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# Discussion on drivers and proposition of approaches to support the transition of traditional electricity consumers to prosumers

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**Daniel Fioresi Botelho**

**Discussion on drivers and proposition of approaches to support the transition of traditional electricity consumers to prosumers**

Thesis submitted to the Graduate Program in Electrical Engineering of the Federal University of Juiz de Fora as a partial requirement for obtaining a Doctor's degree in Electrical Engineering.
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**ABSTRACT**

In recent years, traditional power systems have undergone a significant transition, mainly related to the massive penetration of Renewable Energy Sources (RES). More specifically, the transformation of residential consumers into prosumers has been challenging to the traditional operation of electricity markets. This transition brings new challenges and opportunities to the power system, leading to new Business Model (BM). One widely discussed change is related to a consumer-centric or prosumer-driven approach, promoting increased participation of small consumers in power systems. The present thesis aims at discussing the recent BMs as enablers of the increasing prosumers' role in the energy market and power system worldwide, deepening the discussion with a holistic view of the Brazilian context. To do so, it defines the main features of prosumers and their general related regulation as well as possible market designs within power systems. Moreover, the work intends to contribute to the knowledge, identification and understanding of the main regulatory barriers and enablers for the development of those BMs in the Brazilian energy market. In addition, it discusses enabling technologies to properly create the conditions that sustain new prosumer-driven markets. Then, it presents a comprehensive review of existing and innovative BMs and a discussion on their future roles in modern power systems and, in the Brazilian regulatory framework seeking to guide the decisions for the country to develop its political and regulatory environment in the future. Moreover, a set of recommendations for promoting these BMs in the power system worldwide is provided along with policy recommendations to promote prosumers aggregation in the Brazilian energy sector. An important conclusion is that, even though economically possible, not all innovative BMs can spread around the world due to regulatory issues. Seeking to further explore one of the prosumer-driven approaches presented and the challenges imposed by this innovative BM, a study of energy and reserve markets based on the Peer-to-Peer (P2P) structure is carried out. This structure is very promising for the prosumers' promotion but presents some challenges for the network operation. A critical challenge is to ensure that network constraints are not violated due to energy trades between peers and neither due to the use of reserve capacity. Therefore, two methodologies are proposed. First, is proposed a three-step approach (P2PTDF), using Topological Distribution Factors (TDF) to penalize peers responsible for violations that may occur in the network constraints, ensuring a feasible solution. Second, it is proposed a new integrated prosumers-DSO approach applied in P2P energy and reserve tradings that also ensures the feasibility of both energy and reserve transactions under network constraints. The proposed approach includes the estimation of reserve requirements based on the RES uncertain behavior from historical generation data, which allows identifying RES patterns. The proposed models are assessed through a case study that uses a 14-bus system, under the technical and economic criteria. The results show that the approaches can ensure a feasible network operation.
Key words: Business models. Enabling technology. Network constraints. Peer-to-peer energy and reserve market. Prosumer. Regulation. Renewable energy integration.

# RESUMO

Nos últimos anos, os sistemas tradicionais de energia passaram por uma transição significativa, principalmente relacionada à penetração massiva de fontes de energia renováveis (do inglês, *Renewable energy sources*-RES). Mais especificamente, a transformação de consumidores residenciais em prosumidores tem desafiado a atual operação do mercado de energia elétrica. Essa transição traz novos desafios e oportunidades para o sistema elétrico, levando a novos modelos de negócios (do inglês, *Business Models*-BM). Uma mudança amplamente discutida está relacionada a uma abordagem centrada no consumidor ou direcionada ao prossumidor, promovendo maior participação de pequenos consumidores nos sistemas de energia. A presente tese tem como objetivo discutir os recentes BMs como facilitadores do crescente papel dos prosumidores no mercado de energia e no sistema elétrico mundial, aprofundando a discussão com uma visão holística do contexto brasileiro. Para tanto, define as principais características dos prosumidores e sua regulamentação geral relacionada, bem como possíveis *designs* de mercado dentro dos sistemas de energia. Além disso, o trabalho pretende contribuir para o conhecimento, identificação e compreensão das principais barreiras regulatórias e facilitadoras para o desenvolvimento desses BMs no mercado brasileiro de energia. Assim como, discutir as tecnologias importantes para criar adequadamente as condições que sustentam novos mercados orientados ao consumidor final. Em seguida, apresenta uma revisão abrangente dos BMs existentes e inovadores e uma discussão sobre seus papéis futuros nos sistemas de energia modernos e, no quadro regulatório brasileiro, buscando orientar as decisões para que o país desenvolva seu ambiente político e regulatório no futuro. Além disso, um conjunto de recomendações para promover esses BMs no sistema de energia em todo o mundo é fornecido juntamente com recomendações de políticas para promover a agregação de prosumidores no setor de energia brasileiro. Uma conclusão importante é que, mesmo sendo economicamente possível, nem todos os BMs inovadores podem se espalhar pelo mundo devido a obstáculos regulatórias. Buscando explorar ainda mais uma das abordagens orientadas ao prosumidor apresentadas e os desafios impostos por este BM inovador, é realizado um estudo dos mercados de energia e de reserva com base na estrutura ponto a ponto (do inglês, *peer-to-peer*-P2P). Esta estrutura é muito promissora para a promoção dos prosumidores mas apresenta alguns desafios para o funcionamento da rede. Um desafio crítico é garantir que as restrições da rede não sejam violadas devido a negociações de energia entre pares e nem devido ao uso da capacidade de reserva. Portanto, duas metodologias são propostas. Primeiramente, é proposta uma abordagem em três passos (P2PTDF), utilizando Fatores de Distribuição Topológica (do inglês, *Topological Distribution Factors*-TDF ) para penalizar os peers responsáveis por violações que possam ocorrer nas restrições da rede, garantindo uma solução viável. Em segundo lugar, é proposta uma nova abordagem integrada de prosumidores-DSO aplicada em transações P2P de energia e reserva que também garante a viabilidade de transações de energia e reserva sob restrições de rede. A abordagem proposta inclui a estimativa dos requisitos de reserva com base no comportamento incerto da RES a partir de dados históricos de geração, o que permite identificar padrões de RES. Os modelos propostos são avaliados através de um estudo de caso que utiliza um sistema de 14 barras, sob os critérios

técnico e econômico. Os resultados mostram que as abordagens podem garantir uma operação de rede viável abrangendo energia e mercados de reserva.
Palavras-chave: Modelos de negócios. Tecnologias facilitadoras. Restrições de rede. Mercado P2P de energia e reserva. Prosumidor. Regulamentação. Integração de energias renováveis.

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SUMARY

## List of Acronyms

*ABRACEEL* Brazilian Energy Traders Association, in portuguese Associação Brasileira dos Comercializadores de Energia

*AC – PF* Alternating Current Power Flow

*ACL* Free Electricity Market, in portuguese Ambiente de Contratação Livre

*ACR* Regulated Electricity Market, in portuguese Ambiente de Contratação Regulada

*ANEEL* Brazilian Electricity Regulatory Agency, in portuguese Agência Nacional de Energia Elétrica

*AS* Ancillary Services

*BM* Business Models

*BRP* Balancing Responsibility Provider

*CC* Cloud Computing

*CCEE* Chamber of Electric Energy Commercialization, in portuguese Câmara de Comercialização de Energia Elétrica

*CDF* Cumulative Distribution Function

*DG* Distributed Generation

*DR* Demand Response

*DSO* Distribution System Operator

*EaaS* Energy-as-a-Service

*EEG* Renewable Energy Act

*EMS* Energy Management Systems

*ESaaS* Energy Storage as a Service

*ESS* Energy Storage System

*EU* European Union

*EV* Electric Vehicles

*FERC* Federal Energy Regulatory Commission

*FiT* Feed-in Tariffs

| | |
|---|---|
| *GBP* | Generator's Behavior Pattern |
| *ICT* | Information and Communication Technology |
| *IoT* | Internet of Things |
| *LV* | low voltage |
| $m-ISODATA$ | modified Iterative Self-Organizing Data Analysis Technique Algorithm |
| *MCS* | Monte Carlo Simulation |
| *MME* | Ministry of Mines and Energy |
| *ONS* | Brazilian ISO, in portuguese Operador Nacional do Sistema |
| *P2G* | Prosumer-to-Grid |
| *P2P* | Peer-to-Peer |
| *PD* | Product Differentiation |
| *PDF* | Probability Density Function |
| *PL* | Senate Bill, in portuguese Projeto de Lei |
| *PPA* | Power Purchase Agreement |
| *PROINFA* | Program to Stimulate Alternative Electricity Sources, in portuguese Programa de Incentivo a Fontes Alternativas |
| *PV* | Photovoltaic |
| *RES* | Renewable Energy Sources |
| *SEG* | Smart Export Guarantee |
| *SHS* | Solar Home Systems |
| *SNA* | Shared Network Access |
| *TDF* | Topological Distribution Factors |
| *TOU* | Time-of-Use |
| *TSO* | Transmission System Operator |
| *UK* | United Kingdom |
| *US* | United States |

# 1 INTRODUCTION

## 1.1 BACKGROUND AND MOTIVATION

Renewable and decentralized energy sources are changing the power system operation perspective (AGENCY., 2018). The current global demand for energy is mostly supplied by centralized non-renewable energy sources (DALE et al., 2022). However, there is a strong appeal for the energy sector decarbonization (VATS; MATHUR, 2022; GERBAULET et al., 2019). The contemporary BM of the conventional power grid neglects the end consumer as an active participant, depending only on the interaction between the distribution and transmission sectors.

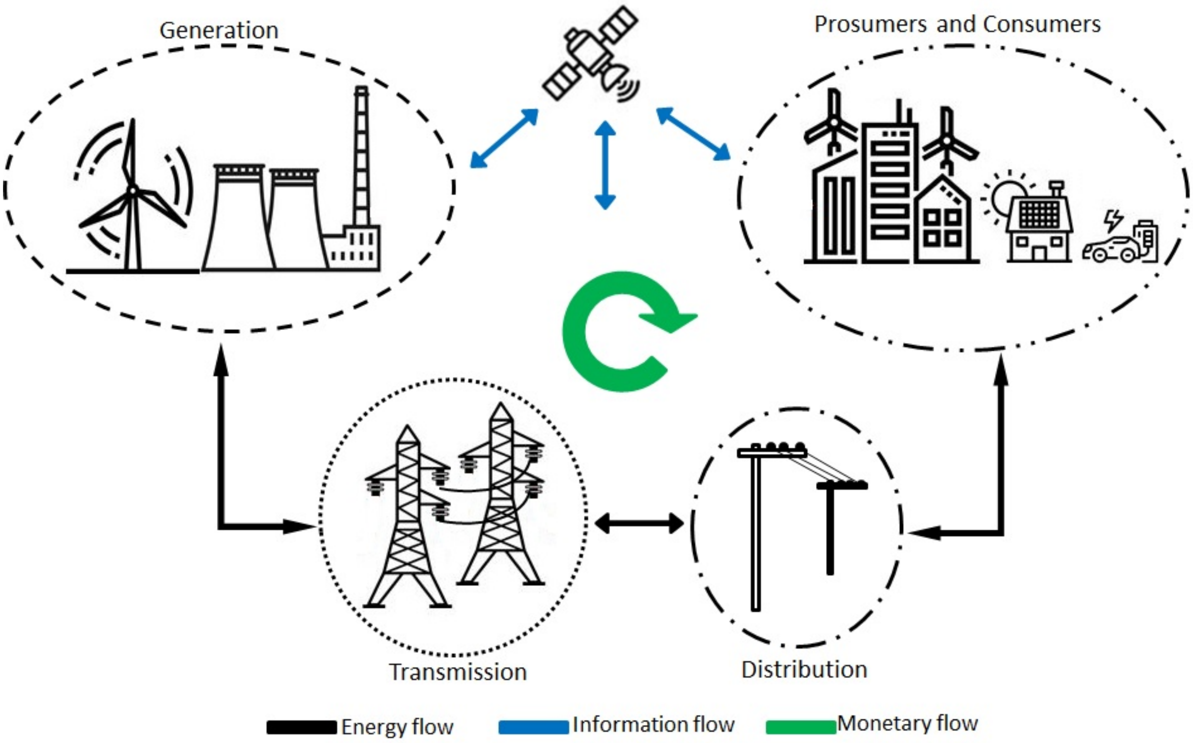
A global energy transition is driven by the trend to minimize the environmental impacts of non-renewable sources, provide energy democratization, and improve the power system reliability (HEFFRON, 2022; BRYANT; STRAKER; WRIGLEY, 2019). This transformation will bring about significant changes in the way society as a whole interacts with the power system, which will have to undergo a total reformulation (GIELEN et al., 2019b). The energy sector transformation is currently guided towards digitalization, decentralization and decarbonization (ASIF, 2022; VAHIDINASAB; MOHAMMADI-IVATLOO, 2023; HEYMANN et al., 2023). Guided mainly by these three factors, the electric sector is evolving from a structure in which the energy and monetary flow were unidirectional (the first always going from generation to consumers and the second taking the opposite path) to a structure in which energy, money and information flows are bidirectional. This new structure, shown in Figure 1, highlights how all the stages of the energy supply chain will interact with each other.

In addition to those aspects highlighted before, this transition also aims at reducing the costs involved in the power system and encourage the end-consumer to take a more active role and control over their own energy decisions. The prosumers[1] figure is gaining more prominence in this scenario. Strengthening this new "prosumer concept" is required, for instance (PENA-BELLO et al., 2022; MELENDEZ et al., 2019), by implementing new technologies, such as smart meters (KABALCI; KABALCI; SIANO, 2022; AVANCINI et al., 2019; AUBEL; POLL, 2019); advances in Information and Communication Technology (ICT) devices (LEE; YUAN; WANG, 2022; MUÑIZ; CUERVO, 2018) and the continuous integration of distributed energy resources (KERSCHER; ARBOLEYA, 2022; JEDDI et al., 2019; LI et al., 2019).

With greater integration between prosumers and all of these technologies, decentralized market solutions (WU; VARAIYA, 1999) become feasible to be adopted in future power systems. Individuals and communities are gaining more control over their energy generation and consumption. Such ideas benefit the emergence of concepts such as local energy markets (CAPPER et al., 2022), energy community (PENA-BELLO et al., 2022; MORONI et al., 2019) and P2P energy trading (ZHENG et al., 2022; SOUSA et al., 2019).

[1] Prosumer is a consumer who can also produce and sell electricity. This term is better defined in section 2.1.

Figure 1 – New energy system structure.




**Source**: Author's figure.

Regarding the Brazilian context, diversification in the RES supply has started to reduce the systemic risks related to the great dependence on hydroelectric energy, as well as to mitigate the social and environmental impacts associated with the construction of large dams. From diversification, the country has become the largest wind energy market in South America, presenting 25.2 GW of installed capacity, together with 8.4 GW of Photovoltaic (PV) in 2023. The fact that the Brazilian electric matrix is already strongly based on RES can be a great advantage for the country. In other words, the country starts with a significant advantage over most other countries in the world concerning the electricity sector's decarbonization goals and in developing policies and regulations aimed at greater RES inclusion beyond hydropower plants. Following the global trend in the energy sector, the Brazilian Electricity Sector[2] is promoting changes in the regulatory, commercial, and operational framework, seeking to create conditions for more active participation of consumers in managing their energy consumption and individual choices.

Existing BMs are not adequate for prosumers, proactive consumers, and industries, in order to give them incentives to act efficiently and make profits in the new energy landscape. There are two generic BMs most frequently addressed in the specialized literature (RICHTER,

[2] The Electricity Sector includes stakeholders that provide electricity generation, transmission, distribution, and marketing services for customers (industrial, commercial, public, and residential), in addition to institutions that regulate the sector.

2012): (i) the customer-side BM and the (ii) utility-side BM.

In a study on BMs for renewable energy, Richter (2012) focuses on explaining the importance of utilities starting to develop a customer-driven BM, even without encouraging the development of the largest prosumer inclusion in these BMs and in the energy market. On the other hand, the study by (PARAG; SOVACOOL, 2016) identifies promising markets for the prosumer's integration based on P2P models or prosumer communities, but without considering the required technologies or regulations. Sousa et al. (2019) provide an overview of new P2P markets focused on further integration of prosumers. The authors provide a detailed study of existing P2P models and present the basic mathematical model for each proposed alternative, but without a detailed discussion on BMs and technologies to guarantee the functioning of the market strategies. A complete review of P2P markets, challenges and suggestions for their proper implementation in power systems are done in (ZHENG et al., 2022; SOUSA et al., 2019; SHRESTHA et al., 2019; MORSTYN; TEYTELBOYM; MCCULLOCH, 2018).

Seeking to further explore one of the prosumer-driven approaches presented and the challenges imposed by this innovative BM, a study of energy and reserve markets based on the P2P structure is carried out. This structure, where players can negotiate with each other in a distributed fashion, is very promising for the prosumers' promotion, but presents some challenges for the network operation.

The P2P market design was chosen because with it we can understand how to effectively enable prosumers to participate in the energy market, empowering them to generate and sell their excess electricity to other consumers. This integration promotes the use of RES, as prosumers often rely on renewables for their electricity production. Moreover, by actively engaging prosumers in the market, we can unlock their potential to contribute to grid stability, demand response, and local energy optimization, for example. Thus, studying P2P energy markets to enhance the participation of prosumers can accelerate the transition to a more sustainable, resilient, and consumer-centric energy system.

Several works on P2P energy markets have been published in recent years. Most of these works consider some other aspects together with bilateral energy transactions. The studies in (FENG et al., 2022; SAMENDE; CAO; FAN, 2022; MORSTYN; MCCULLOCH, 2018; BAROCHE et al., 2019; KHORASANY; MISHRA; LEDWICH, 2019) take into account aspects related to distribution networks. Product differences and peers' preferences are covered in (KARAMI; MADLENER, 2022; MORSTYN; MCCULLOCH, 2018; KHORASANY; MISHRA; LEDWICH, 2019; SORIN; BOBO; PINSON, 2018). Other P2P market-related topics comprising blockchain (DONG et al., 2022; WANG et al., 2019; KANG et al., 2017), electric vehicles (ANNAMALAI et al., 2022; KANG et al., 2017), microgids (SPILIOPOULOS et al., 2022; ZHANG et al., 2018), and AS[3] (KHORASANY et al., 2022; ZHANG et al., 2020; BJARGHOV

[3] Ancillary service refers to those supporting services that are required for the correct operation of the electricity system (transmission and distribution).

et al., 2019) have been addressed in the literature. However, trading energy reserve also by applying a P2P mechanism is considered only in (GUO et al., 2020), and a feasible network operation under any reserve capacity scenario is not guaranteed. In addition to the application of P2P to energy markets, this market design can also be applied in the context of the energy reserve market (GUO et al., 2020). The reserve helps system operators to maintain a reliable electrical system, by dealing with supply and demand imbalances and supporting the system restoration after eventual outages (COBOS et al., 2018). With the advance of RES participation in power systems, the reserve requirement becomes more important to manage the variability and uncertainty inherent to this generation (IRENA, 2019b). Although storage using batteries at the consumer/prosumer level can be a possible solution to mitigate RES uncertainty, it still represents a high investment (GUEDES et al., 2022).

The system operator is currently responsible for acquiring the necessary reserve to ensure the power system security. The increase in RES leads to an increase in reserve requirements and even costs. In the near future, it is expected that RES agents should predict how much uncertainty they will bring and be responsible for compensating for it. In addition, the system operator should be responsible for the decision on dispatching the contracted reserve. Thus, RES agents might negotiate the reserve they need in a P2P market, taking into account that this mechanism can provide only trades between peers, but in principle without impacting the existing system operation mechanism. Thus, it is relevant to develop a methodology capable of verifying whether the operation of the distribution network will be feasible when the system operator needs to make use of the reserve that was negotiated between the peers. As this approach can model the interaction between prosumers and the Distribution System Operator (DSO), it can help build the basis for a fully decentralized and independent market.

Therefore, this thesis fills the gap in the literature by presenting an overview of innovative BMs for prosumers. It provides a detailed description on BMs and market designs that are currently being implemented to develop and encourage prosumer participation in the energy market worldwide, highlighting some technologies needed to enable these new BMs and market design, such as data metering and control, cloud computing and blockchain. Solidify the knowledge, identify and understand the main regulatory challenges and opportunities for the emergence and development of prosumers and prosumer-driven BMs in the Brazilian electricity market, providing a starting point to trace the policy implications for introducing and/or improving relevant legal frameworks for prosumers' aggregation in Brazil. Thus, one can support regulators, the research community, policy analysts, and decision-makers in designing a way forward that can promote prosumers' proliferation. As a result of studying these different prosumer-driven BMs, papers (BOTELHO et al., 2021) and (BOTELHO et al., 2022b) were published. The first having a global perspective on the subject and the second with a specific approach to the Brazilian electricity market.

Aiming at solving the problem presented above, this thesis proposes two methodologies capable of establishing an adequate market for energy and energy/reserve, through a P2P mechanism that considers the requirements for a feasible power system operation. The first proposed methodology contributes with a smart iterative methodology to solve and coordinate both the P2P market and the electrical network problems. This methodology proposition resulted in the publication of the paper (BOTELHO et al., 2021a). In particular, the second approach can determine whether the energy and reserve transactions carried out between peers are feasible under the electrical grid constraints, as well as the adjustments in trades to make the system operation feasible. In addition, the presented method also includes an approach to handle RES uncertain generation through historical generation data. All these aspects and propositions resulted in the approval of paper (BOTELHO et al., 2022a). These uncertainties could also be addressed with the use of Gaussian distribution (BOUFFARD; GALIANA, 2008) or even by versatile distribution as in (GUO et al., 2020). The approach estimates the reserve required to cover the RES uncertainty from historical generation data, using two different algorithms for comparison purposes: (i) the well-known Monte Carlo Simulation (MCS) (MOONEY, 1997), and (ii) the new clustering algorithm of (PAULA et al., 2021; PAULA et al., 2020), called modified Iterative Self-Organizing Data Analysis Technique Algorithm (m-ISODATA).

## 1.2 OBJECTIVES

This doctoral thesis studies: the proliferation of prosumers in the futuristic electricity markets worldwide and then deepen the discussion with a holistic view of the Brazilian context, innovative BMs that allow greater integration of this new player, and contribute to the improvement of solution methods for P2P energy and reserve market.

Therefore, the main contributions of this thesis proposal are presented:

- Present an overview of innovative BMs for prosumers, providing a detailed description of BMs and market projects that are currently being implemented to develop and encourage the prosumer participation in the energy market, highlighting some technologies necessary to enable these new BMs.
- Present the main regulatory challenges and opportunities for the emergence and development of prosumers and prosumer-driven BMs in the Brazilian electricity market. Seeking to guide the decisions that need to be taken nowadays so that the country can develop its political and regulatory environment aiming at taking advantage of all benefits that the RES prosumer adds to the energy system.
- A smart iterative methodology to solve and coordinate both the P2P market and the electrical network problems. The proposed model uses the TDF method to find exchanges and peers that may cause congestion and voltage problems, being these peers penalized.

- A novel iterative sequential energy and reserve P2P market model able to ensure that all tradings meet the network operating constraints. From the proposed solution, all energy and reserve transactions are technically feasible, even for the system's worst reserve scenario (use of the entire negotiated reserve.)
- An approach to handle RES uncertain generation through historical generation data by using two different algorithms for comparison purposes: (i) MCS and (ii) m-ISODATA.

## 1.3 RELATED PROJECTS AND PUBLICATIONS

The work developed in the scope of this thesis 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).

The research developed during this thesis resulted in the publication of some articles.

A) Botelho, D. F., Dias, B. H., de Oliveira, L. W., Soares, T. A., Rezende, I., Sousa, T. (2021). Innovative business models as drivers for prosumers integration-Enablers and barriers. Renewable and Sustainable Energy Reviews, 144, 111057.

DOI: https://doi.org/10.1016/j.rser.2021.111057

B) Botelho, D. F., de Oliveira, L. W., Dias, B. H., Soares, T. A., Moraes, C. A. (2022). Prosumer integration into the Brazilian energy sector: An overview of innovative business models and regulatory challenges. Energy Policy, 161, 112735.

DOI: https://doi.org/10.1016/j.enpol.2021.112735

C) Botelho, D. F., de Oliveira, L. W., Dias, B. H., Soares, T. A., Moraes, C. A. (2022). Integrated prosumers–DSO approach applied in peer-to-peer energy and reserve tradings considering network constraints. Applied Energy, 317, 119125.

DOI: https://doi.org/10.1016/j.apenergy.2022.119125

D) Botelho, D., Peters, P., de Oliveira, L., Dias, B., Soares, T., Moraes, C. (2021, June). Prosumer-centric P2P energy market under network constraints with TDF's penalization. In 2021 IEEE Madrid PowerTech (pp. 1-6). IEEE.

DOI: 10.1109/PowerTech46648.2021.9495048

E) Botelho, D. F., Soares, T. A., Barbosa, P. H. P., Dias, B. H., de Oliveira, L. W., Moraes, C. A. (2021, August). Transações peer-to-peer de energia elétrica considerando as restrições da rede de eletricidade. In 2021 14th IEEE International Conference on Industry Applications (INDUSCON) (pp. 69-75). IEEE.

DOI: 10.1109/INDUSCON51756.2021.9529549

Other work not included in the thesis:

F) Oliveira, C., Botelho, D. F., Soares, T., Faria, A. S., Dias, B. H., Matos, M. A., de Oliveira, L. W. (2022). Consumer-centric electricity markets: A comprehensive review on user preferences and key performance indicators. Electric Power Systems Research, 210, 108088.

DOI: https://doi.org/10.1016/j.epsr.2022.108088

## 1.4 THESIS STRUCTURE

In addition to this introductory chapter, this doctoral thesis is divided into four more chapters.

Chapter 2 presents a comprehensive review of prosumers' innovative business models, defining the prosumer main features and studying the current regulations in some countries related to this topic. In addition, it presents an overview of existing BMs for prosumers and future trends.

Chapter 3 presents a holistic regulatory and policy overview of the prosumer and prosumer-driven BMs' inclusion in the Brazilian electricity market.

In chapter 4, the two proposed methodologies for solving the P2P energy and energy/reserve market problem are presented in detail.

Finally, the conclusion, in Chapter 5, lists the main contributions of this work, together with a summary of the possibilities for its evolution.

# 2 PROSUMERS’ BUSINESS MODELS

## 2.1 THE PROSUMER

According to EURELETRIC (2015), "*prosumer is a customer who produces electricity primarily for his own needs but can also sell the excess electricity*". It is primarily connected to the distribution network with small or medium installed capacity. The figure of prosumer has gained prominence in the power system, which has been facilitated by affordable ICT devices and the development of smart grids and affordable distributed energy resources technologies like PV and batteries. The possibility of selling the surplus electricity produced in combination with broader service packages has been encouraging consumers to become prosumers (EURELETRIC, 2015). The study (LAMPROPOULOS; VANALME; KLING, 2010) was the first to mention the concept of prosumer in the specialized literature.

### 2.1.1 **Main barriers**

In general, the energy from prosumers comes from RES, most of them are stochastic resources (GRŽANIĆ et al., 2022; SINSEL; RIEMKE; HOFFMANN, 2019). The proper management of those generation sources requires investments in ICT devices, smart grids, and a more flexible power distribution mechanism. This can also mean less reinforcement of the electric network with new lines and substations (MARARAKANYE; BEKKER, 2019).

DSOs are expected to balance demand and supply, which will be more volatile in the best possible way. For that, they will have to modernize their grids with new layers of ICT, as the energy flows will become bidirectional. Further integration of prosumers also involves a new regulatory framework as well as an electricity sector restructuring.

As noted in Richter (2012), prosumer-BMs will now supply a wide range of products and not just electricity or heat/cold. Energy services such as consulting, greater interaction with customers, rental of goods and services, new communication channels, and help with financing, should be provided. Companies will need to collaborate with local suppliers and installation companies to serve the customer locally and also have the ability to handle a large number of small-scale assets.

According to the study (BRYANT; STRAKER; WRIGLEY, 2019), the problems caused by the increasing number of variables RES inserted in the system are properly handled by current government policies. This continues harming the traditional energy BMs viability. Only questions about system reliability and security remain the focus of most current actions, and few of them pay attention to the fact that innovative BMs are needed to deal with the changes that are taking place in the energy market. It is rarely considered the impact on BMs that the increases of variable RES may cause. To achieve the ideal transition to a more sustainable energy sector, energy policies and BMs are needed to support the complete integration of renewable energy into the grid.

