community after the topic returned to the public eye, Sousa *et al.* (2019) presented an overall comprehensive review on the subject. In it, the consumer-centric market models are mainly divided into the Full Peer-to-Peer (P2P), the Community-Oriented Markets (CM) and the Hybrid Market, which is a combination of both. The paper addresses main strengths and flaws of each model, provides a description on the mathematical optimization models and elaborates on potential future developments in this field.

In the meantime, studies continued discussing approaches to solve problems that arise from market and network integration. Complications of their assimilation often involve problems related to line congestion and voltage constraints. A coordination methodology between DSO and P2P to apply additional tariffs to prosumers that cause grid limit violations was proposed by Orlandini *et al.* (2019).

Evaluating other approaches to the integration of small-scale DER into electricity networks, Guerrero *et al.* (2020) addresses transactive energy in different categories. The technical gains related to P2P trading were analyzed and compared to other existing models.

Recent studies in the field of market and network integration cover other successful techniques. A method of estimating each prosumer's allowed power injection enables one to determine how to best engage in P2P energy trading (JIA; WAN; LI, 2022). This strategy focuses on quantifying the network usage cost for each prosumer and promoting local transactions among prosumers at the same bus. Another method introduces a set of mathematical models considering P2P flexibility trading at the distribution system, while assisting the DSO and TSO in solving the congestion, voltage and frequency problems (MARQUES, 2022).

As a seminal study for many other works in the area, Tang *et al.* (2020) proposes a stochastic mathematical model that uses energy storage in reserve markets to provide valuable grid services. Their proposition is based on a day-ahead joint energy and reserve market operation while ensuring the use of battery systems as a storage technology.

Other studies related to battery integration into the community market optimization have been published since then. One of them, particularly relevant for the development of this work, provides a set of equations to emulate the behavior of batteries as market agents (GUEDES *et al.*, 2022). These equations act as constraints during the optimization of consumer-centric markets and cover possible representations of batteries as different types of market agents.

Trailing after a series publications on the subject of consumer-centric markets, some works started to be published with case studies pertaining specific scenarios. One of these focused on optimizing said markets, mainly P2P and CM, using data of energy consumers and producers in Brazil (BARBOSA; DIAS; SOARES, 2020).

Following the same tendency of research in the area of market and network integration, more studies were published using strategies to penalize prosumers whose transactions cause violations in the network (BOTELHO *et al.*, 2021a; BOTELHO *et al.*, 2021b).

Furthermore, although not directly related to consumer-centric markets, other works have provided results that proved supplementary to this specific study. One of them pertains a technical-economical analysis of Photovoltaic Systems (PV) under the perspective of Brazilian prosumers and DSO (IGLESIAS, 2021). Another, focuses on a technical-economical analysis of battery storage for residential solar PV systems in the Brazilian regulatory context (DEOTTI *et al.*, 2020). One last study evaluates what regulatory measures are needed to the liberalization of Brazilian energy markets and to the updates of price formation mechanisms (PSR, 2022).

Needless to say, but there are still many studies and topics to be explored in the area of consumer-centric markets. Liu, Yang e Zhou (2021) shows that the optimization model can be expanded for other kinds of energy storage. More specifically, hydrogen based energy storage in P2P trading optimizations on net-zero energy communities. Others, not entirely related to optimizing transaction, are concerned with Key Performance Indicators (KPI) of the services provided by a consumer-centric market (OLIVEIRA *et al.*, 2022), or the future prospects of energy trades using blockchain technologies (ANDONI *et al.*, 2019; MARTINS, 2019; PETERS *et al.*, 2022).

Last but not least, a highly relevant study for future developments of this work is related to the optimal sizing of PV and battery storage and their distribution grid impacts (WECKESSER *et al.*, 2021).

Differently from the previously mentioned studies concerned with solving problems that arise from integrating market and network by creating additional tariffs to agents, this study employs a different strategy. This strategy consists of adding batteries to a system as an attempt to mitigate complications that arise from integrating market and distribution network.

This shall become clearer in the next section where the objectives of this study will be thoroughly exposed.

1.2 OBJECTIVES

This study aims to address the subject of integrating consumer-centric markets to the existing distribution network through a series of computational simulations in order to answer the following research questions:

> RQ1: Are there economical gains to be made by inserting battery agents in a realistic consumer-centric market model?

> RQ2: What are the consequences of forming consumer-centric market models in existing distribution networks?

> RQ3: What are the electrical and energetic consequences of adding batteries in such situations? More specifically, are battery banks capable of solving distribution network violations while actively participating in the energy market?

> RQ4: How effective is the strategy proposed in this work? What are the main prerequisites, and can it be applied in large-scale systems?

There are many pathways towards reaching the general objective delineated as integrating consumer-centric markets to existing distribution networks. To answer these research questions, this work establishes specific objectives as milestones towards a full model capable of solving the main issues commonly found while conducting the research. By doing so, this work compartmentalizes the greater and more complex objective into many smaller and easier to achieve objectives. The specific objectives of this work were:

(i) Implement a consumer-centric market model into an optimization tool to determine economical gains or losses related to inserting battery agents into the model.

(ii) Implement a realistic distribution network into a power flow simulation tool to analyze how the system operates normally.

(iii) Integrate market optimization results, initially without batteries, into the distribution network simulation tool and compare power flows to determine how market affects operation.

(iv) Add batteries to the market optimization problem and determine how the storage technology affects the system as a whole.

(v) Filter relevant results and plot meaningful graphs and distribution network maps.

1.3 DISSERTATION'S STRUCTURE

Beyond the Introduction, which brings the state of art, this document is divided into four other chapters.

Chapter 2 establishes the theoretical basis of this work by reviewing the concept of two consumer-centric market models. Moreover, updates along the lines of integrating battery resources, agent modeling and electricity grid constraints are added to the models.

In Chapter 3 one will find a description of the methodology used in this work. In addition, the chapter also offers a brief description of the Case Studies simulated in this research.

To verify how effective the model framework is, Chapter 4 presents an analysis and discussion of each Case Study simulation results. Each one consisted of applying the model to a group of agents connected to a distribution network and measuring if results obtained improve.

The last chapter summarizes the observations made in this study, presents answers to the Research Questions (RQs), describes conclusions related to the framework and gives indications towards possible future works in the area.

1.4 RELATED PROJECTS AND PUBLICATIONS

The work developed in the scope of this dissertation partially concerns the objectives and results of two research projects, namely:

- DECARBONIZE - Development of strategies and policies based on energy and non-energy applications towards CARBON-neutral cities via digitalization for citizens and society (NORTE-01-0145-FEDER-000065);

- DECMERGE – Decentralized decision-making for multi-energy distribution grid management (2021.01353.CEECIND).

Furthermore, over the length of the masters program, the candidate has taken part in the development and publishing of the following papers related to energy markets and optimization:

(BOTELHO *et al.*, 2021a) – An article concerning the consumer-centric energy market integration into the electricity network. Focuses in using Topological Distribution Factors to trace and penalize peers for violations that may occur to the system.

(BOTELHO *et al.*, 2021b) – A similar study on the integration of consumer-centric energy market into the electricity network. Deploys a different tracing and penalization strategy.

(PETERS *et al.*, 2022) – An overview on the application of blockchain technology in consumer-centric energy markets. A recount of the main existing strategies and preeminent project already in operation.

(PETERS *et al.*, ongoing) – A study of the integration of consumer-centric markets into distribution networks, considering operational constraints and battery units installation.

2 CONSUMER-CENTRIC ENERGY MARKET MODELS AND DISTRIBUTION NETWORK

Considering the introduction given on the subject and literary production reviewed for this work, it can be said that the Full Peer-to-Peer (P2P) and the Community-Oriented Market (CM) models have currently risen to prominence. This brings about a variety of studies on how these models can be best employed and integrated to the existing electricity networks.

By offering its participants an opportunity to choose their trade partners and seek preferable energy transaction deals, both markets above show outstanding potential when evaluating possible gains by organizing small prosumers located in low voltage networks. The option of energy prosumers finding common ground, associating themselves and collaborating for the sake of specific purposes or objectives is another appealing selling point of the models studied.

In this context, several methods for the integration of these models to the distribution network have been evaluated. As a result, concerns related to violation on the grids operational constraints have arisen. To address this, some works propose penalizing energy market transactions that promote violations in the electricity grid. However, this work proposes addressing these issues by installing batteries to the network and making them active market agents, draining or injecting energy into the system as a normal market peer would.

This chapter will focus on describing the consumer-centric market models and how their transactions can be optimized. Afterwards, it also offers an approach on how battery resources can be translated into market agents and what mathematical constraints it entails to the optimization model. In addition, a brief description on how agents are modeled is provided, followed by an explanation on how distribution networks operational constraints are incorporated by the mathematical model.

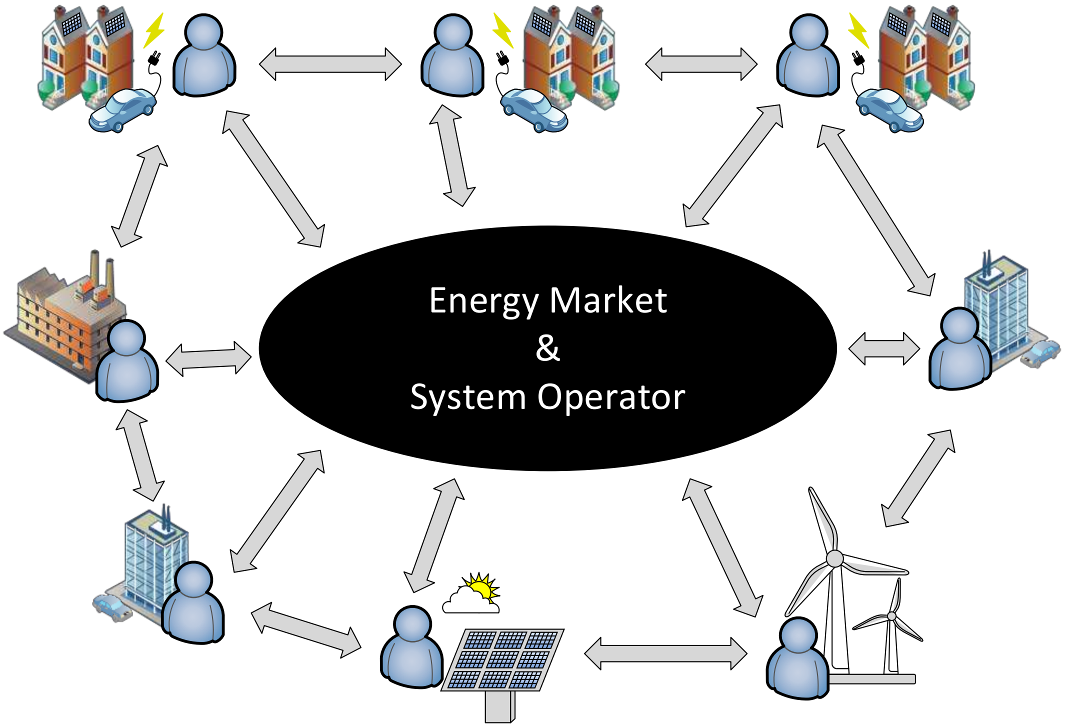
2.1 FULL PEER-TO-PEER MARKET MODEL

The P2P market model is organized so that all its members, also called peers, are able to trade energy with each other. Consequently, this structure enables prosumers that are part of it to define who will be their trade partners, the amount of energy that will be traded and at what cost.

The absence of a supervisor or market controller is a particular quality of this model, most of all when it comes to individual freedom and the independence to determine details pertaining each transaction. While this configuration grants its peers certain liberties, such benefits are not without drawbacks. When a market using this framework grows and conflicts between peers surface, the lack of a mediator or an authority figure favors growing dissension among peers. In extreme situations, unsolved conflicts between peers may fester and eventually plunge the market into complete anarchy.

Based on the premise that all peers must be treated as equals and are allowed to satisfy their energetic demands as they will, it is possible to imagine that market members are presented with an extensive and diverse list of trade partners. In order to illustrate this possibility, Figure 2 shows an example of the possible transactions each market peer would be faced with.

Figure 2 – Graphical representation of transactions in Full Peer-to-Peer market.



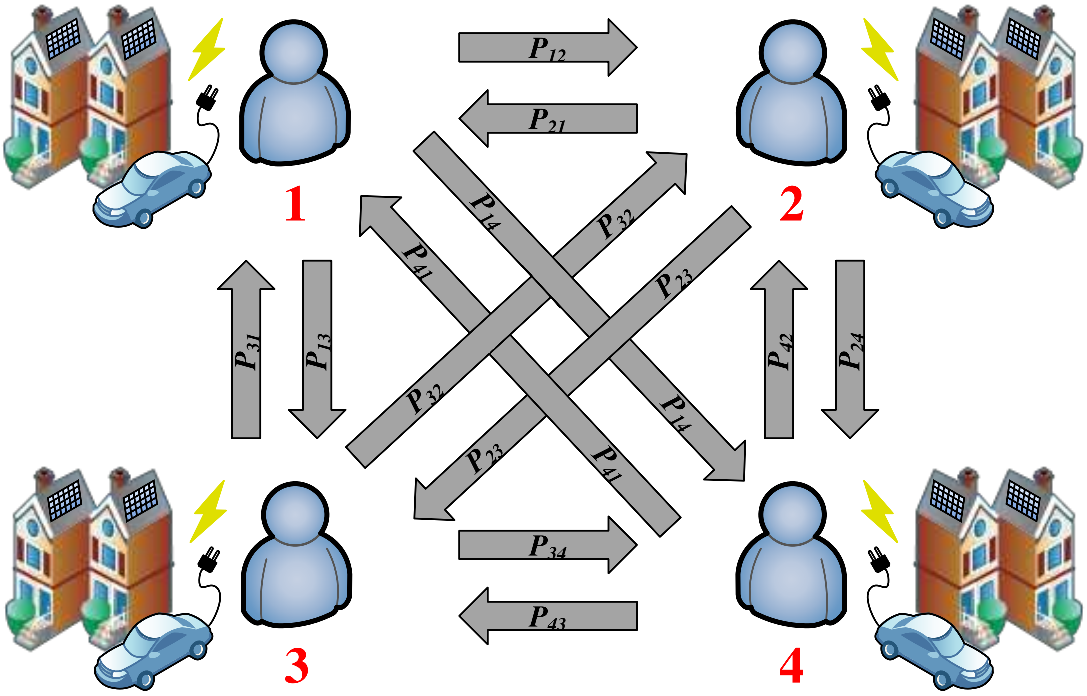
Source: Adapted from (BARBOSA, 2021).

Aspiring to illustrate how a simplified P2P market would take place, Figure 3 shows an example of a small scale system of 4 peers. The possible trade partners and resulting transactions are represented by the gray arrows. More importantly, this representation enables one to create a mathematical model capable of optimizing negotiations considering each peers costs and energy prices.

To assure optimal energy trades, one can determine maximum economical returns – also called social welfare – as the objective for the whole process. Therefore, (2.1) demonstrates the total systemic gains as the sum of each individual peer's income or expenditure. That value is obtained by determining what optimal amount of energy (P_n) each peer should trade within the bounds imposed by the problem constraints.

The first constraint, shown in equation (2.2) determines the total energy traded by peer n as the sum of all individual trades n made with its partners.

Figure 3 – Example on the transaction variables of a Full Peer-to-Peer market.



Source: Adapted from (BARBOSA, 2021).

Following this, equation (2.3), also known as the balance constraint, binds variables determining that outgoing trades (P_{nm}) are equal to incoming trades (P_{mn}). By doing this, the optimization model ensures the amount each peer bought or sold is delivered in its entirety.

Additionally equation (2.4) incorporates each peers limitations to energy production or consumption as lower and upper bounds to the trade variables. Finally, for the sake of mathematical precision, equation (2.5) determines all consumer trades as positive and equation (2.6) determines all producer trades as negative. The reader should bear in mind this convention for the following chapters.

$$\underset{D}{max} \sum_{n \in \Omega} \frac{a_n}{2} \cdot P_n^2 + b_n \cdot P_n \tag{2.1}$$

subject to:

$$P_n = \sum_{m \in \omega_n} P_{nm} \tag{2.2}$$

$$P_{nm} + P_{mn} = 0 \qquad \forall \ \ (n{,}m) \in (\Omega{,}\omega_n) \tag{2.3}$$

$$\underline{P_n} \leq P_n \leq \overline{P_n} \qquad \forall \ \ n \in \Omega \tag{2.4}$$

$$P_{nm} \geq 0 \qquad \forall \ \ (n{,}m) \in (\Omega_c{,}\omega_n) \tag{2.5}$$

$$P_{nm} \leq 0 \qquad \forall \ (n,m) \in (\Omega_p,\omega_n) \tag{2.6}$$

As stated previously, the objective of this model is focused on maximizing the income from transactions, all the while ensuring that energy supply to the loads is maintained. Although this is a simplified version of the model encompassing transactions between 4 peers, it has been proven that it can also be applied to larger scale systems (BARBOSA; DIAS; SOARES, 2020), as well as incorporate peer preferences (MORET; PINSON, 2018) or network constraints (BOTELHO *et al.*, 2021b).

2.2 COMMUNITY ORIENTED MARKET MODEL

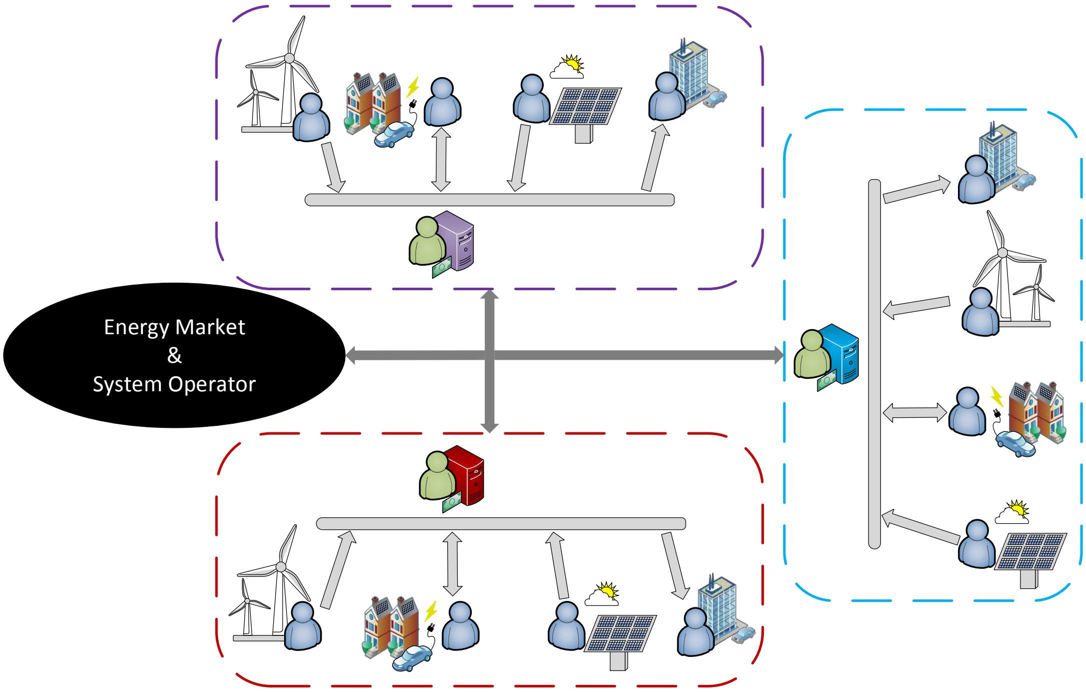
The Community Oriented Market (CM) model is organized as a structure in which all peers participating in the market are allowed to trade only within the community where they are located. This means prosumers taking part in this market as agents can define their trading partners, the amount of energy in each transaction and corresponding costs but only within the community's bounds.

Differently from P2P, in the CM it can be said that each peer's trade freedom extends only to the frontiers of their community. This means that an alignment of interests, commitment and objective between peers during establishing stages of the community becomes a cornerstone for its success as an enterprise. Furthermore, another difference between models is related to the community manager, represented in Figures 4 and 5 as the agent in green. As the entity responsible for supervising trades and organizing the community, a manager plays the fundamental role of ensuring the energetic balance of the community, deliberating on conflicts or dissensions and determining parameters for energy transactions.

Based on the premise that all peers are allowed to trade energy within the community, it is possible to imagine that market members are presented with a reduced and less diverse list of trade partners in comparison to P2P. Additionally, community managers are also supposed to seek out trade partners either in the traditional grid or with other managers to reach the best energy outcome for his/her community. In order to illustrate this possibility, Figure 4 shows an example of the possible transactions each market peer and community manager would be faced with.

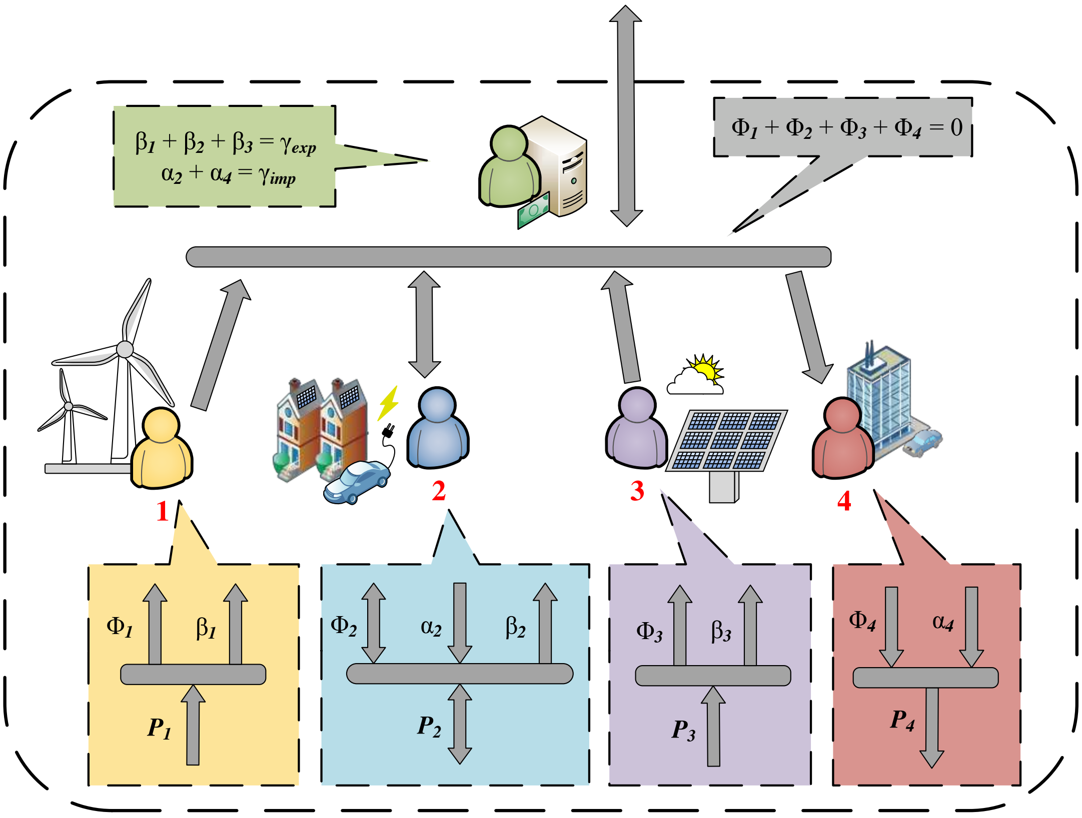
In a similar fashion to the example shown for the P2P, Figure 5 is a graphical representation of a small scale community with 4 peers and a manager. The possible trade partners and resulting transactions are represented by the gray arrows. More specifically, this representation allows the creation of a mathematical model capable of optimizing negotiations in the system given each peers costs and energy prices. Although similarities between models are remarkable, some differences must be considered during optimization.

Figure 4 – Graphical representation of transactions in Community Oriented Market.



Source: Adapted from (BARBOSA, 2021).

Figure 5 – Example on the transaction variables of a Community Oriented Market.



Source: Adapted from (BARBOSA, 2021).

