Local Flexibility Market for Congestion Management at the Distribution-Level

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Abstract

In response to increasing demand and the rise of renewable energy, Distribution System Operators (DSOs) often resort to grid reinforcement measures. However, the smart grid paradigm offers an alternative solution by utilizing demand flexibility for congestion management. This paper proposes a flexibility market led by DSOs to address distribution grid congestions, supported by a user-friendly market clearing algorithm that considers the energy rebound effect. The approach leverages aggregators as ”flexibility providers” to gather and coordinate consumer flexibility, reducing the need for immediate infrastructure investments. The algorithm ensures compatibility with existing grid analysis tools, streamlining operations and reducing complexity for DSOs. wo case studies from a simulated distribution network based on the north-centre city of Viseu, Portugal validate the proposed approach, showcasing its effectiveness in managing grid congestions. The results emphasize the practical applicability and benefits of the flexibility market framework. This research contributes to the integration of demand flexibility into distribution grid management, promoting a transition to a more flexible and sustainable energy ecosystem. The proposed approach offers DSOs a viable pathway to harness demand-side resources, optimizing grid operations and minimizing infrastructure costs. The findings highlight the potential for future advancements in grid management, facilitating the transition towards a resilient and sustainable energy landscape.

Keywords

Keywords: demand side flexibility, flexibility market, load reduction, load increase, rebound effect

Resumo

Em resposta ao aumento da procura e ao aumento das energias renováveis, os Operadores das Redes de Distribuição (ORDs) recorrem frequentemente a medidas de reforço da rede. No entanto, o paradigma das redes inteligentes oferece uma solução alternativa ao utilizar a flexibilidade de procura para gestão de congestionamento. Este trabalho propõe um mercado de flexibilidade liderado por ORDs para lidar com congestionamentos na rede de distribuição, apoiado por um algoritmo de compensação de mercado amigável que considera o efeito de recobro de energia. A abordagem utiliza agregadores como ”fornecedores de flexibilidade” para reunir e coordenar a flexibilidade do consumidor, reduzindo a necessidade de investimentos imediatos em infraestrutura. O algoritmo garante a compatibilidade com as ferramentas de análise de rede existentes, simplificando as operações e reduzindo a complexidade dos ORDs. Dois casos de estudo de uma rede de distribuição simulada com base na cidade de Viseu, no centro-norte de Portugal validam a abordagem proposta, mostrando a sua eficácia na gestão de congestionamentos da rede. Os resultados enfatizam a aplicabilidade prática e os benefícios da estrutura do mercado de flexibilidade. Esta pesquisa contribui para a integração da flexibilidade de procura na gestão da rede de distribuição, promovendo uma transição para um ecossistema energético mais flexível e sustentável. A abordagem proposta oferece aos ORDs um caminho viável para aproveitar os recursos do lado da demanda, otimizando as operações da rede e minimizando os custos de infraestrutura. As descobertas destacam o potencial para avanços futuros na gestão da rede, facilitando a transição para um cenário de energia resiliente e sustentável.

Palavras Chave

Keywords: flexibilidade do lado da procura, mercados de flexibilidade, redução de carga, aumento de carga, efeito de recobro

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Acronyms

DSO	Distribution System Operator
TSO	Transmission System Operator
BRP	Balance Responsible Party
DER	Distributed Energy Resource
DG	Distributed Generation
DR	Demand Response
LFM	Local Flexibility Market
LFMO	Local Flexibility Market Operator
FMO	Flexibility Market Operator
DSM	Demand Side Management
DF	Demand Flexibility
PV	Photovoltaic
BSS	Battery Storage System
EV	Electric Vehicle
AS	Ancilliary Services
PF	Power Flow

1

Introduction

1.1 Context

Currently, the global energy sector is undergoing a profound transformation, as a result of the change in the collective consciousness of society. There is a greater focus on environmental problems and energy depletion around the world, which has led to a search for decarbonization of the electricity grid and a commitment to renewable generation.