Despite all the technological progress in ICT, there are still barriers related to technology. In particular, we are far from the point of mass roll-out of infrastructure for real-time data (e.g., smart meters). Additionally, privacy concerns regarding data are the main obstacles for end-user acceptance of digitalization in the power system.

### 2.1.2 Regulatory overview

Although the term is widespread nowadays in the European Union (EU), for example, there is still no exact definition of who fits the prosumer concept. The lack of a clear definition makes the rights and obligations of prosumers unclear, varying across EU member states. The 2016 winter package (RINGEL; KNODT, 2018), a document providing an analysis of EU member states' economic and social situation, brings a prosumer definition at EU level for the first time. However, it uses the term active client instead of prosumer (COMMISSION, 2016).

More recently, given the growing importance of self-consumption, the EU Directive 2018/2001 (COMMISSION, 2018), approved in December 2018, brought the definitions of "renewables self-consumer", "jointly acting renewables self-consumers"and "renewable energy community", as seen in articles 21 and 22. Knowing this directive points to a trend towards encouraging self-consumption, it is important to highlight that self-consumption is profitable for consumers only if the costs of local renewable generation are lower than retail electricity prices. This means that when there is a parity between the retail electricity market cost and self-consumption, Feed-in Tarifs (FiT) can be eliminated.

The paper (FRIEDEN; ROBERTS; GUBINA, 2019) presents a review to understand and compare the emerging regulatory frameworks with those already in place in EU member states. According to the authors, while a few countries have already made significant progress in the transition process to the EU framework, most are still only at the beginning of these changes. For example, the German system is based on regulatory incentives for domestic microgeneration, self-consumption, and specific laws for renewable energy-based generator connection as a way to stimulate energy prosumers.

In a short overview, the German government has adopted a unique PV generation subsidy program since 1990, as a way to test the practical functionality of these small, decentralized, grid-connected PV systems. Another important mark was the Renewable Energy Act (EEG) adoption in 2000 and last updated in 2017 (BMWI, 2017). The basic provisions of this law include a scheme to support renewable sources, a purchase obligation for network operators, and the solidarity principle to bear the costs of implementing RES. The EEG offered a high degree of planning certainty to investors. Traditionally, owners of PV generators are instigated to consume the electricity produced with a premium paid for each kWh consumed by themselves. This scheme was replaced by a simpler self-consumption scheme. This new scheme drives a large part of the PV market. The surplus of PV electricity is remunerated through the “market integration model": a feed-in premium on top of electricity market prices. A minimum requirement of 10% of self-consumption is demanded for installations between 10 kW and 1 MW (MASSON; BRIANO; BAEZ, 2016). The German government approved a law in 2017 for a plant operator in a multifamily house, to sell locally produced electricity to nearby tenants. The established precondition is that the PV plant is installed in a residential building and has a maximum capacity of 100 kW. To receive support, the plant operator can sell the electricity to the building's tenants or apartment owners in the building (FRIEDEN et al., 2019). Prosumer was never defined as an official term in Germany but it is a driver of changes in terms of RES support and integrative legislation.

In the United Kingdom (UK), the support and multiplication of domestic PV and other microgeneration from renewable sources were massive between 2010-2015. Different incentives and policy initiatives (like FiT) have enabled the rapid growth of domestic PV prosumer (OFGEM, 2019). Self-consumption, for systems below 30 kW, has been encouraged through a generation tariff and an export tariff, applicable to the electricity fed into the grid. The prosumer gets the generation tariff for all PV generated electricity, and an export tariff is also applied to the energy fed into the grid (MASSON; BRIANO; BAEZ, 2016). However, the UK's FiT scheme for small-scale renewable sources was officially closed on 31 March 2019 (GOVERMENT, 2018). For almost 9 months there was uncertainty about the new scheme and finally, the British government launched the Smart Export Guarantee (SEG) (OFGEM, 2020; GOVERMENT, 2020) on January 1st, 2020. To receive a payment, guaranteed by the SEG, for the surplus energy they inject into the network, prosumers must sign a so-called "SEG tariff"with one of the companies participating in the program, companies like EOn (E.ON, 2020), Octopus Energy (ENERGY, 2020a), Bulb (BULB, 2020), EDF Energy (EDF, 2020), OVO Energy (ENERGY, 2020b), Shell Energy (ENERGY, 2020c), Scottish Power (POWER, 2020) and others. The main difference of this new program in relation to FiTs, is that the SEG pays only for the excess electricity that is exported to the grid, and not for all the electricity generated. So, the SEG is paid by energy companies who buy the power and not by the government. To define the term prosumer, UK policies use terms such as "microgeneration"or "decentralized power generation"(INDERBERG; TEWS; TURNER, 2016). RES and the search for a more sustainable economy with a focus on mitigating climate change guided the support for prosumers in the UK.

The Council of Ministers of Portugal proposed the Decreee-Law 162/2019 of 25 October 2019 (PORTUGAL, 2019), which aimed at promoting the self-consumption of renewable energy. This decree facilitates the connection of self-consumption facilities, regulates the mode of collective self-consumption and the creation of the Renewable Energy Communities Scheme. These activities' legalization will allow individuals, companies and other public and private entities to produce, consume, share, store and sell energy produced from RES, actively participating in the energy transition. Decree-Law 15/2022 (PORTUGAL, 2022) establishes the organization and functioning of the National Electric System of Portugal, incorporated the provisions related to renewable self-consumption, updating Decree-Law 162/2019. Decree-Law

15/2022 covers matters such as the commercial relationship between the intervening entities, the measurement, and provision of data, the energy sharing modes between self-consumers or the application of regulated tariffs and prices.

In Spain, the self-consumption of electricity for grid-connected users is regulated by two Royal Decrees 15/2018 (ESPAñA, 2018) and 244/2019 (ESPAñA, 2019). The first one deals with the urgent energy transition and consumer protection measures. The second decree regulates the technical, economical and organizational aspects of the electricity self-consumption. The Royal Decree-Law 15/2018 guides the energy transition towards a renewable energy-based model. The “solar tax” (ESPAñA, 2015) is extinct, shared self-consumption is recognized by law and greater dissemination of Electric Vehicles (EV) is encouraged. To complement the previous decree on self-consumption, Royal Decree-Law 244/2019 was published. Among other actions, this decree defines the different types of self-consumption, recognizes the collective self-consumption, and defines the idea of a "production facility close to those of consumption and associated with them". This last one authorizes the self-consumption for generation facilities in the same house or other facilities nearby.

The French government is also an example of passing laws and regulations in the last few years to increase consumer-side decisions (FRANçAISE, 2017c; FRANçAISE, 2017b; FRANçAISE, 2017a). These laws define self-consumption (FRANçAISE, 2017c), which can be total or partial, individual or collective, on the scale of a construction, a co-ownership, or a district. Electricity sharing is also regulated (FRANçAISE, 2017b). The concept of "*collective self-consumption*" allows geographically close prosumers to share energy. Amends to the regulatory framework were approved in the law (FRANçAISE, 2017a), in which the conditions for the purchase of PV generated energy up to 100 kW were defined.

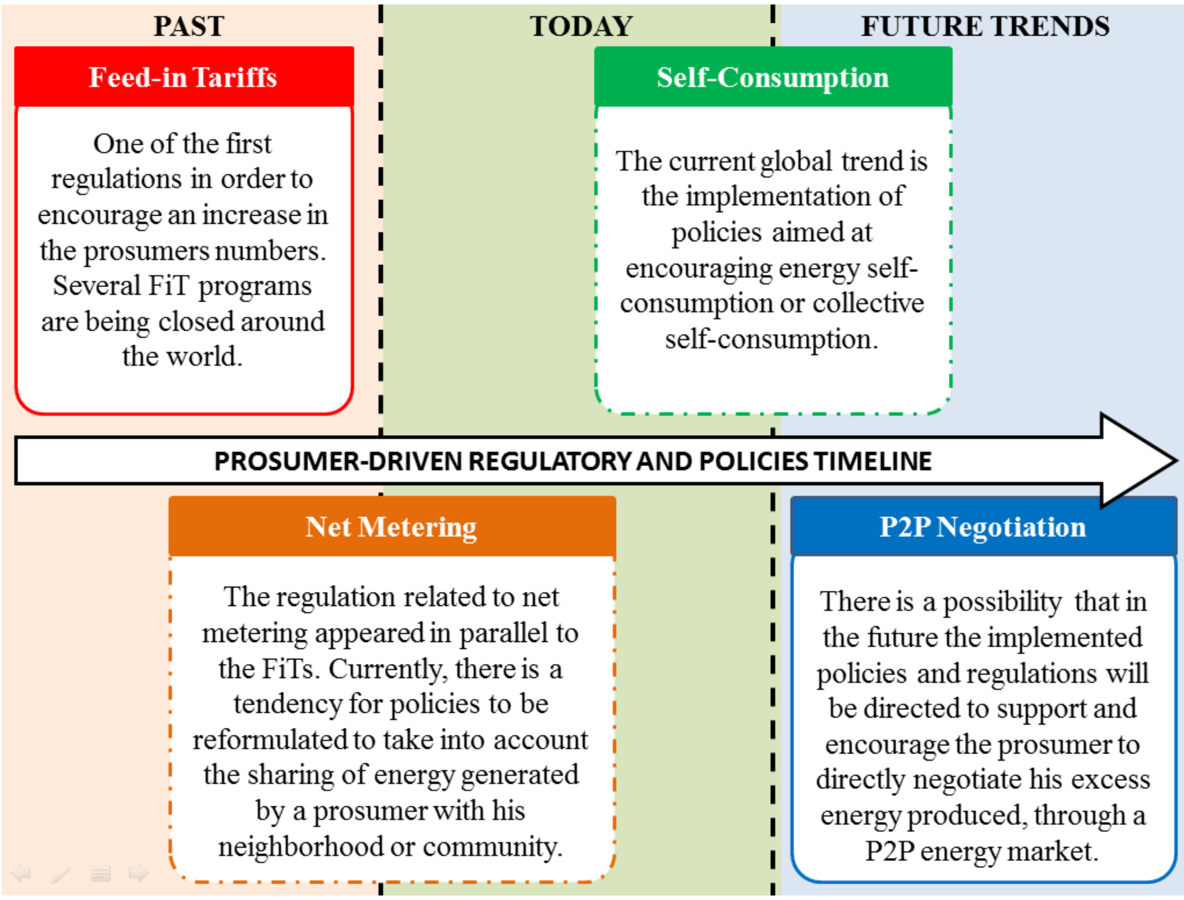
Italy started using the net-metering mechanism in 2009. The systems included in this change were, initially, those below 200 kW. However, in 2015 this limit became 500 kW. This change can be seen as a proposal that mixes self-consumption with net billing features. After the end of the FiT law, net billing is the only scheme left. Above the 500 kW limit, a pure self-consumption scheme is used (MASSON; BRIANO; BAEZ, 2016).

In Denmark, prosumers may apply to sell their surplus electricity back to the system through the DSO permission (ENERGINET, 2019). The net-metering scheme used in Denmark is similar to the others previously explained. In Denmark, collective self-consumption is allowed on a building scale. For this purpose, the generation plant and also all consumers must have a utility meter in common, connecting everyone in a private network. Hourly net metering and instant net metering are in effect nowadays. The building owner, using each tenant’s meters, can perform internal billing. Therefore, the building owner is responsible for meter administration (FRIEDEN et al., 2019).

#### 2.1.2.1 *Regulatory summary through a timeline*

After the literature survey prepared in the previous section, it is possible to summarize the main policies and regulations that have been implemented and adopted by different countries in order to benefit, encourage and allow greater participation by the prosumer in the energy market. Figure 2 shows a timeline comparing what was the focus of these regulations and policies in the past, what is prioritized today and what may happen as a future trend.

Figure 2 – Regulatory timeline for prosumers proliferation in the power system.




**Source**: Author's figure

FiT policies played a prominent role in encouraging distributed generation through the deployment of prosumers worldwide. This incentive worked because it allowed a fixed and secure return on investments made by prosumers in the equipment and technologies necessary for the implementation of their generation systems, giving them the certainty of investing in technology that was still uncertain. However, now the technology is already tested and well known. Thus, in recent years, many countries have begun to move away from FiTs, replacing them with more market-driven mechanisms to encourage greater inclusion of prosumers. The UK, Germany, Denmark and Spain are examples of countries that are moving away from the FiTs and looking for new alternatives.

The net metering scheme increases the system's flexibility, encouraging self-consumption of energy by prosumers. Like FiTs, it tends to lose space for market-driven alternatives. One of these alternatives is Net Billing (ANISIE; OCENIC; BOSHELL, 2019), which is a mechanism in which the prosumer's compensation is based on the real market value of the kWh consumed or injected into the grid. Another innovative trend is an arrangement where it is possible to apply this mechanism, even if generation and consumption are located in different physical locations (also known as virtual net billing) (SHAW-WILLIAMS; SUSILAWATI, 2020).

Self-consumption policies are the current global trend, more specifically, policies and regulations dealing with collective self-consumption, for example, the EU Directive 2018/2001 (COMMISSION, 2018). Collective self-consumption legislation still needs to move forward (FRIEDEN et al., 2019). Currently, the promotion of self-consumption policies follows the trend of 3D's, seeking more energy security and minimizing the sector's environmental impacts. Existing collective self-consumption laws are still insufficient to provide a solid regulatory framework for the prosumer or the prosumer communities. As it is very likely that new BMs and financial models will emerge, the new laws and regulations that are created must take into account the potential for existing innovation and allow some level of experimentation. To this end, they must have legal provisions that allow periodic monitoring and evaluations to facilitate specific changes, guaranteeing the necessary future improvements in the legislation (FRIEDEN et al., 2019).

Possibly, the evolution of the P2P energy markets will contribute strongly to the development and implementation of policies and regulations, in order to legally support and encourage prosumers to negotiate their excess energy directly with other players in the energy market. The success of this new market model is directly linked to the type of regulatory and energy policy that will be adopted worldwide. P2P electricity trade is a novelty, therefore, several fundamental regulatory questions still need to be studied in detail and answered. The regulations and laws that emerge must be able to clearly establish the role of each participant in a P2P energy market, be it a prosumer who has scaled his generation for self-consumption and only sells any excesses or the prosumer who purposely oversized his generation to benefit from the opportunities in this type of market.

## 2.2 BUSINESS MODELS

In the energy sector regulation, BMs, and market models intertwine and can often be confusing due to their interdependent nature. Regulation sets the framework and rules that govern the energy sector, including market operations, pricing mechanisms, and consumer protection. BMs, on the other hand, define how companies operate within this regulatory framework, outlining their value propositions, revenue streams, and customer relationships. Market models encompass the structures and mechanisms through which electricity is traded and consumed, such as wholesale markets, retail markets, and emerging P2P platforms. However, these concepts can overlap and create complexity as regulatory decisions impact BMs, which, in turn, influence the design and functioning of market models. The interaction between regulation, BMs, and market models requires careful analysis to ensure coherence, transparency, and fair competition in the electricity sector. This thesis explores the interdependence between regulation, BMs, and market models, recognizing their inherent interconnectedness. It acknowledges the challenge of separating these concepts as they are closely intertwined. By examining these themes together, this research aims to provide a comprehensive understanding of how they interact and influence the energy sector dynamics.

The reformulation of government policies and regulatory framework are essential to promote greater participation of prosumers in the electricity market. This new paradigm can lead to innovative BMs that will be crucial for prosumers to profit from investing in renewable sources (FERROUKHI; SAWIN; SVERISSON, 2017). Many new BMs are reshaping the way renewable energy projects are conducted. Some of these models are completely innovative when they bring a new concept or technology to improve the business. On the other hand, there are also some BMs already used in diverse areas but consisting of new applications in the energy sector.

In (MOURA; BRITO, 2019), the authors claim that policies for integrating prosumers with the energy market increase the market potential of distributed generation and helps to improve traditional self-consumption policies. Although the adoption of new policies aimed at aggregating prosumers leads to new BMs, these are not necessarily essential. In many cases, new legislation is not necessary for prosumers to be able to participate in the electricity market. SOM Energia (ENERGIA, 2019), Sonnen (SONNEN, 2019), and Powerpeers (POWERPEERS, 2019) are good examples of projects that make it possible to integrate the prosumer without changing existing regulations.

SOM Energia, a Spanish company, has been developing some renewable energy projects. The company provides its customers/members with the opportunity to supply all their electricity consumption through 100% renewable sources, all at a price very similar to that paid for conventional energy. There is a fixed contribution to become a member. This amount is paid only once, with no annual fee and is refundable if the member leaves the community. Sonnen is a battery manufacturer (sonnenBatterie), with sonnenCommunity being a community formed by sonnenBatterie owners. Every member can share the energy produced with other members. The balance between energy supply and demand for all sonnenCommunity members is achieved through central software, where everyone is monitored continuously. The company charges a monthly membership fee. Powerpeers makes energy matching between small RES and consumers, charging a fee for the app usage. It allows consumers to choose which producer they want to buy depending on the price of energy, type of technology, geographical location, and type of business involved.

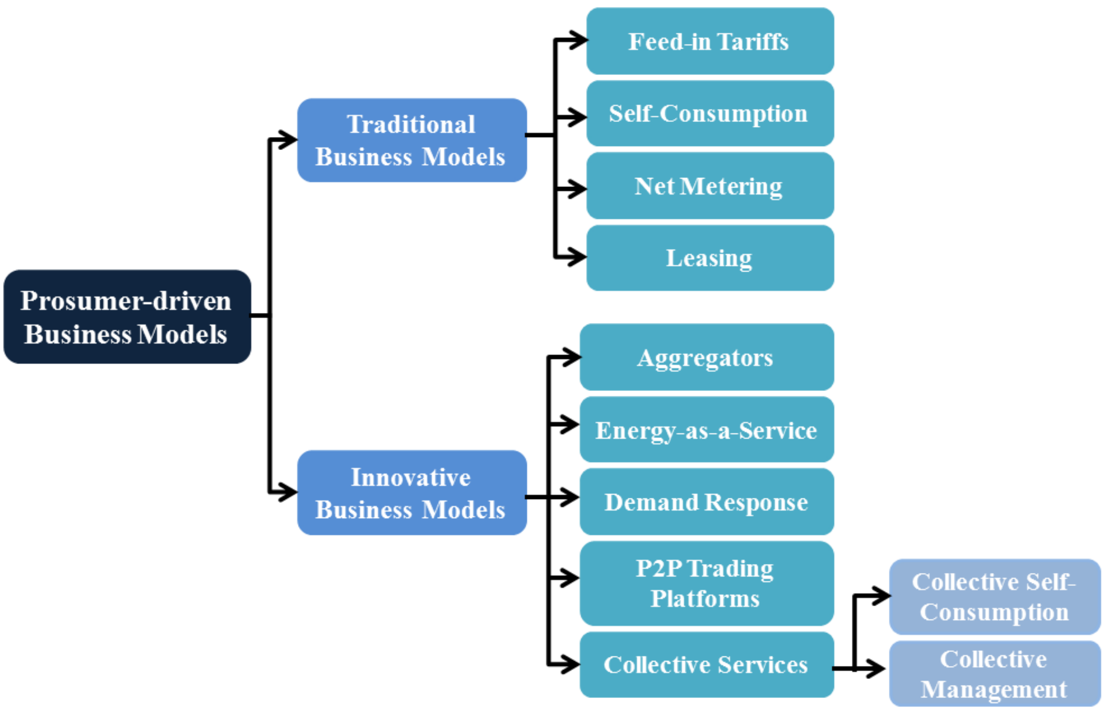
In terms of energy storage, before focusing on BMs, it is important to understand the historical regulatory framework developed according to traditional distribution grid infrastructure.

Thus, the Energy Storage System (ESS) may be technically able to provide essential grid services that are used to pay off new network investments and to avoid dispatch risks or network violations. In most regulations around the world, ESSs are associated with Ancillary Service (AS), network support and the reserve market. These services are connected to the transmission and distribution network (medium voltage) in most cases for large-scale service.

In the case of the battery ESS BM, there are still non-defining rules for regulating its application for small-scale services, such as for prosumers. Therefore, regulators need to address the classification of ESS services and applications in the P2P environment at two options: system support resource and prosumer asset. In the first case, the ESS can be used to improve the grid flexibility and enable the dispatch of other resources for participating in the P2P market. In the second, the ESS can be a prosumer integrated into another resource, such as PV or load. In the United States (US), the largest competitive wholesale electricity markets for battery ESS, the Order 841 of the Federal Energy Regulatory Commission (FERC) established guidelines for market operators to develop rules for encouraging storage units' participation in the energy, capacity, and AS markets. Moreover, prosumer aggregation policies to the energy market are essential and enhance the RES market potential and traditional self-consumption policies (MOURA; BRITO, 2019).

Based on the above analysis, prosumer-driven BMs could be categorized into traditional BMs and innovative BMs. The main BMs of each category were highlighted, as shown in Figure 3.

Figure 3 – Business models classification.




**Source**: Author's figure.

Essentially, traditional BMs were considered to be those based on the first forms of incentive to include the prosumer in the energy market, such as FiTs, Net metering, Self-consumption and Leasing, heavily based on government incentives and subsidies. On the other hand, innovative BMs were considered to be those that depend on the further development of new technologies, such as smart devices, Internet-of-Things (IoT), ICT, etc and also businesses that have a market-driven BM, such as P2P trading platforms, for example.

### 2.2.1 **Traditional prosumer business models**

In a review study presented by Medved et al. (2017), there is an exhibition of new BMs and technologies that can enable and maximize the efficiency of the proposed business concepts for the future. Notable among these are the concepts already mentioned such as Net-metering (VIEIRA; SHAYANI; OLIVEIRA, 2016) and self-consumption (VIEIRA; MOURA; ALMEIDA, 2017).

The self-consumption BM decreases the network load and increases its stability, contributing to a viable long-term solution. This has been encouraged by the EU, as mentioned earlier. The self-consumption included in this section is the most common type of self-consumption, where a prosumer generates his energy by installing a PV system in his home, for example. Other types of self-consumption were classified as innovative, so they are explained in section 3.2. Traditional self-consumption is commonly associated with Net-metering or FiTs.

Net metering is a model of contract in which a consumer who owns his generation is linked to the energy utility in his region. In this contract, the prosumer performs self-consumption, and the excess electricity produced is injected into the network. The consumer receives credits as a form of payment for energy produced in excess. The customer can use the credits received in previous months to reduce the amount of his monthly invoice (the credits are generally valid for one year) (ROUX; SHANKER, 2018). Briefly, the net-metering scheme is an incentive for energy self-consumption through a tax exemption.

Other models may be based on FiTs (WINTER; SCHLESEWSKY, 2019; HITAJ; LÖSCHEL, 2019). The evolution of this model for PV generation generally follows the following sequence:

- Excess PV electricity gets a FiT;
- Excess PV electricity gets a Feed-in Premium above the market price;
- Excess PV electricity gets the market price through an aggregator; and
- Excess PV electricity gets the market price directly.

Another example of a growing BM is Leasing, in which customers hire a company to install a renewable energy system and pay rent for that system or a fixed price per energy generated. At the contract's end, customers can purchase the system, extend the contract, or remove the system for free. Thus, without a large initial investment, an individual can become a prosumer by renting a generation system. The leasing model employed in small-scale wind-based has the potential to modify the market and benefit prosumers (GROOM, 2016).

Vivint Solar's (VIVINT, 2019) customers can lease a system or purchase energy based on a long-term contract, a Power Purchase Agreement (PPA). In this PPA scheme, only the amount of electricity that the PV system actually produces is converted into a fee that customers must pay. The fee is proportional to the kWh consumed. In the lease scheme, customers pay a monthly amount, which is calculated taking into account a forecast of what will be generated by the PV system. If the leased system does not reach the agreed generation level, the company guarantees the customer a payment corresponding to the contracted system.

Sunrun Inc. (SUNRUN, 2019) is a US-based residential solar electricity provider with a BM in which it offers customers either a lease or a PPA BM. In this case, homeowners pay for electricity usage, but have not purchased solar panels yet, reducing the initial capital outlay required by the homeowner. The company performs the installation and maintenance of the equipment as well as the necessary monitoring and repairs. In the leasing case, the company receives a percentage of the amount saved by the customer on the energy bill.

Like popular solar lease programs, United Wind's (WIND, 2019) lease program allows farmers or other landowners, at no initial cost, to power their homes or businesses through small wind turbines, producing from half to all their electricity needs, reducing total energy costs. Monthly customer payments are United Wind's primary source of revenue. The distributed wind becomes cost-competitive with power from the network, as it is qualified to obtain federal tax credits and state incentives.

### 2.2.2 **Innovative business models**

Increased environmental awareness among consumers means that innovative BMs are gaining more and more space. Thus, when the prosumer has no physical space available or does not have the financial means to pay for his renewable energy system, he has the opportunity to acquire the asset through models where the necessary investment is shared. Collective management of energy assets through community schemes allows members of an energy community to share the benefits of a renewable energy system (MORONI et al., 2019). Medved et al. (2017), briefly introduce energy cooperatives (HERAS-SAIZARBITORIA et al., 2018), crowdfunding (LAM; LAW, 2016), and the possibility of additional income for prosumers by providing AS such as voltage control and power reserve provision.

The innovative BMs presented here are divided into 5 subsections for better organization and understanding, highlighting the main characteristics of BMs and also pointing out examples of companies that use them. It is worth noting that after a detailed analysis of the specialized literature and the BMs of different companies, it is observed that some companies may have a

BM that fits at the same time in more than one of the subgroups highlighted below.

2.2.2.1 *Aggregators BMs*

To manage a small prosumers group and thus create capacity similar to that of a conventional power plant, aggregators appear (also called virtual plants). Aggregators use ICT-based systems to be able to virtually control distributed RES. In this way, aggregators can sell electricity or AS in the wholesale energy market (MORSTYN et al., 2018). Some countries already have specific regulations for aggregators, like Australia, Belgium, France, Germany, Netherlands, UK, and the US (GIELEN et al., 2019a). Aggregators, by definition, are legal entities whose goal is to optimize, technically and economically, energy consumption and production. Consumers and producers can be included in the aggregated pool, which can operate both in multiple electricity markets or in only one. In order to address issues around aggregation the BestRES (VERHAEGEN; DIERCKXSENS, 2016) project was initiated with Horizon 2020 (HORIZON, 2016) research funding support. The program ended on February 28, 2019. In this study, one can identify some ready-to-implement BMs, like:

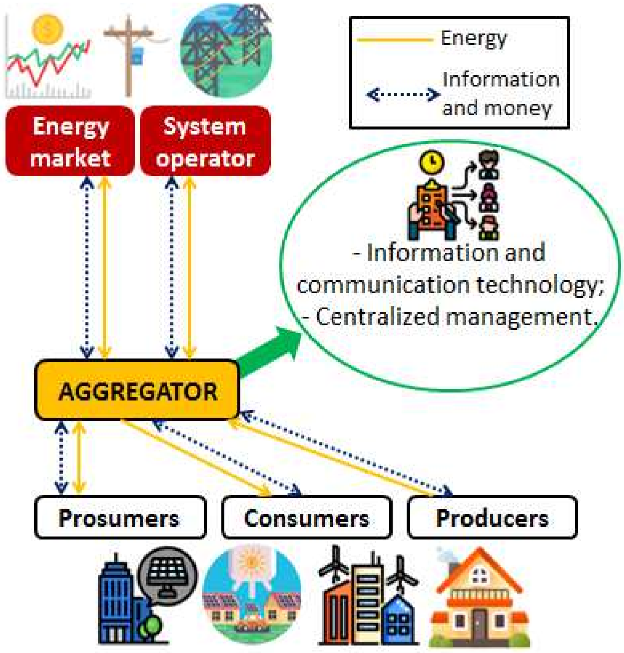
- **Combined aggregator-supplier:** There is only one Balancing Responsibility Provider (BRP) at the connection point, and a package is offered for supply and aggregation;
- **Combined aggregator-BRP:** The supplier is compensated for imbalances. The independent aggregator and the supplier are on the same connection point;
- **Independent aggregator as a service provider:** The aggregator does not sell to potential buyers on its own but provides services for one of the other market actors;
- **Independent delegated aggregator:** The aggregator sells to the Transmission System Operator (TSO), the BRP or the wholesale electricity markets on its own risk; and
- **Prosumer as aggregator:** A big prosumer becomes an aggregator of his portfolio.