To bring about the optimal energy trades, one can determine maximum economical returns – also called social welfare – as objective for the whole process. Therefore, in addition to the terms used for the social welfare calculations of a P2P market, it can also be seen from equation (2.7) that energy importation and exportation must also be accounted in the CM model.

The first constraint, equation (2.8), also known as the balance constraint, binds variables determining the sum of trades made by a peer as zero. By doing this, the optimization model ensures the amount each peer bought or sold is delivered in its entirety.

Following this, equation (2.9) incorporates each peers limitations to energy production or consumption as lower and upper bounds to the trade variables.

Additionally, equation (2.10) determines the energetic balance of a community – meaning that the amount of energy sold within the community equals the amount that is bought. Meanwhile, equation (2.11) and equation (2.12) ensure that the sum of all individual energy importation or exportation equals the amount imported or exported by the community.

Finally, for the sake of mathematical precision, equation (2.13) determines all consumer trades as positive and equation (2.14) determines all producer trades as negative. The reader should bear in mind this convention for following chapters.

$$\max_{D} \sum_{n\in\Omega} \frac{a_n}{2} \cdot P_n^2 + b_n \cdot P_n + \gamma_{exp} \cdot C_{exp} - \gamma_{imp} \cdot C_{imp} \tag{2.7}$$

subject to:

$$P_n + \Phi n + \beta_n - \alpha_n = 0 \quad \forall \ n \in \Omega \tag{2.8}$$

$$\underline{P_n} \leq P_n \leq \overline{P_n} \quad \forall \ n \in \Omega \tag{2.9}$$

$$\sum_{n\in\Omega} \Phi_n = 0 \tag{2.10}$$

$$\sum_{n\in\Omega_c} \alpha_n = \gamma_{imp} \tag{2.11}$$

$$\sum_{n\in\Omega_p} \beta_n = \gamma_{exp} \tag{2.12}$$

$$P_n \geq 0 \qquad \forall \ n \in \Omega_c \tag{2.13}$$

$$P_n \leq 0 \qquad \forall \ n \in \Omega_p \tag{2.14}$$

As previously mentioned, the objective of this model is focused on maximizing the income from transactions, all the while ensuring that energy supply to the loads is maintained. This is a simplified version of the model encompassing transactions related to 4 peers and a manager in a single community. However, it has been proven that the model can also be applied to larger scale systems (BARBOSA; DIAS; SOARES, 2020) as well as incorporate peer preferences (MORET; PINSON, 2018) or network constraints (BOTELHO *et al.*, 2021b).

2.3 BATTERY MODELING

Another expansion, most relevant to this study, that one can make to the optimization model is by adding variables and constraints to emulate the behavior of batteries as market agents. In that regard, Guedes *et al.* (2022) provides a set of equations for this exact purpose.

To that end, it is first necessary to present battery parameters commonly used by the optimization to determine the variables associated to battery agents. These parameters, related to the electrical properties of the standard equipment connected to the network, are determined by each battery manufacturer and are direct indicators of how each agent can behave in the community. An example of these parameters can be found in Table 1.

Table 1 – Standard Battery Unit Parameters.

UNITS	**POWER [kW]**	**CAPACITY [kWh]**	**SoC % [Max, Min, Init]**	**EFF % [Ch, Dis]**	**RATE % [Ch, Dis, Autodis]**
1	2.56	10.24	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72e-05

Upon closer inspection the reader may see that all values exposed in the table correspond to a single battery unit or module. However, in certain circumstances, an individual battery agent may be comprised of more modules and, consequently, its properties are amplified accordingly.

Other parameters such as module power are important when considering an agent's trade limitations. Furthermore, once involved into sequential and time constrained simulations, power and capacity parameters become intricately intertwined. Along these lines, the State of Charge (SoC) values are also fundamental to constraints when dealing with sequential simulations. It is through this parameter that one hour results are woven as the entry data for the next hour's simulation.

In a similar fashion, the rates of charge, discharge and autodischarge (RATE) parameters are responsible for constraining the maximum input or output of the equipment in a single time step simulation. Finally the efficiency parameter (EFF) determines how the amount of energy delivered or drained by a battery agent is affected during trades.

Having presented the necessary parameters, a battery behavior can be reproduced in the mathematical model by the following equations:

- An additional term to the objective function, as highlighted in equation (2.15), to incorporate a battery agent's energy trade income.

$$\underset{D}{max} \sum_{n \in \Omega} \frac{a_n}{2} \cdot P_n^2 + b_n \cdot P_n + \mathbf{CB_n} \cdot \mathbf{S_n} + \gamma_{exp} \cdot C_{exp} - \gamma_{imp} \cdot C_{imp} \tag{2.15}$$

- An additional variable to the balance constraint, as highlighted in equation (2.16), to ensure that battery agents input or output of energy is in accordance to the amount traded.

$$P_n + \mathbf{S_n} + \Phi n + \beta_n - \alpha_n = 0 \quad \forall \ n \in \Omega \tag{2.16}$$

- A constraint responsible for the calculations of an agent's State of Charge at the end of an optimization run. As shown in equation (2.17), the constraint is reliant on values of a previous State of Charge and binds results to a specific time-step during sequential simulation.

$$\mathrm{SoC}_n^t = \mathrm{SoC}_n^{(t-1)} \cdot (1 - \lambda_{sd}) + \frac{S_n}{cap_n} \tag{2.17}$$

- Additional constraints for the maximum and minimum amounts of energy a battery peer can trade during a single run, shown in equations (2.18) and (2.19), respectively. The constraints must consider SoC, efficiency and capacity limitations.

$$S_n \cdot \eta_{cha} \leq (\overline{\mathrm{SoC}}_n - \mathrm{SoC}_n) \cdot cap_n \tag{2.18}$$

$$-S_n \cdot \eta_{dis} \geq (\mathrm{SoC}_n - \underline{\mathrm{SoC}_n}) \cdot cap_n \tag{2.19}$$

- Final constraints on the amount of energy an individual peer may inject into or drain from the system.

$$S_n \leq \lambda_{cha} \cdot cap_n \tag{2.20}$$

$$-S_n \geq \lambda_{dis} \cdot cap_n \tag{2.21}$$

As it happens, this work aims to address issues by installing batteries in specific points of the distribution network and comparing results for the system with and without such resources. With the proper adjustments, one can take an existing consumer-centric market optimization model and update it to incorporate batteries. This procedure shall be explained in the following chapter.

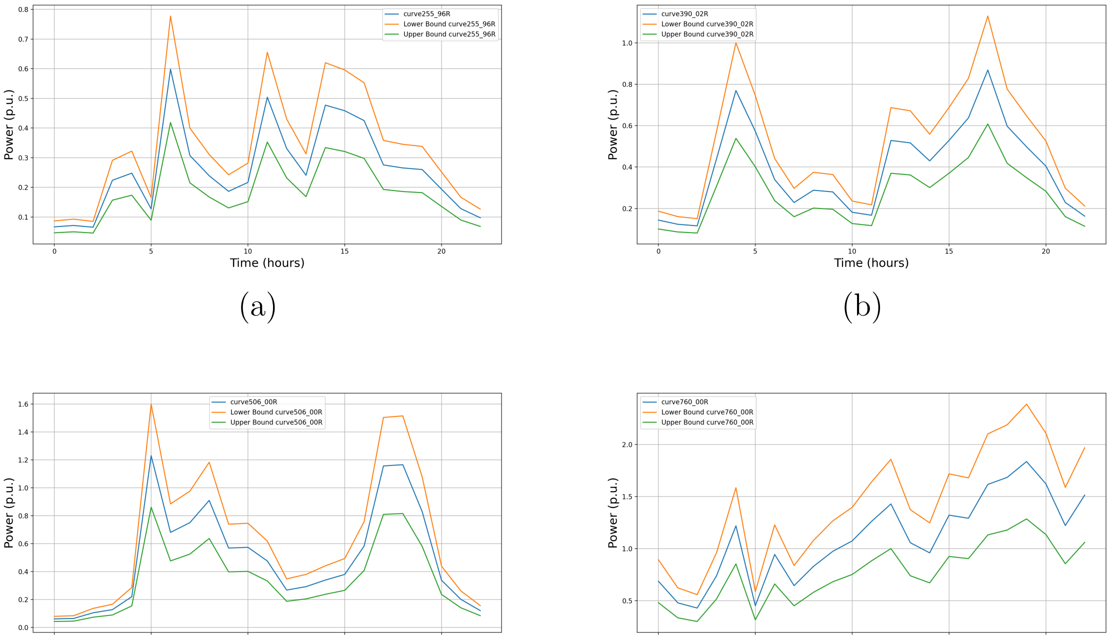
2.4 AGENT MODELING AND DISTRIBUTION NETWORK

Giving sequence to the idea of analyzing sequential market optimizations, it is also possible to surmise that a prosumer's behavior is influenced by energy resources demand and availability at set periods of time. That is to say, for instance, no amount of solar energy can be generated at night using current technology.

As ludicrous as such an example statement is, the same "time constraints" principles can be applied to other, similar situations. In order to integrate this conditions to the optimization models, a sequential market can make use of agent profile curves. These curves are, in essence, a measurement of an agent's energetic behavior, be it a consumer or a producer, in a certain period of time.

To demonstrate how a consumer agent can have its energy demand modeled over an interested time frame, Figure 6 shows some of the loadshape profile curves (in blue) used in this work. The reader may also notice additional curves in orange and green. The former determines a consumer maximum energy consumption while the latter indicates the minimum energy consumption bound. This implies a flexibility that is expected from loads when consuming energy.

Figure 6 – Examples of different loadshape profile curves for energy consumers.



(a) (b)

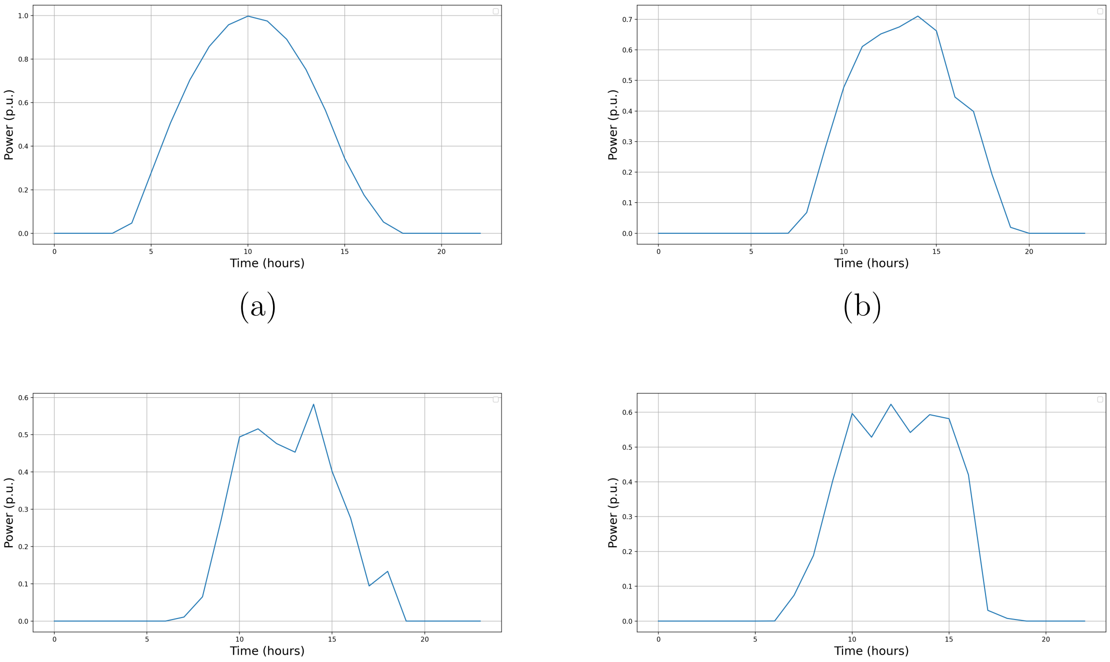
(c) (d)

Caption: Four different loadshape curves and their respective lower and upper bounds: (a) curve255_96R; (b) curve390_02R; (c) curve506_00R; (d) curve760_00R.

Source: Elaborated by author (2023).

Similarly to the LOADSHAPE profile curves, GENSHAPE determine the behavior of energy producers. It can be seen by inspecting Figure 7 that generators also have to abide by certain limitations. In this specific case, solar generators are bound by the irradiance absorbed by their panels.

Figure 7 – Examples of different genshape profile curves for energy producers.



(a) (b)

(c) (d)

Caption: Four different genshape curves: (a) PVprofile ; (b) GENSHAPE01; (c) GENSHAPE02; (d) GENSHAPE03.

Source: Elaborated by author (2023).

The simulations gain relevance by interlinking results of a single frame with those before and afterwards, every time this method is used. Therefore, this technique grants a sense of continuity to the whole process of sequential market simulations.

Afterwards, once a market model has been optimized, the peers and community managers need to verify if their choices on trades are detrimental to operating the electricity grid. More specifically, as mentioned in the previously, bus voltage and line thermal capacity violations are commonplace occurrences in distribution networks.

In light of such concerns, following the market optimization one would have to run power flows to determine whether a community or a specific set of peers are responsible for any particular network violation. Once done, results would have to be analyzed and meet the convened standard of a certain region. Were these standards not to be met, measures must be taken to ensure that whatever problems the transactions are causing can be lessened or entirely averted.

In that regard, this work establishes the network operating bounds in accordance to the equations shown in equations (2.22) and (2.23). Those parameters presented in the equations can be adjusted to a specific system or region.

$$0.95\ p.u.\ \leq\ V_k\ \leq\ 1.05\ p.u. \quad \forall\ k \in \Omega_k \tag{2.22}$$

$$LineCurrent_j\ \leq\ LineThermalCapacity_j\ \% \quad \forall\ j \in \Omega_L \tag{2.23}$$

To further explore the integration of consumer-centric markets into a distribution network, this work uses a dataset based on the physical infrastructure of a neighborhood in Costa Rica. This data has been shared by Bitencourt *et al.* (2021), in which a network was simulated during a study on optimal placement of Electric Vehicles (EV) charging stations in a neighborhood. The same network is described in Chapter 3 and was used for the Case Study simulations.

This chapter presented an overview of the main consumer-centric market models addressed in literature, namely the Full Peer-to-Peer and the Community Oriented Market. The chapter also presents additional equations, which can be coupled to the model, that enable the implementation of batteries' behavior in the market they are located. Accompanying the consumer-centric models description, the chapter also presents a strategy commonly used to model agents energy generation and consumption in time constrained market optimization and power flow simulations. The next chapter shall present more details on the specific methodology used in this work and the case studies created to evaluate if the strategy proposed is effective.

3 COMPLETE MODEL: METHODOLOGY AND CASE STUDIES

This chapter presents the methodology and Case Studies used in this work. It starts by describing the complete model, as it can be seen in Figure 8. Afterwards, the Case Studies simulated in this research are briefly introduced.

3.1 COMPLETE MODEL

In view of the optimization models presented thus far, market and network operation can be joined into a harmonious process. Furthermore, whenever one starts to affect the other negatively, this works proposes the use of batteries to amend the situation.

As seen in the previous section, a consumer-centric would be able to operate in a distribution network by obeying a set of rules and ensuring certain standards. Whenever these standards are not observed and violations occur, the community must update the amount of modules a battery agent is entitled to for the sake of determining if a greater peer energy capacity is capable of solving network violations.

That being the case, this study applied the framework shown by the flowchart of Figure 8 to determine if battery agents installation can be beneficial to the system. The entire process can be described as a series of stages that need to be simulated for each time step.

The first stage, which is the simulation initialization, is concerned with importing market agents and the distribution network data sets. Once their data has been properly processed, it is sent to the market optimization problem.

The second stage focuses in hourly simulations of market optimization given the energy resources available at each time step. The model used for each hourly run of the optimization process can be described by Equations (3.1) to (3.15). It should be mentioned that changes must be made to the model depending on the amount of communities simulated or the time steps used for the optimization.

$$\underset{D}{max} \sum_{n \in \Omega} \frac{a_n}{2} \cdot P_n^2 + b_n \cdot P_n + CB_n \cdot S_n + \gamma_{exp} \cdot C_{exp} - \gamma_{imp} \cdot C_{imp} \tag{3.1}$$

subject to:

$$P_n + S_n + \Phi n + \beta_n - \alpha_n = 0 \quad \forall \;\; n \in \Omega \tag{3.2}$$

$$\underline{P_n} \leq P_n \leq \overline{P_n} \quad \forall \;\; n \in \Omega \tag{3.3}$$

$$\sum_{n \in \Omega} \Phi_n = 0 \tag{3.4}$$

$$\sum_{n\in\Omega_c} \alpha_n = \gamma_{imp} \tag{3.5}$$

$$\sum_{n\in\Omega_p} \beta_n = \gamma_{exp} \tag{3.6}$$

$$\mathrm{SoC}_n^t = \mathrm{SoC}_n^{(t-1)} \cdot (1-\lambda_{sd}) + \frac{S_n}{cap_n} \tag{3.7}$$

$$S_n \cdot \eta_{cha} \leq (\overline{\mathrm{SoC}}_n - \mathrm{SoC}_n) \cdot cap_n \tag{3.8}$$

$$-S_n \cdot \eta_{dis} \geq (\mathrm{SoC}_n - \underline{\mathrm{SoC}_n}) \cdot cap_n \tag{3.9}$$

$$S_n \leq \lambda_{cha} \cdot cap_n \tag{3.10}$$

$$-S_n \geq \lambda_{dis} \cdot cap_n \tag{3.11}$$

$$P_n \geq 0 \qquad \forall \;\; n \in \Omega_c \tag{3.12}$$

$$P_n \leq 0 \qquad \forall \;\; n \in \Omega_p \tag{3.13}$$

$$\alpha_n, \;\; \beta_n \geq 0 \qquad \forall \;\; n \in \Omega \tag{3.14}$$

$$P_n, \;\; S_n, \;\; \Phi_n \quad free \qquad \forall \;\; n \in \Omega \tag{3.15}$$

The third stage prioritizes the update of each agent's profile curves based on the hourly market optimization results. It is important to say that, although this work used hourly simulations, the model is capable of running with smaller or larger time steps.

Once the profile curves have been properly updated, their data is imported by the power flow simulation in stage four. These profile curves are used to determine each loads energy intake and generators energy output during the entire time of interest. The power flow in this stage can be calculated using a variety of methods available in literature. During the development of this specific research, this stage simulates three-phase power flows using the software `OpenDSS`. According to its documentation, the software uses a current injection method to solve its power flows (DUGAN, 2016). It has been shown in literature that this solution method enables the use of flexible load models, which are highly relevant in analysis of energy efficiency studies. Furthermore, it is a method capable of assisting the analysis of balanced and unbalanced systems, regardless of the network structure, existing controls or distributed generation, and is proven as efficient and robust in large scale systems simulations (PENIDO *et al.*, 2008).

Once this stage simulations are through, results of bus voltage and line current are obtained. Afterwards, stage five analyses if any bus or line experienced violations during the simulation time. For this specific distribution network, the operational constraints are determined by Equations (3.16) and (3.17).

$$0.95\,p.u. \;\leq\; V_k \;\leq\; 1.05\,p.u. \quad \forall \;\; k \in \Omega_k \tag{3.16}$$

$$LineCurrent_j \;\leq\; 100\% \quad \forall \;\; j \in \Omega_L \tag{3.17}$$

If the system experienced any violations, batteries are added to relevant buses or lines in stage six and the iterative process restarts. Otherwise, market optimization and power flow results are outputted in a report in stage seven. The following section puts this framework in action during Case Study simulations.

3.2 CASE STUDIES

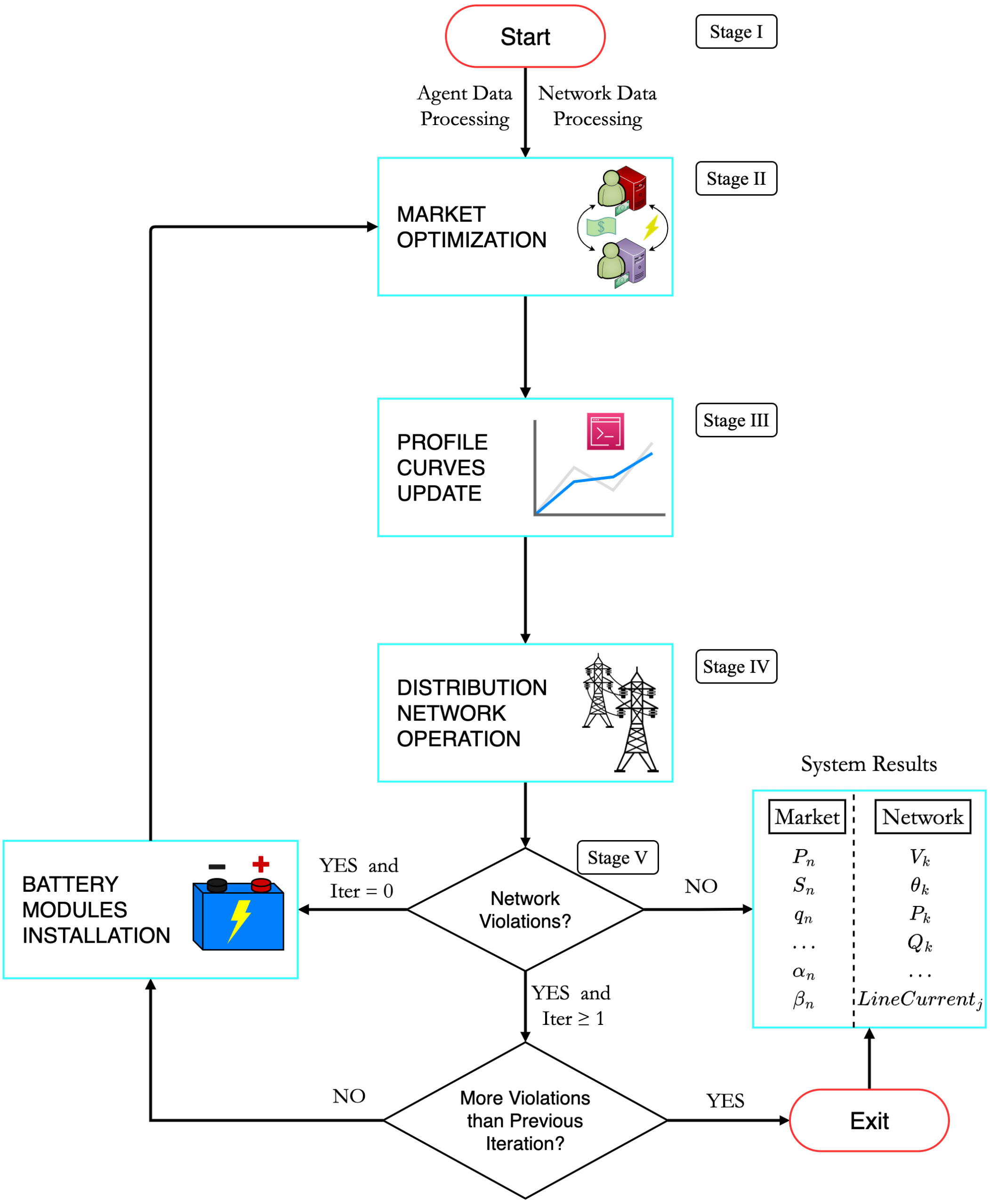
In order to validate the model described in the previous chapter, this work focused on reproducing a realistic distribution system network with hourly simulations of energy market negotiations and grid dispatch.

The entire process has been simulated using the `Python` programming language in conjunction with `OpenDSS` software. These tools were chosen owing to the fact that both are currently open-source and amply adopted by scientific studies in similar fields and some electricity utilities (BITENCOURT *et al.*, 2021). This, in turn, contributes to the reproducibility of this study for different scenarios and contexts, as well as increases its auditability by other professionals and researchers working on this field. Furthermore, it can be said that the `Python` programming language was fundamental to the development of this research given the vast documentation material available on the many existing libraries. Among the several packages used in the development of this research, the most notable ones were *numpy*, *pandas*, *pandapower* and *pydss-interface*.