In fact, renewable energies have had a remarkable growth in the last decade and it is expected that this growth will continue in the future. Resources such as wind and solar have been preferred in connection with the distribution grid, to the detriment of traditional fuel resources which, despite still constituting a majority of energy consumption, are beginning to be discontinued in connection with the grid. [1]

The share of renewable generation in the context of world electricity production is 25% and the path being treaded is to increase this percentage. In Europe, a series of regulatory targets have been set for the development of renewable energy. The ”2020 climate & energy package” determined that 20% of European energy was to come from renewable sources by 2020 [2]; this goal was achieved, with the share of renewables sitting in the 22.1% [3]. Moreover, by 2030, at least 32% of the energy share was to come from renewables, as determined by the ”2030 climate & energy package” [4] and by 2050, Europe intends to act a long-term strategy to achieve carbon neutrality. [5]

In the case of Portugal, the target would be, according to the National Energy Strategy (ENE 2020), to reach a percentage of 31% of all final energy consumed [2], as a result of renewable generation and by 2030, according to the National Energy and Climate Plan 2021-2030 (PNEC 2030), to reach 47%. [6]. Portugal also subscribes the carbon neutral goal of 2050, with its own project, the RNC2050, in which Portugal will implement energetic, economic and social measures in order to reach the process of decarbonization. [7]

These investments in renewable generation bring their own challenges, namely intermittence, variability and thus, uncertainty in energy production, as they depend on external factors such as wind speed and solar irradiance, asynchrony of production in relation to the grid frequency and location constraint, since renewable energy has , often to be produced far from load centers. [8]

At the same time, there is also an increase in demand for electricity, due to the electrification of large parts of the residential and transport sectors. This increase significantly influences the peak load in the electrical system [9] which in turn might be a cause for a congestion of the grid. A network congestion can be defined as a situation that the demand for active power exceeds grid’s transfer capability. [10]

Given the growth in electrification and intermittent renewable generation it becomes urgent to introduce measures that allow for better management of available resources. [9]

Fortunately, we've also been observing the phenomenons of decentralization of resources and digitization of the grid, which can be helpful in order to solve the issues brough up by the massive increase in renewable generation and electrification of the grid.

Users of the electricity grid are progressively evolving from consumers to "prosumers", that is, users who actively participate in the energy market, both consuming and producing. The increase in distributed energy resources (DERs) in residential areas and smart buildings, which mainly include distributed generators (DGs), energy storages and controllable loads allow this type of involvement. These new prosumers intervene in the energy generation and consumption process, through the management of these DERs and communication with other prosumers, through aggregation services (aggregators). [11]

This joint aggregation gave rise to a new concept – Micro-grids – which are groups of interconnected loads and decentralized resources with well-defined electrical limits and that work as a single controllable entity in relation to the grid. [12] Thanks also to this intensive implementation of DERs, traditional energy systems are undergoing a transformation. Also, most installations that produce energy from renewable sources are decentralized and small-scale, which contributes to distribution systems evolving from centralized and uni-directional to decentralized bi-directional systems.

Thus, the increased implementation of DERs allows for more versatility on the demand side. In fact, the storage provided by the existence of resources such as electric vehicles can help, storing excess energy from renewables at peak times on the grid, preventing curtailment and offloading it back to the grid when necessary. The most pressing issue is ensuring that DERs are used when and where they are most needed. [13]

The pervasive digitization of society has given rise to the Internet of Things, which enables information interchange between every component of the energy system. Networks, also more digitized, together with more intelligent measurement systems, allow consumers and their distribution system operators (DSOs) to know, in real time, production and load patterns.

The European Commission's Directorate-General for Energy predicted that 77% of consumers would be equipped with smart meters by 2024, as the prerequisite of a cost-benefit analysis to show positive results. The consumers with smart meters would have more detailed information about consumption and production. For system operators, using them provides all kinds of information of network quality. With the data, coming from the smart meters, it is possible to create incentives for consumers to adjust their consumption according to the pricing fluctuation. [14]

In this context, the traditional electrical system becomes progressively more intelligent, becoming what is beginning to be called a “smart grid”. It is possible to observe this transition all over the world, particularly in Europe, the United States and China.

A more widespread digitalization allows monitoring, control and management of the entire electrical system and all its interconnected components, whose benefits include:

- Improved reliability and resilience due to self-healing technologies;
- Increase in revenue and decrease in operating costs;
- Reduction of the carbon footprint due to the optimization of planning and operation;
- Ease of penetration of renewable generation and DERs, due to intelligent control;
- Flexible integration of Demand Response (DR) activities; [15]

1.2 Motivation

It is then observed that the electrical system and markets are in need of changes stemming from these issues. There’s a need for studies and simulations of market models for power transactions that take into account both the problems raised by renewable generation and massive electrification as well as the opportunities from decentralized resources and widespread digitization of the grid.