On the one hand, combined aggregators do not demand significant regulatory changes, and therefore, are more compatible with the existing electricity markets. On the other hand, independent aggregators can provide a greater market opening to new players as they increase competition.

Aggregators use systems with centralized information and communication technologies to remotely control distributed RES, optimizing their operation. They can provide services such as load shifting, balancing services for transmission system operators, local flexibility for DSOs, other ancillary services for system operators, and other services (IRENA, 2019a). The basic aggregator's operation structure can be seen in Figure 4.

The development of this type of BM requires a liberalized wholesale energy market, with clear price signals to guide the aggregators' operations, since the variation between prices is the

Figure 4 – Aggregators' structure.




**Source**: Author's figure.

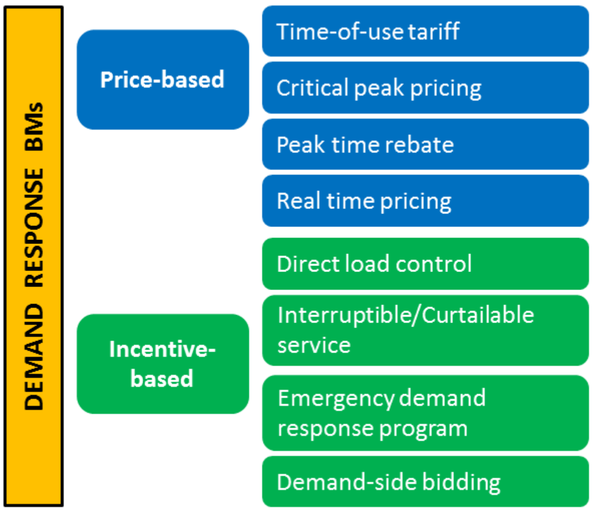
main incentive for the aggregator's BMs. Aggregators must be supported by legislation to be able to participate in both the electricity and AS markets (ROSSETTO; REIS; GLACHANT, 2019). Advanced measurement and forecasting infrastructure with real-time data acquisition technologies, ICT and network digitalization are essential, as aggregators operate by optimizing supply and demand, depending on the energy price at different times or providing AS when needed. Companies like Tesla (TESLA, 2019) develop projects based on energy aggregators, like South Australia's Virtual Power Plant (PLANT, 2020).

#### 2.2.2.2 *Demand response BMs*

There are also other models based on Demand Response (DR) (LYNCH et al., 2019), driven by recent advances in information technology and control. DR has gained increasing importance at the domestic level with the maturation of the IoT. For large players in the market, DR is already a reality. However, the concept is relatively new when applied to small and medium prosumers (MCPHERSON; STOLL, 2020; PALLONETTO et al., 2020). Leutgöb et al. (2019) points out that, despites the existence of technological solutions for DR-based programs, it is still necessary to develop appropriate BMs for small and medium prosumers.

According to the Smart Energy Demand Coalition (COALITION, 2016) there are two ways to monetize DR. Depending on the signal given to the consumer, DR-based BMs can be categorized into price-based (also known as "Implicit use of DR") or incentive-based (also known as "Explicit use of DR"). The first refers to the change in the energy use profile as a result of price variation over the hours of the day. In this way, the consumer prioritizes energy use when the price is lower and reduces energy usage when the price is higher. The main variations of this program are: time-of-use tariff (CELEBI; FULLER, 2012), critical peak pricing (HERTER, 2007), peak time rebate (VUELVAS; RUIZ, 2017), and real-time pricing (ALLCOTT, 2009). The second category offers consumers financial incentives to reduce demand at critical moments in the system, when the supply margin is low or when there is a drop in reliability. The flexibility of these consumers must be dispatchable, as they are triggered through a dispatch order from the operator. The main variations of this second category are: direct load control (CHEN; WANG; KISHORE, 2014), interruptible/curtailable service (AALAMI; MOGHADDAM; YOUSEFI, 2010), emergency demand response program (AGHAEI et al., 2016), and demand-side bidding (ADIKA; WANG, 2014). A summary of the DR-based BM is shown in Figure 5.

Figure 5 – Demand response business models summary.




**Source**: Author's figure.

Leutgöb et al. (2019) categorized five types of DR-BMs:

- **Explicit DR as stand-alone service:** The DR potential of many small consumers is grouped and managed by a third party. For the success of this BM, access to switched equipment and better forecasting software is required.
- **Explicit DR combined with energy efficiency services:** This BM seeks to optimize the interaction between DR and energy efficiency in the consumer's daily life. Only a few pilot projects have been carried out in this area (YORK; RELF; WATERS, 2019).
- **Implicit DR service for optimal use of Time-of-Use (TOU) contracts:** This BM is based on the variation in the price of electricity depending on the time when the energy is used. Currently, only TOU (CELEBI; FULLER, 2012) contracts are an option for small and medium-sized prosumers, but it is expected in the future that prosumers will be able to opt

for more market-driven options such as those based on real-time-pricing (JIANG et al., 2019; WANG et al., 2017). The value generation of this BM depends on the difference between the highest and lowest energy price on the day.

- **Implicit DR including power supply:** Combination between DR services and the retailer's role in the energy market are the basis of this BM. It takes a step beyond TOU contracts including the active management of customers' consumption profiles. The subsidy for smart devices, the availability of software to control these devices and the training and information of small and medium prosumers are essential for this BM success.

- **Microgrid Management:** It consists of managing the operations of all energy resources of an energy microgrid (OLIVARES et al., 2014). If operated in an isolated manner, the use optimization of the energy storage equipment is essential. If connected to the grid, the manager can use any of the previous BMs to generate value for all prosumers and consumers who are part of the microgrid.

Companies using one or more of the BMs presented above are highlighted below. An example of a DR-based BM is that used by the Swiss company Tiko (TIKO, 2019). The company is already managing more than 6,500 homes using professional DR to, for example, provide AS and improve customer energy efficiency.

Tiko Energy operates in the automated management of devices such as batteries, heat pumps, water heaters, solar panels, and electrical outlets. The company allows users to control their energy consumption according to their specific needs and energy budget, through a personalized dashboard that groups all data related to the energy consumption of the various devices that these users may have.

The control of energy production and consumption are planned and implemented through methods based on Energy Management Systems (EMS). Energy cost savings and conservation, climate control, and protection are the most important objectives. Rainforest Automation (RAINFOREST, 2019) provides devices and services that work together to automate and optimize residential power usage.

Other models based on Batteries (LONG et al., 2018) and EVs (ALVARO-HERMANA et al., 2016) drive household self-consumption at much higher rates. Companies like Tesla (TESLA, 2019) are already developing home battery systems to increase end-user independence on energy prices and promote self-generation and self-consumption.

#### 2.2.2.3 *P2P trading platforms BMs*

The study (ROCHA; VILLAR; BESSA, 2019) points out that the P2P energy market is quite important in the context of "*local energy markets*". P2P BMs can generate value through energy cost savings, grid cost savings or by offering new grid services. Prosumers can trade their energy freely in the market and the peers involved in trading are protected from the volatility of retail markets. Since energy exchanges occur locally, between neighbors, there is a reduction in electrical losses in the system (DULĂU; ABRUDEAN; BICĂ, 2014). Additionally, by pooling resources from several small prosumers, flexibility services can be offered to TSO, DSO or BRP (VILLAR; BESSA; MATOS, 2018).

The large-scale implementation of P2P trading platforms, which provide a strong incentive for prosumers, still requires regulatory adaptations. Some examples of countries that already have projects in progress in this area are Bangladesh with SOLShare (SOLSHARE, 2019), Germany with Lumenaza (LUMENAZA, 2019) and sonnenCommunity (SONNEN, 2019), the Netherlands with Vandebron (VANDEBRON, 2019) and Powerpeers (POWERPEERS, 2019), and the UK with Piclo (PICLO, 2019).

SOLshare has developed SOLbazaar, an IoT-driven trading platform which enables prosumers to trade the excess solar energy generated by Solar Home Systems (SHS). Consider the SOLbazaar as an energy marketplace where SHS users can sell their excess generation to other users. The company charges a fee for each KWh shared between neighbors.

Lumenaza connects local producers and consumers of renewable energy, using the software called "utility-in-a-box", with the intention of creating and stimulating a green, regional, community, and transparent electricity market. The system can virtually handle all the functions of an energy service provider in a modular and highly automated manner: Monitoring renewable power production, balancing supply and demand, and organize billing. This BM includes the one-time calculation of the set-up effort for a project as well as variable license fees depending on the number of customers supplied and the amount of electricity purchased.

Vandebron is a green energy company that delivers electricity and gas to individual or business customers. Although the company does not generate energy itself, it negotiates and sells electricity from independent energy producers. Producers are located on farms or larger wind parks, and the energy is obtained from solar, wind, and biomass resources. Customers are free to choose which producer they want to buy the energy needed to supply their demand. Producers, on the other hand, determine what price they will offer for the energy they generate. The company's revenue comes from a subscription fee that is paid by consumers and producers.

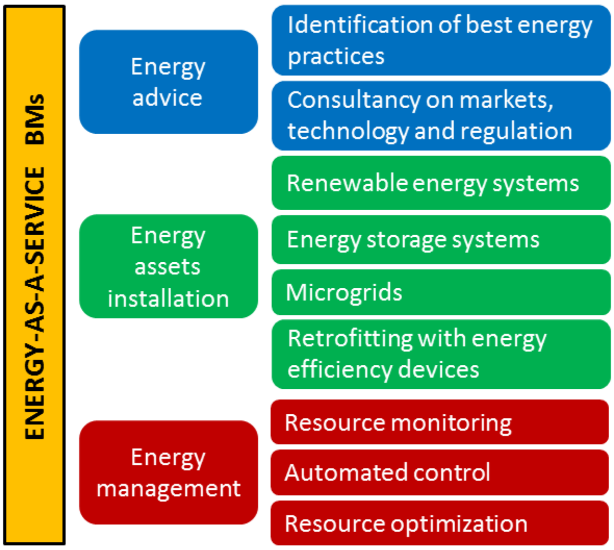
With Piclo, consumers and producers can buy and sell their electricity or flexibility through an online trading platform, backed with intelligent peer-matching algorithms. The company's users can choose the renewable source that will supply them and can also view every 30 minutes, the amount of generated energy during the day.

P2P electricity trading can theoretically function as a business model regardless of the existing market. However, this is generally not the case in practice. Most existing P2P platforms operate in conjunction with the traditional energy market (SOEST, 2018).

#### 2.2.2.4 *Energy-as-a-Service BMs*

Instead of only selling energy, the prosumer can explore selling a full range of electricity-related services. The so-called Energy-as-a-Service (EaaS) (VELLA, 2019) operates behind-the-meter services such as demand management, energy storage, electricity exchange between local networks, energy-saving advice, and comfort and safety measures. Companies like Germany's E.on (E.ON, 2020) are active in this area. An overview of the services that can be made available by an energy service provider is shown in Figure 6.

Figure 6 – Services offered by energy service providers.




**Source**: Author's figure.

EaaS-BMs generally take the form of a partnership between companies and external energy specialists, where this specialist investigates all aspects of energy management and supply. It combines all this information with his energy sector knowledge to propose energy solutions that are beneficial to the company. The proposed solutions can be: ways to save energy, how to make operations more efficient or the best way to obtain the energy you use, including how to produce and store it. The best technology in terms of EMS and smart devices can be made more accessible through EaaS companies. The application of EaaS-BM for residential and community solar systems is a good example of how EaaS has been used to overcome barriers to the use of low carbon technologies. Companies like SunRun (SUNRUN, 2019) and Vivint Solar (VIVINT, 2019) stand out by combining EaaS with leasing.

In (XU; AHOKANGAS; REUTER, 2018), the authors categorized four types of EaaS-BM:

- **Energy Connection-as-a-service:** Companies that provide connectivity solutions with one or more networks. This BM is based on the concept of Shared Network Access (SNA) for DSOs (LI et al., 2017). Through SNA BM, the DSO shares its access to the assets and operations of the power grid with licensed third parties, receiving a lease. This other participant receives the name of "secondary DSO"and can introduce new service offers on the market even without having the physical distribution network that remains the DSO's property.

- **Energy Supply-as-a-service:** This BM combines the existing network infrastructure with the energy supply infrastructure. Its value generation comes from RES integration and power quality. Companies like Senec (SENEC, 2020) and Lichtblick (LICHTBLICK, 2019) use this type of BM. These companies manage energy generation or storage using ICT tools to maximize the distributed RES supply.
- **Energy Data-as-a-service:** This BM is based on software and data platforms. The increasing energy sector digitalization allows a large amount of data accumulation that, together with ICT and artificial intelligence technologies, allows the development of BMs that create value from the collected data analysis, increasing network reliability and providing flexibility. An example of this BM is Fingrig's Datahub (FINGRID, 2020), a platform that provides open access to consumption data and retail electricity prices. The value creation of this BM comes from the development of new applications and intelligent energy services.
- **Energy Application-as-a-service:** It is a BM that groups energy and data supplies and also provides a specific application or market for energy, data or connectivity negotiations to take place. This BM seeks to reduce the barriers between end consumers and producers, in addition to allowing greater prosumer integration in the energy market. Companies that have this BM operate, mostly, through e-commerce software or application. Companies like Vandebron (VANDEBRON, 2019) use this type of BM.

Another BM that should be mentioned is the Energy Storage as a Service (ESaaS) that enables a facility, even without buying the battery system, to take advantage of an ESS through a service contract. ESS provides a set of services with a focus on improving electricity resilience, generating more revenue, and increasing savings. The operation of the ESaaS system through a service contract or even through an EMS, both based on an advanced battery storage system, can add value to the business by providing this energy reliably and economically.

#### 2.2.2.5 *Collective services BMs*

Finally, BMs based on collective services, like self-consumption are gaining prominence. The EU promotes the principle of energy communities. A local, virtual and flexible community where every customer/user is connected to an energy point (the same low-voltage substation, for example) could join or leave this community quickly and easily, which can be achieved through collective self-consumption. Under the current regulation, only energy community where members are at the same point is allowed, but a relaxation of the regulation is expected to allow the energy community in a broader sense.

The emergence of specific and multiple models of collective self-consumption through an existing legal framework or within pilot initiatives is due to the lack of a clear legal framework in the various European countries.

The Council of European Energy Regulators categorized three different BMs (BRASSAR XAVIER HANSEN; VöGEL, 2019):

- **Community owned generation assets:** This is the most common case. Renewable energy, in this case, is resold to a supplier instead of being consumed by the community members. Revenues are shared among members or re-injected into other renewable production projects. Citizens' cooperatives that have their own renewable energy generators are usually part of this structure;
- **Virtual sharing over the grid:** The community uses the public electricity grid to share all the renewable energy produced among its members. The balance between generation and consumption is carried out by a common energy supplier who is also responsible for organizing the sharing; and
- **Sharing of local production through community grids:** In this BM that has traditionally developed on disconnected energy islands, the community uses a private network to share the energy produced. However, initiatives based on this model have also emerged in regions with public networks, motivated by the desire to reduce grid tariffs and produce/consume energy locally.

An example of a local energy community is LEF (LEF, 2019) in the Hoog Dalem district in Gorinchem, the Netherlands. An energy community is formed by a group of approximately 15 homeowners that generates its own electricity. LEF's purpose is to perform electricity self-consumption as well as, if necessary, the mutual exchange of electricity between community members. The necessary electricity can also be bought from the grid, if there is not enough self-production to serve everyone, through the use of flexibility or AS.

The local energy market works based on blockchain technology. This allows local end-users to bid for electricity supply or demand. The software collects data from household appliances, matches that data to the weather, and thus allows bids to be generated. The data collected allows a more accurate forecast of energy demand and, from that, a market emerges from this game of supply and demand.

Another category included in collective services is the *energy cooperatives*. Consumer cooperatives is a company created by the union of several small and medium-sized prosumers and consumers that aims to better meet the energy needs of all its members. The study (DILGER;

KONTER; VOIGT, 2017) provides a conceptual framework for this BM and categorize it depending on the members' roles. The authors of (HERBES et al., 2017) highlight that the main barriers faced by energy cooperatives are: risk aversion, possible environmental impacts, and the lack of competence from cooperative managers. An example of using this type of BM is the Dutch Windcentrale (WINDCENTRALE, 2019), which allows the consumer to co-own a wind turbine. Any Dutch citizen can buy equity shares for 250-300 euros. One share equals approximately 500 kWh per year. Windcentrale manages the project only by taking a fixed fee per share (10%), so it does not own equity.

### 2.2.3 **Other real examples of prosumer-driven Business Models**

The study (BURGER; LUKE, 2017) presents an empirical analysis of the most common BMs for implementing power management and DR systems, PV solar resources, and electricity or heat storage. A detailed analysis of 144 BMs is made comprising the electricity service technology, the captured revenue stream, customer segment as well as DR resource for each model. This study highlights that the current BMs for distributed energy resources are driven more by regulatory and political factors than by technological factors.

Table 1 lists some real companies that contribute to foster the prosumers integration, their BMs, and the services that are provided by them. The basic ideas for each BM presented in this table were detailed in the previous sections.

For the business viability of providing electricity services, specific regulations and policies are extremely important because they guide the formation of BMs. Thus, regulators and policymakers must adapt themselves and contribute to the structuring and sustainability of long-term BMs. Continuous research is needed to achieve ideal policies and regulations aiming at avoiding over-reliance on these aspects. Evidence suggests that lower dependence levels are achieved through market-oriented schemes. Regulatory and political dependence is a tangible and significant risk for innovative businesses and technology.

### 2.2.4 **Business models' summary**

A brief summary of the different BMs characteristics detailed above is presented in Table 2. This summary presents and classifies which areas need further development for the successful implementation of the BM, i.e., the areas on which the BM is most dependent. The classification was carried out on a theoretical basis taken from the studied references.

## 2.3 TECHNOLOGIES

Coupled with innovative BMs are the new technologies needed to better and further develop the infrastructure that is essential for promoting full prosumer integration into the energy market.

Table 1 – Real examples of companies and their respective BMs.

| Business Model | Electricity Service | Typical Services | Exemple |
|---|---|---|---|
| Demand Response | Large DR resources | Firm capacity, operating reserves and constraint mitigation. | Enel X (ENEL, 2019) and Restore (RESTORE, 2019) |
| | Small DR resources | Firm capacity, operating reserves and constraint mitigation. | Ohmconnect (OHMCONNECT, 2019), Encycle (ENCYCLE, 2019) and Lichtblick (LICHTBLICK, 2019) |
| Energy Management System | EMS Providers | Non-electricity services. | Gridpoint Energy (ENERGY, 2019b), Blue Pillar (ENERGY, 2019a), Rainforest Automation (RAINFOREST, 2019) and Wiser/Schneider Electric (WISER, 2019) |
| Electricity and thermal storage for network services | Network Services | Firm Capacity, operating reserves, network constraint mitigation. | Invenerge (INVENERGY, 2019), Greensmith (GREENSMITH, 2019), Younicos (YOUNICOS, 2019), AES Energy Storage (AES, 2019), Ecoult (ECOULT, 2019) and Ambri (AMBRI, 2019) |
| Energy storage for end-user optimization | Energy Storage | Firm capacity. | Stem (STEM, 2019), Younicos, SolarCity\Tesla (TESLA, 2019), Sungevity (SUNGEVITY, 2020) and Sonnen (SONNEN, 2019) |
| Storage for end-user and system co-optimization | Energy Storage | Firm Capacity, operating reserves and network constraint mitigation. | Stem, Green Charge Network (NETWORK, 2019), Ice Energy (ENERGY, 2019c), Advanced Microgrid Solutions (SOLUTIONS, 2019) and Vcharge (VCHARGE, 2019) |
| Solar-plus-storage for end-user and system co-optimization | Solar Energy and Storage | Energy, firm capacity and operating reserves. | Sunverge (SUNVERGE, 2019) and Solar Grid Storage/SunEdison (SUNEDISON, 2019) |
| Distributed solar PV finance and installation | Solar Energy | Energy. | SolarCityTesla, Solairedirect (SOLAIREDIRECT, 2019), SunRun (SUNRUN, 2019) and Vivint Solar (VIVINT, 2019) |
| Community solar | Solar Energy | Energy. | NexAmp (NEXAMP, 2019) and Mosaic (MOSAIC, 2019) |

**Source**: Author's table.

Table 2 – Business models' summary.

| | | Characteristics | | | | |
|---|---|---|---|---|---|---|
| Business models | | Regulatory Framework | Market enviroment | Technology dependence | New infrastructure needs | Summary |
| Traditional BMs | Feed-in Tariffs | + | + | + | n/a | Section 2.2.1 |
| | Self-Consumption | + | + | + | n/a | Section 2.2.1 |
| | Net metering | + | + | + | n/a | Section 2.2.1 |
| | Leasing | + | + | n/a | n/a | Section 2.2.1 |
| Innovative BMs | Aggregators | ++ | ++ | ++ | ++ | Section 2.2.2.1 |
| | Energy-as-a-Service | ++ | +++ | ++ | + | Section 2.2.2.4 |
| | Demand Response | + | ++ | +++ | ++ | Section 2.2.2.2 |
| | P2P Trading Platforms | +++ | ++ | +++ | ++ | Section 2.2.2.3 |
| | Collective Services | ++ | + | ++ | ++ | Section 2.2.2.5 |

+++ More dependent
+ Less dependent
n/a Not applicable

**Source**: Author's table

### 2.3.1 **Data metering and control**

In the coming decades, energy systems tend to become increasingly connected, so digital technologies will play a key role. The energy sector digitization is imminent. Future digitized power systems will be able to supply energy at the right time and place, at the lowest possible cost, to anyone who needs (DIGITALIZATION, 2017).

Big data and artificial intelligence combined contribute enormously to the value creation of the new prosumer-oriented BMs. Moharm (2019) provides a review of the big data application in microgrids.

Another technology that has gained prominence in the energy sector is IoT technologies. IoT enables real-time Internet communication between home appliances, facilitating information collection and exchange. Al-Ali (2016) presents the IoT's role in integrating renewable energy resources into the electricity grid. The IoT association with smart meters for monitoring power quality and reliability is also a study subject (AL-TURJMAN; ABUJUBBEH, 2019). The use of advanced infrastructure based on ICT and control for the total prosumers integration in a smart grid environment is essential since, in this environment, it is necessary to deal with bidirectional data and energy flow (ZAFAR et al., 2018).

### 2.3.2 **Database platforms**

Blockchain can be an important ally in the inclusion of prosumers in the energy market. With this technology, it is possible to manage all devices connected to the grid through intelligent automated contracts, so prosumers and system operators can benefit from the flexibility and real-time pricing (IRENA, 2018). Smart contracts would signal the system when initiating transactions. The balance between demand and supply occurs automatically under predefined rules to ensure that all energy flows involved in the process are controlled. In this way, blockchain technology could directly control network flows and storage facilities (HASSE et al., 2016). Hwang et al. (2017) present a service model based on prosumers applying blockchain. This allows multiple power sources, users and producers to connect more easily.

Another important feature worth mentioning is Cloud Computing (CC). Cloud-based systems allow users to access information with greater flexibility. Information and data from various systems can be obtained, stored, accessed, and analyzed by users through different electronic devices, like applications (CAPEHART; TURNER; KENNEDY, 2006).

The study (BERA; MISRA; RODRIGUES, 2014) shows CC applications within the smart grid concept, focusing on power management, information management, and security. In (YIGIT; GUNGOR; BAKTIR, 2014), CC applications for smart grids are presented in terms of efficiency, security, and usability. Projects such as Globus (GLOBUS, 2019) and OpenNebula (MILOJIČIĆ; LLORENTE; MONTERO, 2011; OPENNEBULA, 2019) are examples of using CC applied for smart grid enhancement. Studies on smart cloud meters are also found in the specialized literature (FANG et al., 2012).

### 2.3.3 **Prosumer market design**

Significant changes are expected to occur in the current energy market structure. Multiple players operating a decentralized power grid will likely be a reality, then policymakers and companies must be prepared for this. Therefore electricity markets need to be restructured so that all participants can benefit from the increasing inclusion of prosumers. The possible market models that integrate prosumers according to study (PARAG; SOVACOOL, 2016) are P2P models, Peer-to-Grid (P2G) integration models, and communities.

Where:

- **P2P model:** prosumers directly interconnect, buying and selling energy services;
- **P2G model:** prosumers provide services to a microgrid that is connected to a larger network;
- **P2G model:** prosumers provide services to an isolated and autonomous microgrid; and
- **Community model:** prosumers gather resources or form a virtual power plant, i.e., a community.

Users on the demand-side of a market with a structure focused on the prosumer can actively offer services that other prosumers or system operators and energy utilities need and not just react to the price signals of the market (HVELPLUND, 2006). Another market design is proposed by Morstyn et al. (2018), where the concept of the federated power plant is created, like a virtual power plant formed through P2P transactions between self-organizing prosumers. Alvaro-Hermana et al. (2016) implemented the P2P energy trade between EVs.

As highlighted by Sousa et al. (2019), recently, the P2P electricity market has emerged as a new proposal to enable prosumers to directly share their electricity and investments. Consumers can freely choose how and from whom they buy their electricity. An alternative structure that should be highlighted is the community-based market (SOUSA et al., 2019). These local prosumer markets are likely to operate in a smart city environment.

Finally, in (ESPE; POTDAR; CHANG, 2018), the authors considering publications in renowned energy and technology journals from 2009 to 2018, present a literature review on the prosumer-community focused on smart grid.

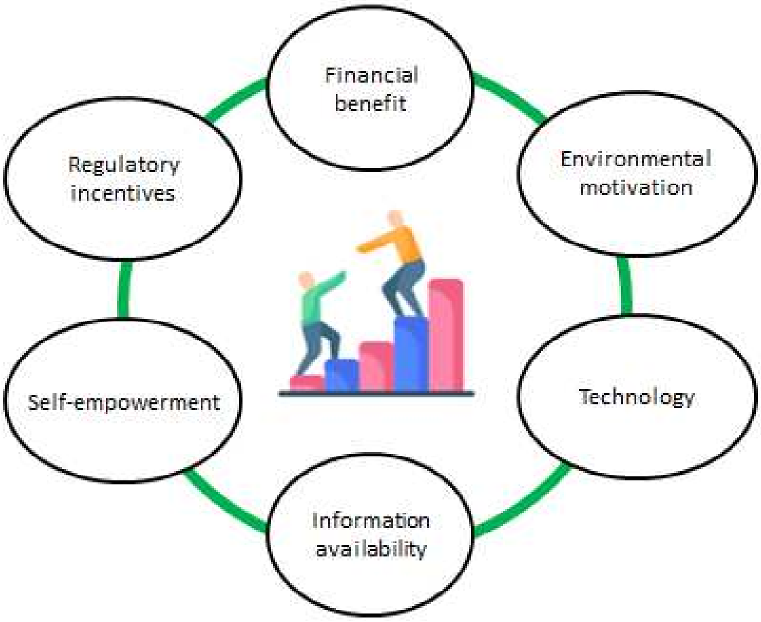
## 2.4 PARTIAL REMARKS

This section is divided into three items regarding the prosumers integration in the energy markets. First, enablers are presented. The second subsection shows the main barriers that must be overcome by prosumers. Finally, the opportunities and recommendations on the topic identified by the authors are exposed.

### 2.4.1 Enablers

There are a number of issues that allow, facilitate and direct the emergence of innovative BMs, the development of prosumer-driven traditional BMs and also the greater prosumer inclusion in the energy market. As enablers, were considered characteristics that can encourage society to want greater prosumer inclusion, encouraging the development of related prosumer-driven BMs, helping to overcome the subsequently established barriers (see section 2.4.2). All issues considered relevant are shown in the Figure 7 and highlighted below.

Figure 7 – Enablers for the prosumer-driven BMs development.