Each Case Study presented in this chapter will simulate the entire iterative process of Figure 8 using a `Python` based algorithm. To do so, the Case Study simulations first have to import relevant information about market agents and the distribution network related to the energy community, or communities, of interest. An example of the information about the agents data used during simulations can be found in Tables 18 through 24 in Appendix A.

The agent's data shown in Table 2 illustrates which agents are observed during each Case Study simulation. This means that each Case Study has its own sets of agents –

Figure 8 – Flowchart of the iterative simulation process.



Source: Elaborated by author (2023).

which can be represented in similar tables – and focuses on the optimization of the data given to the mathematical model.

In Table 2, the second column shows what communities are simulated in each Case Study. In addition column three shows the consumer agent names while column four shows the producer agent names used in Case Study simulation.

Another relevant comment about the simulations is that Case Studies A, B and C, shown in Table 2, proved unrealistic and unnecessary to formulating the conclusions presented in this work. Due to the scant amount of prosumers in these individual cases and the oversizing of their local distribution network, very few observations could be made.

More importantly, none of the findings were exclusive to the referred cases and, in fact, such findings were far more pronounced and easily observed in other cases. That being said, all three initial Case Studies were discarded and their prosumers were taken to enrich the systemic view of the network shown in Case Studies 03 and 04.

As a sequence of Table 2, in Table 3 it is possible to see an overview of each Case Study discussed in this chapter. Besides the number of network violations observed in each simulation, the table also presents information on the amount of standard battery units connected, at the final iteration of Figure 8, to each bus or line that experienced violations. One interesting observation is that Case Studies 02 and 04 use different amounts of batteries modules in the last iteration of the simulation process. This happens due to the recurring violations in some of the network's buses or lines. The different amounts of battery modules used in each Case Study results will be discussed further on.

The next Section will briefly describe the standard battery unit used in this work and how it affects each Case Study.

Table 2 – Agent simulated by Case Study.

Case Study	**Community Analyzed**	**Consumer Agents**	**Producer Agents**	**Battery Agents**
A*	1	1FFLX001 ∼ 1FFLX015	PV1FFLX001 ∼ PV1FFLX015	**
B*	2	1FFLX016 ∼ 1FFLX025	PV1FFLX016 ∼ PV1FFLX025	**
C*	3	1FFLX026 ∼ 1FFLX036	PV1FFLX026 ∼ PV1FFLX036	**
01	4	3FFLX037 ∼ 3FFLX052	PV3FFLX037 ∼ PV3FFLX052	**
02	5	1FFLX053 ∼ 1FFLX136	PV1FFLX053 ∼ PV1FFLX136	**
03	1, 2, 3	1FFLX001 ∼ 1FFLX036	PV1FFLX001 ∼ PV1FFLX036	**
04	1, 2, 3, 4, 5	1FFLX001 ∼ 1FFLX136	PV1FFLX001 ∼ PV1FFLX136	**

Caption: * - discarded case studies; ** - verify in each Case Study results.

Table 3 – Case Studies overview.

Case Study	**Number of Communities**	**Base Scenario Violations**	**Stressed Scenario Violations**	**Amount of SBUs at Last Iteration**
A*	1	×	5	10
B*	1	×	2	10
C*	1	×	1	10
01	1	×	6	10
02	1	61	×	1 *and* 5
03	3	×	1	10
04	5	61	×	1 *and* 3

Caption: * - discarded case studies; SBUs - Standard Battery Units.

3.3 STANDARD BATTERY UNIT

The Standard Battery Unit expression used in this work refers to the electrical characteristics of a single battery component connected to the distribution network's buses during simulations. The unit's data can be found in Table 4.

Table 4 – 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

As shown in Section 2.3, battery behavior is simulated by the model, in each case study, according to such parameters. Considering the nature of this work in emulating the connection of a storage unit connected to the distribution network, the values used in the standard battery unit are a representation of parameters commonly found in commercial batteries available in the market. That being said, the parameter values do not represent a specific commercial battery model, only a unit for the sake of simplicity.

Although all battery units are considered identical in the simulations, battery banks are made by an integration of multiple standard units. Therefore, battery agents represented during simulations may have different sizes and energy storage capacities depending on the amount of stackable modules that each agent decides to deploy. In order to illustrate this difference, Table 5 shows different hypothetical battery agents created by employing this strategy. It can be seen that all agents share the same battery data, aside the “Power [kW]” and “Capacity [kWh]” fields which are determined by the amount of modules used.

Table 5 – Battery Bank 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
10	25.6	102.40	0.8	0.2	0.5	0.96	0.96	0.25	0.9375	1.72e-05

3.4 DISTRIBUTION NETWORK

Prior to the description of each individual case study, it is necessary, first and foremost, to define the characteristics of the distribution network used in the simulations. The entire network operates under a set of three line-neutral base voltages:

- 138 kV for the high voltage system;

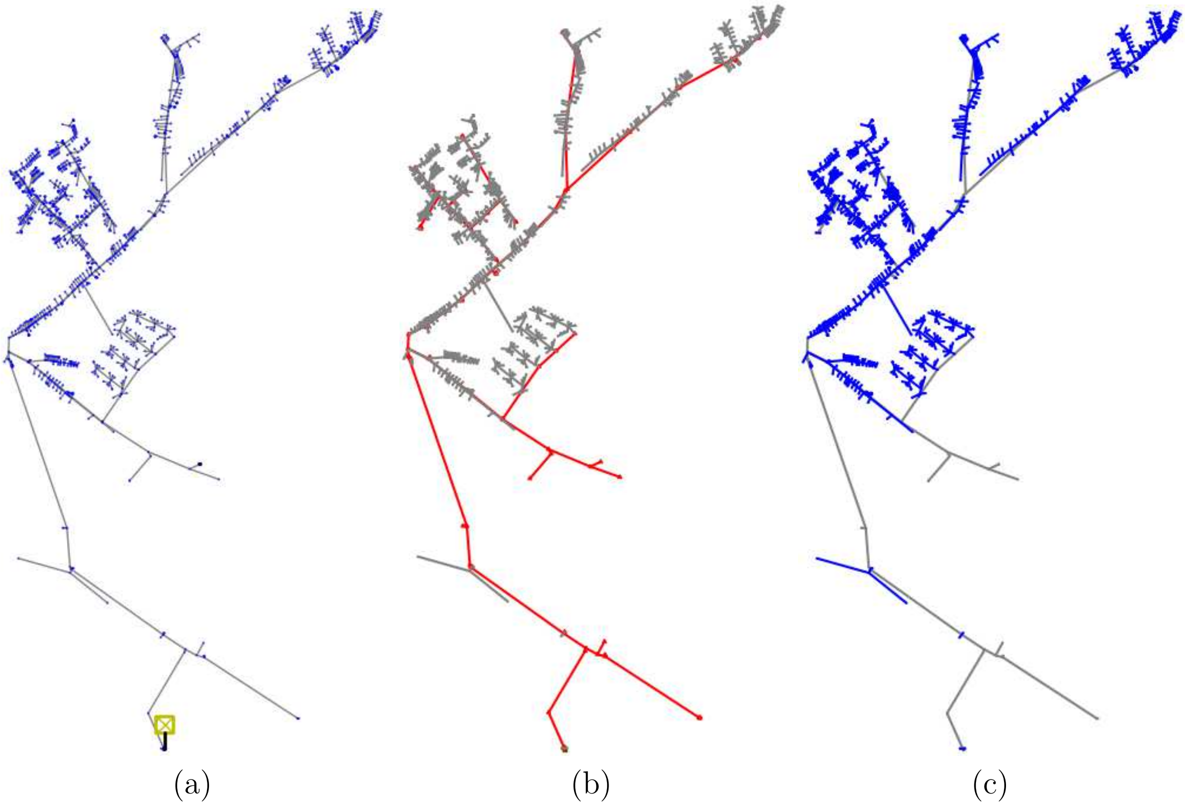
- 19.9 kV for the medium voltage system;
- 120 V for the low voltage system.

In order to highlight the relevant systems operating in accordance to the base voltages described, Figure 9 shows a graphical representation of the realistic distribution network used for the simulations (BITENCOURT *et al.*, 2021).

Upon inspection, Figure 9a shows both the medium and low voltage buses of the system in blue, interconnected by medium and low voltage lines and transformers. The bottom most part of the figure also highlights, using a yellow square, the connection point of the distribution network with the high voltage transmission network.

In order to assist the identification of the medium voltage buses and lines, Figure 9b shows highlights in red. Meanwhile, Figure 9c highlights low voltage buses and lines in blue. It should be pointed out that this color scheme will be used continuously throughout this chapter.

Figure 9 – General depiction of distribution network used during simulations.



(a) (b) (c)

Caption: (a) Overview of distribution network highlighting high voltage connection point (yellow); (b) Highlighting medium voltage buses and lines (red); (c) Highlighting low voltage buses and lines (blue).

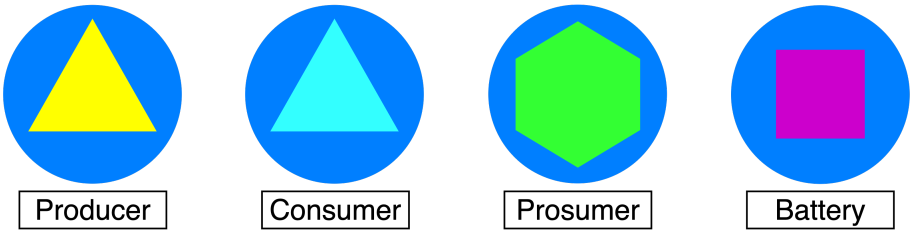
Source: Elaborated by author (2023).

Overall the network analysis was divided in accordance to the operational voltages observed. The grid can be divided into 1526 buses (1 high voltage, 125 medium voltage and 1400 low voltage) or 3274 nodes – depending on the number of phases that each bus possesses – interconnected by 1491 lines (123 medium voltage, 1368 low voltage lines). As a consequence of the grid's dimensions, the sum of line lengths reaches a total of 17554.60 meters worth of cables. Furthermore, the interconnection between different voltage subsystems is complemented by 33 transformers (1 three winding and 32 two wingdings). Finally, the entire network is responsible for feeding 653 loads scattered among the buses (2 commercial, 3 industrial, and the other 648 residential).

As mentioned in Chapter 1, the aim of this study is to evaluate the benefits and consequences of a energy community located in the distribution network, especially in its low voltage buses and lines, since that is the location of most small loads and generators. Therefore, aside the color scheme used in Figure 9, another relevant graphical representation to this study is related to each type of agent existing in the energy community market. The agents relevant to each case study and their respective location in the energy community network will be represented in the map by geometrical symbols in accordance to Figure 10.

On that account, the market participants known as producers, consumers, prosumers and storage units are represented, respectively by a yellow triangle, a cyan triangle, a green hexagon and a purple square. Considering that all agents are connected to low voltage buses, the agent's geometric symbol is inserted inside a blue circle, so to represent their connection point. These graphical representation of market agents will appear in each Case Study maps in the following chapter.

Figure 10 – Graphical representation market agents in the distribution network.



Source: Elaborated by author (2023).

This chapter presented the methodology used during simulations to verify if the strategy proposed is effective in solving network violations. The chapter also describes how the process of sequential market optimization and power flow simulations was applied to seven different Case Studies. It is also demonstrated how each case study is comprised by combinations of different energy consumers and producers. Additionally to the methodology and case studies, this chapter presented the standard battery parameters used during simulations. Finally, the distribution network and its main characteristics, relevant to the power flow simulations, were also presented in this chapter. The next chapter will present detailed information about each Case Studies results.

4 SIMULATIONS RESULTS

This chapter analyses and discusses four Case Studies result obtained from simulations using distribution network data from Costa Rica (BITENCOURT *et al.*, 2021). The network was chosen to this study because it represents a real infrastructure that would enrich and further validate the strategy proposed.

It should be pointed out that all case studies were simulated in a laptop with 3 GHz `Intel Core i7` processor and a 8 Gb RAM memory. As for the simulation times, although varying depending on the Case Study in question, the shortest run took approximately 1 minute while the longest took no more than 3 minutes.

4.1 CASE STUDY 01

Case study 01 focuses on simulating the energy transactions and power flows of a small amount of prosumers located in the same electrical vicinity. The prosumers are connected to low voltage buses which, in turn, are part of a short low voltage branch located at the end of a feeder. The general organization of the agents can be seen in Figures 11 and 21.

This community was chosen as the starting point for the simulations by virtue of the great deal of operational violations that the end terminals of distribution network feeders usually experience. Furthermore, the simulations focus on analyzing the general response of the community market and distribution network to the installation of energy storage devices when in stress conditions. For that reason, it was first necessary to determine how far the community could push its power drain or injection before it would violate the network's operating bounds shown in Section 2.4.

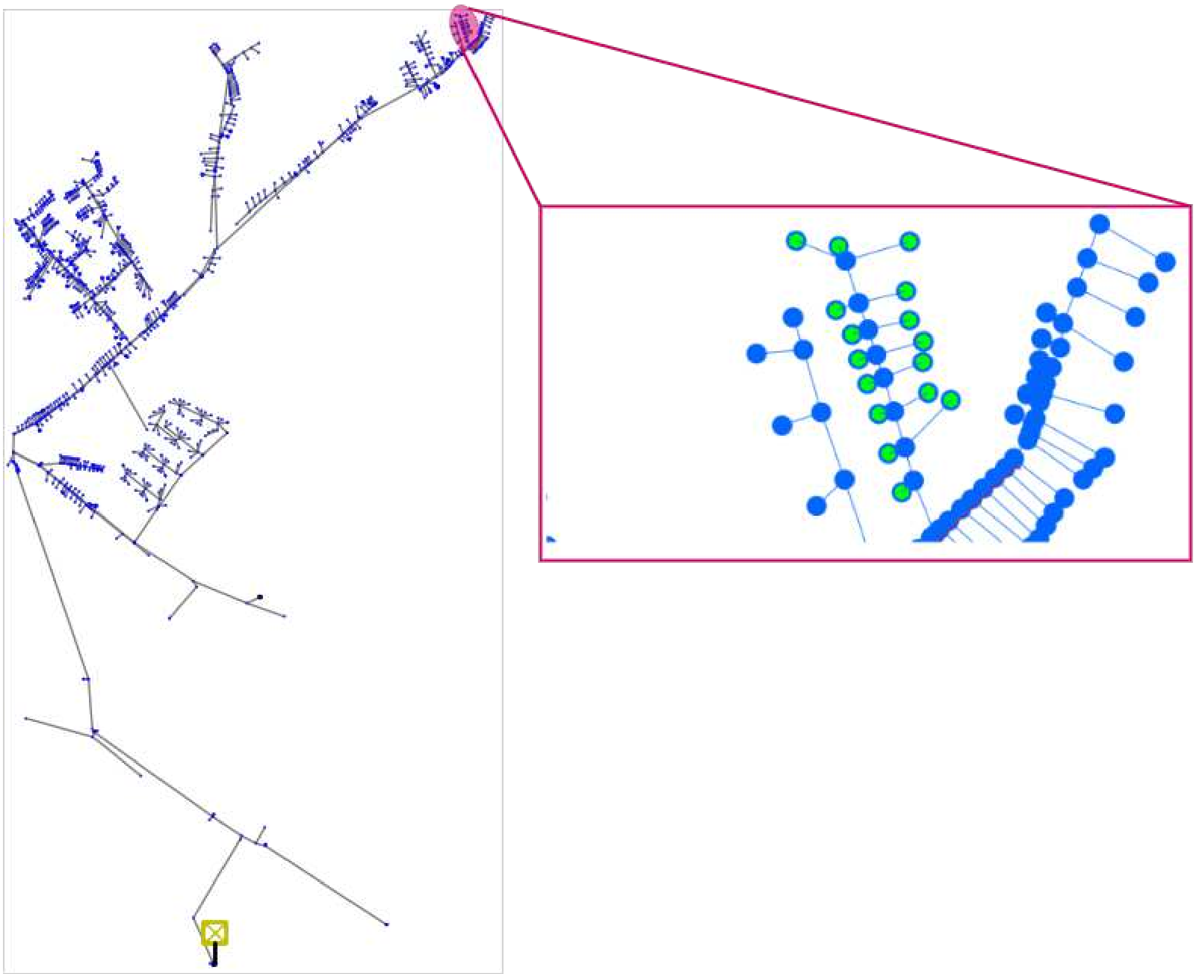
When it comes to the oversizing of distribution networks, as expected as it may be, it was not until the load factor of the prosumers was raised by 2× that the community's power drain started to violate the network's operating bounds. The loading factor went through gradual unitary increments to determine when the network starts to experience violations. It should be pointed out that the 2× loading factor does not imply the real network hosting capacity, but simply indicates a loading factor that causes violations to the network operation. Further observations on the oversized distribution network will be addressed in the next chapter.

Once the system has been pushed to a stressing point, the simulations were rerun with the addition of battery power banks in the buses that presented violations of any sort. The initial concept was to place the battery power banks near the electrical violations and increment the power and energy output by adding standard battery units until the issues were solved. The entire process was arbitrary and future works aim to address the optimal sizing and placement of these resources.

4.1.1 Results - Community Without Storage Units

As it has been previously mentioned, the simulations initially focused on the transactions and power flows without taking into account the existence of storage units scattered through the community. The general location of the prosumers that are part of this community can be seen in Figure 11.

Figure 11 – Graphical representation of Case Study 01 energy community without storage in the distribution network.

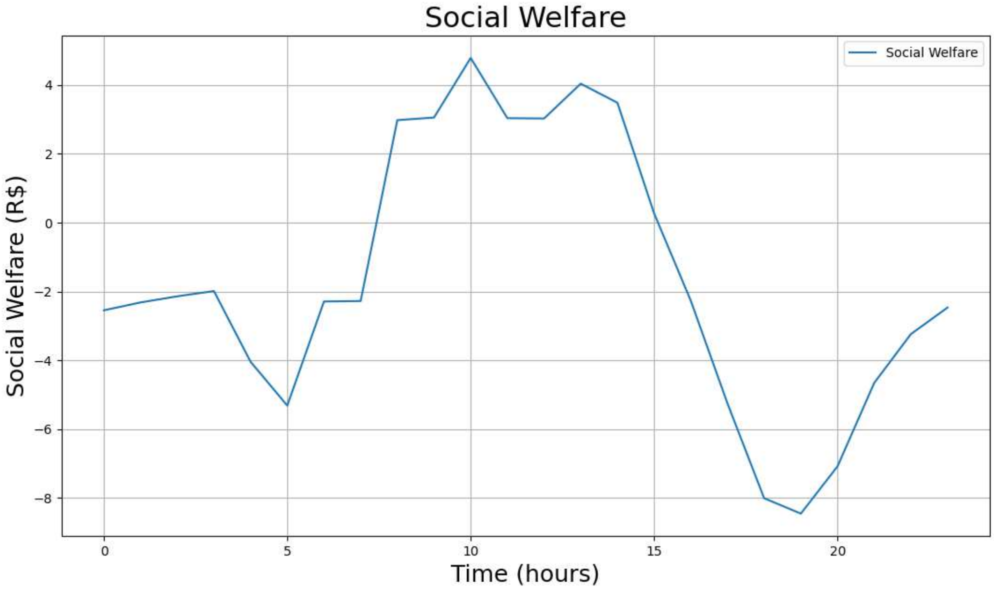


Source: Elaborated by author (2023).

For the sake of presenting how the social welfare of the community as a whole is affected by the energy transactions, Figure 12 shows results for the hourly social welfare gains in the community over the course of one day. As an initial consequence of the stressed scenario shown in the figure, it is possible to observe the negative social welfare during intervals when the loads force the community to import energy from the external grid's markets players. Overall, the more severely energy dependent on external resources the community is, the lower its social welfare will be.

As a result of the optimization, one can notice the behavior of individual loads in Figure 13 and the general behavior of all loads in Figure 14. In this community, the

Figure 12 – Case Study 01 hourly social welfare results for the stressed scenario without batteries.



Source: Elaborated by author (2023).

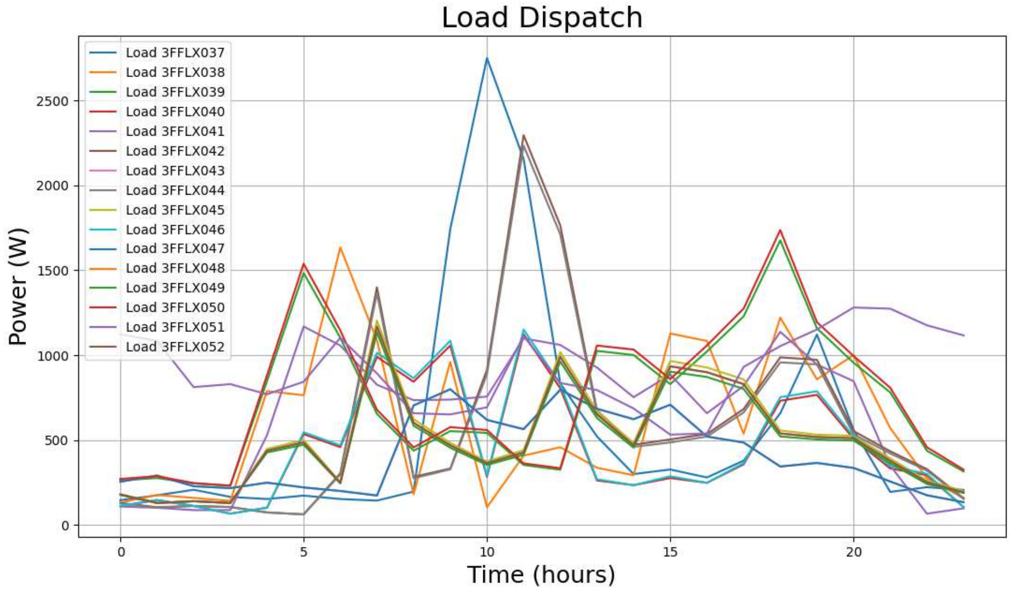
hourly loads dispatch show three peaks for energy consumption in different moments of the day – one in the morning, one in the afternoon and one in the start of the evening. This contributes to the relevance of the study since it enables the analysis of whether the strategy proposed is effective in different moments of power generation and consumption in the day.

The generators, in light of the stressed load conditions which the system has been put into, experience no growth during simulations. Consequently, their base power remains the same throughout the entire process. Their results are shown in Figures 15 and 16.

It also becomes clear by studying the generator dispatch curves that, although their profiles are identical on account of their geographical proximity, they could also experience generation according to different profile curves as described in Section 2.4. The total hourly generation energy dispatch is merely represented as the sum of the hourly individual generators dispatch. It should be pointed out that the graphs show negative values for generation in respect to the convention that generators assume negative values and loads assume positive values for their energy dispatch.

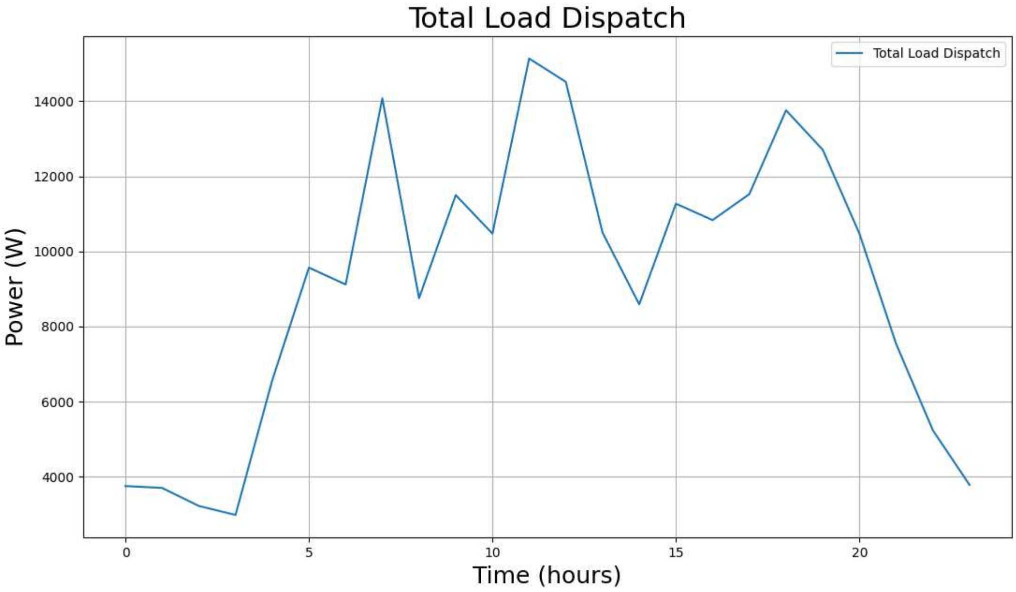
After exposing the dispatch of both loads and generators in greater detail, it is possible to filter the main community curves analyzed for each Case Study in Figures 17, 18 and 19. In that way, Figure 17 gives an overview of the energetic balance of the community. The reader should bear in mind that when negative, the energy balance enables the community to improve its standing and social welfare by exporting excess energy, whereas when positive, the community is forced to import energy so as to supply

Figure 13 – Case Study 01 hourly individual load dispatch results for the stressed scenario without batteries.