New technologies like intelligent smart meters, autonomous load controllers, and advanced information and communication automations are capable of providing sustainable minute-by-minute information to efficiently deploy demand response (DR) programs as well as balancing and constraint management services for distribution networks, even though the widespread adoption of low carbon technologies has posed many challenges to those networks. [16]

One of the concepts that’s been popularized in power and energy industry is Flexibility. Flexibility, according to [17], is the ability of a power system to cope with variability and uncertainty in both generation and demand while maintaining a satisfactory level of reliability at a reasonable cost over different time horizons. Power systems have traditionally been designed to provide flexibility in a context where demand is met by bulk generation. However, the integration of variable and uncertain renewable generation sources, such as wind, increases the flexibility needed to maintain the load-generation balance. As such, there is a need for flexibility not in terms of a system but as a capability of a resource, to be accessed more easily. As [8] puts it, flexibility is described as the ability of a resource, whether any component or collection of components of the power system, to respond to the known and unknown of power system conditions at various operational timescales.

This means that the flexibility that is sought is not a specific object that can be integrated into the network. It is a skill that a certain resource can provide. It can be a component or a set of components of the energy system and that allows responding to foreseen or unforeseen variations in system conditions. That's why ”flexibility buying and selling” is done in the context of the specific component or assembly that provides it and not as a separate commodity. [18]

In order to address the primary flexibility problem, which has existed since the inception of energy markets, and to encourage levels of flexibility that better permit controlling the fluctuation and uncertainty of total loads, a number of approaches have been proposed. They include convex-hull-based marginal pricing, novel design components for market balancing (pay-for-performance regulation), explicit products for variable ramping supplies, and the use of cutting-edge technology, such demand response (DR) and energy storage, to provide flexibility. Yet there hasn't yet been agreement on any particular design feature that fosters flexibility in system operation. [8]

Thus, the present work intends to study and implement, in simulation, one promising approach to a possible solution, which is a Local Flexibility Market. According to [15], a LFM can be defined as an electricity flexibility trading platform to trade flexibility in geographically limited areas such as neighborhoods, community, towns, and small cities. So, similarly to a local energy market, where consumers and operators can interact in order to transact energy in a given area, the same agents interact in order to trade flexibility instead, allowing better tools for DSOs to solve issues in the grid, such as congestions, as well as allowing consumers to be compensated for their resources.

1.3 Objectives

Since the concept of local flexibility markets (LFM) is a novel idea, there is a bit of uncertainty regarding its usefulness as a possible solution to the challenges raised by the increasing levels of renewable power generation, either as a type of market connected to other kinds of markets or as an independent one. There has been research made regarding the possible utilities of LFM independently, especially from the demand-side.

That being said, the central purpose of this master thesis is to investigate and define how to optimize the utilization of Distributed Energy Resources in a new LFM with the objective of supporting the DSO in solving congestions. This LFM will operate in distribution networks, during the day-ahead and considering the portuguese context in DERs and energy usage.

To achieve this goal, the thesis will also include the following steps:

- Study of the various types of flexibility, especially on the demand-side, flexibility markets and the portuguese energy system.
- Simulate a distribution network in Pandapower, a tool that permits the modeling of electric grids,

by specifying its components like lines, transformers, generators and loads along with their corresponding parameters.

- Compile and utilize the information available from E-Redes and academic studies done in energy utilization and DERs, in order to design the LFM.
- Analyse the results of the market
- Create a set of recomendations for future work.

1.4 Outline

This thesis is divided in six chapters.

The First Chapter, an introductory chapter, contains an overview on the topic of the thesis, the motivation for the research and where the objectives are declared.

The Second Chapter covers a brief review of the current literature about Flexibility, especially on the demand-side. What is Demand Flexibility, its providers and consumers, as well as, the barriers that prevent it to be a mainstream option in power systems.

The Third Chapter is about Flexibility Markets starting from large-scale to local markets, analyzing their main intervenients, models and market clearing methods. It also covers already existent Local Flexibility Market platforms in other countries as well as giving context about the portuguese power system and markets and how the portuguese grid handles congestions.

In the Fourth Chapter a set of models for the creation of a Local Flexibility Market is proposed, and its structure and inner workings is explained.

The Fifth Chapter is the application of the methodology from the previous chapter in two case studies and the Sixth and final Chapter concludes on the insights gained by the work and proposes points of action for future work.