**Source**: Author's figure.

- **Environmental motivation:** a strong motivator for the development of new energy market models with the inclusion mainly of the RES-based prosumer are the environmental issues. The ambition to make the electrical matrix increasingly green and carbon free, allied with the concern to make society less dependent on fossil fuels;
- **Self-empowerment:** the possibility of controlling its own power generation, making it less dependent on centrally generated electricity, sold by a utility. Having the feeling of greater energy security;
- **Financial benefit:** the decrease in costs related to some forms of distributed generation and the increase in prices of energy from traditional sources can make self-production

more accessible and competitive. Especially for energy communities that may have a better potential for financial return;

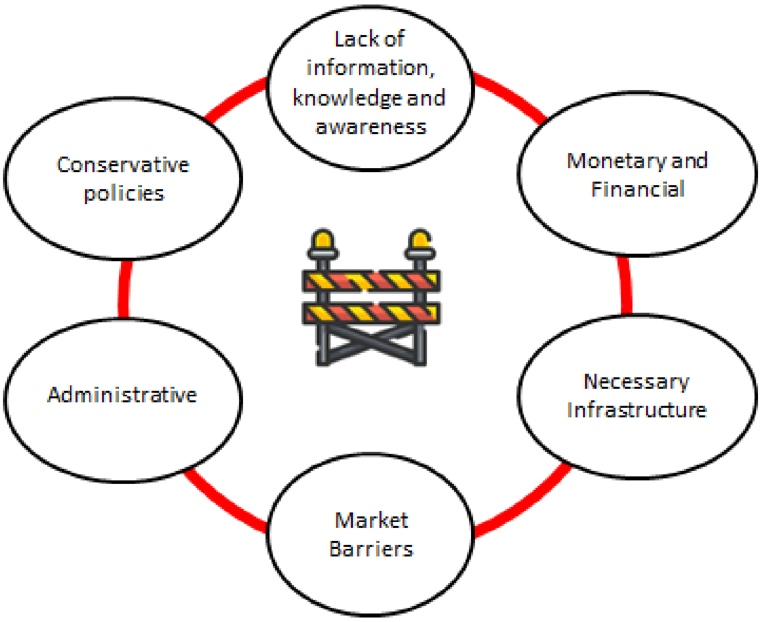
- **Technology:** The emergence of new technologies are extremely important for the formation and development of new BMs. The ability of prosumers to interact with each other and also with the power grid is greatly benefited by advances in EMS, ICT, smart devices and IoT;
- **Regulatory incentives:** a stable regulatory framework is needed to stimulate innovation and provide an attractive business environment for the development of innovative solutions, technologies and services, enabling the emergence of innovative BMs. The regulatory framework must aim to benefit the prosumer's economic development, as well as contribute to a fair allocation of costs and benefits. Becoming a prosumer and investing resources in the development of BMs should become attractive. The regulations developed should make prosumers integrated into the market and the energy system without too many complications. Support schemes must be designed and developed in such a way that they are cost-efficient, transparent and do not cause market distortion. In many regions, states are willing to approve regulations friendly to prosumers;
- **Information availability:** Increasing prosumer participation in the energy market and the innovative BMs development is only possible if these players are well informed, trust the data and information available and have the ability to use technologies and smart devices. New ICT, IoT, blockchain technology and infrastructure such as smart grids are facilitators of the successful formation and management of prosumer groups.

### 2.4.2 Remaining barriers

In addition to the main barriers faced by the prosumer, described in subsection 2.1.1, this section presents what the authors consider as the six key barriers points. These barriers, illustrated in Figure 8, may still delay the development of the prosumer-driven BM and its greater market inclusion.

- **Lack of information, knowledge and awareness:** the lack of information, knowledge and training on the characteristics of the prosumers, P2P energy markets and specific legislation can lead to delays in the development of potential BMs aimed at the greater prosumer inclusion in the energy market. This topic can also lead to insecurity regarding the privacy of personal data related to P2P energy/monetary transactions.
- **Monetary and financial:** refer to the costs and investments required for the prosumer, especially small-scale ones, to acquire the technologies and equipment necessary for the assembly, maintenance and operation of their generation systems. With the decrease in government incentives and the lack of good opportunities for financing small RES, this

Figure 8 – Remaining barriers for the prosumer-driven BMs development.




**Source**: Author's figure.

problem becomes worse. There may still be long payback periods and the financial risks involved may be high;

- **Necessary infrastructure:** availability of the physical and technological infrastructure necessary to efficiently incorporate the prosumer into the existing energy market can be a problem. It is necessary to advance the smart meters technology and also make them cheaper, for example. The development of BMs associated with IoT and online platforms requires a lot of innovative knowledge to increase prosumer-driven BM's viability;

- **Administrative:** the lack of institutions/authorities dedicated to supporting the development of the new market structure necessary for the greater prosumer integration; complicated bureaucratic procedures; difficulty in acquiring technologies and equipment; inadequate planning guidelines; and complex, slow or time-consuming permission and operation processes. Political resistance or institutional corruption can hamper the development of innovative BMs;

- **Market barriers:** it can be quite difficult for the small prosumer to compete competitively with the big utilities. The decentralized energy markets development poses a threat to utilities, which currently apply a BM almost entirely focused on centralized generation, sales and electricity distribution. Some utility companies may resist the energy markets evolution, facing prosumers with their distributed energy systems as a threat;

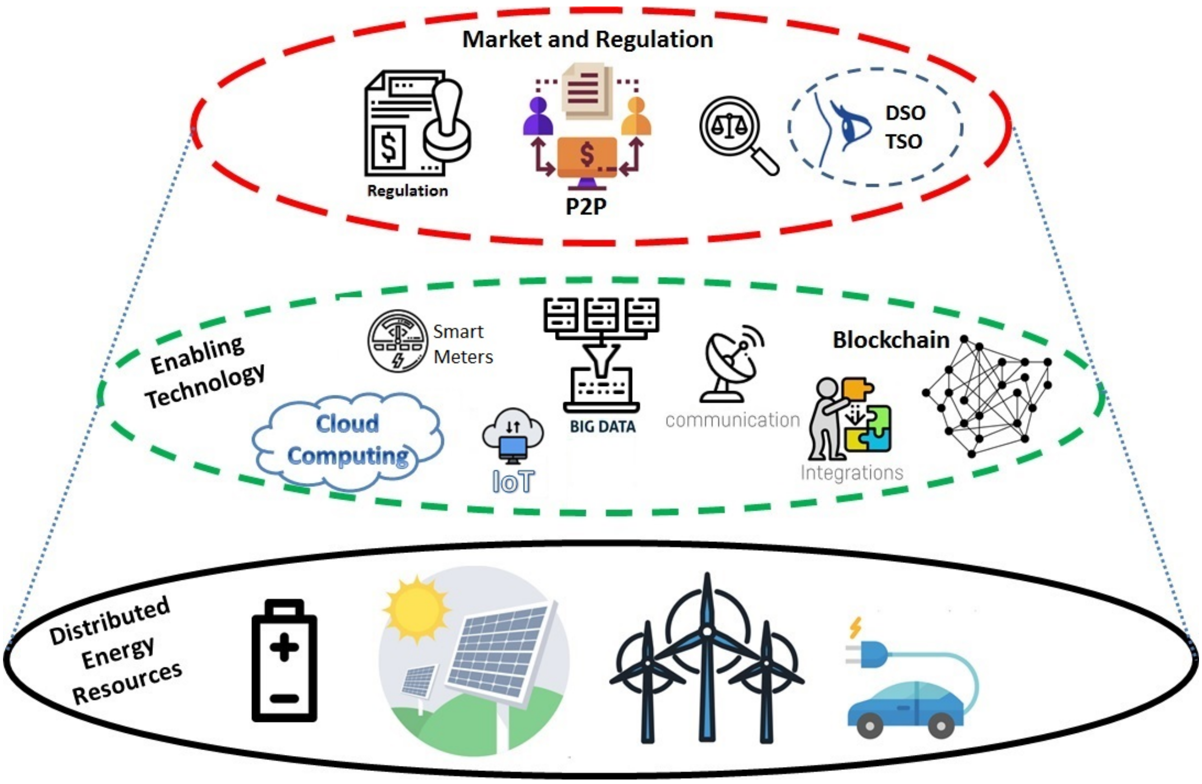
- **Conservative policies:** include inadequate policies, some policies discontinuation, unfavorable or inconsistent policies and lack of transparency can be an issue. Political uncertainties significantly hinder the expansion and development of new BMs and the greater inclusion of the prosumer.

### 2.4.3 Opportunities and recommendations

In a general view, there is a global trend to reduce or even extinguish governmental incentives primarily related to renewable generation sources, such as FiT (MURDOCK et al., 2018). So, to keep the increase of those carbon-free sources, the prosumers need to monetize their investments somehow.

The prosumers integration in the electricity market depends on different aspects, as shown in Figure 9. To start with, the integration of those layers would benefit the feasibility of the market for small scale players.

Figure 9 – Innovative Business Models Structure.




**Source**: Author's figure

In the base of those developments are the distributed RES, which in the case of the small scale players are presently related to rooftop solar, and an increasing number of EVs. Although, there is also an expectation for the deployment of battery storage in the near future. From the increase of the distributed RES and the possibility to exchange energy, information, and money, some technological developments play an important role in the measurement, control, communication, and security of the distributed market. This layer is represented by big data, CC, IoT, and Blockchain, among others.

On another layer, there is the need to rethink the market design and related regulation to properly allow and encourage prosumer participation. This must be done considering different aspects and points of view, i.e., not only the consumers' benefits but also the grid operators' challenges, and their possible benefits must be accounted for. This layer includes the development of P2P and community market designs as an example. In practice, the development and implementation of such markets strongly depend on the regulatory framework imposed by each country, which depends on the law decision-makers and also on the willingness of system operators to operate and manage more locally. Changes in the last 2 years in regulation in most European countries encourage self-consumption of energy as a way to slowly integrate prosumers into the system without significantly impacting grid operation. In this case, new BMs (e.g., combining PV generation and storage devices) may emerge and grow in the coming years, providing an opportunity to decentralize the system. Still, energy exchange among prosumers would be the ultimate goal to streamline the current way of trading energy and managing the system.

The aforementioned points raise important questions, such as the viability of the distribution systems and the possibility of the utility death spiral. For instance, in the case of distributed energy resources and storage devices, the need for network usage is lower most of the time, thus increasing the cost for the rest of the consumers that still need the distribution network (COSTELLO; HEMPHILL, 2014; CASTANEDA et al., 2017). Considering the evolution of the DSOs, their future main role seems to be to provide the distribution service through a regulated tariff, a role similar to what TSOs currently play in present deregulated markets. Even though this evaluation is beyond the main objective of this paper, this problem is also addressed by proper regulatory development, which could also allow distribution companies to participate in some type of BMs. Simultaneously, the role of the energy communities is initially stated, leaving the door open for emerging new BMs tailored to small local energy communities. For instance, a group of prosumers could aggregate their demand or generation surplus and negotiate as a collective with retailers. A clear picture of the role and responsibilities of the energy community agent has not yet been defined in a regulatory environment, which is crucial for the smooth integration of these energy communities.

There is room for some BMs, even considering the present laws and regulations. Although, the proper change in those regulatory aspects, including more active participation of prosumers, DSO, and TSO in the discussion of those new models, is of importance to foster the development of the energy sector. To sum up, these identified opportunities and recommendations follow the 3Ds paradigm for modern power systems, which are the decarbonization, decentralization and digitalization of the system.

## 2.5 PARTIAL CONCLUSIONS

Today, energy entities and governments are promoting the integration of innovative prosumers' BMs into the power system to achieve higher levels of economic and environmental sustainability. This thesis contributes for this discussion through a detailed review of prosumers BMs, pointing out the main identified barriers and enablers for their smooth integration into the power system in the coming years.

From this literature review, one can conclude that for the smooth and successful integration of prosumers in the power system, three aspects are essential: (i) the proliferation of RES and ESS through consumers, enabling self-consumption and supplying surplus energy to other consumers; (ii) technological developments for safe and controlled energy exchange; and (iii) update and improve the market design and regulatory framework. The ultimate combination of these aspects will motivate the design and development of appropriate BMs that will encourage conventional consumers to engage and participate in the system. Innovative business models can enable faster integration of prosumers in the system by combining the economic, environmental, and social aspects and characteristics of consumers. From the BMs gathered in this review, some of the BMs that better fit all these three aspects are the collective services as BMs. The main enabler for these BMs is the proximity and trust between the energy manager and the prosumers. On the other hand, the regulatory framework is the main obstacle to the success of such BMs, as the current regulation in many countries neglects such options. Therefore, the applicability of such BMs is often dependent of the lobby made by the community with the government agencies, network operators and retailers.

Furthermore, this review shows that innovative BMs are emerging that the primary focus is the prosumer preference. A very promising BM, if supported by appropriate regulations (third aspect), are those based on the prosumer-centric energy markets. Although there has been extensive research on this type of market in the past two years with multiple initiatives and trading options around the world, further research needs to be conducted to harmonize technologies and regulations in such a way that eases the adoption of such solutions. P2P-BMs can easily receive greater support from society, as they follow the global trend of a collaborative economy.

The main barriers to the development of innovative BMs for prosumers observed in this review are, in addition to the already mentioned lack of regulation, the high price of the necessary equipment and technologies in many countries/regions, the low levels of information and technical knowledge, unavailability of support from local/district/national authorities and lack of well-established IoT and ICT technologies. Nevertheless, almost all BMs identified under this review have the ultimate goal of integrating prosumers into the power system. Hence, prosumers have a more active role in the power system, turning them into key players in the energy markets, not just selling electricity but also providing energy services.

This chapter focuses on the review of the most innovative BMs in the field, discussing the main barriers and enablers for prosumer integration in the system. Thus, a broad view including, the characteristics of those consumers, regulation aspects involved in their role, and the market structures that encourage their participation, are discussed. Even more, it presents a review of existing business models and evaluates the necessity to give proper incentives to those consumers to take a more proactive role in the near future. An important conclusion is that, even though innovative BMs encourage cost-effective and sustainable prosumers integration, they do not always have a successful implementation, as the regulatory framework and inertia of system entities take time to change, and must present a holistic approach to obtain the desired results, which depends on the regulatory history and the preferences of each country or region.

For the successful implementation of the innovative BMs, further directions must be considered. For instance, a comprehensive study of the evolution of recent regulations related to small consumers and prosumers in different countries, including possible future outcomes and providing some hints on regulatory paths. In addition, the evolution of the roles of electricity market players and the simulation of their impact on BMs, such as changes in the role of the distribution companies in future market design.

# 3 PROSUMER IN THE BRAZILIAN CONTEXT

Taking into account the current world scenario and thinking about the future of Brazilian energy policies, it should be considered the prospect of transition from a centralized energy system to a more decentralized one, accounting for social, political, economic, and technological challenges (BURKE; STEPHENS, 2018). Such a transition must be gradual to guarantee the necessary conditions without a huge disruption in the current electricity market rules. This change can introduce new roles and opportunities for prosumers.

The Brazilian Electricity Sector is promoting changes in the regulatory, commercial, and operational framework, seeking to create conditions for more active participation of consumers in managing their energy consumption and individual choices. In April 2019, the Ministry of Mines and Energy (MME), through MME law 187/2019 (MME, 2019a), created the working group called "GT Modernização"to seek solutions that allow the development of proposals for electric sector modernization, aiming at providing electricity to consumers in a competitive way and promoting the market opening.

## 3.1 BRAZILIAN REGULATORY OVERVIEW

The fundamental characteristic of the Brazilian electricity sector is that it is planned in a centralized manner. The electricity market development is heavily influenced by the federal government and regulatory bodies, which determine new energy auctions and price limits, thus guiding the generation expansion in Brazil. The use of RES as the basis of the country's energy policy is due to Law 9478/1997 (BRASIL, 1997). The Brazilian medium and long-term energy policies are proposed in the Ten-Year Energy Expansion Plan (EPE, 2020b) (updated annually) and by the National Energy Plan 2050 (EPE, 2020a), respectively.

The Brazilian energy sector comprises a wholesale market composed of the Regulated Electricity Market (ACR) and the Free Electricity Market (ACL). The ACR is composed of utilities and captive consumers[1]. It is fully regulated by the Brazilian Electricity Regulatory Agency (ANEEL) and the energy is contracted through auctions. The ACL is composed of free consumers[2], generators, and trading companies. ACL participants can negotiate their energy volumes, prices, and contract terms and conditions. According to the Brazilian Energy Traders Association (ABRACEEL), the amount of energy negotiated in the free market was 36% of the total consumption in Brazil in September 2021 (ABRACEEL, 2021). This represents about 16110 GWh in a single month. Although ACL participants are free to trade their energy, this

[1] A consumer who is only allowed to buy energy from the utility holding the concession or permission in the area where the system user's facilities are located, and who is served under regulated conditions (ANEEL, 2012).

[2] Those that are served at any voltage and with demand contracted from the distributor equal to or greater than 1.5 MW (MME, 2019b). Additionally, Special free consumers, with demand greater than 0.5 MW, but must purchase from specified renewable sources.

market is reserved for large consumers and some conditions for participation in this market are defined throughout this section. However, this thesis focuses on the potential small and medium-sized prosumers and their greater integration into the energy market. In other words, the focus is on current ACR participants who may become free from future regulatory changes.

Law 10848/2004 (BRASIL, 2004) created a regulated market for electricity companies and qualified consumers, alongside a market for free customers (defined as having an electricity demand $\geq$ 3 MW). This 3 MW limit was reduced to 1.5 MW in January 2021 through Ordinance 514/2018 (MME, 2018a). This limit tends to decrease even more in the coming years, reaching 1MW in 2022, 0.5MW in 2023, and the full opening of this market in 2024, according to Ordinance 465/2019 (MME, 2019b). The core of this legal instrument is an organized energy supply scheme for regulated distribution companies through short, medium, and long-term auctions of power purchase agreements. Auctions are currently the main policy instrument for expanding and diversifying the RES supply, covering three-quarters of the national electricity market.

In 2002, Brazil launched the Program to Stimulate Alternative Electricity Sources (PROINFA), through Law 10438/ 2002 (BRASIL, 2002). PROINFA was a hybrid scheme to develop a total RES generation capacity of 3,300 MW, equally distributed among wind, biomass, and small hydroelectric projects. Resolution 482/2012 (ANEEL, 2012), later updated through Resolution 687/2015 (ANEEL, 2015b), provided net metering for small producers ($<$1MW) of PV, wind, hydro, and biomass energy. This scheme provided the generation of credits in case of production surplus, which can be used for future consumption in up to 60 months.

Another program called INOVA ENERGIA (BNDES, 2013) provided subsidies of up to 90% of the project costs for Research & Development (R&D) related to smart grids, renewable energy, hybrid vehicles, and energy efficiency in transport. In addition, the National Program for Distributed Generation (DG), called ProGD (MME, 2018b), was launched through Ministerial Decree 538 of the Brazilian government and created a working group to evaluate new measures to promote DG development (LIMA, 2010).

It is important to highlight that, so far, all regulatory and policy development in the Brazilian electricity sector is mainly focused on large renewable generators, thus the wholesale market, according to the aforementioned laws and resolutions. The only current regulation that encompasses the small prosumer is based on net-metering (POULLIKKAS; KOURTIS; HADJIPASCHALIS, 2013).

In November 2017, the ANEEL established the criteria and conditions for a DR program through Normative Resolution 792 (ANEEL, 2017b). The basic concepts on the topic are defined, as well as the requirements for consumers to participate in the program.

The number of prosumers in Brazil is increasing due to some factors, such as the reduction in the DG equipment cost, the increase in regulated electricity tariffs, and the rules for credit sharing, introduced in Brazilian regulation by Normative Resolution 687/2015 (ANEEL, 2015b), from March 1, 2016. In early February 2021, the Federal Senate approved the Senate Bill (PL) 232/16 (FEDERAL, 2021), which intends to modernize the commercial model of the electricity sector and the concessions for electric power generation in the country. This bill represents important advances in the sector, mainly due to the inclusion of access to the so-called free contracting environment for low-voltage consumers.

PL 616/2020 (FEDERAL, 2020) proposes the regulatory framework for the prosumer. According to PL 616/2020, a consumer registered with ANEEL or with the local energy utility, capable of producing electricity at his own risk, is considered a prosumer. It also elucidates the concept of local and remote prosumer, where "local"is when the generating source is electrically close to the load and "remote"is when the generating source is electrically separated from the load, regardless of the voltage level and the distribution utility.

Law 14300/2022 (BRASIL, 2022) establishes the legal framework for distributed microgeneration and minigeneration, the electric energy compensation system and the social renewable energy program. This Law allows existing consumer units to continue, for another 25 years, the benefits currently granted by ANEEL through the electric energy compensation system. It also defines the rules that will prevail after 2045 and what rules will apply during the transition period. For more details see (BRASIL, 2022).

Figure 10 presents a timeline with the main legislation in the Brazilian electricity sector to summarize the advances in the regulation within the context of the present work.

## 3.2 OUTLOOK FOR THE BRAZILIAN MARKET

First, an analysis of traditional BMs (subsections 3.2.1 to 3.2.3), which are already applied in Brazil or which could be applied without a significant update in the current regulatory context of the country, is presented. Subsequently (subsections 3.2.4 to 3.2.8), innovative BMs that are emerging in a decentralized and RES scenario from technological developments and spreading of smart energy systems are addressed.

### 3.2.1 **Feed-in tariffs**

Brazil adopted the FiT scheme only in the first half of the 2000s (the first phase of PROINFA), focused mainly on the implementation of large RES generating facilities, but due to the lack of process transparency, the country switched to an auction system (DUTRA; SZKLO, 2008; KISSEL; KRAUTER, 2006). Currently, FiTs are politically not feasible in Brazil. There is no regulation on the issue and, therefore, the FiTs are not applied. FiT programs can provide benefits (GROVER; DANIELS, 2017), but they also bring challenges to be faced (BAKHTYAR et al., 2013). The basic idea behind FiT programs is to ensure a market for RES electricity, motivating investors to expand new technologies more safely. The authors of (PYRGOU;

Figure 10 – Timeline of the Brazilian electricity sector's regulation.


**Source**: Author's figure.

KYLILI; FOKAIDES, 2016) discuss the advantages and disadvantages of different remuneration schemes based on existing FiTs.

Nevertheless, FiT schemes usually end after a certain period, as has been happening in recent years (Government UK, 2018). With this global trend of ending FiT policies, it is more advantageous for policy-makers in Brazil to think ahead, about a post FiT era. The study (RÖVEKAMP et al., 2021) perform an analysis covering five RES BM archetypes for the post FiT era. The authors emphasize that it is necessary to develop other BMs to encourage greater integration of the prosumer and RES in the system.

### 3.2.2 **Self-consumption and Net metering**

These two BM concepts are combined here because they are mixed in the Brazilian regulatory environment in most cases. Self-consumption is decoupled from net metering only when the prosumer is isolated from the system, having its battery energy storage system (DIVYA; ØSTERGAARD, 2009).

Net metering is one of the few prosumer-driven BMs that is covered by current Brazilian regulations, allowing electric power generation from RES or qualified cogeneration[3], with an installed capacity of up to 5 MW[4] in consumer units.

The prosumer having DG within the previous conditions is categorized as microgeneration (up to 75 kW) or mini-generation (from 75 kW to 5 MW), and the installation where the DG is connected is treated as a consumer unit. Compensation occurs in terms of electricity (kWh). However, for the prosumer who is connected at high voltage[5], the tariff varies according to the day's period when the energy is consumed: peak or off-peak. This tariff difference must be taken into account in the final energy credits valuation. According to ANEEL Normative Resolution 687 (ANEEL, 2015b), there are four possible types of net metering:

- **Conventional net metering:** It is when the energy is generated and compensated in the same place, being the simplest type of net metering. It is important to note that even having enough energy for its own supply, the prosumer must pay the utility a minimum monthly amount, corresponding to the "network availability cost"(ANEEL, 2010).
- **Virtual net metering:** It is known in Brazilian regulation as "Remote self-consumption"and allows the prosumer to use the surplus generation from one of his consumer units in another one. Both units must be connected to the main grid by the same utility. This BM can be

[3] Qualified cogeneration is a concept defined by ANEEL in Normative Resolution 235/2006 (ANEEL, 2017a) that establishes a minimum total efficiency to generate electric and thermal energy from natural gas.
[4] Except for hydro that has a 3 MW power limit.
[5] In this study's context, it is considered high voltage when higher than 2.3 kV and Low-Voltage (LV) when lower than this same value (ANEEL, 2010).

interesting for prosumers who own more than one house but have no available area for installing their generation in all consumption locations.

- **Condominium net metering:** Brazilian regulation allows DG sharing among prosumers of the same condominium. This BM is regulated in Brazil under the name of "enterprise with multiple consumer units". It is noteworthy that all the generated energy is injected directly into the network and the compensation is later carried out, since the condominium residents are not forced to participate in the DG system and, thus, compensation is made only for those who participate in the project.

- **Community net metering:** In this BM, also known in Brazilian regulations as "shared generation", several consumers in the same concession area can be integrated into an energy community (consortium or cooperative) to invest in a generation system far from their consuming units, using the respective energy to reduce their consumption from the main grid. The techno-economic feasibility of this BM is analyzed through a case study by (VIEIRA; SHAYANI; OLIVEIRA, 2016).

A challenge for the successful dissemination of these self-consumption/net metering BMs in Brazil is the regulatory uncertainty about charging (or not charging) for grid use in the case of generation and consumption at different times or in different places. The mentioned uncertainty is related to subsidies or exemptions. For instance, under the current legislation, the micro and mini DG are exempt from network usage fees. However, since 2018, discussions have taken place between entities in the electricity sector and the government on the need to review this exemption. Another challenge is that under the rules of the Brazilian net metering, residential prosumers who adhere to the mechanism would continue to use the grid, contributing to the peak in the same way they did before DG, without, however, paying for that use. As a result, consumers who do not install DG will have their electricity bill increased to subsidize the grid usage by those who installed it.

From the previous reasons, the valuation of the energy injected into the network by prosumers should be the subject of research, discussion, and reassessment by policy decision-makers to avoid the existence of cross-subsidies in tariffs (EID et al., 2014). However, this change can lead to a reduction in the economic attractiveness of these BMs (especially, net-metering schemes) and, thus, it must be carried out with caution to guarantee the regulatory stability necessary for the market's evolution.

### 3.2.3 **Leasing**

In the current Brazilian regulatory environment, leasing has to be combined with the self-consumption/net metering BM. Brazilian companies like "Wise energia inteligente"(WEI, 2021), "MRCA solar"(MRCA, 2021), "Solar 21"(S21, 2021), and "Edsun investimento solar"(EIS, 2021) are examples of companies that currently have this BM as the base of their business. The

"Evolua energia"company (EE, 2021) provides plan options to its customers, without the need to invest in their unit. Customers subscribe to "Evolua"plans in a totally digital way, compensating their electricity consumption, due to the energy injected into the distribution network by "Evolua", which becomes credits for the consumer. The company has its renewable generation park and shares the energy injected into the network with its subscriber customers.

### 3.2.4 **Aggregators**

Currently, a player that has a role close to that of an aggregator in the Brazilian regulatory framework is only in the context of the DR pilot program[6] from the Chamber of Electric Energy Commercialization (CCEE). The entity has the function of representing and grouping consumer units that meet the criteria required by the ANEEL Normative Resolution 792/2017 (ANEEL, 2017b). The aggregator's function is to group the consumer units' loads so that they meet the minimum requirement of the previous resolution together to participate in the program.

Currently, in Brazil, aggregators are not allowed to set up a portfolio made up of distributed RES from a mix of small prosumers. However, the market has been gaining an increasing level of flexibility, such as that given to micro and mini-generation through the compensation system, which paves the way for the development and elaboration of regulations that encompass the aggregators' BMs. One possible advantage, if this BM is regulated, is that aggregators can focus their business exclusively on the purchase and sale of energy in an optimal way, without worrying about all other services inherent to the operation and maintenance of the distribution grid. This remains under the responsibility of the local energy utility or DSO.

### 3.2.5 **Energy-as-a-service**

In Brazil, the "EDP Smart"company (EDPS, 2021), a subsidiary of "EDP Brasil"(EDPB, 2021), has a portfolio aimed at offering solutions in the area of energy efficiency and demand response to corporate and residential consumers, providing energy management services through digital platforms. This digital platform uses artificial intelligence to identify measures to reduce consumption and meet demand.

For the increase of this BM in Brazil, a considerable investment in technologies and infrastructure is needed to acquire real-time data from energy networks. In this particular, information and communication technologies, advanced signal measurement infrastructures and intelligent devices are essential. In this way, an ANEEL research and development project in partnership with Enel (EB, 2021) foresees the installation of 300,000 smart meters. The devices will allow consumers to monitor and optimize electricity consumption, in addition to allowing the utility to perform some activities remotely and offer new services (ENELGROUP, 2021). Another example is the installation of 23,000 smart meters carried out by Elektro (EL, 2021) in

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[6] More details in section 3.2.6 and reference (ANEEL, 2017b).