Source: Elaborated by author (2023).

Figure 14 – Case Study 01 hourly total load dispatch results for the stressed scenario without batteries.

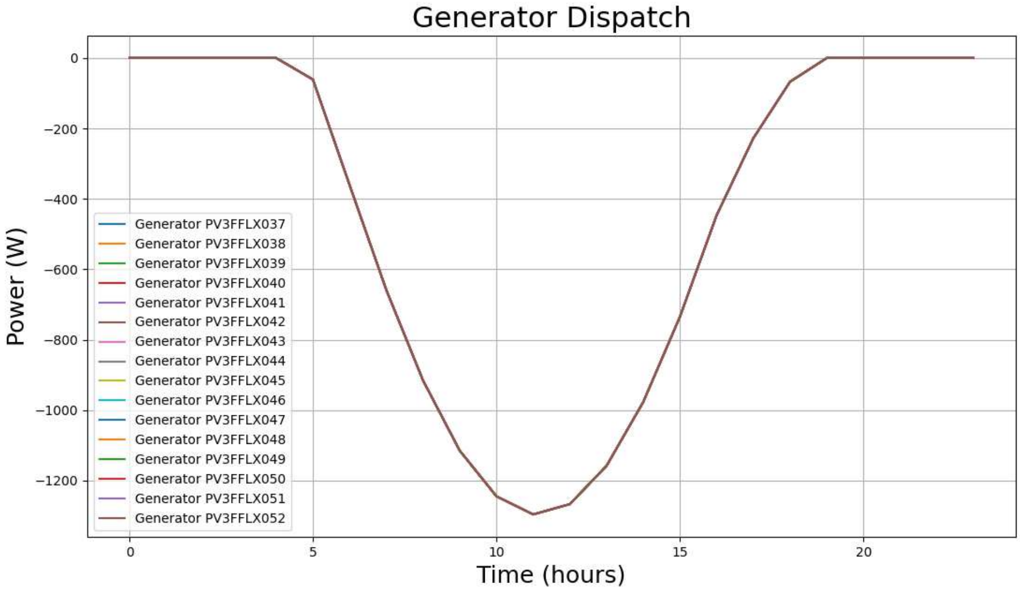


Source: Elaborated by author (2023).

for its inner demand. The figure shows the hourly optimization results of total load dispatch (in red), the total generator dispatch (in yellow), as well as the resulting energy balance (in blue) – obtained from the sum of all available energy resources.

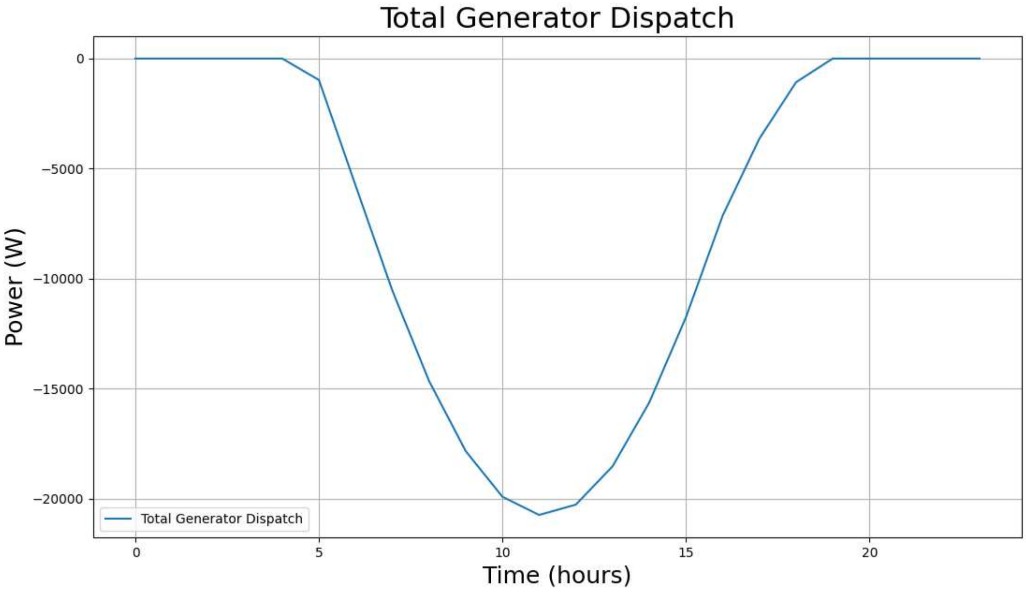
After studying the general dispatch curves provided by the energy market trans-

Figure 15 – Case Study 01 hourly individual generators dispatch results for stressed scenario without batteries.



Source: Elaborated by author (2023).

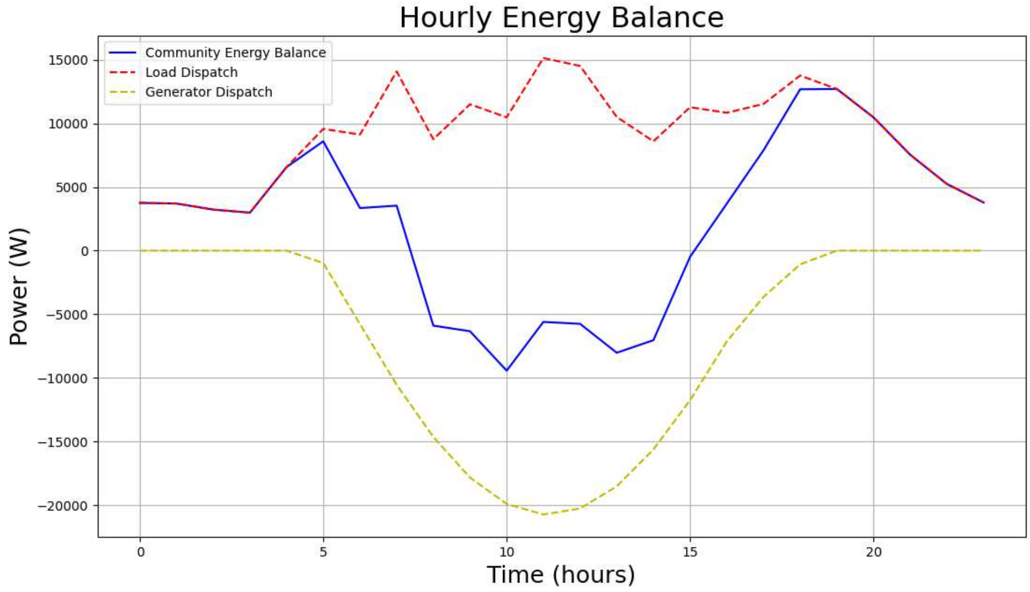
Figure 16 – Case Study 01 hourly total generator dispatch results for stressed scenario without batteries.



Source: Elaborated by author (2023).

actions, the community manager or the system operator have to take into account the repercussions that trades made by the market players have over the network in which they are connected. In that regard, Figure 18 shows an analysis of the community's line loadings whilst Figure 19 shows the hourly results for the community's bus voltages for

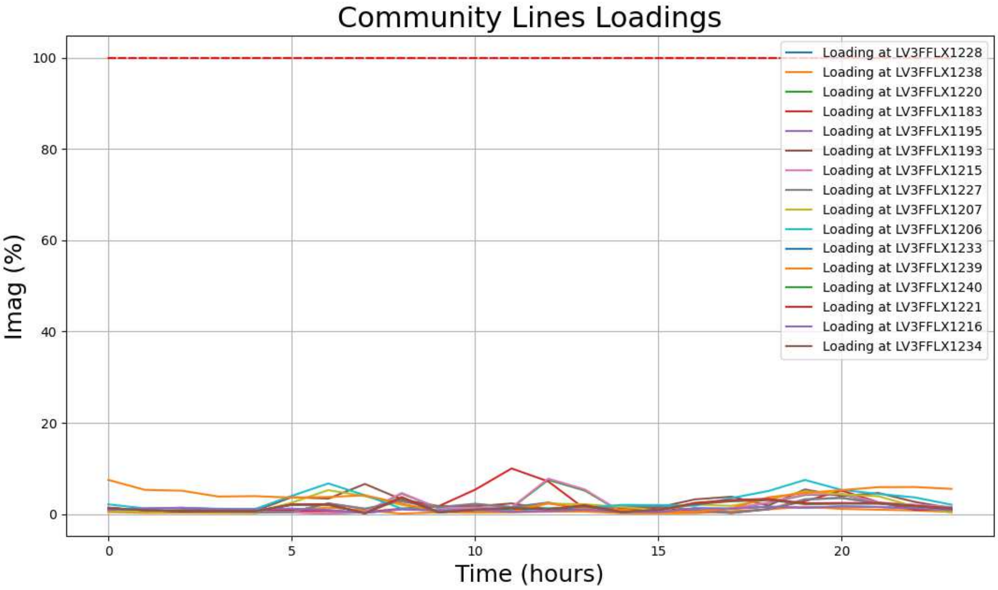
Figure 17 – Case Study 01 hourly community's energy dispatch results for stressed scenario without batteries.



Source: Elaborated by author (2023).

the stressed scenario.

Figure 18 – Case Study 01 hourly line loading results for stressed scenario without batteries.



Source: Elaborated by author (2023).

On the one hand, it is possible to see that in this case study there have been no violations to the system's line loadings, even though it is forced to operate under stressed conditions. On the other hand, it is precisely due to the stressed conditions in which

Figure 19 – Case Study 01 hourly bus voltage results for stressed scenario without batteries.

Source: Elaborated by author (2023).

the network was forced to operate that some of the buses hosting community agents experienced under voltage violations during peak energy consumption hours. These buses and their respective voltages are shown in Figure 20. It is these operating violations that the battery power banks installation will aim to address in the Subsection 4.1.2.

Figure 20 – Case Study 01 bus voltages violations for the stressed scenario without batteries.

Source: Elaborated by author (2023).

Analyzing the figures shown so far, one can draw a summary of the violations experienced by the community's distribution network during the entire simulation period. Such summary is presented in Table 6, and specifies the type of operational violation, the location of this violation as well as the hour of occurrence. It should be pointed out that, although the network may experience other violations throughout its other buses and lines, the violation summary focuses solely on those experienced by the generators and loads which are part of the consumer-centric market simulated. This happens since it would be the main concern of the community to solve whatever problems may arise in its immediate vicinity due to the energy trade activity, as it is the scope of this work.

Table 6 – Violations summary of Case Study 01 without batteries.

N°	Violation Type	Location	Hour
1	Under Voltage	BUSLVFLX1264	19
2	Under Voltage	BUSLVFLX1270	19
3	Under Voltage	BUSLVFLX1271	19
4	Under Voltage	BUSLVFLX1272	19
5	Under Voltage	BUSLVFLX1271	20
6	Under Voltage	BUSLVFLX1272	20

4.1.2 Results - Community With Storage Units

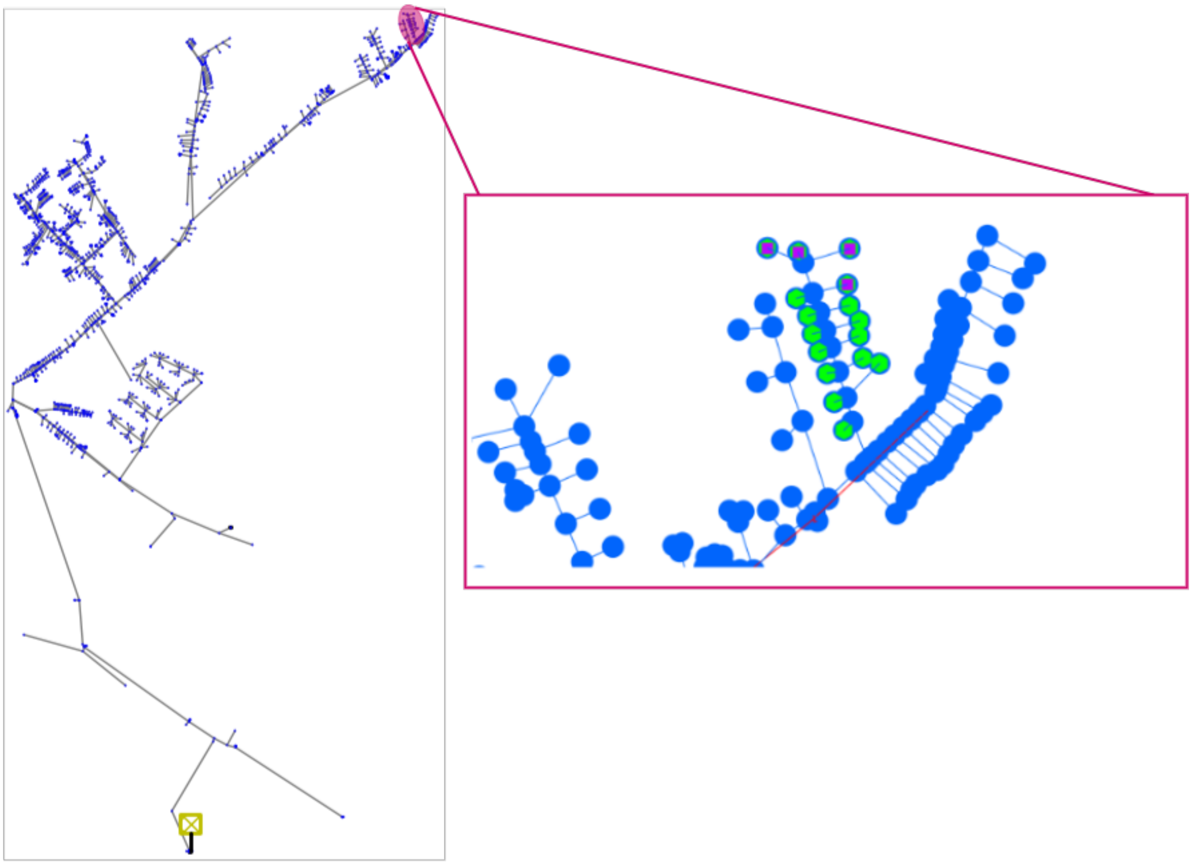
As stated previously, once the network violations were determined in the stressed scenario, battery agents were connected to the network in accordance to the scheme shown in Figure 21. In this specific case study, batteries were connected to the four buses with voltage violations. Resuming the simulations with simple batteries placed in these buses, the optimization results enables one to draw new figures in order to measure the effect that the storage technologies have over the energy market and the distribution network.

Considering the strategy employed, the initial integration of battery resources to the system proved insufficient to solve the issues that arise from the stressed operation scenario. That being the case, the entire chain of steps presented in Figure 8 restarts while entering into the loop so as to update the amount of battery modules added to each bus that presents violations.

It can be seen from Table 3 the successive addition of battery modules was incapable of solving the issues at hand. Therefore, simulations stopped once the battery bank reached the maximum value of 10 modules.

Assuming that the readers are able to glean at the total generator dispatch and total load dispatch curves from the "Energy Balance" figure, the graphs presented from here on are focused entirely on the simulated system social welfare, energy balance, battery integration consequences and violations reports. Furthermore, the results shown in the

Figure 21 – Graphical representation of Case Study 01 energy community with storage in the distribution network.



Source: Elaborated by author (2023).

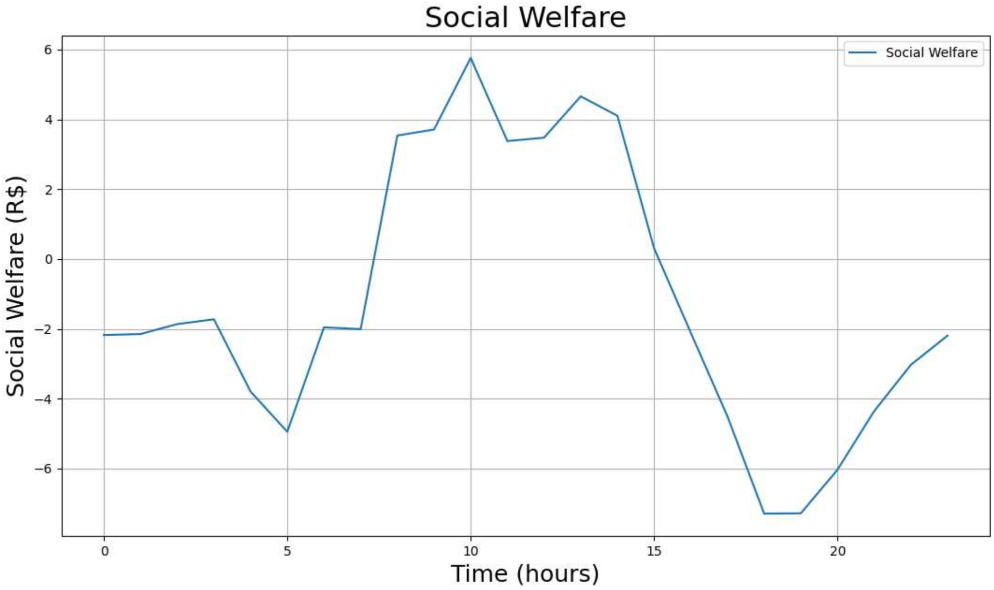
following figures will present a step by step analysis of the battery activity in the system in order to expedite the presentation of results in next Case Studies.

First, once the iterative process is finished, it is possible to study the effects of the battery integration to the social welfare of the system. That being the case, the hourly social welfare optimization results are shown in Figure 22. Although the curve “profile” shown in the figure is similar to the one shown in Figure 12, one can identify differences related to the scale of the image, as a consequence of the economical gains expected from the participation of batteries in the market.

A complete comparative presentation of the social welfare results at the end of each simulated iteration is shown further on.

Following the economical analysis of the integration of battery resources, the reader may see in Figure 23 the system’s energy balance optimization results for the last run of the iterative process, corresponding a battery bank comprised of 10 modules. In this figure the reader will be able to identify the total generator dispatch (in yellow), the total load dispatch (in red), the total battery dispatch (in green) and, finally, the sum of all hourly dispatches (in blue).

Figure 22 – Case Study 01 hourly community's social welfare results for stressed scenario with batteries.



Source: Elaborated by author (2023).

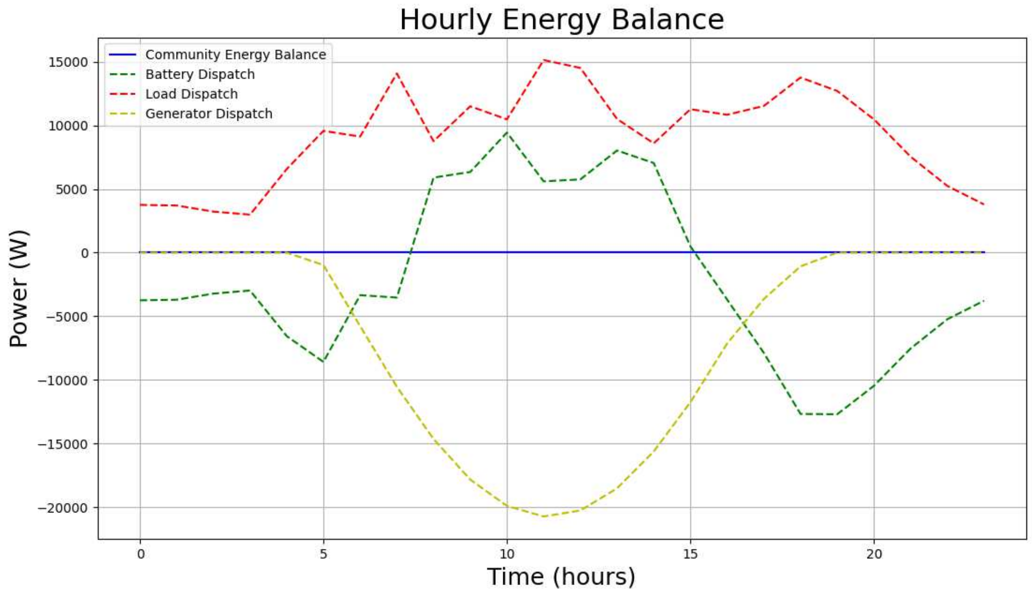
As a consequence to the integration of the maximum amount of battery modules, the community is able to maintain its energy balance (in blue) as zero during the entire simulation period. In practice, this means that while the community once had to import or export energy in certain intervals, as shown in Figure 17, now it could store its surplus energy generation or supply its increased energy consumption using batteries.

Once the energy balance has been thoroughly explored, it is possible to verify the batteries state of charge during the entire simulation period in Figure 24. By careful inspection of the figure it should be clear that, given the size of the battery banks, the energy drained to and from the modules is far from enough to push each battery to its charge threshold.

However, after examining the energy balance and the battery state of charge in greater detail, it can be seen that one reflects the decisions of the other. That is, the energy contributions each battery agent makes to the community's market directly affects its state of charge in proportion to the size of the contribution, and vice-versa.

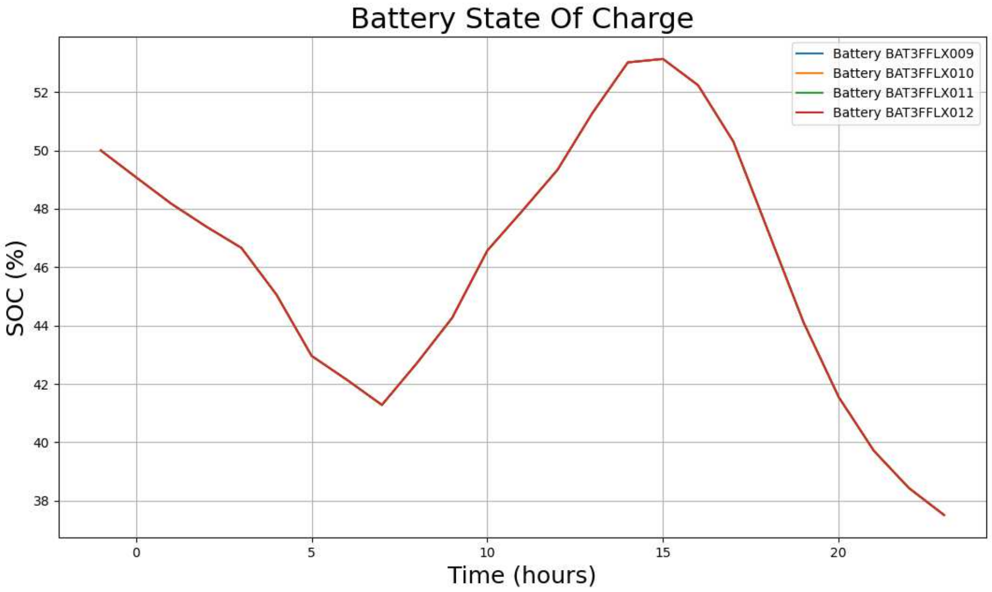
The seasoned reader may have already drawn such conclusions with ease. However, in hopes of assisting the analysis of newcomers to the subject, Figures 25 and 26 present the same curves shown previously with annotations in relevant parts of the graph. It can be seen on both figures that the charging and discharging intervals are clearly defined by both "Reference Lines". Furthermore, upon closer inspection it can be seen in Figure 26 that although simulations start at $Time = 0$, there is already an initial state of charge value respective to the variable SoC_{init} declared for each battery agent.