2

Flexibility in Eletric Systems

This section will define flexibility in the electricity system, outline its benefits, and describe how flexibility may be provided. Additionally, the idea of demand flexibility will be discussed, along with the factors that are considered crucial from that perspective.

2.1 Definition of flexibility in the eletric system

The definition of flexibility is quite straightforward. According to the IEA, flexibility is the capacity of a power system to manage the variability and uncertainty of demand and supply across all important timescales, from guaranteeing short-term power system stability to promoting long-term supply security. [19] Traditionally, mainly through thermal and hydro units, it has been a part of the electricity system as the answer to dealing with shifting loads, inaccurate weather predictions, and generation or transmission line failures. [20] The two most common methods: generation planning and reserves, managed, so far to accomplish its objectives, especially the latter, being used to secure system stability in the case of sudden generation outages or transmission line breakdowns. [21] This type of flexibility has been dubbed generation or supply-side flexibility. It is the most common and the most popular, due to its longevity.

However, due to the growing percentage of intermittent renewable energy sources, the prevalence of dispersed energy generation, and the strain placed on power systems, there is a need for additional flexibility of various types and origins.

Flexibility as a term encompasses not only generation side but demand side and even grid-side flexibility as well [15]. Controlling the grid and grid equipment enables the grid to be flexible. With the aid of equipment like remotely controllable switches (RCSs), that enables configuration changes in networks [22], the topology and parameters of the electric distribution network can be changed. As a result, the distribution system's performance could be enhanced. This is what is called grid-side flexibility

Regarding the demand-side, it has generated interest recently due to its significant technological potential. In modern power systems, it may be provided using energy storage, responsive distributed generation [21], demand side management (DSM) and demand response (DR) programs. DR are programs designed to persuade end-user consumers to reduce their electricity consumption in response to fluctuating electricity prices or incentive payments. Demand-side flexibility will be explored further ahead.

According to Zegers [23], flexibility in electrical systems can be looked at from both a technical and a commercial dimension. While the latter encompasses the market and regulatory-related factors that affect system flexibility, the technical dimension concerns the system's capacity to take advantage of technical opportunities to assist the electrical grid. Like himself, most researchers [8, 21, 23–25] argue for and emphasize the need for flexibility in power systems. Moreover, he argues that flexibility needs can be summarized in four categories:

- Power Flexibility
- Energy Flexibility
- Transfer capacity flexibility
- Voltage flexibility

The first one has to do with maintaining and sustaining the stability of the frequency, which is often threatened by intermittent energy sources. The second is to make sure that there is a balance maintained between the supply and demand of energy. The third one is crucial to prevent any potential congestion. The fourth one is utilized to keep bus voltage values within the necessary ranges, which are threatened by intermittent and bi-directional power flows [26].

In order to satisfy the many types of demands, it can be interesting to look at which key elements, that make up flexibility, give the full information about the provision possibilities. According to [8], as well as [27, 28] these include - the energy capacity [MWh] that can be provided continuously, the maximum (and minimum) power output [MW] and the ramp rate [MW/min] to indicate how fast an unit may change its output. Because they are better able to adapt to shifting power system conditions, resources with a wide range of absolute output levels between their minimum and maximum capacity levels might be categorized as being more flexible. Resources with higher ramp rates can also be categorized as being more flexible since they can respond more quickly to changes in the speed-dependent conditions of the power system. Last but not least, resources that can maintain energy levels for longer periods of time can be described as being more flexible since they can better accommodate power system conditions that endure for lengthy periods of time.

Numerous constraints in many of the currently used generating technologies could have varying effects on the absolute power range, the rate at which power output changes, and the energy levels. Thermal plants, for instance, will be restricted in terms of how and when they can be turned on or off. This includes minimal start and stop hours, minimum starts per day caps, and additional commitment restrictions. At certain power restrictions, hydro plants may experience rough zones where they are unable to produce power without suffering damage [29]. Additionally, there are limitations on how combined-cycle plants may be set up and how configurations can change [30]. The limitations imposed by the resource may impact the absolute power range. Therefore, we can also see how, since the absolute power range can be set between zero and the maximum capacity, units that are simple to be turned ON and OFF, offer more and can be considered more flexible.