Atibaia, São Paulo. The meters will allow consumers to access system information so they can actively manage their energy consumption (CANALENERGIA, 2021).

### 3.2.6 **Demand response**

Currently, DR mechanisms have been the subject of debate and cause of regulatory changes in Brazil. The CCEE, together with the Brazilian ISO (ONS), is carrying out the DR pilot program (which is an incentive-based program) established by ANEEL Normative Resolution 792/2017 (ANEEL, 2017b) and Ordinance MME 460/2020 (MME, 2020), which runs until April 30, 2022. The objective is to reduce the supply costs of the Brazilian electricity system, providing greater reliability and low tariffs to end consumers. For this purpose, options are developed by the ONS aiming at avoiding dispatching thermal plants outside the merit order. In this way, consumers can reduce their electricity consumption and receive financial compensation. The new rules of the DR program will be defined by ANEEL Normative Resolution 1040/2022 (ANEEL, 2022), which must undergo a specific public consultation in the year 2023.

The optimization of this service is carried out by the ONS through a cost comparison between the dispatch of thermal plants outside the merit order and the cost of activating the DR offered by consumers. Then, the lowest cost between the two options, accounting for the operating conditions, is triggered by the operator. A study carried out in (SANTOS et al., 2019) shows the operational savings that can be obtained through demand reduction simulations, considering the DR pilot project for 2018. Unfortunately, the program does not include small consumers.

Since January 2020, the option for the so-called "white tariff", a price-based incentive, has been available for all consumer units connected at LV (ANEEL, 2015c). The white tariff signals to small consumers the variation of the energy value according to the day and time of consumption. From this new tariff, consumers can pay different amounts depending on the time and day of the week in which they consume electricity. On weekdays, the white fare has three values: peak, intermediate and off-peak. These periods are established by Utility and are different for each one (ANEEL, 2015a). Saturdays, Sundays, and holidays have a non-peak tariff throughout the whole day.

From a DR-based BM, LV consumers in a free market can negotiate small DR contracts with an aggregator, utility, DSO, or balance responsible parties[7].

### 3.2.7 **Collective services**

In 2016, the first shared distributed generation cooperative in Brazil was founded. The Brazilian Renewable Energy Cooperative (COOBER, 2021) has a capacity of 75 kWp and serves 18 consumer units. Other similar ventures were developed in subsequent years. The

[7] Entity responsible for maintaining the balance between the energy supply and the system demand through its own portfolio.

Energy Consumers Cooperative (ENERCRED, 2021) was created in 2017 and has two PV power plants totaling 180 kWp and serving 200 houses. Another example is the Solar Energy Cooperative (COOPSOLAR, 2021), which began operating in 2020, with 75 kWp and serving 15 consumer units. However, it should be noted that all these cooperatives have their BM based on net metering, the only one allowed by the current Brazilian regulation. All the energy from the RES plants owned by the cooperative is injected into the distribution network, generating electricity credits that are shared among all the cooperative members. It is necessary to improve the Brazilian regulatory framework, so that energy communities and other collective BMs can monetize with energy sales among members, and not only through net-metering schemes.

The laws needed to provide a solid regulatory framework for collectives services BMs, such as prosumer communities, still need improvements. The new laws must have mechanisms that allow the incorporation of technological advances and the emergence of new BMs (FRIEDEN et al., 2019). Thus, with the monitoring and continuous improvement of the regulatory framework, an environment more conducive to the BMs' success can be made viable.

### 3.2.8 **Peer-to-Peer trading platforms**

Nothing about P2P-BM is mentioned in any current Brazilian regulation. However, some recent works have studied the applicability of P2P energy trading in the Brazilian context (BARBOSA; DIAS; SOARES, ; XAVIER et al., 2015). This BM can help, in the future, to develop a more decentralized energy market in Brazil.

### 3.2.9 **Business models overview**

An overview containing the BM's deployment status, the current regulatory problems, and recommendations for regulation is presented in Table 3.

In addition, to better compare the challenges related to the implementation and/or development of those different BM schemes, an assessment including technical, social/community, environmental and regulatory criteria, including the current applicability in the Brazilian context have been considered as presented in Table 4.

The assessment was carried out guided by the following criteria:

- **Technical Challenge:** some models can be implemented with little or no technological change, such as those that can be implemented with a smart meter. At the intermediate level, are those that need more data communication or even a certain degree of control over the asset. On the extreme edge, to properly support the BM, the P2P model needs a complete restructuring of the market, regulation and in the DSO structure.
- **Policy/Regulatory Challenges:** some models can exist with little effort in regulation or small political pressure, and many of those models are in use all around. Under this

Table 3 – BM status.

| Business model | Current BM's deployment status[1] | Current regulatory problems[2] | Recommendation for regulation to support the BM[3] |
|---|---|---|---|
| **Feed-in Tariffs** | - There is no regulation. | - Not applicable | - There are no support recommendations for this BM. Policy-makers must think ahead, developing other BMs. |
| **Self-consumption** | - Always associated with net metering BM, since surplus energy is injected into the grid, generating energy credits. | - There is no possibility to directly negotiate and sell the surplus energy. | - Policy-makers should focus on developing a regulatory environment aimed at collective self-consumption. |
| **Net metering** | - It allows electricity generation from RES or qualified cogeneration with an installed capacity of up to 5 MW in consumer units.<br>- Virtual, collective and individual net metering are also regulated. | - There is no possibility to directly negotiate and sell the surplus energy;<br>- Uncertainty overcharging (or not charging) for the grid use. | - To value the electricity injected into the network by prosumers to avoid the existence of cross-subsidies in tariffs. |
| **Leasing** | - Always associated with self-consumption/net metering BM, where the consumer only needs to pay a monthly fee.<br>- Establishment of long-term contracts. | - There is no possibility to directly negotiate and sell the excess energy. | - To allow the direct sale of the excess energy. |
| **Aggregators** | - Appears only in the context of DR programs. | - There is no possibility to set up a portfolio made up of distributed RES from a mix of small prosumers. | - To legally define the aggregator's figure so that it can focus exclusively on the purchase and sale of electricity in an optimal way. |
| **Energy-as-a-service** | - Some companies in the electricity sector provide consultancy based on this BM. | - There is no broad regulation. | - To promote subsidy policies for investments in technologies and infrastructure for the electricity sector digitization. |
| **Demand response** | - The DR pilot program is ongoing, coordinated by CCEE together with ONS. | - Only large consumers who participate in ACL can participate in the program. | - To expand access to DR programs so that small and medium-sized consumers can participate. |
| **P2P tradings platforms** | - There is no regulation | - Not applicable | - To establish policies that allow the prosumer to participate in energy market pools, bilateral or multilateral contracts. In addition to regulating and enabling P2P trading platforms, making possible direct energy trading between prosumers. |
| **Collective services** | - Energy cooperatives, communities, and condominiums are allowed but always associated with self-consumption/net metering. | - Allows only the sharing of energy credits;<br>- There is no possibility to directly negotiate and sell excess energy. | - Policy-makers should focus on developing a regulatory environment aimed at prosumer energy communities. |

[1]Presents an overview of the BMs' implementation situation, highlighting how each one appears in the Brazilian market context. [2]Highlights the main current regulatory problems found in the BMs implementation. [3]Exposes the main regulatory recommendation for the BMs development in the Brazilian context.

**Source**: Author's figure.

classification, the most difficult models are those that need a complete restructuring in regulation, such as P2P or those like the FiT that is even used by many countries, nowadays it has been changed by other models.

- **Environmental Benefits:** in general, all the BMs presented are related to an increase in renewable generation. Those models that increase the participation of small consumers and more distributed resources are more relevant.

- **Social/Community Integration:** some models are known for the increase of interac-

Table 4 – Comparison between different business models.

| Business model | Technical Challenges[1] | Policy/Regulatory Challenges[2] | Environmental Benefits[3] | Social/Community Integration[4] | Current applicability in Brazil[5] |
|---|---|---|---|---|---|
| **Feed-in Tariffs** | Minor technological change | Regulatory restructure needed | Intermediate relevance | Little relevance | Underdeveloped |
| **Self-consumption/ Net metering** | Minor technological change | Adaptation of existing regulations | Intermediate relevance | Little relevance | In use |
| **Leasing** | Minor technological change | Little effort needed | Intermediate relevance | Litle relevance | In use |
| **Aggregators** | New IT solutions needed | Adaptation of existing regulations | Great relevance | Intermediate relevance | Initiated |
| **Energy-as-a-service** | New IT solutions needed | Little effort needed | Little relevance | Little relevance | Initiated |
| **Demand response** | New IT solutions needed | Adaptation of existing regulations | Intermediate relevance | Intermediate relevance | Initiated |
| **P2P trading platforms** | Market restructure needed | Regulatory restructure needed | Great relevance | Intermediate relevance | Underdeveloped |
| **Collective services** | New IT solutions needed | Regulatory restructure needed | Great relevance | Great relevance | Initiated |

IT = Information technology
[1]Emphasizes the level of technological development necessary for the BM's successful implementation. [2]Highlights the degree of regulatory development necessary for the BMs' implementation. [3]Portrays the intrinsic BMs' environmental relevance. [4]Shows how the BM promotes the integration between consumers and prosumers within a community. [5]Highlights the current BMs' implementation status in the Brazilian context.

**Source**: Author's figure.

tion between consumers and prosumers, increasing the sense of community. A major contribution to the increased sense of community classifies the BM as "great relevance".

- **Current applicability in Brazil:** Regarding applicability, the BMs that are already in use or were used for some time in Brazil are classified as "In use". BMs that have already started, in some way, to be explored receive "Initiated", and BMs that still need many regulatory development are classified "Underdeveloped".

## 3.3 CHALLENGES AND OPPORTUNITIES

The main objective of this chapter was to provide a basis for understanding how different BMs can help in the proliferation of prosumers and RES in the Brazilian electricity market, in a way that can benefit the country and Brazilian citizens toward a more sustainable and decentralized system. To provide the necessary environment for prosumers, a set of changes must be taken, considering the regulatory context. Among the required changes, it can be highlighted:

- One of the main challenges to be overcome is the integration between prosumers and the utilities responsible for managing the network in Brazil, thus reshaping their current role. Therefore, utilities tend to become DSO, that is, an active system manager. Such a change may lead to an increase in DSO costs arising from the planning, development, operation, and balancing of their networks (PICCIARIELLO et al., 2015), which will require a restructuring of the DSOs' tasks and remuneration. If this transition is not done in a systematic and well-structured way, it can lead to the utility death spiral.

- Regarding the BMs covered in the present work, a potential market for self-consumption BMs, mainly collective ones, should be better explored and developed, making it accessible even for those who do not have the appropriate local conditions (FELDMAN et al., 2015). A consumer who is unable to accommodate a renewable generation system in his own consumption unit may buy energy from closer prosumers or in a "beyond-the-meter scheme[8]". Policies aimed at exploring the "beyond-the-meter" market and not exclusively "behind-the-meter[9]" can bring economic benefits and technical potential, such as economy of scale and reduction of peak generation surplus.

- Facilitating market access for emerging participants is crucial for prosumer aggregation policies. In this context, the aggregator's figure associated with a less rigorous set of rules for a player to enter the market can be a promising solution (VERHAEGEN; DIERCKX-SENS, 2016; HANCHER; WINTERS, 2017). The aggregator BM can be beneficial to both prosumers and network operator. The management of different prosumers, with different demand profiles and generation portfolios, can provide a more accurate balance between local generation and consumption (VERGADOS et al., 2016). Combining heterogeneous prosumers' demand and generation profiles can help ensure network balance (SILVA; ILIĆ; KARNOUSKOS, 2013). Recently, regulations were created to expand the electricity market towards smaller consumers. The creation of the retailer (CCEE, 2021), which in Brazil represents the aggregation of these small consumers, is the first step in this direction. In addition, the possibility for these consumers to participate in the market has been gradually expanded. According to the Brazilian Electricity Market modernization plan, it is expected that in 2023, consumers with a load of 500 kW will be allowed. Further studies may reduce this limit even more by 2024. Nevertheless, it is necessary to expand the legal definition of these new agents to clearly establish their responsibilities, rights, and duties.

- Despite the existence of the DR pilot program, small consumers do not have the means to trade directly in the energy market, nor the equipment needed to manage their energy resources. This can be a barrier and discourage the adoption of these new technologies by consumers. DR-based BMs can provide significant benefits to utilities and consumers by

[8] Refers to power equipment located off-site. Outside the consumer's property.
[9] Refers to power equipment located on-site, on consumer's property.

reducing energy consumption during peak hours. The authors of (RAMOS et al., 2020) highlight that an efficient pricing system, capable of signaling an adequate use of resources, can be the main driver for the success of this BM in Brazil. Incentive policies, training courses, and advertisements to disseminate information about DR programs' functioning should be explored to attract more commercial and residential customers. Residential, industrial, and commercial buildings can play an important role in this type of program by providing system flexibility.

- Small prosumers must have access to electricity market pools, and bilateral or multilateral contracts. In this context, a market structure based on P2P is very promising. This BM brings greater energy democratization. According to (SOUSA et al., 2019), the retail market, in general, lacks competition, and the P2P market can be a solution to this problem. For this BM, the prosumer must have a management system capable of collecting, analyzing, and optimizing demand and generation data, as well as information on current market conditions (TUSHAR et al., 2018). From this, the prosumer can decide whether to participate in the P2P market or not. Prosumers face some challenges in this market design, including a reduction in the energy cost, increase and maintenance of sustainable RES use, and improvement in their social engagement. However, the DSO must preferably have a participatory and non-invasive oversight role to ensure the reliable operation of the power system, although in the worst case this may imply the imposition of strong constraints by the DSO. Thus, policies and methodologies that integrate prosumers and DSO are essential for the success of P2P-based BM.

For these changes to prosper, some auxiliary reforms are needed. The shift from the "business-as-usual"for key players in the energy sector is essential for implementing prosumers' aggregation policies (SIOSHANSI, 2014).

The reformulation of the current regulation will be imperative for the greater integration of prosumers into the system while ensuring compliance with network standards (BURGER; LUKE, 2017). Interconnection regulations and equipment certification to allow online measurement of prosumers must be provided. Such measures tend to boost the energy sector digitization and promote the implementation of technologies such as smart meters. These advances lead to the issue of who should be responsible for the required financing and investment, as well as to information security issues (ZAFAR et al., 2018). To ensure the required investments, an essential step is the faster smart metering infrastructure deployment, enabling the electrical network management at the prosumer level. This has been done in Brazil for many customers by distribution companies. As an example, Copel has recently installed 50,000 smart meters, in a plan to massively deploy smart meters benefiting 4.5 million people (COPEL, 2021).

National policies that can subsidize access to renewable generation technologies for small and medium-sized consumers, as well as campaigns to encourage energy efficiency throughout the entire electricity supply chain (from generation to final use) are fundamental. Another measure is to establish partnerships with developed countries to promote a solid technology transfer structure, preserving intellectual property rights.

In summary, it is extremely important to plan, think and develop regulations considering the needs of both the prosumers and the power system. The entities responsible for the operation and maintenance of the electrical infrastructure must be fairly remunerated while providing quality services at competitive prices to consumers. The democratization of access to electricity markets should be the ultimate goal of the prosumers' aggregation policies.

## 3.4 PARTIAL CONCLUSIONS

A description of how innovative BMs can help prosumers further integrate into the Brazilian electricity market is presented. A comprehensive review of the current specific regulation was carried out, as well as an analysis of how innovative BMs fit into the Brazilian context. Incorporating new BMs into the market offers new ways for prosumers to monetize, and generate new income sources, besides potentially helping the network.

Taking into account the topics presented in the discussion section and the current policy and regulatory environment in Brazil, the main policy recommendations that can help to overcome barriers for greater integration of prosumers into the electricity market and for prosumer-driven BMs are:

- To redefine the utilities' role and responsibilities, recognizing them as an active DSO in network management;
- To make access to DR programs more flexible, allowing small and medium prosumers to participate under the management of an energy community or an aggregator;
- To accelerate the market opening for small and medium consumers, reducing the requirements to participate in the wholesale market, in addition to focusing on creating a community-level retail market;
- To allow energy communities to be autonomous, thus being able to manage their energy resources independently, as an aggregator;
- To allow the access of electricity market pools, bilateral or multilateral contracts to small and medium-sized prosumers.

A great opportunity lies before Brazil's policy-makers. Counting on the experience of other countries with an electricity market that already incorporates small size prosumers, Brazil can adopt more corrective measures for the development of its regulatory environment in the future. Regulatory barriers, technical and cultural challenges still need to be overcome for the success of prosumers' aggregation policies and the prosumers themselves.

# 4 PROPOSED METHODOLOGIES

Seeking to further explore one of the prosumer-driven approaches presented and the challenges imposed by this innovative BM, two methodologies are proposed and detailed below. Section 4.2.1 provides the necessary background on P2P markets; section 4.2.2 presents the iterative P2P market approach for energy and reserve negotiation; Section 4.2.3 evaluates the proposed model by using a well-known 14-bus distribution system and one-year data set; and section 4.2.4 provides the main conclusions.

## 4.1 P2P MARKET VIA DISTRIBUTION FACTORS

The proposed P2PTDF methodology determines all P2P energy transactions between prosumers and consumers in a local energy market without any constraints being violated. The proposed model uses the TDF method to find exchanges and peers that may cause congestion and voltage problems, being these peers penalized. The P2PTDF is fair, as it only encourages peers who can cause congestion and voltage problems to renegotiate in the local energy market.

### 4.1.1 **Energy market problem**

To solve the energy problem of P2P transactions, the general mathematical formulation for the so-called "*Full P2P market*"presented in (SOUSA et al., 2019) was used. This market design is based on peers trading electricity directly with each other.

Therefore, the basic mathematical formulation of the energy problem can be defined as (4.1a) - (4.1e) for a given period $t \in T$:

$$\min_{D} \quad \sum_{n\in\Omega} C_{n,t} \left[ \sum_{m\in\omega_n} E_{nm,t} \right] \tag{4.1a}$$

$$\text{s.t.} \quad \underline{E_{n,t}} \leq \sum_{m\in\omega_n} E_{nm,t} \leq \overline{E_{n,t}} \quad \forall n \in \Omega, \forall t \in T \tag{4.1b}$$

$$E_{nm,t} + E_{mn,t} = 0 \quad \forall (n,m) \in (\Omega, \omega_n), \forall t \in T \tag{4.1c}$$

$$E_{nm,t} \geq 0 \quad \forall (n,m) \in (\Omega_p, \omega_n), \forall t \in T \tag{4.1d}$$

$$E_{nm,t} \leq 0 \quad \forall (n,m) \in (\Omega_c, \omega_n), \forall t \in T \tag{4.1e}$$

where $D = (E_{nm,t} \in \mathbb{R})_{n\in\Omega, m\in\omega_n}$, with $E_{nm,t}$ corresponding to the energy exchange between peers $n$ and $m$ at time $t$, for which a positive value means sales/production (4.1d) and a negative value is equal to a purchase/consumption (4.1e). $\Omega$, $\Omega_p$ and $\Omega_c$ as sets for all peers, producers and consumers, respectively (hence $\Omega_p$, $\Omega_c \in \Omega$, $\Omega_p \cap \Omega_c = \emptyset$). The set $\omega_n$ contains the trading partners of a certain peer $n$. Bilateral negotiations $E_{nm,t}$ have the property of reciprocity, as defined by (4.1c). It is noteworthy that the dual variable $\lambda_{nm,t}$ associated with the exposed problem represents the price for each bilateral trade at time $t$. According to (4.1a) the objective is to minimize the total cost of all bilateral trades carried out between the peers.

The function $C_{n,t}\left(E_{n,t}\right)$, shown in (4.2), corresponds to the production cost and a quadratic function is used as in (HUG; KAR; WU, 2015).

$$C_{n,t}\left(E_{n,t}\right) = \frac{1}{2} \cdot ae_n \cdot E_{n,t}^2 + be_n \cdot E_{n,t}, \quad ae_n, be_n \geq 0, \forall t \in T \tag{4.2}$$

For producers, this function reflects the production cost of energy $E_{n,t}$, while for consumers it represents how much they are willing to pay for $E_{n,t}$. It is noteworthy that it is quite common to model such cost functions in a quadratic form (SOUSA et al., 2019; BAROCHE et al., 2019; SORIN; BOBO; PINSON, 2018; HUG; KAR; WU, 2015). According to (SORIN; BOBO; PINSON, 2018), such functions are seen as realistic for a large class of conventional generators, small consumers and prosumers.

From (HUG; KAR; WU, 2015), $ae_n$, $be_n \geq 0$; $E_{n,t} \geq 0$ for producer and $E_{n,t} \leq 0$ for consumer. In the case of the producer, the function reflects the cost to produce $E_{n,t}$, whereas for a consumer, it represents the amount the load is willing to pay for $E_{n,t}$.

### 4.1.2 **Network operating problem**

The validation of P2P transactions under network constraints is an important problem for ensuring the feasibility of P2P market solutions. $E_{nm,t}$ values between peers from the P2P market solution are used to establish the setpoints $E_{n,t}$ for all peers, hence used by the Alternating Current Power Flow (AC-PF) to analyze grid conditions. Assuming that P2P transactions will occur in low and medium voltage distribution networks, an AC-PF model using pandapower (THURNER et al., 2018), which is a python-based tool, was used. Pandapower allows the modeling of radial or meshed electrical networks and includes a Newton-Raphson (YPMA, 1995) method to solve the AC-PF.

Note that reactive power is considered to be fixed for consumers while generators have voltage control capability. The voltage level and maximum active power generation for each generator and the load demand of each consumer is defined and fixed for each hour analyzed. However, the reactive power generation will depend on the generation's type, varying within pre-established limits. Lastly, a slack bus has to be defined in pandapower with the voltage level and angle fixed at 1 $p.u.$ and 0°, respectively. In this work, the node representing the connection between the local community and the external network (upstream connection) is defined as the slack bus.

The voltage level and maximum active power generation for each generator, as well as the load demand of each consumer, are predefined. As physical network constraints, the limits for nodal voltage and line thermal condition are considered in (4.3) and (4.4), respectively.

$$V_i^{min} \leq V_{i,t} \leq V_i^{max}, \quad i = 1,...,n_i, \forall t \in T \tag{4.3}$$

$$I_{l,t} \leq I_l^{max}, \quad l = 1,...,n_l, \forall t \in T \tag{4.4}$$

where $V_{i,t}$ is the voltage at bus $i$ at time $t$; $V_i^{min}$ and $V_i^{max}$ are voltage limits, $n_i$ is the number of system buses; $I_{l,t}$ is the current of line $l$ at time $t$, $I_l^{max}$ is the maximum current capacity of line $l$, and, finally, $n_l$ is the number of lines in the system.

### 4.1.3 **Tracing power flow**

As previously mentioned, it is extremely important to know which peer is responsible for the violation of the pre-established network constraints. To this end, a power flow tracing method is implemented, which allows determining the contribution that each generator and consumer have individually on all lines of the network. The TDF method proposed by Bialek (BIALEK, 1996; BIALEK, 1997), highlighted in appendix A, was applied. This method has been chosen due to its good performance under distribution grids with high penetration of distributed energy resources and bidirectional power flow (SOARES et al., 2015). For a detailed description of the TDF method, the reader are referred to (BIALEK, 1996; BIALEK, 1997).

### 4.1.4 **Iterative Methodology**

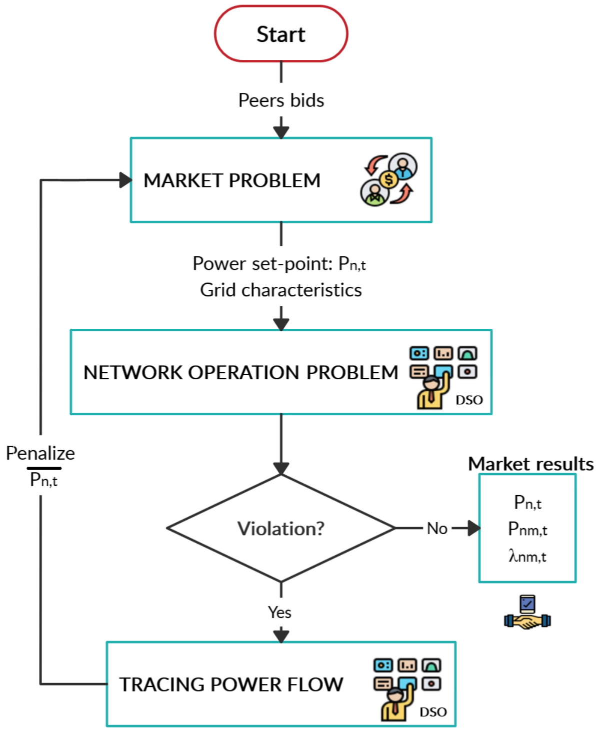
A three-step iterative approach to solve the complete problem of bilateral energy transactions between peers through the P2P market, accounting for distribution grid operation is proposed. The P2PTDF has been designed to allow penalizing both the generator and the consumer. Based on this premise, it is possible to identify the peers that are responsible for the network constraints violation. It then becomes possible to penalize them, encouraging such peers to renegotiate their bilateral energy transactions in the local energy market.

It is worth mentioning that to penalize a generator, in this case, means limiting its maximum dispatch capacity, and penalizing a consumer, in turn, means limiting its maximum load demand. So, penalizing consumers has the same effect as reducing their energy consumption profile. This effect is known in the literature as load flexibility and is an undesirable operational condition. Moreover, only consumers with a certain flexibility level are able to meet this profile. In light of the previous feature, the present thesis follows the strategy of penalizing generators, when necessary, instead of consumers.

Defining how much to penalize a peer can be tricky. To avoid an excessive penalty, the generator's power bid[1] must be decreased by a certain value $\delta\%$ at each iteration, where $\delta$ should not be a high value.

[1] In a P2P electricity market, the sellers and buyers submit bids for sell/buy energy. Bids represent how much power the sellers or buyers are willing to trade and are usually presented in the form of a price and quantity quotation. This definition can be extended to reserve bid.

Figure 11 – Iterative methodology flowchart.




**Source**: Author's figure.

Figure 18 represents the flowchart of the proposed iterative approach, consisting of three main steps:

- **Step 1:** Optimizes the P2P market (4.1a) - (4.1e) without considering network constraints. Analyzing the bids and purchase offers of all peers, the values of $E_{n,t}$ and $E_{nm,t}$ are calculated. These values are used as input data for step 2;
- **Step 2:** Reads input data and network characteristics. Based on $E_{n,t}$ and $E_{nm,t}$ values, the proposed transactions feasibility is verified through an AC-PF. The AC-PF determines the flows $P_{ij,t}$ between all lines $l \in L$ of the system and the voltage levels $V_{i,t}$ of all buses $i \in n_i$, for all $t \in T$. The stopping criterion used is the verification of network congestion (4.4), that is, if the lines power flow is above its maximum capacity, as well as if the buses voltage level is out the limits (4.3). If any of the constraints are violated, the method goes to step 3. Otherwise, the iterative process is stopped and the results $E_{n,t}$, $E_{nm,t}$ are displayed;
- **Step 3:** This step is composed by the TDF algorithm. Based on the data calculated by the AC-PF (Step 2), this algorithm determines the share of a specific generator in every line flow $E_{ij,t}$, for all $t \in T$. In other words, it means determining which peers make use of a specific system line or contribute to the violation of some constraints. Then, it is possible to penalize the power bid of the generator that caused the violation. Returns to step 1.

It is well known that one of the problems caused by power injection of distributed generation in the distribution grid is the increase in the buses' voltage, in which the generation is allocated (TONKOSKI; TURCOTTE; EL-FOULY, 2012). Thus, the proposed method helps to minimize this problem, since it tends to decrease the generators' power injection that overload the system.