Figure 23 – Case Study 01 hourly community's energy dispatch results for stressed scenario with batteries.



Source: Elaborated by author (2023).

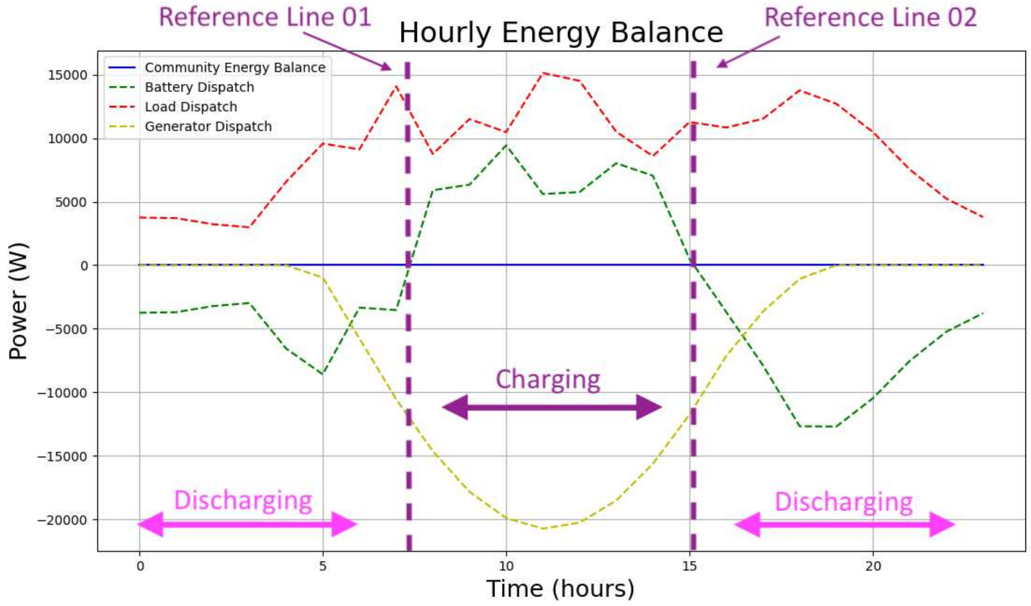
Figure 24 – Case Study 01 hourly state of charge results for stressed scenario.



Source: Elaborated by author (2023).

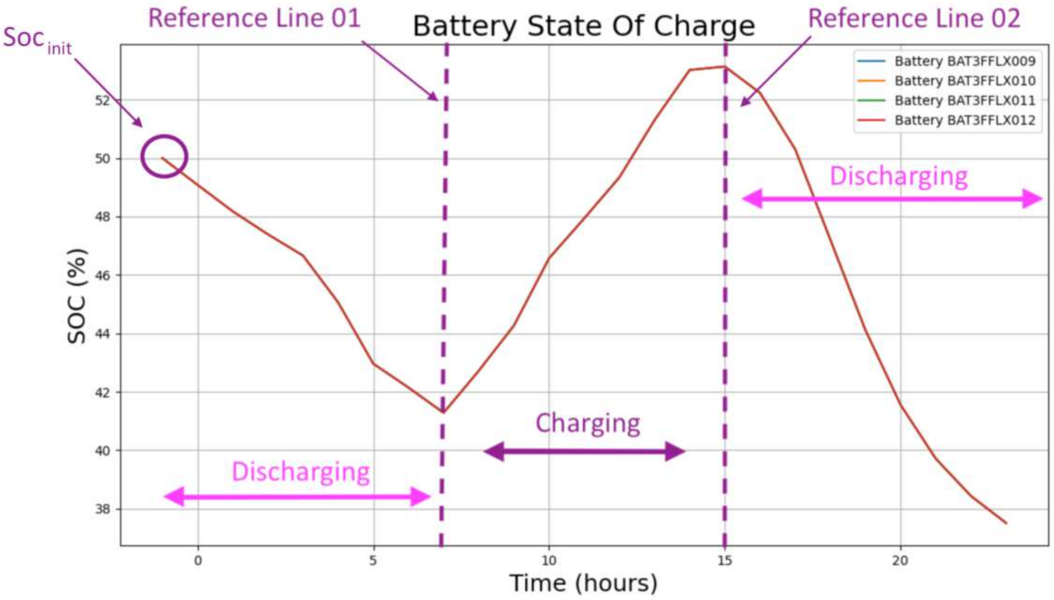
As a consequence of the strategy employed, Figure 27 shows the results for buses with voltage violations during the simulation period. It is possible to see that not only there is a decrease on the amount of violations experienced by the distribution network, but there is also a reasonable difference to the voltage profile of the buses that maintained their voltage violations.

Figure 25 – Case Study 01 hourly community's energy dispatch results for stressed scenario with batteries and observations.



Source: Elaborated by author (2023).

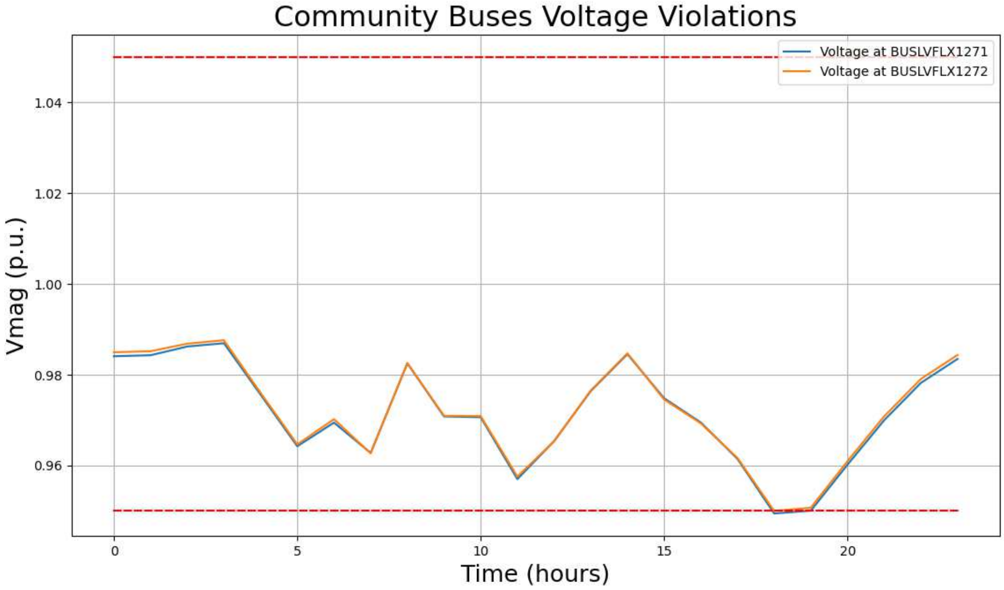
Figure 26 – Case Study 01 hourly state of charge results for stressed scenario with observations.



Source: Elaborated by author (2023).

In a similar fashion to the exposition of results after simulating a system without energy storage technologies, after the implementation of batteries one can also draw a summary of the violations experienced by the community's distribution network during the entire simulation period. Such summary is presented in Table 7, and specifies the type

Figure 27 – Case Study 01 bus voltages violations for the stressed scenario with batteries.



Source: Elaborated by author (2023).

of operational violation, the location of the violation as well as the hour of occurrence.

It should be reiterated that the violation summary focuses solely on the ones that occur to the buses and lines which are part of the consumer-centric market simulated. All other violations that may, or may not, take place in the distribution network and are outside the consumer-centric market's area of influence are not of concern to the scope of this work.

Table 7 – Violations summary of Case Study 01 with batteries.

N°	**Violation Type**	**Location**	**Hour**
1	Under Voltage	BUSLVFLX1271	18
2	Under Voltage	BUSLVFLX1272	18

Finalizing the entire optimization simulation of the Case Study 01, Tables 8 and 9 present a comparison between the simulations made for this system's community-centric energy market organization. More specifically, Table 8 shows a comparison of the simulation results from the first and last iterations of the market optimization. In this table, it is possible to identify the changes to the social welfare as well as the total generation and load dispatch experienced by the community once batteries started to play an active role in the energy transactions.

Additionally, Table 9 shows a comparison of the social welfare gains, or losses, after each iteration of the process. That is, the economical results obtained from optimizing the system with battery agents comprised by an increasing amount of modules.

Upon investigation of the values shown in Tables 8 and 9, it is possible to see that once all iterations have been simulated, the community would have to compromise so as to decide what is best for its members. When optimizing the system with a single battery module in each violated bus, the total number of violations is the smallest. However, once the amount of modules is increased to five in each violated bus, the optimization returns the best values for social welfare in the community.

Therefore, it would be necessary a proper financial analysis of the entire process of battery installation to determine what is the best course of action. Such a study would have to cover topics related to the acquisition costs of batteries, the possible fines that the voltage violations in the local distribution network may incur, as well as the community's preferences.

An in depth discussion will be explored in Chapter 5 in order to address the relevance of the strategy proposed once all Case Study results have been properly exposed.

Table 8 – Case Study 01 results overview.

Storage	**Social Welfare** (R$)	**Generators** (kWh)	**Loads** (kWh)	**Violations**
No (Size = 0)	-39.666	168.490922	219.572007	6
Yes (Size = 1)	-34.704	168.490922	219.572007	1
Yes (Size = 3)	-29.428	168.490922	219.572007	2
Yes (Size = 5)	-28.490	168.490922	219.572007	2
Yes (Size = 10)	-28.490	168.490922	219.572007	2

Table 9 – Case Study 01 social welfare results comparison.

Storage	**SW** (R$)	**Ratio**
0	-39.666	Reference Value
1	-34.704	↑ 12.509%
3	-29.428	↑ 25.810%
5	-28.490	↑ 28.175%
10	-28.490	↑ 28.175%

4.2 CASE STUDY 02

This Case Study focuses on the simulation of a single community just as it has been done for the previous one. However, differently from the first simulation, the consumer-centric market established in this Case Study is comprised of prosumers scattered over the length of the distribution network. It is, therefore, a disperse energy community where the agents that take part in the market are not located in immediately adjacent buses or lines.

The geographical location of the agents is as shown in Figures 28 and 32. This Case Study was chosen since it can be expected that not all prosumers shall be located in the same vicinity when a energy community market is being established. Consequently, by simulating this system, one can verify the effectiveness of larger consumer-centric markets with such configurations while determining whether they are prone to cause more violations due to the activity of other loads and generators located near the agents.

Another difference from Case Study 01 is that it was not necessary to stress the distribution network in order to identify violations to the proper operation of the system. This means that the greater number, the diversity in profile curves and the different locations of prosumers contribute to the natural occurrence of network violations as it can be seen in Table 3.

The next Subsections will initially focus on simulating the optimal energy market in conjunction by the expected three phase power flow for the system without batteries. Afterwards, the simulations will be rerun for the same system with additional agents representing batteries banks. Considering that the first Case Study has already exposed a thorough analysis of all results obtained from the simulation process, Case Study 02 and those following shall present solely the main results from each optimization run.

4.2.1 Results - Community Without Storage Units

As mentioned previously, the simulations start by focusing on optimizing the energy transactions and calculating the power flows without taking into account the existence of storage units installed through the community. The prosumers location can be seen in Figure 28.

According to the prosumer symbols convention established in Figure 10, it becomes clear by inspecting the disposition of prosumers in Figure 28 why this energy community is classified as disperse. Even though all agents are connected to low-voltage buses, the community members can be found in various segments along the distribution network.

Another relevant piece of information that can be derived from this is that the agent's transactions and the distribution network violations are directly affected by the energy generation and consumption of other agents connected to the system, which are unrelated to the community.

Consequently, while Case Study 01 had to increase the base load to stress the distribution network in the isolated neighborhood of the energy community, Case Study 02 has no such problems given that network violations occur naturally.

In order to analyze the effect of energy transactions over the social welfare of the community and its members, Figure 29 shows the community's hourly optimization results over the simulation period. One can observe that the negative social welfare coincides with the hours of the day with low sunlight irradiance. Incidentally, during such intervals the community is forced to import energy from the external grid's market players to meet loads demands. Conversely, during the hours of high irradiance, social welfare peaks owing to the energy surplus generation that is exported to the external grid.

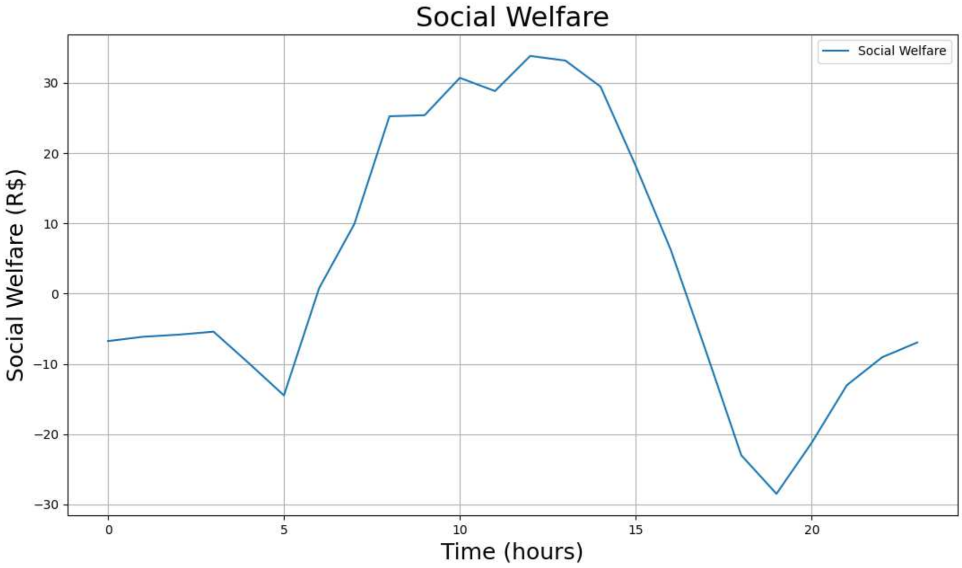
Figure 28 – Graphical representation of Case Study 02 energy community without batteries.

Source: Elaborated by author (2023).

The relationship between social welfare and the community's energy becomes more evident once one compares the hourly income with the energy balance shown in Figure 30. The figure shows three curves – the total load dispatch (in red), the total generator dispatch (in yellow) and the community's energy balance (in blue). This last curve is obtained as a result to the sum of the other two.

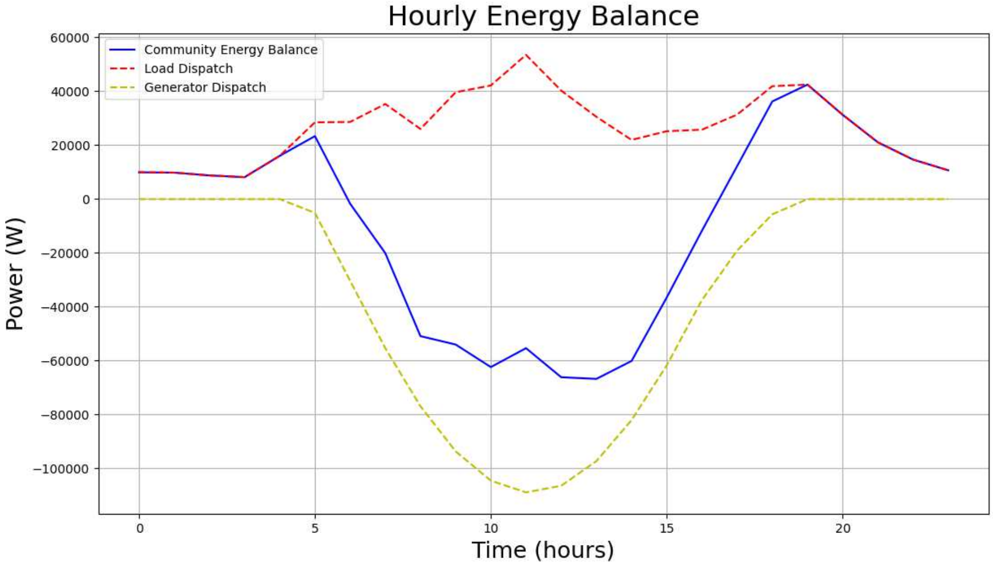
Finally, given greater amount of buses and lines that had to be supervised, buses with under voltage violations became more noticeable during the hours of peak energy consumption and intense trade. These buses and their respective voltages are shown in Figure 31.

Figure 29 – Case Study 02 hourly social welfare optimization results without batteries.



Source: Elaborated by author (2023).

Figure 30 – Case Study 02 hourly energy balance optimization results without batteries.



Source: Elaborated by author (2023).

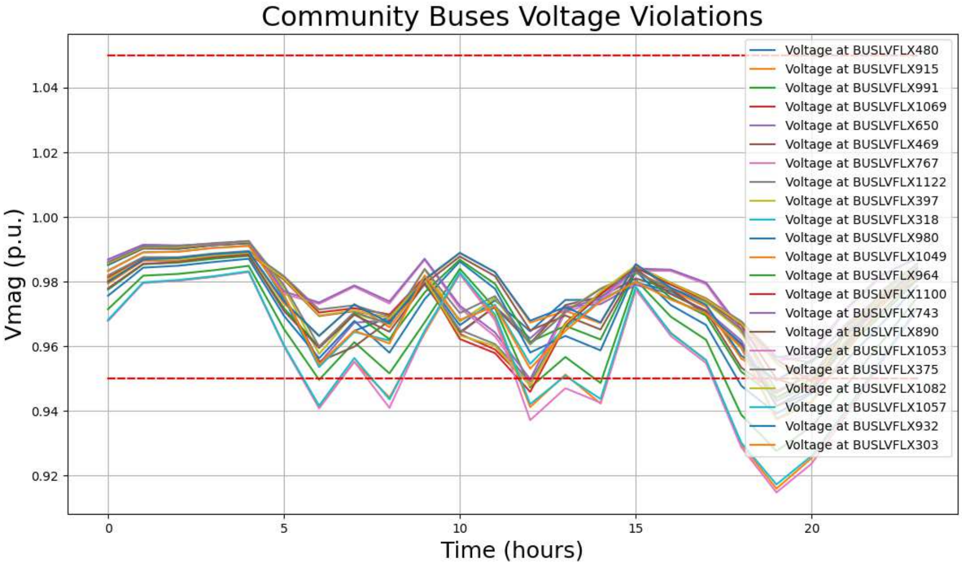
Additionally, these violations can be compiled into a report such as the one shown in Table 10. This report describes the type of operational violation, its location and hour of occurrence. The reader should bear in mind that the violation summary focuses only on the buses which are directly of concern to the community, in light of the reasons that have been mentioned previously.

However, one glaring problem that can be noticed after careful observation of this

Case Study report is that some buses experience multiple voltage violations during the simulation period. This indicates a high energy demand in the vicinity of these buses, coupled with a possible frailty of the local network physical infrastructure. This suggests that renovations or adaptations of the current network may be necessary, instead of prioritizing the installation of battery banks. Nevertheless, the strategy was employed in order to verify its effectiveness in similar cases.

The recurring voltage violations problem in some buses become even more pronounced once it is pointed out that 22 buses experience the 61 under-voltage episodes that the community has to deal with during the simulation period. Those are the buses and operating violations that the battery power banks installation will have to address in the following subsection.

Figure 31 – Case Study 02 hourly bus voltages violations without batteries.



Source: Elaborated by author (2023).

4.2.2 Results - Community With Storage Units

Once the buses with voltage violations were determined, battery agents were connected to the network in accordance to the electricity grid map shown in Figure 32. This specific case study installed batteries to the 22 buses with voltage violations and restarted the simulation process. Once resumed, the simulations with simple batteries placed in these buses enable one to draw new results to measure the effect that storage technologies have over the energy market and the distribution network.

Given the arbitrary nature of strategy employed, the initial integration of battery resources to the system proved insufficient to solve the issues that arise from the new operation scenario. That being the case, the entire chain of steps presented in Figure 8

Table 10 – Violations summary of Case Study 02 without batteries.

N°	**Violation Type**	**Location**	**Hour**
01	Under Voltage	BUSLVFLX991	6
02	Under Voltage	BUSLVFLX1049	6
03	Under Voltage	BUSLVFLX1053	6
04	Under Voltage	BUSLVFLX1057	6
05	Under Voltage	BUSLVFLX1049	8
06	Under Voltage	BUSLVFLX1053	8
07	Under Voltage	BUSLVFLX1057	8
08	Under Voltage	BUSLVFLX991	12
09	Under Voltage	BUSLVFLX767	12
10	Under Voltage	BUSLVFLX1049	12
11	Under Voltage	BUSLVFLX743	12
12	Under Voltage	BUSLVFLX1053	12
13	Under Voltage	BUSLVFLX1057	12
14	Under Voltage	BUSLVFLX1053	13
15	Under Voltage	BUSLVFLX991	14
16	Under Voltage	BUSLVFLX1049	14
17	Under Voltage	BUSLVFLX1053	14
18	Under Voltage	BUSLVFLX1057	14
19	Under Voltage	BUSLVFLX991	18
20	Under Voltage	BUSLVFLX980	18
21	Under Voltage	BUSLVFLX1049	18
22	Under Voltage	BUSLVFLX1053	18
23	Under Voltage	BUSLVFLX1057	18
24	Under Voltage	BUSLVFLX480	19
25	Under Voltage	BUSLVFLX915	19
26	Under Voltage	BUSLVFLX991	19
27	Under Voltage	BUSLVFLX1069	19
28	Under Voltage	BUSLVFLX650	19
29	Under Voltage	BUSLVFLX469	19
30	Under Voltage	BUSLVFLX397	19
[...]	[...]	[...]	[...]
31	Under Voltage	BUSLVFLX318	19
32	Under Voltage	BUSLVFLX980	19
33	Under Voltage	BUSLVFLX1049	19
34	Under Voltage	BUSLVFLX964	19
35	Under Voltage	BUSLVFLX1100	19
36	Under Voltage	BUSLVFLX890	19
37	Under Voltage	BUSLVFLX1053	19
38	Under Voltage	BUSLVFLX375	19
39	Under Voltage	BUSLVFLX1082	19
40	Under Voltage	BUSLVFLX1057	19
41	Under Voltage	BUSLVFLX932	19
42	Under Voltage	BUSLVFLX303	19
43	Under Voltage	BUSLVFLX480	20
44	Under Voltage	BUSLVFLX991	20
45	Under Voltage	BUSLVFLX1069	20
46	Under Voltage	BUSLVFLX650	20
47	Under Voltage	BUSLVFLX469	20
48	Under Voltage	BUSLVFLX1122	20
49	Under Voltage	BUSLVFLX397	20
50	Under Voltage	BUSLVFLX318	20
51	Under Voltage	BUSLVFLX980	20
52	Under Voltage	BUSLVFLX1049	20
53	Under Voltage	BUSLVFLX1100	20
54	Under Voltage	BUSLVFLX1053	20
55	Under Voltage	BUSLVFLX1082	20
56	Under Voltage	BUSLVFLX1057	20
57	Under Voltage	BUSLVFLX303	20
58	Under Voltage	BUSLVFLX991	21
59	Under Voltage	BUSLVFLX1049	21
60	Under Voltage	BUSLVFLX1053	21
61	Under Voltage	BUSLVFLX1057	21

restarts while entering into the loop so as to update the amount of battery modules added to each bus that presents violations.

Having said that, it is also important to mention another relevant detail about the iterative process that took place in this Case Study. Due to the sizes of the optimization and power flow problems in question, the addition of battery modules happened only to the buses in which the voltage violations persisted after each simulation iteration.

Therefore, some of the buses had battery agents with smaller energy capacities while others – more problematic buses – had battery agents with larger energy capacities connected to them. That being the case, the results shown in Figures 33 to 36 were obtained from simulating the system with battery agents combining sizes 1 and 3. This iteration's relevance is warranted as it will be explored further on.