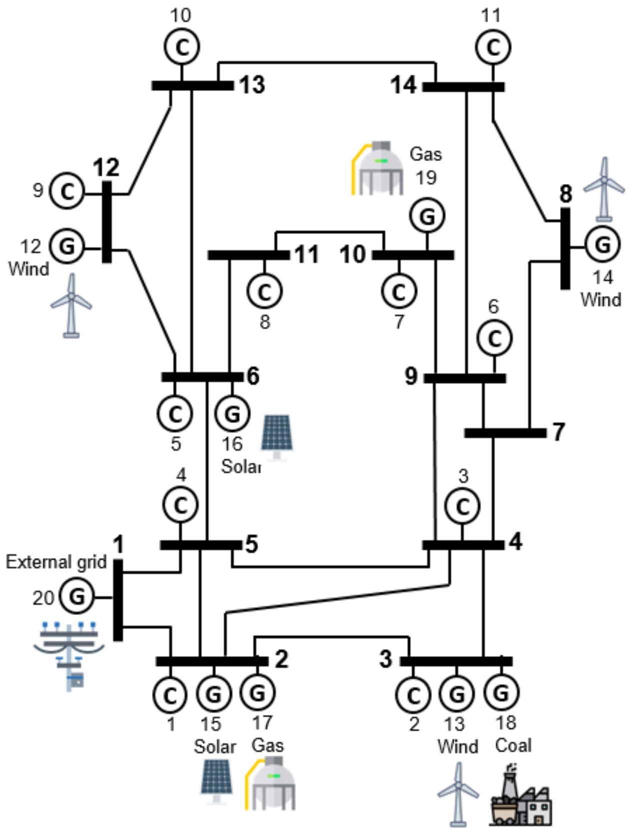
### 4.1.5 **Case Study**

This section presents a case study illustrating the application of the developed iterative method and its performance.

#### 4.1.5.1 *Case Characterization*

The case study is based on a modified 14-bus distribution network with 19 peers and a single external network connection (BOTELHO et al., 2021a), as illustrated in Figure 12. This 13-kV medium voltage distribution network has $I_l^{max}$ = 0.6 kA for all lines $l \in n_l$; $V_i^{min}$ and $V_i^{max}$ are considered as 0.95 p.u. and 1.05 p.u., respectively, for every bus $i \in n_i$.

Figure 12 – Modified IEEE-14 bus system (BOTELHO et al., 2021a).




**Source**: Author's figure.

Daily profiles for all peers, both prosumers and consumers, were considered and detailed in Table 5. More precisely, peers 1 to 11 are prosumers with excess demand (consumers), while

Table 5 – Consumers' hourly load demand.

| **Time [h]** | 00:00 | 01:00 | 02:00 | 03:00 | 04:00 | 05:00 | 06:00 | 07:00 | 08:00 | 09:00 | 10:00 | 11:00 | 12:00 | 13:00 | 14:00 | 15:00 | 16:00 | 17:00 | 18:00 | 19:00 | 20:00 | 21:00 | 22:00 | 23:00 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **C1 [MW]** | 3,57 | 9,77 | 7,68 | 8,26 | 8,72 | 4,19 | 5,89 | 3,86 | 4,87 | 4,40 | 4,72 | 6,26 | 3,93 | 3,92 | 3,92 | 3,91 | 6,51 | 3,84 | 3,73 | 4,80 | 6,21 | 7,72 | 5,47 | 8,60 |
| **C2 [MW]** | 53,09 | 47,80 | 9,91 | 9,73 | 10,13 | 10,04 | 10,25 | 9,47 | 10,43 | 9,12 | 10,22 | 9,03 | 10,08 | 29,75 | 12,05 | 9,52 | 10,13 | 10,17 | 9,03 | 10,30 | 10,43 | 9,21 | 10,30 | 54,45 |
| **C3 [MW]** | 5,05 | 4,95 | 4,95 | 5,06 | 5,06 | 5,14 | 5,12 | 5,08 | 5,06 | 4,82 | 6,57 | 6,43 | 6,89 | 6,67 | 7,76 | 9,42 | 8,87 | 8,12 | 8,18 | 42,10 | 9,27 | 6,06 | 4,98 | 5,09 |
| **C4 [MW]** | 0,65 | 0,65 | 0,60 | 0,59 | 0,63 | 0,60 | 0,60 | 0,60 | 0,80 | 0,81 | 0,58 | 0,78 | 0,64 | 0,64 | 0,73 | 0,62 | 0,60 | 0,65 | 0,61 | 0,57 | 0,59 | 0,61 | 0,81 | 0,62 |
| **C5 [MW]** | 3,98 | 2,84 | 2,75 | 2,81 | 2,68 | 2,51 | 2,57 | 2,75 | 5,27 | 4,93 | 3,80 | 2,87 | 3,28 | 5,67 | 3,04 | 3,32 | 4,23 | 4,39 | 6,13 | 5,67 | 5,94 | 5,22 | 4,96 | 4,58 |
| **C6 [MW]** | 2,62 | 2,53 | 2,43 | 2,59 | 2,44 | 2,39 | 2,50 | 2,64 | 4,04 | 2,83 | 6,12 | 6,04 | 4,57 | 7,55 | 4,75 | 2,31 | 2,15 | 4,59 | 15,96 | 15,65 | 2,23 | 2,24 | 2,14 | 2,27 |
| **C7 [MW]** | 1,06 | 1,05 | 1,06 | 1,05 | 1,05 | 1,04 | 1,03 | 1,02 | 0,99 | 1,75 | 3,24 | 2,43 | 1,12 | 6,53 | 2,35 | 1,89 | 1,38 | 1,30 | 4,23 | 4,00 | 2,57 | 2,66 | 2,78 | 2,06 |
| **C8 [MW]** | 0,41 | 0,42 | 0,42 | 0,41 | 0,44 | 0,41 | 0,41 | 0,41 | 0,41 | 1,11 | 0,46 | 0,41 | 0,44 | 0,41 | 0,41 | 0,44 | 0,41 | 0,43 | 1,03 | 1,61 | 1,64 | 1,88 | 1,76 | 0,41 |
| **C9 [MW]** | 1,91 | 0,50 | 0,52 | 0,49 | 0,46 | 0,50 | 0,52 | 0,44 | 0,44 | 0,48 | 0,49 | 0,44 | 0,44 | 0,51 | 0,45 | 0,44 | 0,96 | 4,37 | 3,22 | 1,64 | 2,75 | 2,06 | 2,15 | 2,00 |
| **C10 [MW]** | 1,49 | 1,33 | 1,28 | 1,34 | 1,42 | 1,42 | 1,71 | 1,44 | 1,56 | 1,44 | 3,30 | 1,65 | 2,17 | 1,62 | 1,46 | 1,56 | 1,31 | 1,23 | 1,15 | 1,31 | 10,42 | 9,74 | 1,59 | 1,53 |
| **C11 [MW]** | 1,94 | 1,95 | 1,87 | 1,92 | 1,94 | 1,76 | 1,95 | 1,82 | 2,02 | 2,26 | 2,42 | 2,28 | 2,25 | 2,29 | 2,15 | 2,21 | 2,79 | 2,24 | 2,60 | 2,34 | 2,51 | 2,21 | 2,27 | 1,89 |
| **G12 [MW] (Wind)** | 45.14 | 45.30 | 45.60 | 41.57 | 22.25 | 17.08 | 25.09 | 32.40 | 34.89 | 46.01 | 35.20 | 45.08 | 47.00 | 44.88 | 40.79 | 47.13 | 45.11 | 45.41 | 46.91 | 44.88 | 46.74 | 47.08 | 45.70 | 41.62 |
| **G13 [MW] (Wind)** | 15.90 | 12.94 | 16.75 | 16.19 | 14.15 | 10.70 | 15.22 | 15.00 | 11.95 | 12.59 | 15.70 | 12.04 | 7.20 | 11.17 | 9.03 | 9.49 | 8.20 | 10.59 | 10.03 | 6.32 | 10.13 | 12.47 | 7.85 | 13.33 |
| **G14 [MW] (Wind)** | 1.65 | 1.57 | 1.55 | 1.14 | 1.19 | 0.80 | 0.51 | 0.78 | 1.11 | 0.68 | 1.74 | 1.69 | 3.18 | 3.87 | 4.82 | 3.57 | 4.33 | 5.23 | 4.43 | 5.27 | 4.99 | 5.25 | 5.09 | 5.03 |
| **G15 [MW] (Solar)** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.30 | 1.39 | 3.33 | 4.91 | 3.87 | 0.99 | 9.17 | 5.56 | 1.59 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **G16 [MW] (Solar)** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.93 | 3.00 | 3.18 | 6.57 | 2.43 | 5.82 | 2.64 | 1.68 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

**Source**: Author's table.

Table 6 – Parameter $a_n$ and $b_n$ for each peer.

| **Peers** | **C1** | **C2** | **C3** | **C4** | **C5** | **C6** | **C7** | **C8** | **C9** | **C10** | **C11** | **G12** | **G13** | **G14** | **G15** | **G16** | **G17** | **G18** | **G19** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $a_n$ | -1.18 | -0.24 | -0.57 | -1.24 | -1.62 | -0.31 | -4.36 | -1.63 | -5.15 | -1.96 | -1.54 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 2.51 | 0.15 | 3.64 |
| $b_n$ | 50.9 | 37.8 | 43.6 | 50.3 | 30.4 | 27.5 | 46.7 | 33.2 | 55.0 | 62.1 | 42.9 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 27.7 | 35.5 | 30.4 |

**Source**: Author's table.

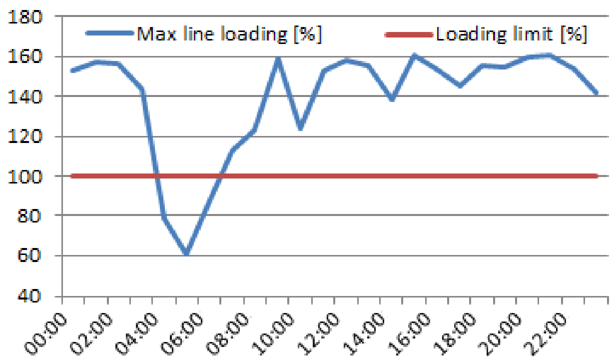
peers 12 to 19 are prosumers with generation surplus (producers).

The producers are categorized by their generation technology, i.e. 3 wind turbines, 2 photovoltaic systems, 2 gas turbines and 1 coal based system. Note that producers 17 (gas turbine), 18 (coal unit) and 19 (gas turbine) have constant maximum generation equal to 20MW, 50MW and 10MW, respectively. Peer 20 represents the external network connection, which can be the local utility network, another energy community, etc. Consumers have flexibility, in their demand, of 10%. The penalization factor $\delta$ is set in 5%.

The AC-PF model used requires the specification of reactive power limits, where $Q_{n,t}$ is the reactive power of peer $n$ at time $t$ $\forall$ $T$. With the same proposal as Orlandini et al. (ORLANDINI et al., 2019), we assume that consumers have a fixed reactive power equal to 20% of the active power traded in P2P market, that is, $Q_{n,t} = 0.2E_{n,t}$. Producers can generate reactive power with an upper limit equal to 40% of the active power traded on P2P market, that is, $0 \leq Q_{n,t} \leq 0.4E_{n,t}$. Consumers are supposed to consume reactive power and producers generate reactive power.

Table 6 shows the parameters $a_n$ and $b_n$ for each peer, to be used in the cost function $C_{n,t}$. Finally, as the purpose of this work is to promote and analyze a local energy market among the peers of the same community, electricity commercialization with the external grid is only allowed as a last resource. Thus, the price to import energy from the external grid was considered equal to 150 \$/MWh and to export energy to the external grid equal to 10 \$/MWh.

Figure 13 – Most loaded line for each time-step [%].




**Source**: Author's figure.

#### 4.1.5.2 *Results*

The test case is simulated over a day with 1 hour time-step. The P2P market is optimized for each hour, and the steps established in the flowchart of Figure 18 are followed until there is no further constraint violation. To properly analyze the proposed method, it is compared with a benchmark. The benchmark corresponds to the first step of the first iteration of the proposed model, i.e., the initial P2P market optimization.

Figure 13 shows the most congested line in each time-step for the benchmark. For almost all scenarios there is a line with loading above 100%. Besides, more than one line may also be congested at certain time-steps.

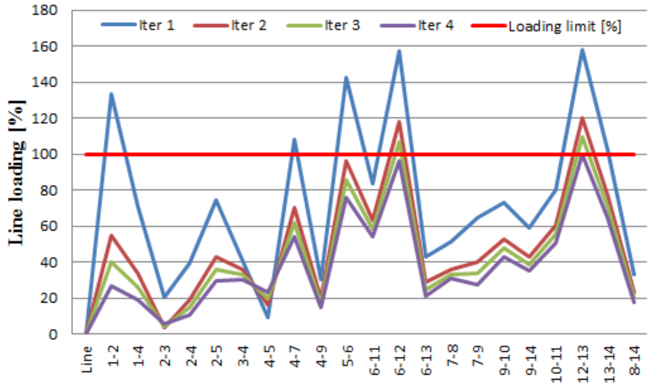
This proves the need for a methodology that can optimize the P2P market taking into account network constraints, as there is a high risk of network congestion.

The P2PTDF is applied to each time-step and, as a final result, no line is overloaded. The resulting power flow for the first iteration (benchmark solution) at 12:00h, when there are the most congested lines (average), is shown in Figure 14. One can see that congestion occurs often in the day, and therefore the benchmark solution is not grid operating feasible. The iterative process reaches a feasible solution after four iterations. This result is achieved by limiting the energy supply of generators that cause congestion. The evolution of line-loading over the four iterations is shown in Figure 14. The last iteration achieves grid operating feasibility, as can be seen in Figure 15. In all the final solutions reached, there is no violation of the pre-established voltage limits.

The social welfare results of the benchmark and the proposed model, as an economic metric, are presented and compared in Table 13. The social welfare tends to decrease with interactions, since the proposed method penalizes the bid of the generator that causes congestion and that generator tends to be among the "cheapest". So another generator (a little more expensive) has to be dispatched to make up the difference, causing social welfare to decrease.

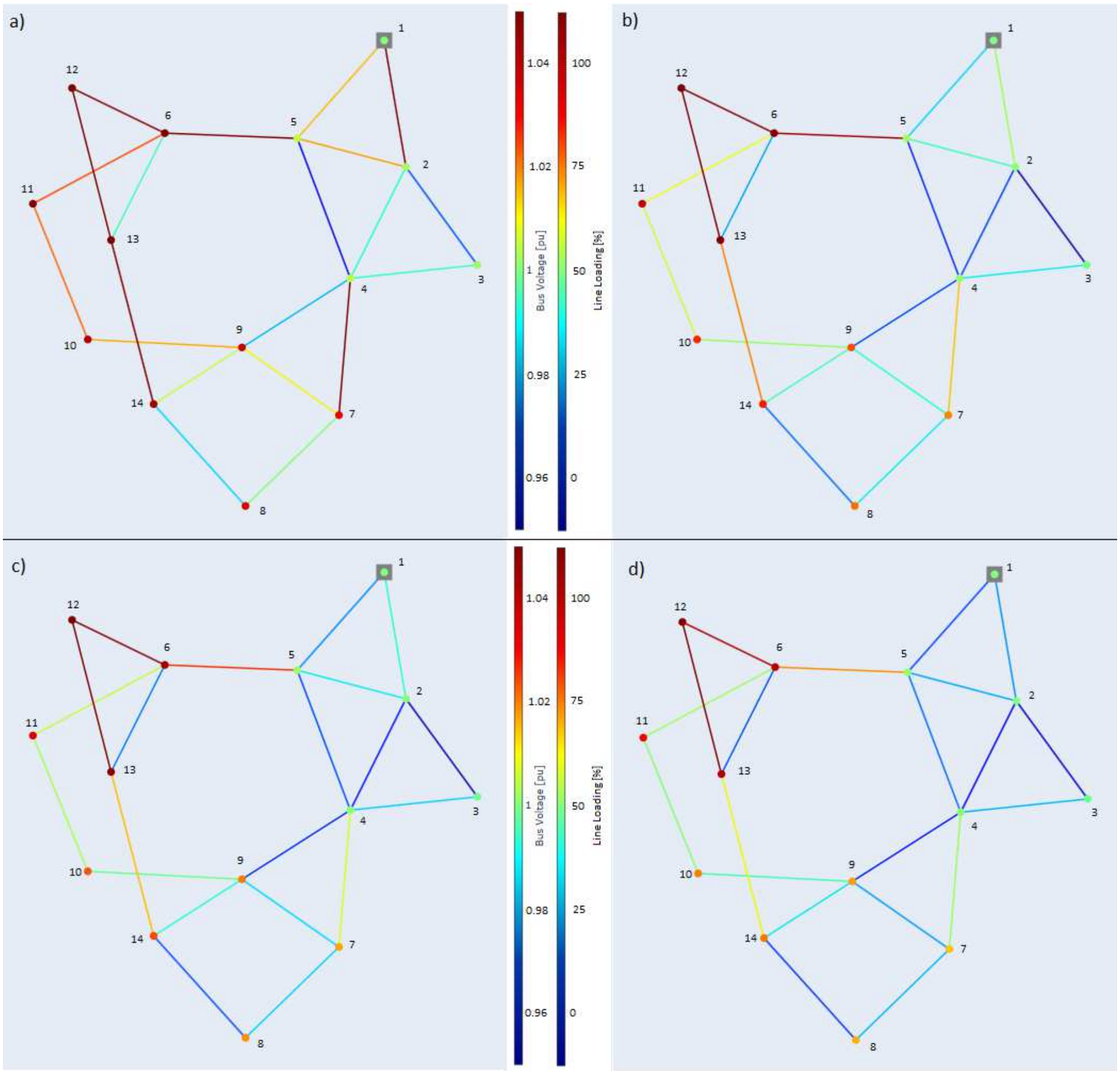
It is noteworthy that despite the decrease in social welfare, the P2PTDF solution repre-

Figure 14 – Power flow over iteration k at time-step 12:00 [%].




**Source**: Author's figure.

Figure 15 – Power flow for the grid at time-step 12:00. a) Iteration 1, b) Iteration 2, c) Iteration 3 and d) Iteration 4.




**Source**: Author's figure.

Table 7 – Benchmark and P2PTDF social welfare for each time-step.

| Time [h] | Benchmark social welfare [$] | P2PTDF social welfare [$] | Time [h] | Benchmark social welfare [$] | P2PTDF social welfare [$] |
|---|---|---|---|---|---|
| 00:00 | 1.876,22 | 1206,87 | 12:00 | 1663,65 | 1419,90 |
| 01:00 | 1.871,77 | 1142,59 | 13:00 | 2020,04 | 1438,51 |
| 02:00 | 1.580,93 | 1364,01 | 14:00 | 1743,41 | 1552,63 |
| 03:00 | 1.548,21 | 1376,14 | 15:00 | 1671,94 | 1420,63 |
| 04:00 | 1.355,31 | 1355,31 | 16:00 | 1687,47 | 1495,31 |
| 05:00 | 1.114,03 | 1114,03 | 17:00 | 1678,62 | 1541,64 |
| 06:00 | 1.338,34 | 1338,34 | 18:00 | 1829,9 | 1363,76 |
| 07:00 | 1.318,11 | 1258,01 | 19:00 | 1264,89 | 506,89 |
| 08:00 | 1.429,63 | 1350,7 | 20:00 | 2065,13 | 1629,22 |
| 09:00 | 1.527,94 | 1314,4 | 21:00 | 1998,03 | 1748,56 |
| 10:00 | 1.707,89 | 1628,67 | 22:00 | 1639,72 | 1470,74 |
| 11:00 | 1.712,12 | 1481,87 | 23:00 | 1724,99 | 1108,72 |

**Source**: Author's table.

sents a feasible network operating solution, while the benchmark solution does not. In a real operating situation, the proposed initial transactions could not take place. More precisely, it would require load shedding and, consequently, decrease the total system generation, reaching a viable operating point that would probably lead to a lower social welfare than that achieved by the proposed methodology.

### 4.1.6 **Partial conclusions**

The P2P markets actively contribute to a greater RES penetration through small and medium-sized prosumers, providing consumers with a higher degree of freedom in the energy trade. However, the impact of this market design on the network's operation still needs detailed studies in order to avoid network congestion and voltage problems. This chapter presents a simple methodology (P2PTDF) for the optimization of bilateral P2P energy transactions taking into account network constraints. To this end, the problem is divided into two sub-problems, energy market and network operation, being solved iteratively. That is, the results of each sub-problem are used iteratively to solve the other sub-problems, converging to a globally feasible solution.

The results obtained for the modified 14-bus system demonstrate that the Benchmark method does not guarantee that the solutions found for the market are feasible in the network's operation. For several hours throughout the studied day, violations of the line loading limits are observed. Thus, it is extremely important to use methodologies in the same guideline as the P2PTDF, capable of verifying whether such violations occur and prevent them. The P2PDF proved to be effective in solving the problem presented, finding viable solutions with few iterations, for all time-steps, as shown in the results section.

## 4.2 ENERGY AND RESERVE MARKETS

### 4.2.1 **P2P fundamentals**

To solve the energy problem of P2P transactions, the general mathematical formulationpresented in the section 4.1.1was used along with the Product Differentiation (PD) concept defined by (SORIN; BOBO; PINSON, 2018). This market design is based on peers trading electricity directly with each other, considering the purchasing preferences, defined by PD, of each peer.

Therefore, the basic mathematical formulation of the energy problem can be redefined as (4.5) for every period $t \in T$:

$$\begin{aligned} \min_{D} \sum_{n \in \Omega} \left[ C^{E}_{n,t}\left(E_{n,t}\right) + \tilde{C}^{E}_{n,t}\left(\varepsilon_{n,t}\right) \right] \quad \forall t \in T \\ \text{s.t} \quad (4.1b) - (4.1e) \end{aligned} \tag{4.5}$$

where $C^{E}_{n,t}\left(E_{n,t}\right)$ corresponds to the energy production cost and $E_{n,t} = \sum_{m \in \omega_n} E_{nm,t}$.It is noteworthy that the dual variable $\lambda^{E}_{nm,t}$ associated with the exposed problem represents the price for each bilateral trade at time $t$.

The second component of the objective function (4.5) is shown in (4.6).

$$\tilde{C}^{E}_{n,t}\left(\varepsilon_{n,t}\right) = \sum_{m \in \omega_n} \left(C^{PD}_{nm,t} \cdot E_{nm,t}\right) \quad \forall t \in T \tag{4.6}$$

where $\varepsilon_{n,t} = \left(E_{nm,t}\right)_{m \in \omega_n}$ and the coefficient $C^{PD}_{nm,t}\left(\varepsilon_{n,t}\right)$ is the PD criteria, being able to consider emissions, distance and peer reputation. For example, the distance criterion would represent that peer $n$ is more willing to negotiate with their physically closer peers $m$, which can encourage energy consumption from local producers and is the criterion used in this work. The reader is referred to (SORIN; BOBO; PINSON, 2018) for more details. It is worth noting, however, that the use of a combination of different PDs presents a great challenge.

In this type of market, it is extremely important to know which peer is responsible for a possible violation of the pre-established network constraints. To this end, a power flow tracing method is implemented, which allows determining the contribution that each peer has on all network's lines, as proposed in (BOTELHO et al., 2021a). This method has been chosen due to its good performance for distribution grids with high penetration of distributed energy resources and bidirectional power flow (SOARES et al., 2015). Though, through this method, each generator/consumer is penalized based on its impact in the line overload.

### 4.2.2 **Proposed methodology**

#### 4.2.2.1 *Determining Reserve*

How to properly represent the RES uncertainty is a complex problem. Generally, a Gaussian distribution (BOUFFARD; GALIANA, 2008) is used for this task. However, (GUO et al., 2020) points out that many studies have shown that this method cannot always model uncertainty accurately, suggesting that data mining approaches can be pursued. Thus, a data mining analysis to represent the RES uncertainty was carried out, considering one year and 30 min time-step based on available Australian data set (RATNAM et al., 2017; DOWELL; PINSON, 2015). More precisely, the production levels of three wind turbines and two PV plants are considered.

Two algorithms are applied and compared, MCS and m-ISODATA, and two analyzes are performed for each method:

- Case 1: complete analysis with all data in the series, and
- Case 2: analysis of the generation history only for a specific hour (12 o'clock) on different days.

##### 4.2.2.1.1 Monte Carlo Simulation algorithm

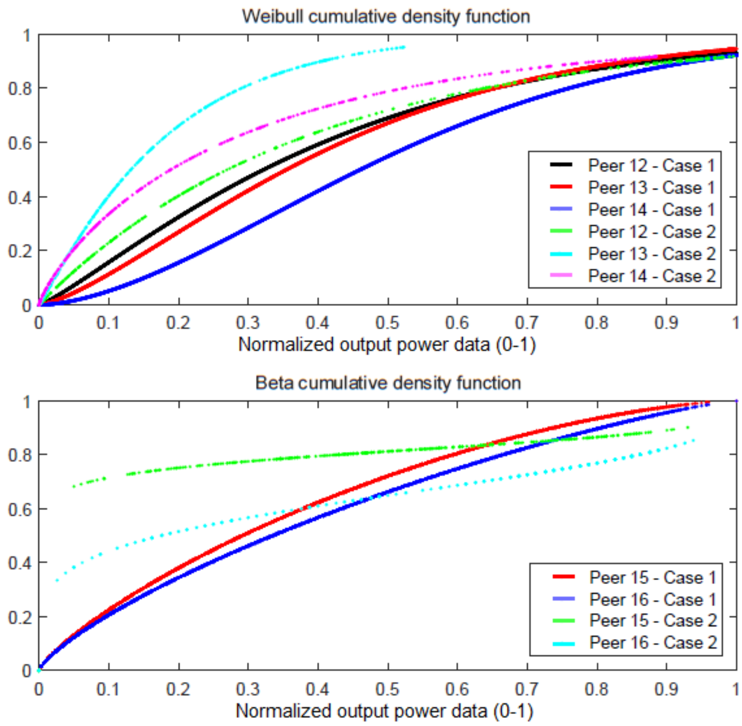
The MCS is a widely used algorithm to deal with stochastic variables due to its simplicity and high precision (CONSTANTE-FLORES; ILLINDALA, 2018). It is a sampling method based on the Probability Density Function (PDF) of stochastic variables that requires a large number of simulations with randomly chosen input values (LI et al., 2013).

The Weibull PDF for wind peers (CARTA; RAMIREZ; VELAZQUEZ, 2009) and Beta PDF for PV peers (SULAIMAN et al., 1999) are used. After estimating the PDFs for each renewable peer in each of the proposed cases, the Cumulative Distribution Function (CDF) is obtained (Figure 16), which enables generating random samples of renewable generation for the MCS.

The shape ($\beta$) and scale ($\eta$) parameters of the Weibull distribution, as well as the shape parameters ($\alpha$ and $\beta$) for the Beta distribution, were calculated for the two cases and renewable peers by using the maximum likelihood estimation method (MYUNG, 2003), as shown in Table 8.

The x-axis of Figure 16 has normalized data in range [0-1] that are obtained by dividing each generation value by the respective value of $E_{n,t}$. Thus, the data are normalized in relation to $E_{n,t}$ and value '1' refers to $E_{n,t}$. Therefore, the expected value from the CDF function, $E_{n,t}^{MCS}$, is limited according to (4.7) since every sample from Figure 16 is limited to $E_{n,t}$.

Figure 16 – Cumulative distribution functions.




**Source**: Author's figure.

$$0 \leq E_{n,t}^{MCS} \leq E_{n,t} \quad \forall n \in \Omega_r, \forall t \in T \tag{4.7}$$

Table 8 – Weibull and Beta distributions parameters.

| Case | Peer 12 | | Peer 13 | | Peer 14 | | Peer 15 | | Peer 16 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\beta$ | $\eta$ | $\beta$ | $\eta$ | $\beta$ | $\eta$ | $\alpha$ | $\beta$ | $\alpha$ | $\beta$ |
| **1** | 0.438362 | 1.19391 | 0.463088 | 1.38261 | 0.573135 | 1.68556 | 0.79392 | 1.52982 | 0.75537 | 1.23097 |
| **2** | 0.39294 | 0.981467 | 0.185981 | 1.06869 | 0.294587 | 0.828193 | 0.064068 | 0.267465 | 0.201679 | 0.358648 |

**Source**: Author's table.

By using the CDFs and applying MCS, the reserve required to cover the uncertainty can be calculated by (4.8).

$$R_{n,t} = E_{n,t}^{MCS} - E_{n,t} \quad \forall n \in \Omega_r, \forall t \in T \tag{4.8}$$

From (4.7) and (4.8), renewable generators have $R_{n,t} \leq 0$ because they need to buy reserve capacity from the market.