Following the analysis process used so far, Figure 29 shows the community's hourly social welfare optimization results over the simulation period. Since the energy generation in the community is strongly reliant on the amount of irradiance each prosumer experiences,

Figure 32 – Graphical representation of Case Study 02 energy community with batteries.

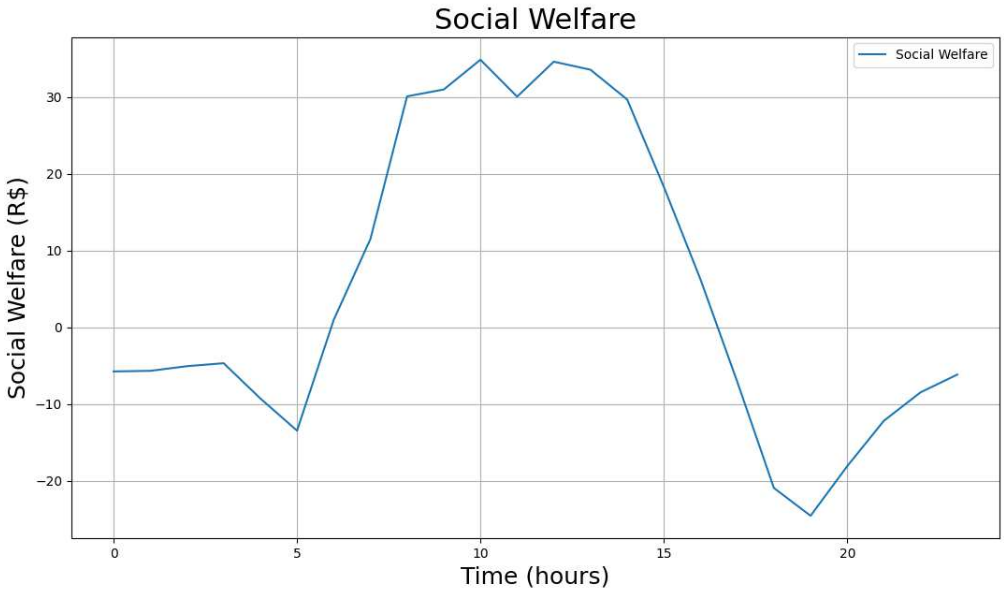
Source: Elaborated by author (2023).

it can be expected that the social welfare should act accordingly as well. That is verified once again by comparing the community's energy balance shown in Figure 34 with the peaks and valleys of the social welfare.

An inspection of the system's energy balance curve reveals a great amount of information about the interaction of battery agents and the energy demand and supply in the community.

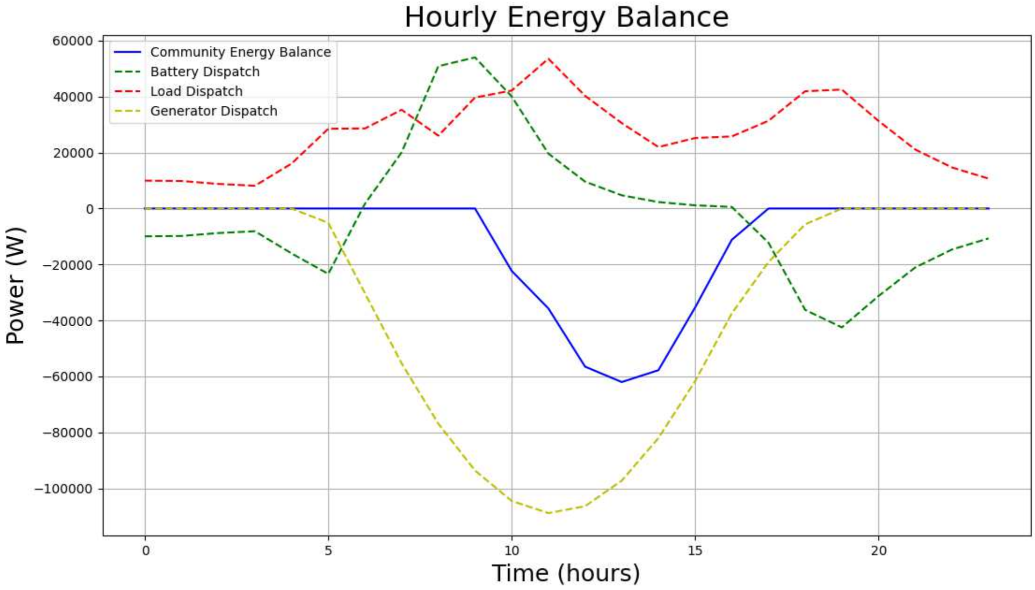
The first 6 to 7 hours of simulation refer to the early hours of a day. In it, the battery agents sell their energy to fellow community members that would otherwise have

Figure 33 – Case Study 02 hourly social welfare optimization results with batteries.



Source: Elaborated by author (2023).

Figure 34 – Case Study 02 hourly energy balance optimization results with batteries.



Source: Elaborated by author (2023).

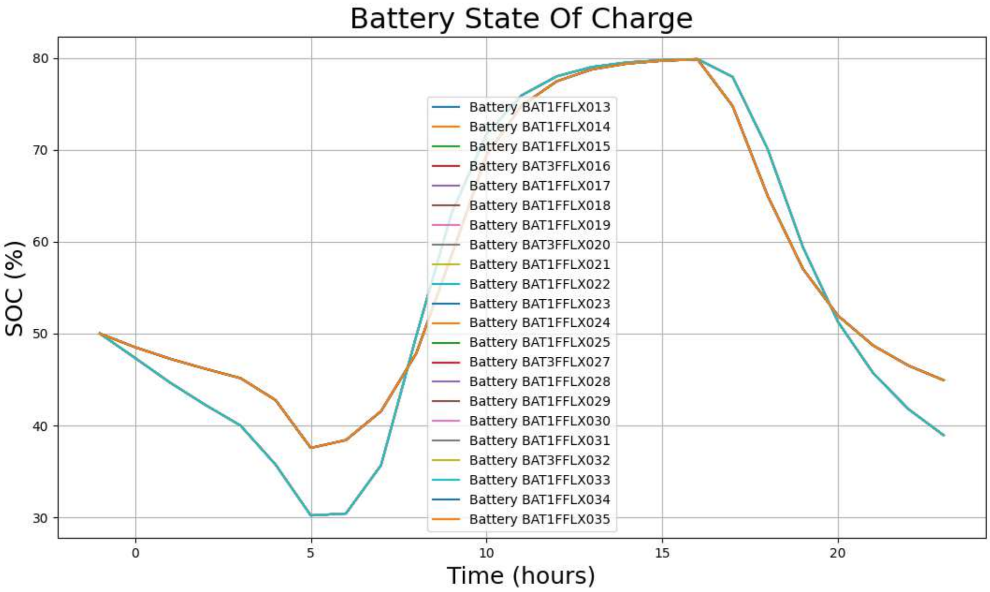
to import from the external grid.

Once photovoltaic generation gradually starts growing, it manages to supply the consumer agents demand, while at the same time granting the battery agents the opportunity to recharge using the surplus generation during the hours of high solar irradiance.

Finally, once dusk starts and photovoltaic generation turns to zero, the battery agents sell the energy which had been bought and stored during the day. This process becomes even more noticeable after the inspection of the battery agents state of charge in Figure 35.

As expected, the battery agents with smaller capacities (size = 1) have greater discharges during the sunless hours while the agents with larger energy storage capacities (size = 3) have smooth discharge intervals. However, both manage to recharge and reach the upper threshold ($\text{SoC}_{max} = 80\%$) due to the energy surplus in the system.

Figure 35 – Case Study 02 hourly batteries state of charge results.



Source: Elaborated by author (2023).

Additionally to this, the voltages violations shown in Figure 36 can be compiled into a report such as the one shown in Table 11. This report describes the type of violation, their locations and hours of occurrence.

Even though the problem of recurring voltage violations in some buses persists, the strategy showed great advances towards solving the issue at hand. In this case, not only has it suggested an increment to the social welfare but it has also showed its effectiveness in certain circumstances. A detailed report on the simulation results from each iteration with different battery agent sizes is shown in Tables 12 and 13.

Another interesting fact becomes clear from the results presented in both tables. Although combining battery agents with sizes 1 and 5 is more desirable to the social welfare of the community as a whole, it causes more voltage violations than simulations of smaller battery size combinations. Due to this, the results related to simulations of battery agents with sizes 1 and 3 were chosen since it is beneficial to a community from

Figure 36 – Case Study 02 hourly bus voltages violations with batteries.

Source: Elaborated by author (2023).

Table 11 – Violations summary of Case Study 02 with batteries.

N°	**Violation Type**	**Location**	**Hour**
01	Under Voltage	BUSLVFLX1049	7
02	Under Voltage	BUSLVFLX1053	7
03	Under Voltage	BUSLVFLX1057	7
04	Under Voltage	BUSLVFLX1069	11
05	Under Voltage	BUSLVFLX1122	11
06	Under Voltage	BUSLVFLX1100	11
07	Under Voltage	BUSLVFLX1082	11
08	Under Voltage	BUSLVFLX991	11
09	Under Voltage	BUSLVFLX767	11
10	Under Voltage	BUSLVFLX1049	11
11	Under Voltage	BUSLVFLX743	11
12	Under Voltage	BUSLVFLX1053	11
13	Under Voltage	BUSLVFLX1057	11
14	Under Voltage	BUSLVFLX1053	12
15	Under Voltage	BUSLVFLX991	13
16	Under Voltage	BUSLVFLX1049	13
17	Under Voltage	BUSLVFLX1053	13
18	Under Voltage	BUSLVFLX1057	13
19	Under Voltage	BUSLVFLX303	18
20	Under Voltage	BUSLVFLX318	18

the social welfare standpoint as well as effective from the network perspective.

Table 12 – Case Study 02 results overview.

Storage	**Social Welfare** (R$)	**Generators** (kWh)	**Loads** (kWh)	**Violations**
No (Size = 0)	83.314	884.577341	643.774588	61
Yes (Size = 1)	109.170	884.577341	643.774588	21
Yes (Size = 1 and 3)	119.195	884.577341	643.774588	20
Yes (Size = 1 and 5)	124.172	884.577342	643.774588	23

Table 13 – Case Study 02 social welfare results comparison.

Storage	**SW** (R$)	**Ratio**
0	83.314	Reference Value
1	109.170	↑ 31.034%
1 and 3	119.195	↑ 43.067%
1 and 5	124.172	↑ 49.040%

4.3 CASE STUDY 03

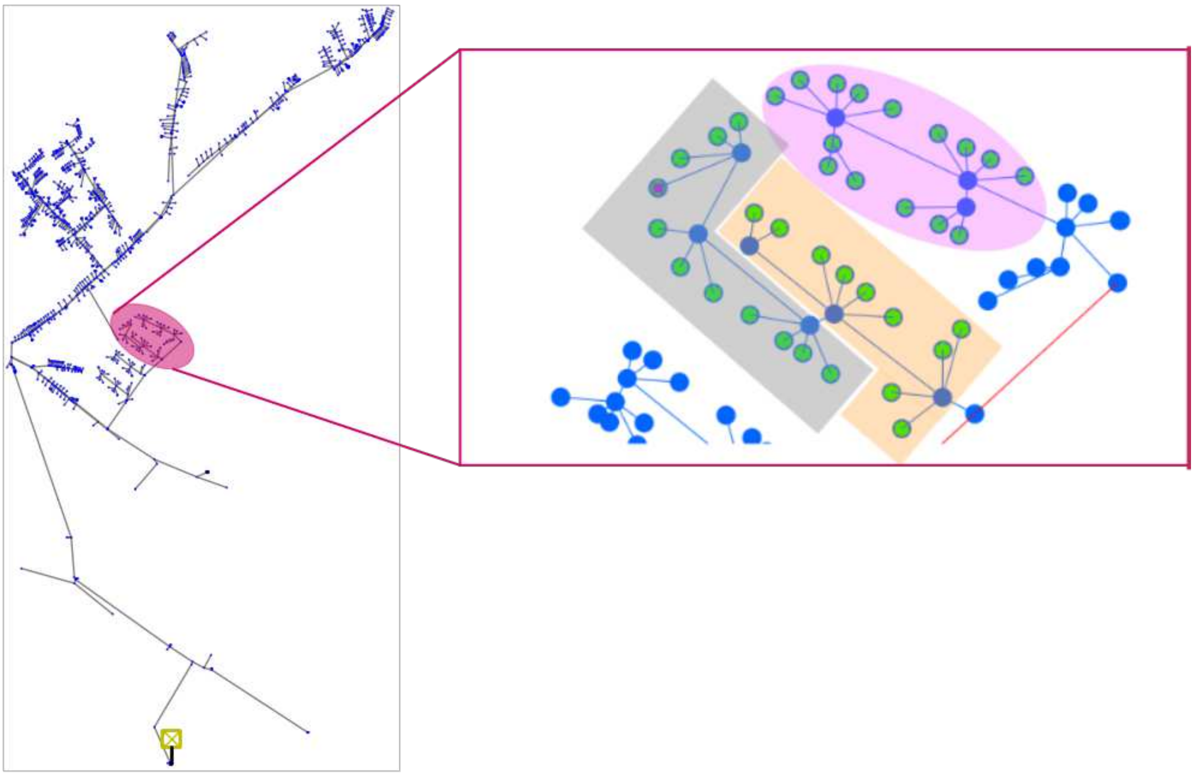
After simulating different Case Studies, the first – small, distant community with agents concentrated in the same area – and the second – large, disperse community with agents scattered in the electricity network – both of which focused on individual communities, Case Study 03 scales up the problem and starts simulation of three separate communities simultaneously. The graphical representation of the communities simulated and their general location in the distribution network is shown in Figure 37.

Before starting the simulations of Case Study 03 with batteries, it was first necessary to determine how far the community could push its power drain or injection so that it would violate the network's operation bounds. As expected as the oversizing of distribution networks usually is, it was not until the base load of the prosumers was raised by a factor of 7× that the community's energy consumption started to affect negatively the network's operation. Even then, it was but a single isolated episode of bus voltage violation that occurred between all three communities as shown by Figure 38.

Once the bus with voltage violation was determined, the same strategy was employed and the iterative process started to gradually add modules to the battery banks. Given the nature of this Case Study and the briefness of conclusions that can be drawn from it, the simulation results for the stressed scenarios with and without batteries will be presented together. For the sake of accelerating the analysis of Case Study 03, it is also possible to notice in Figure 37 that the precise location of the battery bank has already been highlighted.

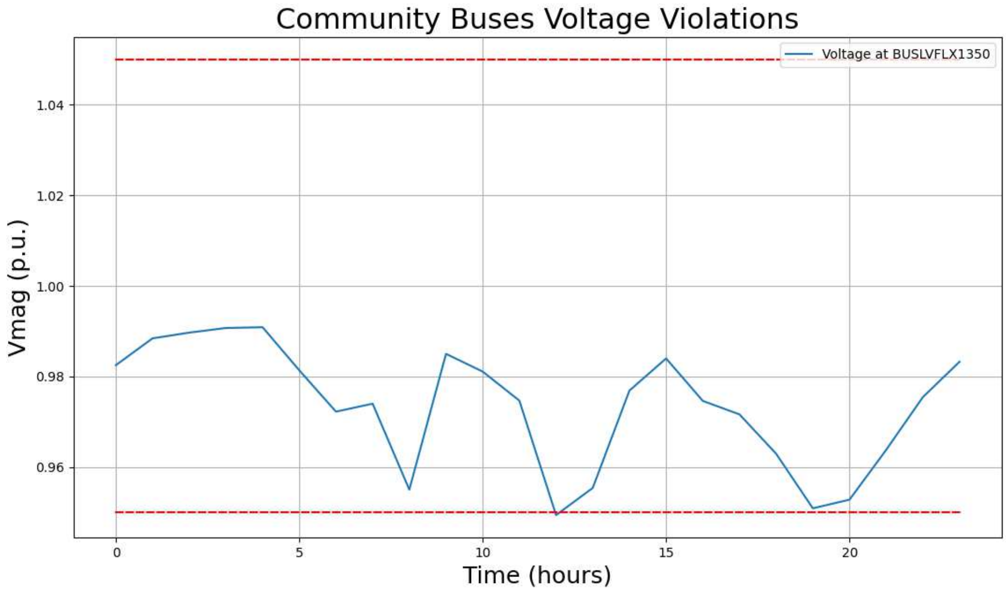
In order to illustrate the effects that the stressed scenario has over the communities trade, Figure 39 shows two graphs that can be obtained from the iterative process. The first iteration corresponding to the stressed operation without batteries is shown in Figure 39(a). The iterative process is complete when the battery agent is added to the system and

Figure 37 – Graphical representation of Case Study 03 energy communities with storage in the distribution network.



Source: Elaborated by author (2023).

Figure 38 – Case Study 03 bus voltages violations for the stressed scenario without batteries.



Source: Elaborated by author (2023).

reaches the maximum amount of modules (size = 10) which corresponds to Figure 39(b).

It becomes clear from both figures that the enhanced energy demand by the communities make them highly reliant on the external grid's resources. This dependency is so severe and their energy demand so pronounced that, once fully discharged, battery agents are unable to recharge and become spectators to the energy transactions in the system.

Once the iterative process was finished, its main results were compiled into the Tables 14 and 15. Although negligible, it can be seen that there are social welfare gains with each additional module installed to the bus that presented violations. Furthermore just before fully discharging and touching the bottom threshold ($\text{SoC}_{min} = 20\%$) in the last iteration, the battery agent manages supply a part of the energy demand to avoid the voltage violation in the bus "BUSLVFLX1350".

The main conclusions that can be obtained from Case Study 03 are threefold. First, and most evident of all, is that the relevance of battery agents as deterrence to the network's violations is inversely proportional to the oversizing of the distribution grid.

Secondly, in the event of stresses in such oversized networks, certain measures could be taken besides installing batteries, that could avoid the violations caused by the increased amount of trades and power flows in the system. One of these measures, and in all likelihood very profitable to the community, would be expanding the existing energy generation capacity of the prosumers.

Thirdly, and most certainly a controversial conclusion, is that although the battery agent at size = 10 managed to solve the voltage violation in Case Study 03, smaller battery agents would have been able to solve the issue as well.

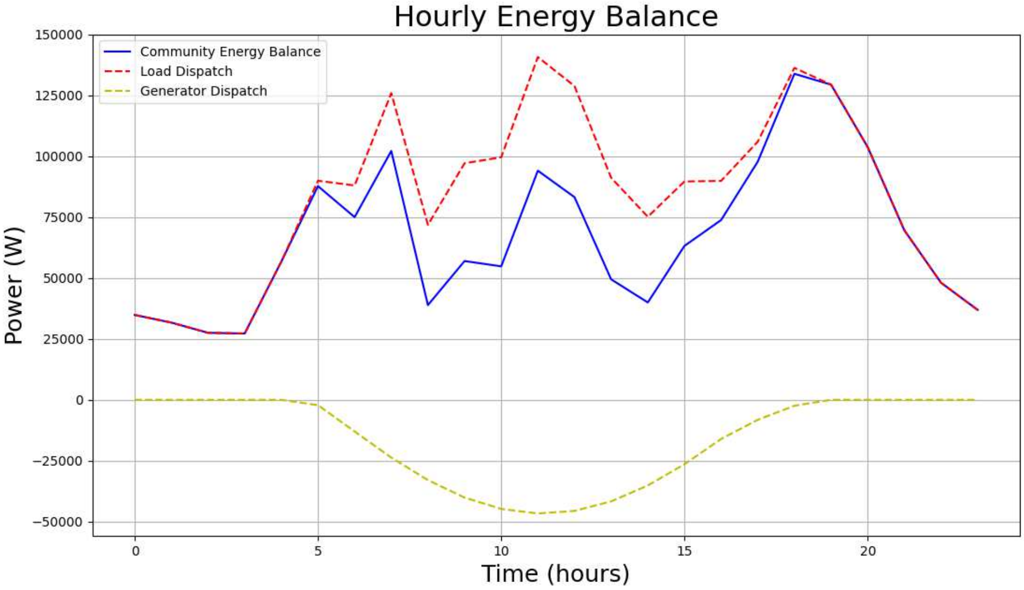
However, for that to happen the battery agent costs would have to be different, ensuring that their energy transactions take place only when the network is about to experience violations. Another possibility would be discarding the battery agent as a single entity and turning it into a shared energy resource by all prosumers in the community. Needless to say, all such measures would touch upon conflicting issues of distribution network governance, energy market manipulation and overriding of an agent's free will.

These conclusions and more shall be explored in depth in the final chapter.

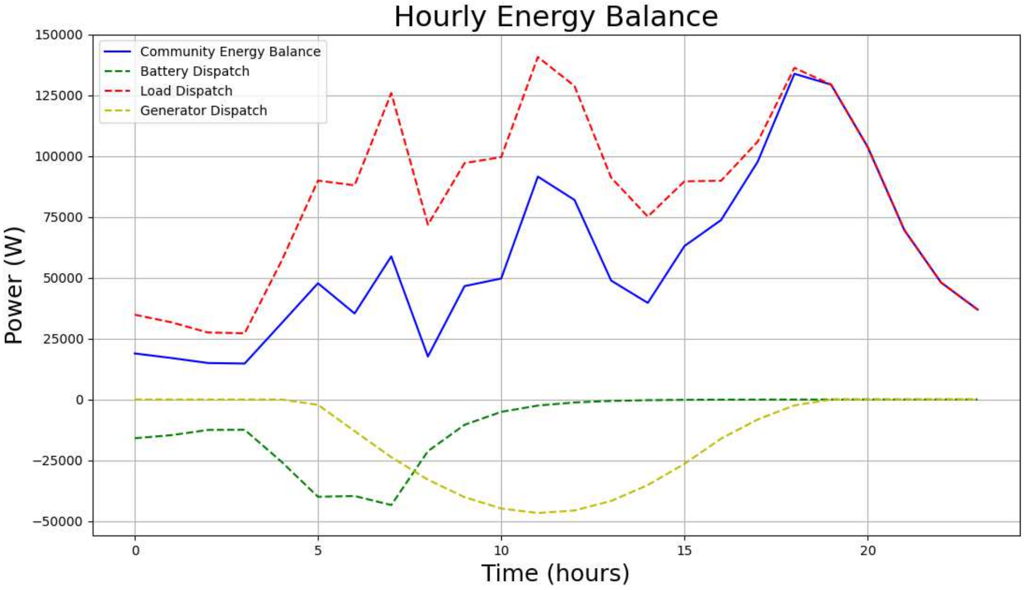
Table 14 – Case Study 03 results overview.

Storage	**Social Welfare** (R$)	**Generators** (kWh)	**Loads** (kWh)	**Violations**
No (Size = 0)	-1048.674	379.104575	1995.613672	1
Yes (Size = 1)	-1046.693	379.104575	1995.613672	1
Yes (Size = 3)	-1043.340	379.104575	1995.613672	1
Yes (Size = 5)	-1040.627	379.104575	1995.613672	1
Yes (Size = 10)	-1032.190	379.104575	1995.613672	0

Figure 39 – Case Study 03 hourly energy balance optimization results.



(a)



(b)

Caption: (a) Stressed scenario simulation without battery (size = 0);
(b) Stressed scenario simulation with battery (size = 10) – last iteration.

Source: Elaborated by author (2023).

4.4 CASE STUDY 04

As the *magnum opus* of this document, Case Study 04 focused on simulating a system that encompasses all prosumers addressed so far in previous Case Studies. The

Table 15 – Case Study 03 social welfare results comparison.

Storage	**SW** (R$)	**Ratio**
0	-1048.674	Reference Value
1	-1046.693	↑ 0.188%
3	-1043.340	↑ 0.508%
5	-1040.627	↑ 0.767%
10	-1032.190	↑ 1.571%

entire process optimized the energy transaction on five different communities, reaching a total of 307 prosumers trading energy during the simulation period.

These prosumers are connected to low voltage buses, just as it has been done in previous Case Studies, and their placement is arranged according to the graphical representation of Figure 40. In the figure the reader will be able to see a similar map to the one shown in Case Study 02. However, there are also some minor differences related to the agents representing prosumers from communities 1 to 4.

Before installing the battery banks to the network it was necessary to determine which buses or lines experienced operational violations during the simulation period. In this way, such violations were mainly expected from energy transactions in community 5 (large and disperse), considering that communities 1 to 4 are located in isolated and, most importantly, oversized areas of the network. Naturally, 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 shown in Table 10.

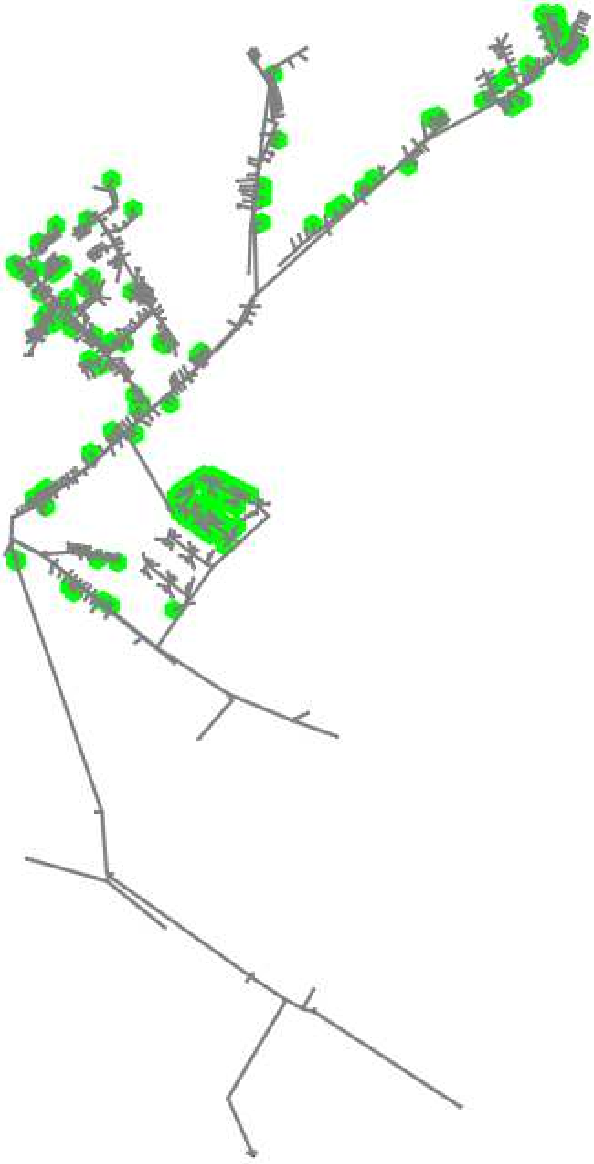
Consequently, given the identical violations report in Case Studies 02 and 04, the same buses were chosen for the installation of battery banks. The graphical representation showing a detailed view of the network, highlighting the prosumers and battery agents can be seen in Figure 41.

In that regard, following the same process of Case Study 02, the simulated battery agents had its 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, and only 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 02, 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 chapter, Case Study 04 will focus on presenting the details that can be obtained from the holistic analysis of the system.

Figure 40 – Graphical representation of Case Study 04 energy communities without storage in the distribution network.



Source: Elaborated by author (2023).

Therefore, the results obtained from this system once simulations are completed – in accordance to the iterative process shown in Figure 8 – were summarized in the reports shown by Tables 16 and 17.

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

Figure 41 – Graphical representation of Case Study 04 energy communities with storage in the distribution network.

Source: Elaborated by author (2023).

Table 16 – Case Study 04 results overview.

Storage	**Social Welfare** (R$)	**Generators** (kWh)	**Loads** (kWh)	**Violations**
No (Size = 0)	136.408	1432.172839	1038.648256	61
Yes (Size = 1)	160.865	1432.172839	1038.648256	14
Yes (Size = 1 and 3)	168.730	1432.172839	1038.648256	16

Table 17 – Case Study 04 social welfare results comparison.

Storage	**SW** (R$)	**Ratio**
0	136.408	Reference Value
1	160.865	↑ 17.929%
1 and 3	168.730	↑ 23.695%

5 CONCLUSION

This work focused on simulating a mathematical model to optimize energy transactions of a consumer-centric market embedded in a distribution network. As a consequence of the transactions between prosumers, the power flows in the grid are affected and operational violations occur. Once these problems are identified, the model assesses if the addition of market agents representing batteries connected to certain buses or lines would manage to prevent the network violations. To each attempt of solving the network's issues by updating the battery agents capacity, results of social welfare, energy dispatch and violations report are generated.

As for the four research questions that were stated in the beginning of this work, after applying the consumer-centric market model to an existing distribution network and evaluating the results, they can be answered as follows:

> *RQ1: Are there economical gains to be made by inserting battery agents in a realistic consumer-centric market model?*

– There are, possibly. Case Studies 02 and 04 especially show that the more grievously violated the network's operating bounds naturally are, the greater would be the gains to a community's social welfare. Check each Case Study's social welfare results comparison table for more details.

> *RQ2: What are the consequences of forming consumer-centric market models in existing distribution networks?*

– The main concerns are related to governance and to violations on the buses voltage and the lines loading levels in the distribution network. Regrettably, in this work, line overload and bus over-voltage were searched to no avail. Most likely, there were no line overloads due to the amount of PV energy injected and the oversized distribution grid. The communities network only experienced under-voltage violations.

> *RQ3: What are the electrical and energetic consequences of adding batteries in such situations? More specifically, are battery banks capable of solving distribution network violations while actively participating in the energy market?*

– Yes. Even though the strategy employed can be improved further, it demonstrated that, under certain circumstances, a project for the installation of batteries in the communities can be profitable and effective in solving violation issues. This course of action, while managing to rectify some problems caused by the market to the distribution network, also brings about a whole other host of matters that must be addressed before one such project takes place.

> *RQ4: How effective is the strategy proposed in this work? What are the main prerequisites, and can it be applied in large-scale systems?*

– Given the proper circumstances, the strategy can be very effective. However, for that to occur, certain conditions would have to be observed. Circumstances regarding the size of the community, how reliant the community's prosumers are on the energy provided by external sources and the oversizing of the local distribution network are some of the main factors to be accounted when evaluating if the strategy should be applied. One constant though, is that large-scale systems tend to perform better when the strategy is deployed on them. The greater interaction between energy producers and consumers can alleviate undesired stress scenarios.

Once answered the questions, other concerns that arise from this study should also be addressed. The first of which is related to the acquisition cost of the standard battery units and, further on, the necessary modules for updates. This first matter intersects another quite relevant concern, regarding the governance of the distribution network. To understand the connection between both of these issues, it should be mentioned that currently the responsibility for solving the distribution network's operating problems falls upon the DSO.

Therefore, considering these circumstances, the community markets technically have no obligation, or an incentive for that matter, to expend its resources on buying batteries and incorporating them as market agents just for the sake of solving problems in the distribution network. A hard-line measure to circumvent this would be if the DSO fined prosumers related to the network violations. In this way, the prosumer would be forced to choose the lesser *malus* – reduce its energy transactions or investment expenses in battery technologies. Another, more moderate measure, would be if the DSO offered incentives for prosumers to invest in solutions to reduce network violations caused by themselves.

One last possible measure regarding the batteries investment expenses issue would be if the DSO and the energy community shared the burden. In this case, the battery agent would behave as an independent market agent, while reserving part of its energy storage for the sake of the DSO. In counterpart, the DSO would receive special administration privileges and a quota of the storage capacity to dispatch the battery during the necessary hours. A proper study on the feasibility of this measure needs to be made since the battery agents would be extricated from the market to some extent and their energy would no longer traded wantonly.

Taking all Case Study results into account, other conclusions can also be outlined. Among them, it is possible to question the relevance of battery units in oversized distribution networks. In such cases, the agents representing the batteries are freer to seek individual economic gains instead of compromising for the distribution network's sake. That happens due to the unlikeliness of trades violating network operating constraints.

Another conclusion is that the batteries installation benefits are multiplied when the community market is less reliant on external energy sources. This can be translated as the energetic self sustaining capability of the prosumers when organized into a consumer-centric market. Case Study 03, for instance, demonstrates that a battery agent's contribution would be negligible to a community highly dependent on energy provided by the external grid. Consequently, proper studies on the technical and economical feasibility must be made to determine if a community should prioritize expanding its energy generation capacity or invest in batteries.

Finally, some questions can also be derived from the analysis of Case Study results. These questions should be explored in further studies of different prosumers in several other realistic distribution networks. That way, one would be granted practical evidence to support reliable answers to the questions. The main concluding research questions can be condensed into:

> CRQ1: Are disperse community markets prone to cause more violations in the distribution network?

> CRQ2: Why does the amount of under-voltage violations increase, in certain cases, when the number of battery modules connected to a bus grows?

So far, the two questions above point to desirable projects and studies in the area.

5.1 FUTURE WORKS

As a result of this work, the author suggests, besides investigating the questions that arose from this research, future investigations on the following subjects:

- A financial viability study on the battery installation and maintenance costs;
- A study reapplying the model to a different network that is known to have line overloads;
- A study on other courses of action that, when allied to battery installation would minimize or solve recurring voltage violations;
- A study on the optimal placement and sizing of the community's battery banks.

REFERENCES

ABRISHAMBAF, O.; LEZAMA, F.; FARIA, P.; VALE, Z. Towards transactive energy systems: An analysis on current trends. **Energy Strategy Reviews**, Elsevier, v. 26, p. 100418, 2019.

ANDONI, M.; ROBU, V.; FLYNN, D.; ABRAM, S.; GEACH, D.; JENKINS, D.; MCCALLUM, P.; PEACOCK, A. Blockchain technology in the energy sector: A systematic review of challenges and opportunities. **Renewable and sustainable energy reviews**, Elsevier, v. 100, p. 143–174, 2019.

BARBOSA, P. H. P. **Análise e otimização de mercados de energia elétrica centrados nos consumidores: estudo de caso no Brasil**. Trabalho de Conclusão de Curso — Universidade Federal de Juiz de Fora (UFJF), 2021.

BARBOSA, P. H. P.; DIAS, B.; SOARES, T. Analysis of consumer-centric market models in the brazilian context. In: IEEE. **2020 IEEE PES Transmission & Distribution Conference and Exhibition-Latin America (T&D LA)**. [S.l.], 2020. p. 1–6.

BITENCOURT, L.; ABUD, T. P.; DIAS, B. H.; BORBA, B. S.; MACIEL, R. S.; QUIRÓS-TORTÓS, J. Optimal location of ev charging stations in a neighborhood considering a multi-objective approach. **Electric Power Systems Research**, Elsevier, v. 199, p. 107391, 2021.

BOTELHO, D.; PETERS, P.; OLIVEIRA, L. de; DIAS, B.; SOARES, T.; MORAES, C. Prosumer-centric p2p energy market under network constraints with tdf's penalization. In: IEEE. **2021 IEEE Madrid PowerTech**. [S.l.], 2021. p. 1–6.

BOTELHO, D. F.; SOARES, T. A.; BARBOSA, P. H. P.; DIAS, B. H.; OLIVEIRA, L. W. de; MORAES, C. A. Transações peer-to-peer de energia elétrica considerando as restrições da rede de eletricidade. In: IEEE. **2021 14th IEEE International Conference on Industry Applications (INDUSCON)**. [S.l.], 2021. p. 69–75.

DEOTTI, L.; GUEDES, W.; DIAS, B.; SOARES, T. Technical and economic analysis of battery storage for residential solar photovoltaic systems in the brazilian regulatory context. **Energies**, MDPI, v. 13, n. 24, p. 6517, 2020.

DRANKA, G. G.; FERREIRA, P. Towards a smart grid power system in brazil: Challenges and opportunities. **Energy Policy (September 2019)**, Elsevier, v. 136, p. 111033, 2020.

DUGAN, R. C. **Reference Guide for The Open Distribution System Simulator (OpenDSS)**. 2016.

GUEDES, W.; DEOTTI, L.; DIAS, B.; SOARES, T.; OLIVEIRA, L. W. de. Community energy markets with battery energy storage systems: A general modeling with applications. **Energies**, MDPI, v. 15, n. 20, p. 7714, 2022.

GUERRERO, J.; CHAPMAN, A. C.; VERBIČ, G. Decentralized p2p energy trading under network constraints in a low-voltage network. **IEEE Transactions on Smart Grid**, IEEE, v. 10, n. 5, p. 5163–5173, 2018.

GUERRERO, J.; GEBBRAN, D.; MHANNA, S.; CHAPMAN, A. C.; VERBIČ, G. Towards a transactive energy system for integration of distributed energy resources: Home energy management, distributed optimal power flow, and peer-to-peer energy trading. **Renewable and Sustainable Energy Reviews**, Elsevier, v. 132, p. 110000, 2020.

HUG, G.; KAR, S.; WU, C. Consensus+ innovations approach for distributed multiagent coordination in a microgrid. **IEEE Transactions on Smart Grid**, IEEE, v. 6, n. 4, p. 1893–1903, 2015.

IGLESIAS, C. R. **Sistemas fotovoltaicos residenciais no Brasil: uma análise técnico-econômica sob a perspectiva de prosumidores e distribuidoras**. Dissertação (Mestrado) — Pontifícia Universidade Católica do Rio de Janeiro, 2021.

JIA, Y.; WAN, C.; LI, B. Strategic peer-to-peer energy trading framework considering distribution network constraints. **Journal of Modern Power Systems and Clean Energy**, SGEPRI, 2022.

LIU, J.; YANG, H.; ZHOU, Y. Peer-to-peer trading optimizations on net-zero energy communities with energy storage of hydrogen and battery vehicles. **Applied Energy**, Elsevier, v. 302, p. 117578, 2021.

MARQUES, J. a. d. S. **P2P Flexibility Markets to Support the Coordination Between the Transmission System Operators and Distribution System Operators**. Dissertação (Mestrado) — Instituto Superior Técnico de Lisboa, 2022.

MARTINS, R. J. P. **Power Share - Blockchain Management System and P2P Energy Trading**. Dissertação (Mestrado) — Instituto Superior Técnico de Lisboa, 2019.

MEEUS, L. **The evolution of electricity markets in Europe**. [S.l.]: Edward Elgar Publishing, 2020.

MENGELKAMP, E.; GÄRTTNER, J.; ROCK, K.; KESSLER, S.; ORSINI, L.; WEINHARDT, C. Designing microgrid energy markets: A case study: The brooklyn microgrid. **Applied Energy**, Elsevier, v. 210, p. 870–880, 2018.

MORET, F.; PINSON, P. Energy collectives: a community and fairness based approach to future electricity markets. **IEEE Transactions on Power Systems**, IEEE, v. 34, n. 5, p. 3994–4004, 2018.

OLIVEIRA, C.; BOTELHO, D. F.; SOARES, T.; FARIA, A. S.; DIAS, B. H.; MATOS, M. A.; OLIVEIRA, L. W. de. Consumer-centric electricity markets: A comprehensive review on user preferences and key performance indicators. **Electric Power Systems Research**, Elsevier, v. 210, p. 108088, 2022.

ORLANDINI, T.; SOARES, T.; SOUSA, T.; PINSON, P. Coordinating consumer-centric market and grid operation on distribution grid. In: IEEE. **2019 16th International Conference on the European Energy Market (EEM)**. [S.l.], 2019. p. 1–6.

PARAG, Y.; SOVACOOL, B. K. Electricity market design for the prosumer era. **Nature energy**, Nature Publishing Group, v. 1, n. 4, p. 1–6, 2016.

PENIDO, D. R. R.; ARAUJO, L. R. de; CARNEIRO, S.; PEREIRA, J. L. R.; GARCIA, P. A. N. Three-phase power flow based on four-conductor current injection method for unbalanced distribution networks. **IEEE Transactions on Power Systems**, IEEE, v. 23, n. 2, p. 494–503, 2008.

PETERS, P.; AQUINO, E. P.; PINTO, D. B.; SOARES, T.; DIAS, B. Blockchain in consumer-centric electricity markets: An overview. In: IEEE. **2022 IEEE PES Generation, Transmission and Distribution Conference and Exposition–Latin America (IEEE PES GTD Latin America)**. [S.l.], 2022. p. 1–6.

PSR. **Caálculos relativos aos efeitos econômicos e financeiros advindos do processo de modernização do Setor Elétrico Brasileiro (SEB), a partir da construção de cenários, que deverão levar em conta diferentes níveis de liberalização do setor - Produto 10 - Relatório final da proposta de transição**. 2022. https://abraceel.com.br/wp-content/uploads/post/2022/09/Relatorio-PSR-Ministerio-da-Economia.pdf.

SOUSA, T.; SOARES, T.; PINSON, P.; MORET, F.; BAROCHE, T.; SORIN, E. Peer-to-peer and community-based markets: A comprehensive review. **Renewable and Sustainable Energy Reviews**, Elsevier, v. 104, p. 367–378, 2019.

TANG, Z.; LIU, Y.; WU, L.; LIU, J.; GAO, H. Reserve model of energy storage in day-ahead joint energy and reserve markets: A stochastic uc solution. **IEEE Transactions on Smart Grid**, IEEE, v. 12, n. 1, p. 372–382, 2020.

WECKESSER, T.; DOMINKOVIĆ, D. F.; BLOMGREN, E. M.; SCHLEDORN, A.; MADSEN, H. Renewable energy communities: Optimal sizing and distribution grid impact of photo-voltaics and battery storage. **Applied Energy**, Elsevier, v. 301, p. 117408, 2021.

WU, F. F.; VARAIYA, P. Coordinated multilateral trades for electric power networks: theory and implementation. **International Journal of Electrical Power & Energy Systems**, Elsevier, v. 21, n. 2, p. 75–102, 1999.

APPENDIX A – CASE STUDY AGENTS DATA

Table 18 – Consumer agents data used in the Case Studies part 1.

NAME	**BUS**	**BASE**$_{KV}$	**BASE**$_{KW}$	**BASE**$_{KVAR}$	**PHASES**	**LOADSHAPE**	**COMMUNITY**
1FFLX001	BUSLVFLX1295	0.24	1.0	0.1	1	curve506_00R	1
1FFLX002	BUSLVFLX1299	0.24	1.0	0.1	1	curve390_02R	1
1FFLX003	BUSLVFLX1300	0.24	1.0	0.1	1	curve255_96R	1
1FFLX004	BUSLVFLX1328	0.24	1.0	0.1	1	curve369_00R	1
1FFLX005	BUSLVFLX1341	0.24	1.0	0.1	1	curve481_00R	1
1FFLX006	BUSLVFLX1348	0.24	1.0	0.1	1	curve248_00R	1
1FFLX007	BUSLVFLX1353	0.24	1.0	0.1	1	curve275_00R	1
1FFLX008	BUSLVFLX1371	0.24	1.0	0.1	1	curve304_21R	1
1FFLX009	BUSLVFLX1372	0.24	1.0	0.1	1	curve423_36R	1
1FFLX010	BUSLVFLX1378	0.24	1.0	0.1	1	curve346_00R	1
1FFLX011	BUSLVFLX1382	0.24	1.0	0.1	1	curve242_00R	1
1FFLX012	BUSLVFLX1385	0.24	1.0	0.1	1	curve459_00R	1
1FFLX013	BUSLVFLX1386	0.24	1.0	0.1	1	curve304_21R	1
1FFLX014	BUSLVFLX1393	0.24	1.0	0.1	1	curve339_00R	1
1FFLX015	BUSLVFLX1396	0.24	1.0	0.1	1	curve269_45R	1
1FFLX016	BUSLVFLX1303	0.24	1.0	0.1	1	curve506_00R	2
1FFLX017	BUSLVFLX1306	0.24	1.0	0.1	1	curve390_02R	2
1FFLX018	BUSLVFLX1310	0.24	1.0	0.1	1	curve255_96R	2
1FFLX019	BUSLVFLX1339	0.24	1.0	0.1	1	curve369_00R	2
1FFLX020	BUSLVFLX1343	0.24	1.0	0.1	1	curve481_00R	2
1FFLX021	BUSLVFLX1352	0.24	1.0	0.1	1	curve248_00R	2
1FFLX022	BUSLVFLX1367	0.24	1.0	0.1	1	curve275_00R	2
1FFLX023	BUSLVFLX1368	0.24	1.0	0.1	1	curve304_21R	2
1FFLX024	BUSLVFLX1383	0.24	1.0	0.1	1	curve423_36R	2
1FFLX025	BUSLVFLX1397	0.24	1.0	0.1	1	curve346_00R	2
1FFLX026	BUSLVFLX1308	0.24	1.0	0.1	1	curve242_00R	3
1FFLX027	BUSLVFLX1313	0.24	1.0	0.1	1	curve459_00R	3
1FFLX028	BUSLVFLX1319	0.24	1.0	0.1	1	curve304_21R	3
1FFLX029	BUSLVFLX1336	0.24	1.0	0.1	1	curve339_00R	3
1FFLX030	BUSLVFLX1344	0.24	1.0	0.1	1	curve269_45R	3
1FFLX031	BUSLVFLX1347	0.24	1.0	0.1	1	curve242_00R	3
1FFLX032	BUSLVFLX1350	0.24	1.0	0.1	1	curve313_00R	3
1FFLX033	BUSLVFLX1360	0.24	1.0	0.1	1	curve332_00R	3
1FFLX034	BUSLVFLX1374	0.24	1.0	0.1	1	curve313_00R	3
1FFLX035	BUSLVFLX1376	0.24	1.0	0.1	1	curve325_00R	3
1FFLX036	BUSLVFLX1379	0.24	1.0	0.1	1	curve255_96R	3
3FFLX037	BUSLVFLX1209	0.24	1.0	0.1	3	curve292_50R	4
3FFLX038	BUSLVFLX1219	0.24	1.0	0.1	3	curve301_77R	4
3FFLX039	BUSLVFLX1232	0.24	1.0	0.1	3	curve369_00R	4
3FFLX040	BUSLVFLX1236	0.24	1.0	0.1	3	curve225_00R	4
3FFLX041	BUSLVFLX1240	0.24	1.0	0.1	3	curve332_00R	4
3FFLX042	BUSLVFLX1242	0.24	1.0	0.1	3	curve313_00R	4
3FFLX043	BUSLVFLX1246	0.24	1.0	0.1	3	curve215_30R	4
3FFLX044	BUSLVFLX1248	0.24	1.0	0.1	3	curve304_21R	4
3FFLX045	BUSLVFLX1253	0.24	1.0	0.1	3	curve269_45R	4
3FFLX046	BUSLVFLX1255	0.24	1.0	0.1	3	curve230_00R	4
3FFLX047	BUSLVFLX1259	0.24	1.0	0.1	3	curve215_30R	4
3FFLX048	BUSLVFLX1262	0.24	1.0	0.1	3	curve264_00R	4
3FFLX049	BUSLVFLX1264	0.24	1.0	0.1	3	curve242_00R	4
3FFLX050	BUSLVFLX1270	0.24	1.0	0.1	3	curve390_02R	4
3FFLX051	BUSLVFLX1271	0.24	1.0	0.1	3	curve459_00R	4
3FFLX052	BUSLVFLX1272	0.24	1.0	0.1	3	curve264_00R	4
[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]

Table 19 – Consumer agents data used in the Case Studies part 2.