#### 4.2.2.1.2 m-ISODATA clustering algorithm

The m-ISODATA is an unsupervised clustering algorithm proposed recently by de Paula et al. (PAULA et al., 2021). This algorithm seeks to capture representative scenarios to represent uncertainties in power system models. One advantage is the ability to automatically obtain the number of scenarios needed to fully capture the historical series' variability. In the present paper, the m-ISODATA clustering method is applied to generate $k$ scenarios that best represent the historical data. Each scenario consists of a centroid associated with a probability of occurrence. Then, the analysis and clustering of the data from each generator allows predicting the Generator's Behavior Pattern (GBP)[2] of each renewable peer. Therefore, the GBP for all five renewable peers of the cases under study is obtained by performing a data-driven analysis of the corresponding real generation data. In other words, the GBP consists of a simplified way to predict the future behavior of a specific generator from its past behavior. Table 9 shows the results obtained by the m-ISODATA clustering algorithm for all the renewable generators of the proposed case studies. In Table 9, the Energy [p.u. MWh] ($E^p_{n,k,t}$) is the normalized predicted energy according to the GBP at time $t$. This is normalized in terms of $E_{n,t}$, i.e., $E^p_{n,k,t} = 1$ refers to $E_{n,t}$. The Probability (%), $P(E^p_{n,k,t})$, is the probability of $E^p_{n,k,t}$.

Table 9 – m-ISODATA scenarios of the renewable generators (GBP).

| Peer 12 (Wind) | | | | Peer 13 (Wind) | | | | Peer 14 (Wind) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Case 1 | | Case 2 | | Case 1 | | Case 2 | | Case 1 | | Case 2 | |
| Energy [p.u. MWh] | Probability [%] | Energy [p.u. MWh] | Probability [%] | Energy [p.u. MWh] | Probability [%] | Energy [p.u. MWh] | Probability [%] | Energy [p.u. MWh] | Probability [%] | Energy [p.u. MWh] | Probability [%] |
| 0,0141 | 7,60 | 0,0219 | 15,62 | 0,0253 | 7,12 | 0,0280 | 0,1753 | 0,0349 | 6,01 | 0,0160 | 0,1945 |
| 0,4483 | 5,83 | 0,4805 | 5,48 | 0,4387 | 5,77 | 0,3828 | 0,0466 | 0,5325 | 6,08 | 0,4179 | 0,0493 |
| 0,2115 | 7,11 | 0,1960 | 6,85 | 0,2121 | 7,11 | 0,1437 | 0,0904 | 0,2871 | 5,94 | 0,1323 | 0,0877 |
| 0,7971 | 6,60 | 0,8604 | 4,93 | 0,7103 | 7,64 | 0,6478 | 0,0658 | 0,8010 | 5,82 | 0,8229 | 0,0767 |
| 0,1106 | 7,62 | 0,0749 | 9,86 | 0,1164 | 7,10 | 0,0870 | 0,1068 | 0,1636 | 6,73 | 0,0747 | 0,1342 |
| 0,5913 | 5,70 | 0,6235 | 7,12 | 0,6206 | 7,21 | 0,5369 | 0,0630 | 0,6598 | 6,56 | 0,5800 | 0,0438 |
| 0,3213 | 6,66 | 0,3096 | 5,75 | 0,3194 | 6,90 | 0,2562 | 0,0658 | 0,4091 | 6,15 | 0,2615 | 0,0548 |
| 0,9009 | 7,18 | 0,9281 | 9,04 | 0,9380 | 8,12 | 0,9345 | 0,0521 | 0,9289 | 5,77 | 0,9218 | 0,0548 |
| 0,0598 | 6,73 | 0,2374 | 7,67 | 0,0713 | 7,85 | 0,4555 | 0,0712 | 0,1071 | 7,05 | 0,4951 | 0,0575 |
| 0,5181 | 5,47 | 0,1282 | 8,49 | 0,5163 | 6,56 | 0,1951 | 0,0877 | 0,5971 | 5,93 | 0,1950 | 0,0575 |
| 0,2651 | 6,87 | 0,7319 | 6,58 | 0,2649 | 6,80 | 0,7294 | 0,0521 | 0,3493 | 6,20 | 0,6699 | 0,0658 |
| 0,1614 | 7,35 | 0,3906 | 7,12 | 0,8001 | 8,28 | 0,3149 | 0,0521 | 0,8643 | 6,27 | 0,3413 | 0,0658 |
| 0,6821 | 6,46 | 0,9732 | 5,48 | 0,1637 | 7,17 | 0,7891 | 0,0712 | 0,2229 | 6,86 | 0,9866 | 0,0575 |
| 0,3819 | 6,36 | - | - | 0,3782 | 6,37 | - | - | 0,7307 | 5,78 | - | - |
| 0,9652 | 6,45 | - | - | - | - | - | - | 0,4713 | 6,06 | - | - |
| - | - | - | - | - | - | - | - | 0,9877 | 6,80 | - | - |

| Peer 15 (Solar) | | | | Peer 16 (Solar) | | | |
|---|---|---|---|---|---|---|---|
| Case 1 | | Case 2 | | Case 1 | | Case 2 | |
| Energy [p.u. MWh] | Probability [%] | Energy [p.u. MWh] | Probability [%] | Energy [p.u. MWh] | Probability [%] | Energy [p.u. MWh] | Probability [%] |
| 0.0266 | 17.78 | 0.0247 | 4.93 | 0.0285 | 16.69 | 0.1084 | 8.49 |
| 0.3691 | 6.36 | 0.597 | 10.96 | 0.4342 | 5.65 | 0.6566 | 7.67 |
| 0.1499 | 7.36 | 0.3721 | 7.12 | 0.181 | 5.42 | 0.3995 | 6.58 |
| 0.6262 | 5.8 | 0.7547 | 5.75 | 0.7008 | 6.48 | 0.8606 | 11.78 |
| 0.0889 | 10.76 | 0.2249 | 4.38 | 0.0794 | 7.21 | 0.2529 | 9.59 |
| 0.4912 | 6.07 | 0.6727 | 8.77 | 0.5774 | 5.1 | 0.8015 | 17.53 |
| 0.2548 | 5.9 | 0.4721 | 10.41 | 0.3001 | 5.54 | 0.5296 | 4.93 |
| 0.7793 | 5.95 | 0.8693 | 6.85 | 0.8127 | 6.89 | 0.9067 | 13.97 |
| 0.4293 | 6.51 | 0.1531 | 6.3 | 0.5045 | 5.61 | 0.7371 | 10.68 |
| 0.2029 | 5.91 | 0.4158 | 4.93 | 0.2363 | 6.1 | 0.9493 | 8.77 |
| 0.7007 | 5.24 | 0.8242 | 5.75 | 0.7564 | 6.1 | - | - |
| 0.5576 | 5.76 | 0.3022 | 6.85 | 0.131 | 6.37 | - | - |
| 0.3112 | 5.61 | 0.5203 | 10.96 | 0.6383 | 5.87 | - | - |
| 0.8643 | 4.98 | 0.9304 | 6.03 | 0.3619 | 5.61 | - | - |
| - | - | - | - | 0.8786 | 5.36 | - | - |

**Source**: Author's table.

From the GBP, the reserve required to cover the uncertainty is calculated by using (4.9) and (4.10). Equation (4.9) calculates the expected energy $E^{mISO}_{n,t}$ that represents, according to m-ISODATA, how much energy peer $n$ can actually generate at time $t$. This is obtained

[2] GBP refers to the behavior pattern of a given generator over time. Such a pattern is found from constant measurement and analysis of the real generation values.

by weighting the scenarios in terms of the respective predicted energy $E^{p}_{n,k,t}$ and probability $P(E^{p}_{n,k,t})$, where $n_c$ is the number of clusters. Equation (4.10), in turn, allows the calculation of the required reserve for every renewable peer $n$ at time $t$.

$$E^{mISO}_{n,t} = E_{n,t} \cdot \sum_{k=1}^{n_c} \left[ E^{p}_{n,k,t} \cdot P\left(E^{p}_{n,k,t}\right)\right] \forall n \in \Omega_r, \quad \forall t \in T \tag{4.9}$$

$$R_{n,t} = E^{mISO}_{n,t} - E_{n,t} \quad \forall n \in \Omega_r, \forall t \in T \tag{4.10}$$

where $E^{mISO}_{n,t}$ represents the expected energy to be generated by peer $n$ at time $t$. From (4.10), the reserve for a renewable generator is equal to the difference between the energy that this generator will actually generate, according to its GBP, and the energy that it negotiates in the energy market. Notice that $R_{n,t} \leq 0$ for renewable generators as previously described for equation (4.8).

4.2.2.2 *Inclusion of the reserve into the P2P problem*

The mathematical modeling used in section 4.2.1 for the energy exchanges between peers can be extended to the reserve market. Thus, the formulation of the P2P reserve market can be defined as (4.11a) - (4.11e) (GUO et al., 2020) for every $t \in T$:

$$\min_{D} \sum_{n\in\Omega} \left[ C^{R}_{n,t}\left(R_{n,t}\right) + \tilde{C}^{R}_{n,t}\left(r_{n,t}\right) \right] \forall t \in T \tag{4.11a}$$

$$\text{s.t.} \quad \underline{R_{n,t}} \leq R_{n,t} \leq \overline{R_{n,t}} \quad \forall n \in \Omega, \forall t \in T \tag{4.11b}$$

$$R_{nm,t} + R_{mn,t} = 0 \quad \forall (n,m) \in (\Omega, \omega_n), \forall t \in T \tag{4.11c}$$

$$R_{nm,t} \geq 0 \quad \forall (n,m) \in (\Omega_g \cup \Omega_c, \omega_n), \forall t \in T \tag{4.11d}$$

$$R_{nm,t} \leq 0 \quad \forall (n,m) \in (\Omega_r, \omega_n), \forall t \in T \tag{4.11e}$$

where $D = (R_{n,t} \in \mathbb{R}^{|\omega_n|})_{n\in\Omega}$, $R_{n,t}$ is the reserve injection of each agent $n \in \Omega$ at time $t$ and $R_{n,t} = \sum_{m\in\omega_n} R_{nm,t}$, with $R_{nm,t}$ corresponding to the reserve exchange between peers $n$ and $m$ at time $t$, for which a positive value means sales (4.11d) and a negative value means a purchase (4.11e). Bilateral negotiations $R_{nm,t}$ have the property of reciprocity, as defined by (4.11c). $\underline{R_{n,t}}$ and $\overline{R_{n,t}}$ are the boundaries of reserve as in (4.11b). It is noteworthy that the dual variable $\lambda^{R}_{nm,t}$ associated with the problem represents the price for each reserve bilateral negotiation at time $t$. The cost function shown in (4.2) can be extended to reserve negotiation, thus the function $C^{R}_{n,t}\left(R_{n,t}\right) = \frac{1}{2} \cdot ar_n \cdot R^{2}_{n,t} + br_n \cdot R_{n,t}$, where $ar_n > 0$ and $br_n > 0$, corresponds to the reserve production cost. Similar to the energy market and according to (4.11a), the objective is to minimize the reserve's total cost of all bilateral trades carried out between the peers.

The reasoning about constraints (4.11d) and (4.11e) is similar to that explained for (4.1d) and (4.1e), as supported by (HUG; KAR; WU, 2015). In particular, $R_{n,t} > 0$ is an available reserve for selling and $R_{n,t} < 0$ means the need for buying additional reserve capacity from the market (in the case of renewable generators, for instance). It can be highlighted that constraint (4.11e) is in accordance with constraints (4.8) and (4.10) in terms of a negative reserve for renewable generators.

An additional constraint (4.12) is required to ensure that no peer can negotiate an amount of energy plus reserve greater than its maximum generation capacity, in the generators' case, or its maximum load flexibility in consumers' case.

$$\underline{E_{n,t}} \leq E_{n,t} + R_{n,t} \leq \overline{E_{n,t}} \quad \forall n \in \Omega, \forall t \in T \tag{4.12}$$

It is worth noting that despite not knowing, in advance, where the system reserve will be activated, the use of PD allows prioritizing the reserve negotiations between neighbors, thus in favour of local prosumers. So the function presented in (4.6) can also be extended to represent the peer's preference in reserve negotiation. Thus, $\widetilde{C^{R}_{n,t}}(r_{n,t}) = \sum_{m \in \omega_n} (C^{PD}_{nm,t} \cdot R_{nm,t})$, where $r_{n,t} = (R_{nm,t})_{m \in \omega_n}$.

The energy $E_{nm,t}$ and reserve $R_{nm,t}$ transactions between peers from the P2P market solutions are used to establish the energy $E_{n,t}$ and reserve $R_{n,t}$ setpoints for all peers, respectively, hence used by the AC-PF to analyze grid conditions. Assuming that P2P transactions will occur in low and medium voltage distribution networks, an AC-PF model using pandapower package (THURNER et al., 2018) is used. Also, the physical network constraints are considered, just like in section 4.1.2.

With the purpose of ensuring that the electrical network can support the negotiated reserve, the $R_{n,t}$ variable is inserted into the network power balance as virtual generators. Thus, a virtual generator is considered as connected to the network bus for every peer, having $R_{n,t} > 0$ for peers who sell reserves (conventional generators and consumers) or $R_{n,t} < 0$ for peers who buy reserve (renewable generators). Therefore, in the power balance equation (4.13), the active power injection (4.14) includes the powers related to the energy and reserve negotiated by the peers at bus $i$.

$$\sum_{n \in \Omega} E^{i}_{n,t} + \sum_{n \in \Omega} R^{i}_{n,t} = \sum_{j \in \phi_i} P_{ij,t} \quad \forall i \in n_i, \forall t \in T \tag{4.13}$$

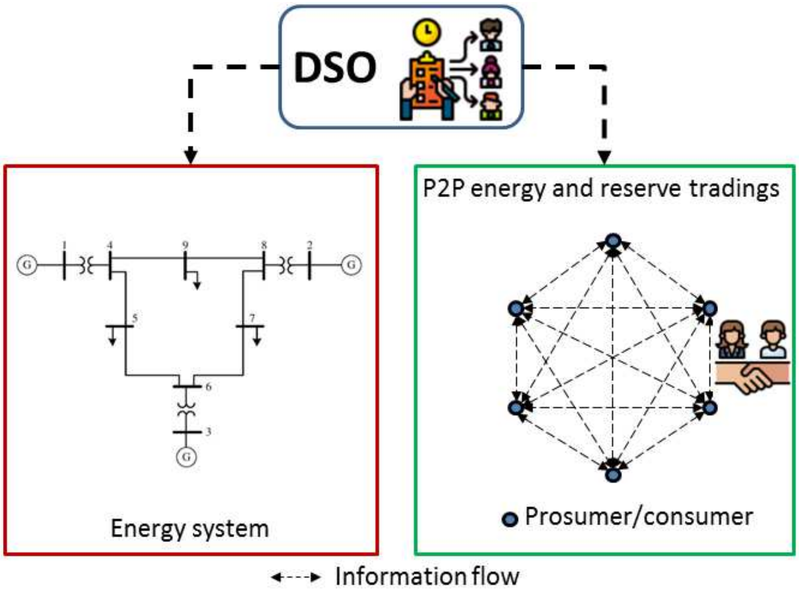
$$P_{ij,t} = V_{i,t} \cdot V_{j,t} \cdot \left( G_{ij,t} \cdot \cos \theta_{ij,t} + B_{ij,t} \cdot \sin \theta_{ij,t} \right) \quad \forall t \in T \tag{4.14}$$

where $E^{i}_{n,t}$ and $R^{i}_{n,t}$ are the power produced (or consumed) and the reserve, respectively, from peer $n$ that is connected to bus $i$ at time $t$; $\phi_i$ is the set of buses connected to bus $i$; $P_{ij,t}$ is the power flow through line $ij$ at time $t$; $G_{ij,t}$ and $B_{ij,t}$ are the condutance and susceptance at time $t$, respectively; $\theta_t$ is the voltage angle at time $t$ (with $\theta_{ij,t}$ = $\theta_{i,t}$ - $\theta_{j,t}$).

4.2.2.3 *Proposed Iterative Algorithm*

An iterative and sequential algorithm to solve the energy and reserve P2P market problem that takes into account the distribution grid operation and allows integration between peers and DSO was proposed. Figure 17 illustrates the proposed integrated prosumer-DSO framework where the DSO is an independent agent responsible for maintaining the balance of energy and reserve in the distribution network while satisfying network constraints. The method has been designed to allow the system operator to penalize the generator or the consumer that causes voltage and congestion problems, with the purpose of encouraging them to renegotiate their bilateral energy/reserve trades in P2P markets.

Figure 17 – Integrated prosumer-DSO framework.



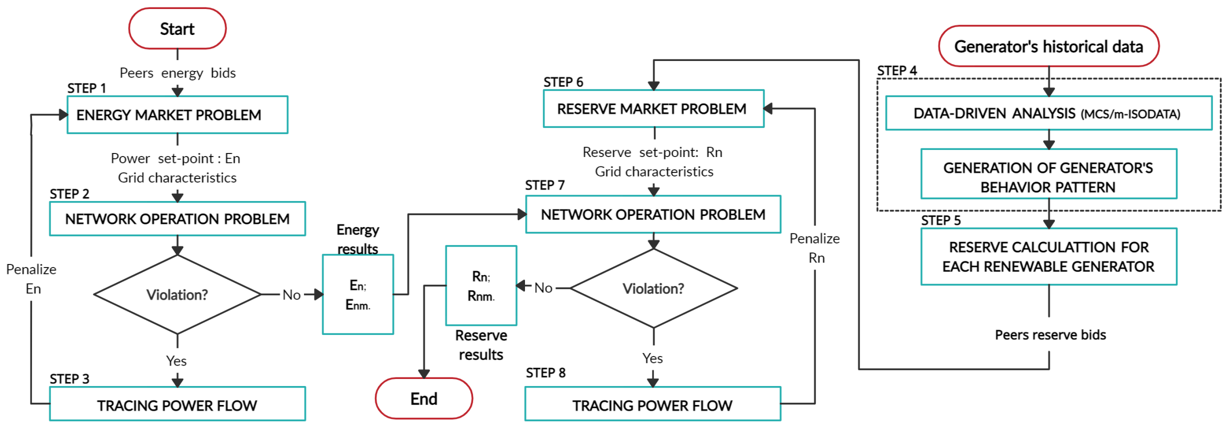

**Source**: Author's figure.

Figure 18 gives the flowchart of the proposed iterative approach.

- **Step 1:** P2P energy market optimization (4.1a)-(4.1e) without considering network constraints. By analyzing the bids and purchase offers from all peers, the values of $E_{n,t}$ and $E_{nm,t}$ are calculated and used as input data for Step 2. In this step, peers can freely trade their energy, define their particular PD criteria and their individual preferences.

- **Step 2:** It consists of the network operation problem. Based on the $E_{n,t}$ and $E_{nm,t}$ values, the DSO checks the feasibility of the proposed transactions through an AC-PF, which determines the power flows $P_{ij,t}$ in all system lines $ij \in n_l$ and the voltage $V_{i,t}$ at all buses $i \in n_i$. If any line in the electrical network has current above the respective limit, thus

Figure 18 – Iterative methodology flowchart.




**Source**: Author's figure.

violating constraint in (4.4), or any system bus has voltage out of its range, see constraint in (4.3), then Step 3 is performed to correct the violation by readjusting the bid of energy. Otherwise, the iterative process is stopped and the results $E_{n,t}$, $E_{nm,t}$ are displayed;

- **Step 3:** This step is formed by the power flow tracing algorithm from Bialek (BIALEK, 1996; BIALEK, 1997). The algorithm is able to determine the specific use of each line in the network by each of the generators and consumers of the system, based on the proportional sharing principle. Usually, more than one prosumer could cause a bottleneck, as the lines of the network are not only used by one single user. Using the power flow tracing method, it is possible to simultaneously determine the share of each generator/consumer in the power flow of all lines in the system. In this way, knowing which line is overloaded, it is also known which generators/consumers are “responsible"for this overload. Then, we penalize each of them according to their share of use of the overloaded line. Based on the AC-PF results (Step 2), the algorithm determines the share of a specific generator in every line power flow $P_{ij,t}$. In other words, it means determining which peers make use of a specific system line or contribute to the violation of some constraints. Then, the DSO can penalize the power bid of the generator that caused the violation. The DSO can directly inform the peer who caused the violation that its bid must be readjusted. The notice could be a private message, for instance, via an online P2P trading platform. After Step 3, the algorithm returns to Step 1. If a generator is penalized for violating a network constraint, in the next iteration, this generator will necessarily negotiate less energy, thus it will alleviate the overload in the region of the system where it is located. Note that each generator contributing to line congestion is penalized according to its share in the use of that line.

- **Step 4:** When m-ISODATA is used, the generators' GBP is created from the generation historical data of renewable peers. From its own generation history, each peer can perform a data-driven analysis to create the GBP for itself and find the values of $E^{p}_{n,k,t}$ and $P(E^{p}_{n,k,t})$. When MCS is used, it finds the values of $E^{MCS}_{n,t}$.

- **Step 5:** With the values calculated in Step 4, the reserve values required by each renewable generator are calculated by them using (4.8) or (4.10).
- **Step 6:** Consists of the P2P reserve market optimization (4.11a)-(4.11e), and (4.12). From analyzing the reserve bids and purchase offers of all peers, the values of $R_{n,t}$ and $R_{nm,t}$ are calculated. These values coupled with $E_{n,t}$ and $E_{nm,t}$ are used as input data for Step 7. In this step, peers can freely trade their reserve, define their particular PD criteria and individual preferences, just as in Step 1.
- **Step 7:** Based on $E_{n,t}$, $E_{nm,t}$, $R_{n,t}$ and $R_{nm,t}$ values, the proposed transactions feasibility is checked by the DSO through an AC-PF, like in Step 2, by using (4.13). If any of the constraints is violated, the method goes to Step 8. Otherwise, the iterative process is stopped and the results $R_{n,t}$, $R_{nm,t}$ are displayed;
- **Step 8:** Similar to Step 3, in Step 8 the DSO determines which peers make use of a specific system line or contribute to the violation of constraints. Then, the DSO can penalize the generator's reserve bid that caused the violation and, after that, the algorithm returns to Step 6.

One highlight that is worth elucidating is that modeling an individual peer or an aggregator/community involving several peers is the same for the proposed methodology, and the method can be generalized to solar-centric or wind-centric generation profiles, since it only depends on the values that the peer intends to negotiate ($E_{n,t}$ and $R_{n,t}$). However, the aim is to offer an alternative solution that fits the currently available regulation and that serves as a transition to a more decentralized environment in the future. The study focuses on a case in which the analysis is performed for a medium voltage network; therefore, the aggregation of residential consumers/prosumers is seen to be the first evolution of those markets. Furthermore, we develop a case study where at least one generator of each type (wind, PV gas and coal) was represented and where the distribution lines were also overloaded, so that it was possible to show the proposed methodology performance. If several distributed generation units were spread out in the test system, the loads would be served locally (generation and load on the same bus), which would lead to low grid usage.

### 4.2.3 **Case study**

This section presents a case study showing the application of the proposed iterative approach and its performance.

4.2.3.1 *Case Characterization*

The case study is based on the network presented in section 4.2.3. The market operation horizon ($T$) is one hour and, thus, the subscript $t$ will be omitted in the variables $E_{nm}$ and $R_{nm}$ from this point.

In the iterative sequential P2P energy and reserve market, each peer can negotiate with any other, and each renewable peer can determine its necessary reserve, with the aid of the proposed GBP algorithm. Peers 1 to 11 are prosumers whose demand is greater than generation (consumers), while peers 12 to 19 are prosumers with generation surplus (producers).

The producers are categorized by their generation technology, and there are three wind turbines, two PV systems, two gas turbines and one coal based system. Peer 20 represents the external network connection, which can be, for instance, the local utility network or another energy community. The penalization factor $\delta$ is set at 1% to penalize peers as little as possible (BOTELHO et al., 2021a). The peers' parameters are summarized in Table 10. Notice that the reserve cost coefficients are defined as smaller than the energy cost coefficients, $ar_n < ae_n$ and $br_n < be_n$, following the work in (GUO et al., 2020).

Table 10 – Peers' parameters.

| **Peer** | **Type** | **Energy** | **Bus** | $E_{min}$ $[MWh]$ | $E_{max}$ $[MWh]$ | $ae$ $[\$/MWh^2]$ | $be$ $[\$/MWh]$ | $R_{min}$ $[MWh]$ | $R_{max}$ $[MWh]$ | $ar$ $[\$/MWh^2]$ | $br$ $[\$/MWh]$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Consumer | - | 2 | 3.54 | 3.93 | 1.18 | 50.9 | 0 | 0.4 | 0.6 | 25.5 |
| 2 | Consumer | - | 3 | 9.1 | 10.08 | 0.24 | 37.8 | 0 | 0.1 | 0.12 | 18.4 |
| 3 | Consumer | - | 4 | 6.21 | 6.89 | 0.57 | 43.6 | 0 | 0.69 | 0.28 | 21.5 |
| 4 | Consumer | - | 5 | 0.6 | 0.64 | 1.24 | 50.3 | 0 | 0.06 | 0.62 | 25.1 |
| 5 | Consumer | - | 6 | 2.96 | 3.28 | 1.62 | 30.4 | 0 | 0.32 | 0.8 | 15.2 |
| 6 | Consumer | - | 9 | 4.12 | 4.57 | 0.31 | 27.5 | 0 | 0.45 | 0.15 | 13.75 |
| 7 | Consumer | - | 10 | 1.01 | 1.12 | 4.36 | 46.7 | 0 | 0.11 | 2.15 | 23.4 |
| 8 | Consumer | - | 11 | 0.41 | 0.44 | 1.63 | 33.2 | 0 | 0.04 | 0.8 | 16 |
| 9 | Consumer | - | 12 | 0.41 | 0.44 | 5.16 | 55 | 0 | 0.04 | 2.6 | 27 |
| 10 | Consumer | - | 13 | 1.96 | 2.17 | 1.96 | 62.1 | 0 | 0.21 | 0.5 | 31 |
| 11 | Consumer | - | 14 | 2.18 | 2.25 | 1.54 | 42.9 | 0 | 0.22 | 0.8 | 21.5 |
| 12 | Producer | Wind | 2 | 0 | 47.0 | 0 | 0 | 16.44 | 16.44 | 0 | 1 |
| 13 | Producer | Wind | 3 | 0 | 7.2 | 0 | 0 | 3.67 | 3.67 | 0 | 1 |
| 14 | Producer | Wind | 8 | 0 | 3.18 | 0 | 0 | 1.36 | 1.36 | 0 | 1 |
| 15 | Producer | Solar | 2 | 0 | 3.87 | 0 | 0 | 1.58 | 1.58 | 0 | 1 |
| 16 | Producer | Solar | 6 | 0 | 6.57 | 0 | 0 | 1.62 | 1.62 | 0 | 1 |
| 17 | Producer | Gas | 2 | 0 | 20 | 2.51 | 27.7 | 0 | 10 | 0.753 | 8.31 |
| 18 | Producer | Coal | 3 | 0 | 50 | 0.15 | 35.5 | 0 | 25 | 0.045 | 10.65 |
| 19 | Producer | Gas | 8 | 0 | 10 | 3.64 | 30.4 | 0 | 5 | 1.092 | 9.12 |

**Source**: Author's table.

Finally, as the purpose is to analyze and promote local energy trading, electricity trade with the external grid is only allowed as a last resort. Thus, the price to import energy from the external grid is 150 \$/MWh, while to export energy is 10 \$/MWh.

#### 4.2.3.2 *Determining reserve needs*

Firstly, it is necessary to calculate the reserve amount that each renewable generator can negotiate. As mentioned earlier, this calculation is performed by using (4.8) if MCS is being used or by (4.10) together with GBP (Table 9) if m-ISODATA is applied. Table 11 shows the reserve values calculated in the two proposed cases for all renewable generators. An illustrative example for calculating the reserve with m-ISODATA can be seen in Appendix B.