NAME	**BUS**	**BASE**$_{KV}$	**BASE**$_{KW}$	**BASE**$_{KVAR}$	**PHASES**	**LOADSHAPE**	**COMMUNITY**
[. . .]	[. . .]	[. . .]	[. . .]	[. . .]	[. . .]	[. . .]	[. . .]
1FFLX053	BUSLVFLX548	0.24	1.0	0.1	1	curve413_00R	5
1FFLX054	BUSLVFLX696	0.24	1.0	0.1	1	curve332_00R	5
1FFLX055	BUSLVFLX281	0.24	1.0	0.1	1	curve445_44R	5
1FFLX056	BUSLVFLX480	0.24	1.0	0.1	1	curve380_00R	5
1FFLX057	BUSLVFLX438	0.24	1.0	0.1	1	curve230_00R	5
3FFLX058	BUSLVFLX1288	0.24	1.0	0.1	3	curve325_00R	5
1FFLX059	BUSLVFLX552	0.24	1.0	0.1	1	curve299_22R	5
1FFLX060	BUSLVFLX915	0.24	1.0	0.1	1	curve242_00R	5
1FFLX061	BUSLVFLX410	0.24	1.0	0.1	1	curve292_50R	5
1FFLX062	BUSLVFLX991	0.24	1.0	0.1	1	curve445_44R	5
3FFLX063	BUSLVFLX1069	0.24	1.0	0.1	3	curve283_00R	5
1FFLX064	BUSLVFLX650	0.24	1.0	0.1	1	curve235_80R	5
3FFLX065	BUSLVFLX1278	0.24	1.0	0.1	3	curve275_00R	5
1FFLX066	BUSLVFLX748	0.24	1.0	0.1	1	curve325_00R	5
1FFLX067	BUSLVFLX116	0.24	1.0	0.1	1	curve313_00R	5
3FFLX068	BUSLVFLX1144	0.24	1.0	0.1	3	curve346_00R	5
1FFLX069	BUSLVFLX469	0.24	1.0	0.1	1	curve530_25R	5
1FFLX070	BUSLVFLX767	0.24	1.0	0.1	1	curve283_00R	5
1FFLX071	BUSLVFLX1028	0.24	1.0	0.1	1	curve369_00R	5
1FFLX072	BUSLVFLX75	0.24	1.0	0.1	1	curve269_45R	5
1FFLX073	BUSLVFLX724	0.24	1.0	0.1	1	curve470_34R	5
1FFLX074	BUSLVFLX60	0.24	1.0	0.1	1	curve459_00R	5
1FFLX075	BUSLVFLX308	0.24	1.0	0.1	1	curve304_21R	5
1FFLX076	BUSLVFLX50	0.24	1.0	0.1	1	curve325_00R	5
1FFLX077	BUSLVFLX459	0.24	1.0	0.1	1	curve530_25R	5
3FFLX078	BUSLVFLX1122	0.24	1.0	0.1	3	curve215_30R	5
1FFLX079	BUSLVFLX109	0.24	1.0	0.1	1	curve292_50R	5
1FFLX080	BUSLVFLX397	0.24	1.0	0.1	1	curve413_00R	5
1FFLX081	BUSLVFLX901	0.24	1.0	0.1	1	curve332_00R	5
1FFLX082	BUSLVFLX749	0.24	1.0	0.1	1	curve380_00R	5
1FFLX083	BUSLVFLX228	0.24	1.0	0.1	1	curve269_45R	5
3FFLX084	BUSLVFLX1229	0.24	1.0	0.1	3	curve230_00R	5
1FFLX085	BUSLVFLX318	0.24	1.0	0.1	1	curve353_33R	5
1FFLX086	BUSLVFLX82	0.24	1.0	0.1	1	curve283_00R	5
1FFLX087	BUSLVFLX100	0.24	1.0	0.1	1	curve269_45R	5
1FFLX088	BUSLVFLX207	0.24	1.0	0.1	1	curve299_22R	5
1FFLX089	BUSLVFLX944	0.24	1.0	0.1	1	curve230_00R	5
1FFLX090	BUSLVFLX980	0.24	1.0	0.1	1	curve242_00R	5
1FFLX091	BUSLVFLX134	0.24	1.0	0.1	1	curve283_00R	5
3FFLX092	BUSLVFLX1152	0.24	1.0	0.1	3	curve530_25R	5
1FFLX093	BUSLVFLX709	0.24	1.0	0.1	1	curve255_96R	5
1FFLX094	BUSLVFLX744	0.24	1.0	0.1	1	curve346_00R	5
1FFLX095	BUSLVFLX1049	0.24	1.0	0.1	1	curve369_00R	5
1FFLX096	BUSLVFLX964	0.24	1.0	0.1	1	curve215_30R	5
1FFLX097	BUSLVFLX231	0.24	1.0	0.1	1	curve481_00R	5
1FFLX098	BUSLVFLX829	0.24	1.0	0.1	1	curve304_21R	5
1FFLX099	BUSLVFLX976	0.24	1.0	0.1	1	curve269_45R	5
3FFLX100	BUSLVFLX1100	0.24	1.0	0.1	3	curve283_00R	5
[. . .]	[. . .]	[. . .]	[. . .]	[. . .]	[. . .]	[. . .]	[. . .]

Table 20 – Consumer agents data used in the Case Studies part 3.

NAME	**BUS**	**BASE**$_{KV}$	**BASE**$_{KW}$	**BASE**$_{KVAR}$	**PHASES**	**LOADSHAPE**	**COMMUNITY**
[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]
1FFLX101	BUSLVFLX212	0.24	1.0	0.1	1	curve292_50R	5
1FFLX102	BUSLVFLX743	0.24	1.0	0.1	1	curve283_00R	5
1FFLX103	BUSLVFLX969	0.24	1.0	0.1	1	curve325_00R	5
3FFLX104	BUSLVFLX1203	0.24	1.0	0.1	3	curve264_00R	5
3FFLX105	BUSLVFLX1134	0.24	1.0	0.1	3	curve283_00R	5
1FFLX106	BUSLVFLX920	0.24	1.0	0.1	1	curve413_00R	5
1FFLX107	BUSLVFLX111	0.24	1.0	0.1	1	curve230_00R	5
1FFLX108	BUSLVFLX422	0.24	1.0	0.1	1	curve339_00R	5
1FFLX109	BUSLVFLX1129	0.24	1.0	0.1	1	curve255_96R	5
3FFLX110	BUSLVFLX1191	0.24	1.0	0.1	3	curve390_02R	5
1FFLX111	BUSLVFLX890	0.24	1.0	0.1	1	curve361_00R	5
1FFLX112	BUSLVFLX520	0.24	1.0	0.1	1	curve255_96R	5
1FFLX113	BUSLVFLX404	0.24	1.0	0.1	1	curve230_00R	5
1FFLX114	BUSLVFLX277	0.24	1.0	0.1	1	curve283_00R	5
1FFLX115	BUSLVFLX885	0.24	1.0	0.1	1	curve361_00R	5
1FFLX116	BUSLVFLX296	0.24	1.0	0.1	1	curve248_00R	5
1FFLX117	BUSLVFLX585	0.24	1.0	0.1	1	curve470_34R	5
1FFLX118	BUSLVFLX726	0.24	1.0	0.1	1	curve353_33R	5
1FFLX119	BUSLVFLX541	0.24	1.0	0.1	1	curve459_00R	5
1FFLX120	BUSLVFLX1053	0.24	1.0	0.1	1	curve313_00R	5
1FFLX121	BUSLVFLX668	0.24	1.0	0.1	1	curve353_33R	5
1FFLX122	BUSLVFLX897	0.24	1.0	0.1	1	curve413_00R	5
1FFLX123	BUSLVFLX375	0.24	1.0	0.1	1	curve304_21R	5
1FFLX124	BUSLVFLX643	0.24	1.0	0.1	1	curve506_00R	5
3FFLX125	BUSLVFLX1225	0.24	1.0	0.1	3	curve264_00R	5
1FFLX126	BUSLVFLX615	0.24	1.0	0.1	1	curve225_00R	5
1FFLX127	BUSLVFLX428	0.24	1.0	0.1	1	curve369_00R	5
3FFLX128	BUSLVFLX1082	0.24	1.0	0.1	3	curve235_80R	5
1FFLX129	BUSLVFLX559	0.24	1.0	0.1	1	curve470_34R	5
1FFLX130	BUSLVFLX1057	0.24	1.0	0.1	1	curve242_00R	5
1FFLX131	BUSLVFLX669	0.24	1.0	0.1	1	curve235_80R	5
1FFLX132	BUSLVFLX259	0.24	1.0	0.1	1	curve248_00R	5
1FFLX133	BUSLVFLX226	0.24	1.0	0.1	1	curve361_00R	5
1FFLX134	BUSLVFLX932	0.24	1.0	0.1	1	curve369_00R	5
1FFLX135	BUSLVFLX1334	0.24	1.0	0.1	1	curve275_00R	5
1FFLX136	BUSLVFLX303	0.24	1.0	0.1	1	curve313_00R	5

Table 21 – Producer agents data used in the Case Studies part 1.

NAME	**BUS**	**BASE**$_{KV}$	**PHASES**	**BASE**$_{KVA}$	**PF**	**BASE**$_{KW}$	**GENSHAPE**	**COMMUNITY**
PV1FFLX001	BUSLVFLX1295	0.24	1	1	1	1	PVprofile	1
PV1FFLX002	BUSLVFLX1299	0.24	1	1	1	1	PVprofile	1
PV1FFLX003	BUSLVFLX1300	0.24	1	1	1	1	PVprofile	1
PV1FFLX004	BUSLVFLX1328	0.24	1	1	1	1	PVprofile	1
PV1FFLX005	BUSLVFLX1341	0.24	1	1	1	1	PVprofile	1
PV1FFLX006	BUSLVFLX1348	0.24	1	1	1	1	PVprofile	1
PV1FFLX007	BUSLVFLX1353	0.24	1	1	1	1	PVprofile	1
PV1FFLX008	BUSLVFLX1371	0.24	1	1	1	1	PVprofile	1
PV1FFLX009	BUSLVFLX1372	0.24	1	1	1	1	PVprofile	1
PV1FFLX010	BUSLVFLX1378	0.24	1	1	1	1	PVprofile	1
PV1FFLX011	BUSLVFLX1382	0.24	1	1	1	1	PVprofile	1
PV1FFLX012	BUSLVFLX1385	0.24	1	1	1	1	PVprofile	1
PV1FFLX013	BUSLVFLX1386	0.24	1	1	1	1	PVprofile	1
PV1FFLX014	BUSLVFLX1393	0.24	1	1	1	1	PVprofile	1
PV1FFLX015	BUSLVFLX1396	0.24	1	1	1	1	PVprofile	1
PV1FFLX016	BUSLVFLX1303	0.24	1	1	1	1	PVprofile	2
PV1FFLX017	BUSLVFLX1306	0.24	1	1	1	1	PVprofile	2
PV1FFLX018	BUSLVFLX1310	0.24	1	1	1	1	PVprofile	2
PV1FFLX019	BUSLVFLX1339	0.24	1	1	1	1	PVprofile	2
PV1FFLX020	BUSLVFLX1343	0.24	1	1	1	1	PVprofile	2
PV1FFLX021	BUSLVFLX1352	0.24	1	1	1	1	PVprofile	2
PV1FFLX022	BUSLVFLX1367	0.24	1	1	1	1	PVprofile	2
PV1FFLX023	BUSLVFLX1368	0.24	1	1	1	1	PVprofile	2
PV1FFLX024	BUSLVFLX1383	0.24	1	1	1	1	PVprofile	2
PV1FFLX025	BUSLVFLX1397	0.24	1	1	1	1	PVprofile	2
PV1FFLX026	BUSLVFLX1308	0.24	1	1	1	1	PVprofile	3
PV1FFLX027	BUSLVFLX1313	0.24	1	1	1	1	PVprofile	3
PV1FFLX028	BUSLVFLX1319	0.24	1	1	1	1	PVprofile	3
PV1FFLX029	BUSLVFLX1336	0.24	1	1	1	1	PVprofile	3
PV1FFLX030	BUSLVFLX1344	0.24	1	1	1	1	PVprofile	3
PV1FFLX031	BUSLVFLX1347	0.24	1	1	1	1	PVprofile	3
PV1FFLX032	BUSLVFLX1350	0.24	1	1	1	1	PVprofile	3
PV1FFLX033	BUSLVFLX1360	0.24	1	1	1	1	PVprofile	3
PV1FFLX034	BUSLVFLX1374	0.24	1	1	1	1	PVprofile	3
PV1FFLX035	BUSLVFLX1376	0.24	1	1	1	1	PVprofile	3
PV1FFLX036	BUSLVFLX1379	0.24	1	1	1	1	PVprofile	3
PV3FFLX037	BUSLVFLX1209	0.24	3	1	1	1	PVprofile	4
PV3FFLX038	BUSLVFLX1219	0.24	3	1	1	1	PVprofile	4
PV3FFLX039	BUSLVFLX1232	0.24	3	1	1	1	PVprofile	4
PV3FFLX040	BUSLVFLX1236	0.24	3	1	1	1	PVprofile	4
PV3FFLX041	BUSLVFLX1240	0.24	3	1	1	1	PVprofile	4
PV3FFLX042	BUSLVFLX1242	0.24	3	1	1	1	PVprofile	4
PV3FFLX043	BUSLVFLX1246	0.24	3	1	1	1	PVprofile	4
PV3FFLX044	BUSLVFLX1248	0.24	3	1	1	1	PVprofile	4
PV3FFLX045	BUSLVFLX1253	0.24	3	1	1	1	PVprofile	4
PV3FFLX046	BUSLVFLX1255	0.24	3	1	1	1	PVprofile	4
PV3FFLX047	BUSLVFLX1259	0.24	3	1	1	1	PVprofile	4
PV3FFLX048	BUSLVFLX1262	0.24	3	1	1	1	PVprofile	4
PV3FFLX049	BUSLVFLX1264	0.24	3	1	1	1	PVprofile	4
PV3FFLX050	BUSLVFLX1270	0.24	3	1	1	1	PVprofile	4
PV3FFLX051	BUSLVFLX1271	0.24	3	1	1	1	PVprofile	4
PV3FFLX052	BUSLVFLX1272	0.24	3	1	1	1	PVprofile	4
[. . .]	[. . .]	[. . .]	[. . .]	[. . .]	[. . .]	[. . .]	[. . .]	[. . .]

Table 22 – Producer agents data used in the Case Studies part 2.

NAME	**BUS**	**BASE**$_{KV}$	**PHASES**	**BASE**$_{KVA}$	**PF**	**BASE**$_{KW}$	**GENSHAPE**	**COMMUNITY**
[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]
PV1FFLX053	BUSLVFLX548	0.24	1	1	1	1	PVprofile	5
PV1FFLX054	BUSLVFLX696	0.24	1	1	1	1	PVprofile	5
PV1FFLX055	BUSLVFLX281	0.24	1	1	1	1	PVprofile	5
PV1FFLX056	BUSLVFLX480	0.24	1	1	1	1	PVprofile	5
PV1FFLX057	BUSLVFLX438	0.24	1	1	1	1	PVprofile	5
PV3FFLX058	BUSLVFLX1288	0.24	3	1	1	1	PVprofile	5
PV1FFLX059	BUSLVFLX552	0.24	1	1	1	1	PVprofile	5
PV1FFLX060	BUSLVFLX915	0.24	1	1	1	1	PVprofile	5
PV1FFLX061	BUSLVFLX410	0.24	1	1	1	1	PVprofile	5
PV1FFLX062	BUSLVFLX991	0.24	1	1	1	1	PVprofile	5
PV3FFLX063	BUSLVFLX1069	0.24	3	1	1	1	PVprofile	5
PV1FFLX064	BUSLVFLX650	0.24	1	1	1	1	PVprofile	5
PV3FFLX065	BUSLVFLX1278	0.24	3	1	1	1	PVprofile	5
PV1FFLX066	BUSLVFLX748	0.24	1	1	1	1	PVprofile	5
PV1FFLX067	BUSLVFLX116	0.24	1	1	1	1	PVprofile	5
PV3FFLX068	BUSLVFLX1144	0.24	3	1	1	1	PVprofile	5
PV1FFLX069	BUSLVFLX469	0.24	1	1	1	1	PVprofile	5
PV1FFLX070	BUSLVFLX767	0.24	1	1	1	1	PVprofile	5
PV1FFLX071	BUSLVFLX1028	0.24	1	1	1	1	PVprofile	5
PV1FFLX072	BUSLVFLX75	0.24	1	1	1	1	PVprofile	5
PV1FFLX073	BUSLVFLX724	0.24	1	1	1	1	PVprofile	5
PV1FFLX074	BUSLVFLX60	0.24	1	1	1	1	PVprofile	5
PV1FFLX075	BUSLVFLX308	0.24	1	1	1	1	PVprofile	5
PV1FFLX076	BUSLVFLX50	0.24	1	1	1	1	PVprofile	5
PV1FFLX077	BUSLVFLX459	0.24	1	1	1	1	PVprofile	5
PV3FFLX078	BUSLVFLX1122	0.24	3	1	1	1	PVprofile	5
PV1FFLX079	BUSLVFLX109	0.24	1	1	1	1	PVprofile	5
PV1FFLX080	BUSLVFLX397	0.24	1	1	1	1	PVprofile	5
PV1FFLX081	BUSLVFLX901	0.24	1	1	1	1	PVprofile	5
PV1FFLX082	BUSLVFLX749	0.24	1	1	1	1	PVprofile	5
PV1FFLX083	BUSLVFLX228	0.24	1	1	1	1	PVprofile	5
PV3FFLX084	BUSLVFLX1229	0.24	3	1	1	1	PVprofile	5
PV1FFLX085	BUSLVFLX318	0.24	1	1	1	1	PVprofile	5
PV1FFLX086	BUSLVFLX82	0.24	1	1	1	1	PVprofile	5
PV1FFLX087	BUSLVFLX100	0.24	1	1	1	1	PVprofile	5
PV1FFLX088	BUSLVFLX207	0.24	1	1	1	1	PVprofile	5
PV1FFLX089	BUSLVFLX944	0.24	1	1	1	1	PVprofile	5
PV1FFLX090	BUSLVFLX980	0.24	1	1	1	1	PVprofile	5
PV1FFLX091	BUSLVFLX134	0.24	1	1	1	1	PVprofile	5
PV3FFLX092	BUSLVFLX1152	0.24	3	1	1	1	PVprofile	5
PV1FFLX093	BUSLVFLX709	0.24	1	1	1	1	PVprofile	5
PV1FFLX094	BUSLVFLX744	0.24	1	1	1	1	PVprofile	5
PV1FFLX095	BUSLVFLX1049	0.24	1	1	1	1	PVprofile	5
PV1FFLX096	BUSLVFLX964	0.24	1	1	1	1	PVprofile	5
PV1FFLX097	BUSLVFLX231	0.24	1	1	1	1	PVprofile	5
PV1FFLX098	BUSLVFLX829	0.24	1	1	1	1	PVprofile	5
PV1FFLX099	BUSLVFLX976	0.24	1	1	1	1	PVprofile	5
PV3FFLX100	BUSLVFLX1100	0.24	3	1	1	1	PVprofile	5
[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]	[...]

Table 23 – Producer agents data used in the Case Studies part 3.

NAME	**BUS**	**BASE$_{KV}$**	**PHASES**	**BASE$_{KVA}$**	**PF**	**BASE$_{KW}$**	**GENSHAPE**	**COMMUNITY**
[. . .]	[. . .]	[. . .]	[. . .]	[. . .]	[. . .]	[. . .]	[. . .]	[. . .]
PV1FFLX101	BUSLVFLX212	0.24	1	1	1	1	PVprofile	5
PV1FFLX102	BUSLVFLX743	0.24	1	1	1	1	PVprofile	5
PV1FFLX103	BUSLVFLX969	0.24	1	1	1	1	PVprofile	5
PV3FFLX104	BUSLVFLX1203	0.24	3	1	1	1	PVprofile	5
PV3FFLX105	BUSLVFLX1134	0.24	3	1	1	1	PVprofile	5
PV1FFLX106	BUSLVFLX920	0.24	1	1	1	1	PVprofile	5
PV1FFLX107	BUSLVFLX111	0.24	1	1	1	1	PVprofile	5
PV1FFLX108	BUSLVFLX422	0.24	1	1	1	1	PVprofile	5
PV1FFLX109	BUSLVFLX1129	0.24	1	1	1	1	PVprofile	5
PV3FFLX110	BUSLVFLX1191	0.24	3	1	1	1	PVprofile	5
PV1FFLX111	BUSLVFLX890	0.24	1	1	1	1	PVprofile	5
PV1FFLX112	BUSLVFLX520	0.24	1	1	1	1	PVprofile	5
PV1FFLX113	BUSLVFLX404	0.24	1	1	1	1	PVprofile	5
PV1FFLX114	BUSLVFLX277	0.24	1	1	1	1	PVprofile	5
PV1FFLX115	BUSLVFLX885	0.24	1	1	1	1	PVprofile	5
PV1FFLX116	BUSLVFLX296	0.24	1	1	1	1	PVprofile	5
PV1FFLX117	BUSLVFLX585	0.24	1	1	1	1	PVprofile	5
PV1FFLX118	BUSLVFLX726	0.24	1	1	1	1	PVprofile	5
PV1FFLX119	BUSLVFLX541	0.24	1	1	1	1	PVprofile	5
PV1FFLX120	BUSLVFLX1053	0.24	1	1	1	1	PVprofile	5
PV1FFLX121	BUSLVFLX668	0.24	1	1	1	1	PVprofile	5
PV1FFLX122	BUSLVFLX897	0.24	1	1	1	1	PVprofile	5
PV1FFLX123	BUSLVFLX375	0.24	1	1	1	1	PVprofile	5
PV1FFLX124	BUSLVFLX643	0.24	1	1	1	1	PVprofile	5
PV3FFLX125	BUSLVFLX1225	0.24	3	1	1	1	PVprofile	5
PV1FFLX126	BUSLVFLX615	0.24	1	1	1	1	PVprofile	5
PV1FFLX127	BUSLVFLX428	0.24	1	1	1	1	PVprofile	5
PV3FFLX128	BUSLVFLX1082	0.24	3	1	1	1	PVprofile	5
PV1FFLX129	BUSLVFLX559	0.24	1	1	1	1	PVprofile	5
PV1FFLX130	BUSLVFLX1057	0.24	1	1	1	1	PVprofile	5
PV1FFLX131	BUSLVFLX669	0.24	1	1	1	1	PVprofile	5
PV1FFLX132	BUSLVFLX259	0.24	1	1	1	1	PVprofile	5
PV1FFLX133	BUSLVFLX226	0.24	1	1	1	1	PVprofile	5
PV1FFLX134	BUSLVFLX932	0.24	1	1	1	1	PVprofile	5
PV1FFLX135	BUSLVFLX1334	0.24	1	1	1	1	PVprofile	5
PV1FFLX136	BUSLVFLX303	0.24	1	1	1	1	PVprofile	5

Table 24 – Battery agents data used in the Case Studies.

NAME	**BUS**	**COMMUNITY**	**POWER** [kW]	**CAPACITY** [kWh]	**SoC %** **[Max, Min, Init]**	**EFF %** **[Ch, Dis]**	**RATE %** **[Ch, Dis, Autodis]**	**BATTSHAPE**
BAT1FFLX001	BUSLVFLX1299	1	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX002	BUSLVFLX1328	1	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX003	BUSLVFLX1341	1	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX004	BUSLVFLX1371	1	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX005	BUSLVFLX1393	1	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX006	BUSLVFLX1303	2	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX007	BUSLVFLX1397	2	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX008	BUSLVFLX1350	3	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT3FFLX009	BUSLVFLX1264	4	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT3FFLX010	BUSLVFLX1270	4	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT3FFLX011	BUSLVFLX1271	4	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT3FFLX012	BUSLVFLX1272	4	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX013	BUSLVFLX480	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX014	BUSLVFLX915	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX015	BUSLVFLX991	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT3FFLX016	BUSLVFLX1069	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX017	BUSLVFLX650	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX018	BUSLVFLX469	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX019	BUSLVFLX767	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT3FFLX020	BUSLVFLX1122	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX021	BUSLVFLX397	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX022	BUSLVFLX318	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX023	BUSLVFLX980	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX024	BUSLVFLX1049	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX025	BUSLVFLX964	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT3FFLX027	BUSLVFLX1100	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX028	BUSLVFLX743	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX029	BUSLVFLX890	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX030	BUSLVFLX1053	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX031	BUSLVFLX375	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT3FFLX032	BUSLVFLX1082	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX033	BUSLVFLX1057	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX034	BUSLVFLX932	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile
BAT1FFLX035	BUSLVFLX303	5	2.56	10.240	0.8, 0.2, 0.5	0.96, 0.96	0.25, 0.9375, 1.72171E-05	BatteryProfile