Table 11 – Reserve for all renewable generators.

| | **m-ISODATA** | | **MCS** | |
|---|---|---|---|---|
| **Case** | **1** | **2** | **1** | **2** |
| $R_{12}$ $[MWh]$ | 16.44 | 16.96 | 16.52 | 16.99 |
| $R_{13}$ $[MWh]$ | 3.67 | 4.04 | 3.57 | 5.06 |
| $R_{14}$ $[MWh]$ | 1.36 | 1.75 | 1.34 | 1.85 |
| $R_{15}$ $[MWh]$ | 2.18 | 1.58 | 2.19 | 2.69 |
| $R_{16}$ $[MWh]$ | 2.95 | 1.62 | 3.01 | 3.11 |

**Source**: Author's table.

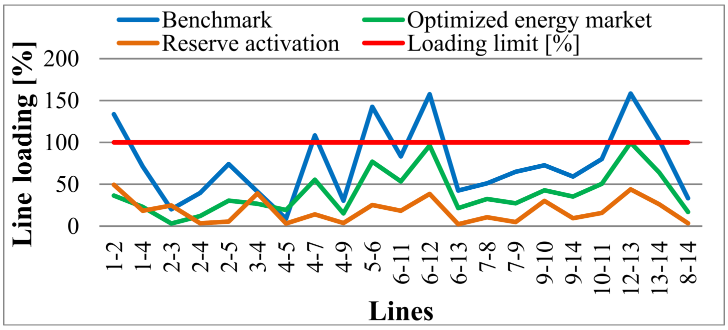
#### 4.2.3.3 *Results*

The reserve values calculated for the wind peers by the m-ISODATA and MCS algorithms are very close. The same occurs for case 2. The biggest difference between them was 1.02 MWh (20.16%), occurred for peer 13 in case 2. For PV peers, the results for case 1 from m-ISODATA and MCS are also close. For case 2, in turn, the biggest difference between them is 1.49 MWh (47.91%) for peer 16. However, despite this difference, the amount in MWh (1.49 MWh) is low, which allows concluding that MCS and m-ISODATA reaches similar results.

To simplify and test the proposed methodology, the renewable peers' reserve values ($R_{min}$ and $R_{max}$) were set as provided in Table 10, by using values calculated using the m-ISODATA clustering algorithm. To properly analyze the proposed method, a benchmark model is used, which refers to the first step of the first iteration of the proposed model, i.e., the initial P2P market optimization.

Figure 19 shows the line-loading of the system for the benchmark solution (blue), the final energy market solution (green) and the condition in which all the reserve is activated (orange). One can see that congestion occurs and thus the benchmark solution consists of an unfeasible condition for the network operation. From this initial point, the iterative process reaches a feasible energy market solution after 20 iterations. This result is achieved by applying the PD and limiting the energy supply from generators that cause congestion. Finally, the system's line-loading in the worst case of activating the power reserve is also within the network's operational limits after just 2 iterations. In all the final solutions, there is no violation of the predefined voltage limits. Data from 12 o'clock of one day, chosen randomly from the available data, were used.

Figure 19 – Line-loading for each line [%].

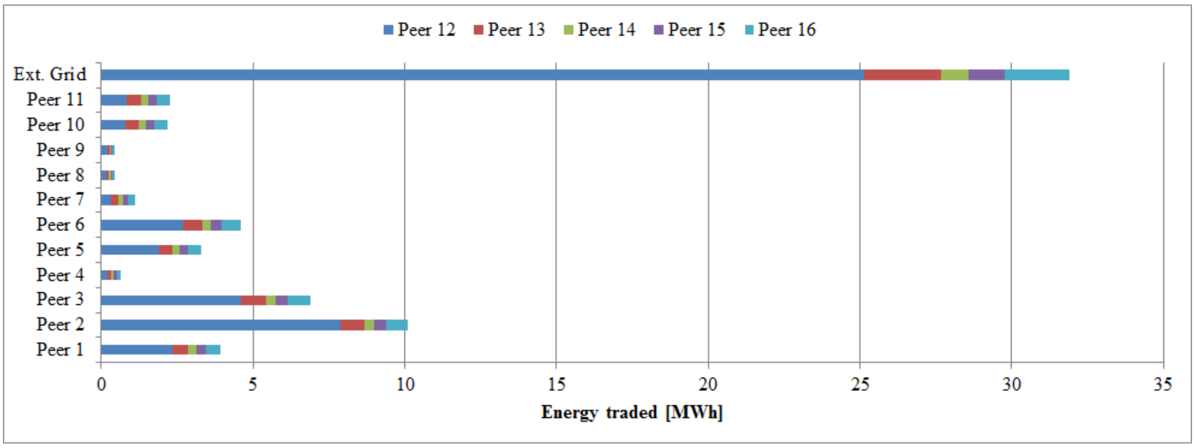



**Source**: Author's figure.

The benchmark solution proves the need for a methodology that allows the integration of the DSO with peers to optimize P2P energy and reserve market taking into account network constraints, as there is a high risk of network congestion, since six lines are overloaded in this solution. The proposed approach is able to achieve a solution in which there are no overloaded lines, both for the energy market and for the worst case of reserve activation.

In the benchmark solution, peers trade with each other without regard to PD. Figure 20 shows the result for the carried out negotiations. In this solution, all generators negotiate with all consumers. As there is more renewable generation than demand, the generation surplus is exported to the external grid.

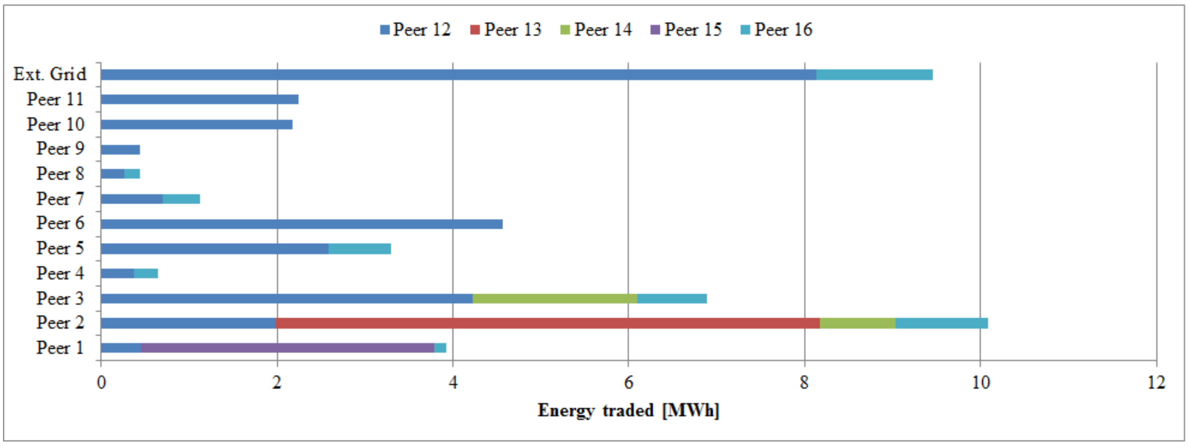
Figure 20 – P2P tradings in the benchmark solution. Peers 1-11 and Ext. Grid are energy buyers and peers 12-16 are energy sellers.




**Source**: Author's figure.

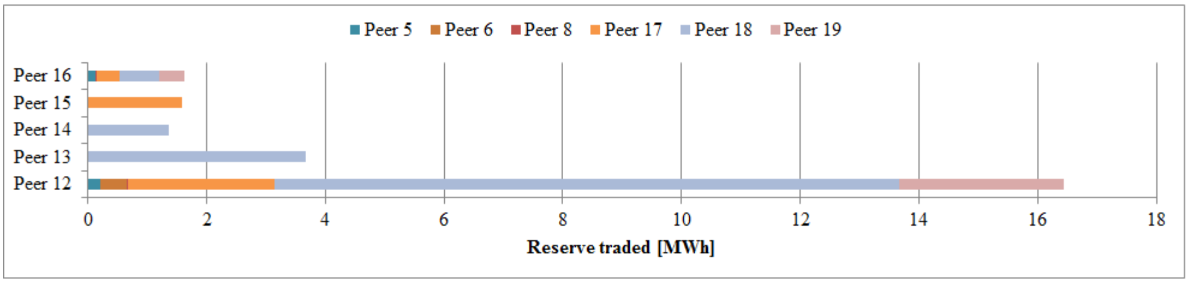
After applying the energy market optimization step of the proposed methodology with PD, the results for trades are shown in Figure 21. As PD is applied, peers tend to negotiate with their neighbors. It is worth mentioning that a smaller amount of energy is sold to the external grid, since some generators are penalized for having caused congestion in the system's lines.

Figure 21 – P2P tradings in the final energy market solution. Peers 1-11 and Ext. Grid are energy buyers and peers 12-16 are energy sellers.




The negotiations carried out in the reserve market are shown in Figure 22.

Figure 22 – P2P tradings in the final reserve market solution. Peers 12-16 are reserve buyers, and peers 5, 6, 8 and 17-19 are reserve sellers.




**Source**: Author's figure.

Table 12 shows the peers' final dispatch for the benchmark, final energy solution and energy plus reserve solution. It is observed that both for the benchmark and for the final energy solution, the entire demand of the consumer peers is met (peers 1 - 11). All the renewable producers (peers 11 - 16) have a decrease in their dispatched energy. This difference corresponds to a smaller amount of energy negotiated with the external grid, which is required to not violate the network constraints.

For the energy plus reserve solution, three consumers (peers 5, 6 and 8) negotiate their demand flexibility in the reserve market together with the three conventional generators (peers 17 - 19). Most of the reserve is supplied by these generators. The energy plus reserve solution corresponds to the case where the entire negotiated reserve needs to be activated. In other words, all the reserve that the renewable peers calculated they might need due to the inherent renewable resources' variability will be necessary, and it is the responsibility of the peers that sold this reserve to provide that energy to the system.

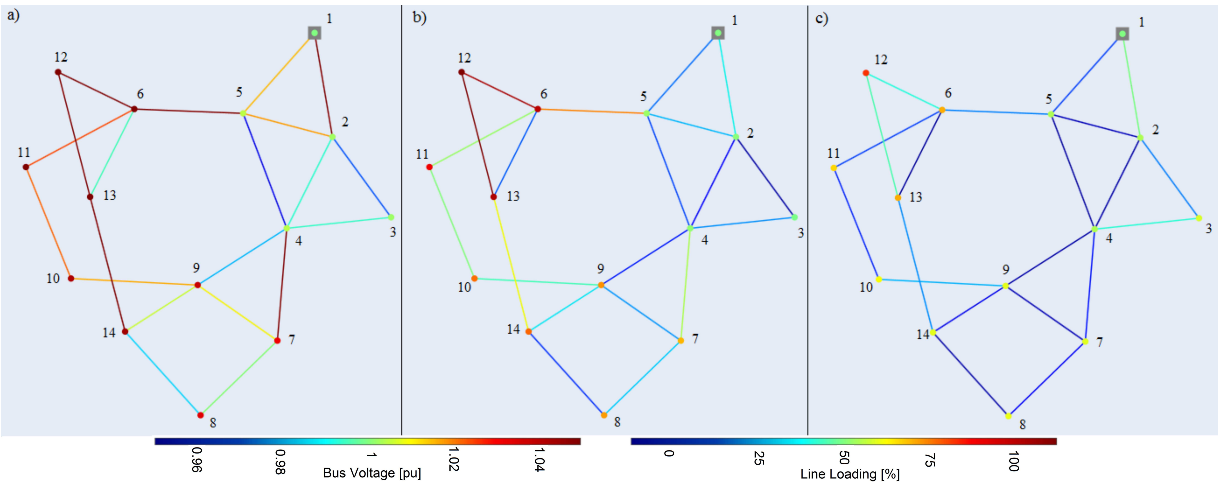
Table 12 – Peers' final dispatch.

| Peer | Consumers | | | | | | | | | | | Producers | | | | | | | | Ext. Grid |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | |
| **Benchmark solution [MWh]** | 3.93 | 10.08 | 6.89 | 0.64 | 3.28 | 4.57 | 1.12 | 0.44 | 0.44 | 2.17 | 2.25 | 47.00 | 7.20 | 3.18 | 3.87 | 6.57 | 0.00 | 0.00 | 0.00 | 26.96 |
| **Final energy solution [MWh]** | 3.93 | 10.08 | 6.89 | 0.64 | 3.28 | 4.57 | 1.12 | 0.44 | 0.44 | 2.17 | 2.25 | 28.14 | 6.19 | 2.74 | 3.33 | 4.86 | 0.00 | 0.00 | 0.00 | 7.85 |
| **Energy plus reserve solution [MWh]** | 3.93 | 10.08 | 6.89 | 0.64 | 2.96 | 4.12 | 1,12 | 0.40 | 0.44 | 2.17 | 2.25 | 11.71 | 2.52 | 1.38 | 1.75 | 3.24 | 4.42 | 16.22 | 3.21 | 9.17 |

**Source**: Author's figure.

The resulting power flow for the first iteration (benchmark solution) is shown in Figure 23a. One can see that congestion occurs and thus the benchmark solution consists of an unfeasible condition for the network operation. From this initial point, the iterative process reaches a feasible energy market solution after 20 iterations. This result is achieved by applying the PD and limiting the energy supply from generators that cause congestion (Figure 23b). Finally, Figure 23c shows the system's line-loading in the worst case of activating the power reserve. In all the final solutions, there is no violation of the predefined voltage limits.

Figure 23 – Power flow for the grid. a) Benchmark solution, b) Final energy solution, and c) Worst case of reserve's activation.




**Source**: Author's figure.

The economic results from the benchmark, the final energy market and the reserve negotiation are presented in Table 13. The final energy market's social welfare tends to decrease at each iteration, when compared to the benchmark solution, since the proposed method penalizes the bid of the generator that causes congestion, which tends to be among the "cheapest"generators. Thus, another generator, a little more expensive than the previous one, has to be dispatched to make up the difference, causing a decrease in the social welfare or an increase in the market shadow price $\lambda$.

It is noteworthy that despite the decrease in social welfare, the final energy solution represents a feasible network operating solution, in contrast to the benchmark solution. In a

Table 13 – Economic results.

| **Economic parameter** | **Benchmark solution** | **Final energy solution** | **Reserve market solution** |
|---|---|---|---|
| Social Welfare [$] | 1595.83 | 1234.48 | 405,66 |
| $\lambda$ [$/MWh] | 23.53 | 26.87 | 16.44 |
| Total traded energy [MWh] | 67.82 | 45.94 | - |
| Total traded reserve [MWh] | - | - | 24.67 |

**Source**: Author's figure.

real operating context, the initial transactions could not take place. More precisely, it would require load shedding and, consequently, decrease the total system generation, reaching a feasible operating point that would probably lead to a lower social welfare than that achieved by the proposed approach. It is also worth mentioning that although the proposed methodology has eight steps, the convergence is quite fast, taking only a few seconds.

#### 4.2.4 **Partial conclusions**

The P2P markets actively contribute to a higher prosumer participation in the energy and reserve market, allowing a greater RES penetration in power systems, giving the market a higher degree of freedom for the energy/reserve trades. However, the impact of this market design on the network operation still lacks detailed studies to avoid network congestion and voltage problems. So, an integrated prosumer-DSO approach applied in an iterative sequential approach for the energy and reserve P2P market taking into account network constraints was proposed, as well as a novel strategy to quantify the reserve required to overcome RES uncertainty. The results obtained for a 14-bus system showed that the proposed methodology is effective to find solutions for the energy and reserve market, while ensuring a feasible network operation and can offer a transition solution to a future more decentralized market environment. Despite the decrease of $361.35 and the increase of $3.34 in the market shadow price, the final solution guarantees the feasible operation of the network. Moreover, it is noteworthy there was a decrease of 21.88 MWh in energy negotiations, since it would be operationally unfeasible to use the 67.82 MWh negotiated in the benchmark. The m-ISODATA and MCS algorithm proved to be effective in determining the reserve required by renewable peers. The largest difference between the two algorithms was 1.49 MWh. It can be an alternative for calculating the reserve needed by the system.

# 5 FINAL CONCLUSIONS AND FUTURE RESEARCH

## 5.1 CONCLUSIONS

The paradigm shift that is currently underway in the energy sector makes studies on topics such as the prosumer, energy and power markets, new BMs for the electric sector and innovative AS, that are the focus of this doctoral thesis, very necessary.

In this context, seeking to contribute mainly to the greater prosumers' inclusion in futuristic and innovative power markets, this thesis addresses two main issues. The first issue concerns the study, development and improvement of BMs aimed at integrating prosumers into the market as presented in Papers A and B. The second focuses on the development of methodologies to assist the prosumers' participation in market negotiations and also to assist the DSO in making decisions taking into account the physical aspects of the electrical network, as those proposed in Papers C, D, and E.

Today, energy entities and governments are promoting the integration of innovative prosumers' BMs into the power system to achieve higher levels of economic and environmental sustainability. In more detail, Paper A, shows a comprehensive review of innovative BMs for prosumers, with a detailed description of BMs and market projects that are currently being implemented to develop and encourage the prosumer participation in the energy market. Innovative BMs can enable faster integration of prosumers in the system by combining the economic, environmental, and social aspects and characteristics of consumers. On the other hand, the regulatory framework is the main obstacle for the success of such BMs, as the current regulation in many countries neglects such options. The lack of regulation, the high price of the necessary equipment and technologies combined with the low levels of information and technical knowledge are the main barriers identified in the study developed in Paper A.

In turn, Paper B intends to identify and understand the main regulatory challenges and opportunities for the emergence and development of prosumers and prosumer-driven BMs in the Brazilian electricity market context. A detailed analysis of the innovative BMs in the Brazilian regulatory scope is carried out, seeking to guide the decisions that need to be taken nowadays so that the country can develop its political and regulatory environment aiming at taking advantage of all benefits that the RES prosumer adds to the energy system. Incorporating new BMs into the market offers new ways for prosumers to monetize, generate new income sources, besides potentially helping the network. In summary, the regulatory issue is still not very advanced in Brazil, few works have presented methodological solutions dedicated to the Brazilian scenario.

In addition to market issues related to the BM used, it is necessary to develop methodologies capable of guaranteeing a feasible operation of the electrical network. In this context, Paper E presents a methodology to optimize a P2P energy market considering the network constraints. To this end, the problem is divided into two sub-problems, energy market and network operation, being solved iteratively. That is, the results of each sub-problem are used iteratively to solve the other sub-problems, converging to a global feasible solution. This methodology applies a penalty to all market participants, in case any network constraints is violated. However, general punishment is not the best strategy. Thus, Paper D presents a solution where only the peers that committed the violation are penalized. This work uses a tracing power flow method to determine which peers are responsible for causing such violations.

In addition to the application of P2P to energy markets, this market design can also be applied in the context of the energy reserve market. The reserve helps system operators to maintain a reliable electrical system. With the advance of RES participation in power systems, the reserve requirement becomes more important to manage the variability and uncertainty inherent to this generation. The system operator is currently responsible for acquiring the necessary reserve to ensure the power system security. In the near future, it is expected that RES agents should predict how much uncertainty they will bring and be responsible for compensating that. In addition, the system operator should be responsible for the decision on dispatching the contracted reserve.

The issue described above was investigated in Paper C. In fact, this work proposes an approach that is able to establish an adequate energy and reserve market, through a P2P mechanism that considers the requirement for a feasible power system operation. In particular, the proposed approach allows DSO to determine whether the energy and reserve transactions carried out between peers are feasible under the electrical grid constraints, as well as the adjustments in trades to make the system operation feasible. In addition, it also includes an approach to handle RES uncertain generation through historical generation data. Which estimates the reserve required, by using two different algorithms for comparison purpose. From the proposed solution, all energy and reserve transactions are technically feasible, even for the system's worst reserve scenario.

Finally, all analyzes and methodologies proposed in this thesis and in the five papers published, clearly show the relevance of the achieved findings to the literature.

## 5.2 FUTURE WORKS

During the development of this thesis, some potential future research directions emerged to improve prosumer integration into power markets. The first possible research line involves more detailed studies within AS. A second line consists of improving the prosumers' RES representation.

Regarding the AS, a comprehensive review at a prosumer level, verifying opportunities for those consumers in futuristic consumer-centric power markets, can be done. Furthermore, investigate and simulate one alternative of AS. For instance, to model and design reactive power markets suited to prosumers' integration.

In what concerns the second direction of future research, probabilistic methods can be developed to better represent the uncertainties arising from the prosumers' RES in energy market problems. Stochastic and/or robust optimization can be implemented for this purpose. If the problem proves to be too complex and requires a large computational effort, meta-heuristics can be applied. These algorithms significantly reduce the computational effort of the model, guaranteeing good solutions.

The proposed methods apply to meshed distribution networks, requiring some adaptations, mainly in the Tracing Power Flow stage, for their use in radial distribution networks. It is also worth noting that voltage limits violations on buses are more common than line loading violations. Identifying the peer responsible for causing voltage imbalances is a little more complex. The improvement of the proposed methodologies to contemplate the items exposed above, as well as the consideration of three-phase distribution networks are items targeted for future studies.

# APPENDIX

## A - TRACING POWER FLOW ALGORITHM

The total flow $P_i$ through node $i$ (i.e. the sum of inflows or outflows) may be expressed, when looking at the inflows, as:

$$P_i = \sum_{j \in \alpha_i^{(u)}} |P_{i-j}| + P_{G_i} \quad \text{for} \quad i = 1,2,...,n$$

where $\alpha_i^{(u)}$ is the set of nodes supplying directly node $i$ (i.e. power must flow towards node i in the relevant lines), $P_{i-j}$ is the line flow into node $i$ in line $j-i$, and $P_{G_i}$ is the generation at node $i$. As the losses have been eliminated, $|P_{j-i}| = |P_{i-j}|$. The line flow $|P_{j-i}| = |P_{i-j}|$ can be related to the nodal flow at node $j$ by substituting $|P_{i-j}| = c_{ji}P_j$, where $c_{ji} = |P_{j-i}|/P_j$, to give:

$$P_i = \sum_{j \in \alpha_i^{(u)}} c_{ji}P_j + P_{G_i} \quad \text{for} \quad i = 1,2,...,n$$

which, on rearrangement, becomes:

$$P_i - \sum_{j \in \alpha_i^{(u)}} c_{ji}P_j = P_{G_i} \quad or \quad \mathbf{A}_u\mathbf{P} = \mathbf{P}_G$$

where $\mathbf{A}_u$, is the $(nxn)$ upstream distribution matrix, $\mathbf{P}$ is the vector of nodal through-flows and $\mathbf{P}_G$, is the vector of nodal generations. The $(i,j)$ element of $\mathbf{A}_u$, is equal to:

$$[A_u]_{ij} = \begin{cases} 1 & \text{for } i = j \\ -c_{ji} = -|P_{j-i}|/P_j & \text{for } j \in \alpha_i^{(u)} \\ 0 & \text{otherwise} \end{cases}$$

Note that $\mathbf{A}_u$, is sparse and nonsymmetric. If $\mathbf{A}_u^{-1}$ exists, then $\mathbf{P} = \mathbf{A}_u^{-1}\mathbf{P}_G$ and its $i_{th}$ element is:

$$P_i = \sum_{k=1}^{n} [\mathbf{A}_u^{-1}]_{ik}\mathbf{P}_{G_k} \quad \text{for} \quad i = 1,2,...,n$$

This equation shows that the contribution of the $k_{th}$ system generator to $i_{th}$ nodal power is equal to $[\mathbf{A}_u^{-1}]_{ik}\mathbf{P}_{G_k}$. Note that the same $P_i$, is equal to the sum of the load demand, $P_{Li}$ and outflows in lines leaving node $i$. A line outflow in line $i-l$ from node $i$ can be therefore calculated, using the proportional sharing principle, as:

$$|P_{i-l}| = \frac{|P_{i-l}|}{P_i} P_i = \frac{|P_{i-l}|}{P_i} \sum_{k=1}^{n} [\mathbf{A}_u^{-1}]_{ik} \mathbf{P}_{G_k} = \sum_{k=1}^{n} D_{il,k}^{G} \mathbf{P}_{G_k} \quad \forall \quad l \in \alpha_i^{(d)}$$

where $D_{il,k}^{G} = |P_{i-l}|[\mathbf{A}_u^{-1}]_{ik}/P_i$, and $\alpha_i^{(u)}$ at is the set of nodes supplied directly from node $i$ (that is power flows from those nodes to node $i$ in the relevant lines). This equation defines $D_{il,k}$ as the topological generation distribution factor that is a portion of generation owing to the $k_{th}$ generator that flows in line $i-l$.

Similarly, the load demand $P_{Li}$ can be calculated from $P_i$, as:

$$P_{Li} = \frac{P_{Li}}{P_i} P_i = \frac{P_{Li}}{P_i} \sum_{k=1}^{n} [\mathbf{A}_u^{-1}]_{ik} \mathbf{P}_{G_k} \quad \text{for} \quad i = 1, 2, ..., n$$

This equation shows that the contribution of the $k_{th}$ generator to the $i_{th}$ load demand is equal to $P_{Li} P_{G_k} [\mathbf{A}_u^{-1}]_{ik}/P_i$ and can be used to trace where the power of a particular load comes from.

## B.1 - EXAMPLE FOR RESERVE CALCULATION

*Illustrative example for m-ISODATA:* To obtain the reserve that Peer 12 needs, the data available in the first two columns of Table 9 are used. The total energy negotiated by $E_{12}$ in the P2P energy market is also necessary, i.e., $E_{12}$ = 28.14 MWh.

Therefore, from (4.9) and (4.10):

$$E_{12}^{mISO} = 28.14 \cdot [(0.0141 \cdot 0.0760) + (0.4483 \cdot 0.0583) + (0.2115 \cdot 0.0711) + (0.7971 \cdot 0.0660) + (0.1106 \cdot 0.0762) + (0.5913 \cdot 0.0570) + (0.3213 \cdot 0.0666) + (0.9009 \cdot 0.0718) + (0.0598 \cdot 0.0673) + (0.5181 \cdot 0.0547) + (0.2651 \cdot 0.0687) + (0.1614 \cdot 0.0735) + (0.6821 \cdot 0.0646) + (0.3819 \cdot 0.0636) + (0.9652 \cdot 0.0645)] = 11.70 MWh$$

$$R_{12} = 11.70 - 28.14 = \mathbf{-\ 16.44MWh}$$

The reserve need for the remaining RES is determined in the same way and presented in Table 11.

## B.2 - SYSTEM DATA

Table 14 shows the line data for the 14-bus distribution system, adapted from (BOTELHO et al., 2021b).

Table 14 – System data.

| Line | From | To | R | X | B | Size (km) |
|---|---|---|---|---|---|---|
| 1 | 1 | 2 | 0.01938 | 0.05917 | 0.0528 | 4.8738 |
| 2 | 1 | 5 | 0.05403 | 0.22304 | 0.0492 | 3.9278 |
| 3 | 2 | 3 | 0.04699 | 0.19797 | 0.0438 | 2.8833 |
| 4 | 2 | 4 | 0.05811 | 0.17632 | 0.034 | 3.3529 |
| 5 | 2 | 5 | 0.05695 | 0.17388 | 0.0346 | 1.7486 |
| 6 | 3 | 4 | 0.06701 | 0.17103 | 0.0128 | 1.7300 |
| 7 | 4 | 5 | 0.01335 | 0.04211 | 0.45 | 2.8835 |
| 8 | 4 | 7 | 0.000 | 0.20912 | 0.55 | 1.7696 |
| 9 | 4 | 9 | 0.000 | 0.55618 | 0.32 | 2.7540 |
| 10 | 5 | 6 | 0.000 | 0.25202 | 0.45 | 2.5671 |
| 11 | 6 | 11 | 0.09498 | 0.1989 | 0.18 | 1.3472 |
| 12 | 6 | 12 | 0.12291 | 0.25581 | 0.32 | 1.8832 |
| 13 | 6 | 13 | 0.06615 | 0.13027 | 0.32 | 1.9912 |
| 14 | 7 | 8 | 0.000 | 0.17615 | 0.32 | 1.0432 |
| 15 | 7 | 9 | 0.000 | 0.11001 | 0.32 | 1.0000 |
| 16 | 9 | 10 | 0.03181 | 0.0845 | 0.32 | 1.2901 |
| 17 | 9 | 14 | 0.12711 | 0.27038 | 0.32 | 1.8344 |
| 18 | 10 | 11 | 0.08205 | 0.19207 | 0.12 | 1.8044 |
| 19 | 12 | 13 | 0.22092 | 0.1988 | 0.12 | 1.5232 |
| 20 | 13 | 14 | 0.17093 | 0.34802 | 0.12 | 2.6787 |
| 21 | 8 | 14 | 0.17093 | 0.3802 | 0.12 | 4.6787 |

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