2.2 Demand Flexibility

We touched previously in demand flexibility but in the following text, we will dissect what it is and what are its utilities, providers, needs and barriers. Demand Flexibility contrasts with the more common supply side flexibility and grid side flexibility for the reason that it focuses more on the agency of the customer in increasing or decreasing its load, providing a helping hand in the security and the reliability of the network.

Demand flexibility (also known as demand-side flexibility or even demand side bidding), is a type of demand response (DR) program based on incentives to the customer. In reaction to these type of changes or in energy pricing over time, DR programs give end-user customers the ability to vary their load behavior patterns with regard to time, load shape, and degree of demand. As such, they can be divided in two types - price-based and incentive-based programs [31–33].

The first include:

- Time-Of-Use (ToU) - different prices at different but clearly defined times
- Critical peak pricing (CPP) - similar but only applies when grid reliability is compromised
- Real-time pricing (RTP) - differs from ToU where the different variable prices are set closer to real time, every 15 min or hour

The last one includes, other than demand flexibility:

- Direct Load Control (DLC) - power utilities can access electrical appliances of the customers and switch them on or off or cycle the loads
- Interruptible/curtailable load (I/C) - financial incentives to reduce energy consumption for customers
- Capacity programs - incentives for consumers who are able to provide load reduction capacities while notifying in the day-ahead

According to [34], Demand Flexibility is the ability to change generating and/or consumption patterns in response to signals from the outside market, which helps the system operator manage its network more effectively. Depending on the flexibility attribute that the utility has, it can be divided in location, purpose and direction, the most adequate flexibility mechanism will be deployed. It depends on at which level, transmission or distribution, the flexibility is traded, if its going to be used in congestion management, portfolio optimization or balancing services and how the demand will change, increasing or decreasing.

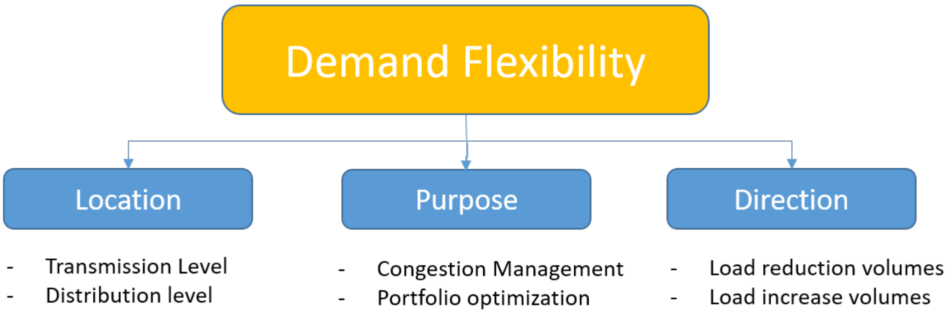

Figure 2.1: Demand Flexibility elements

2.2.1 Benefits of Demand Flexibility

Currently, TSOs are using flexibility services as a balancing tool at the transmission level in fully matured markets. In a similar vein, demand flexibility can be helpful resource for DSOs to improve distribution-level operations [26, 34].

- Network congestions - DF can assist DSOs in managing grid congestions by providing opportunities to change patterns of energy consumption of agents, therefore avoiding demand peaks. [35]. In the form of load reduction volumes, for example, provides a quick and effective mean to get around typical network issues like overloaded lines
- Network upgrades - DF can help defer network expansion by, for example, providing the ability of DSOs to purchase flexibility resources offered from residential customers [36]. As an investment, it may be advantageous over a long time horizon. The DSO will be able to analyze and foresee potential grid restrictions and have a clear perspective of alternatives if the flexibility procurement date and interval are adequate for comparison with the consequences of network expansion. The DSO would then have the option to select the more sound choice.
- High penetration of RES - while the intermittent nature of RES presents DSOs with a number of operation difficulties in distribution networks, DF may help solve this issue [37]. Higher rates of flexibility reduce the curtailment of RES. Because of their nature, RES affects both the precision of their predictions and, as a result, the rate of output. All of these elements could alter the system's voltage levels and result in network failures. Demand flexibility can provide ways to increase or reduce demand-side loads to system operators in order to control the variability of the renewables and avoid the need to restrict their production.

Also as a result of an increasing share of intermittent electricity production, the electricity market and electricity price are feared to suffer from volatility. According to [38], demand flexibility, which balances out electricity demand and mitigates significant price variations, is able to prevent erratic price changes in the electricity market. It also makes it possible for the players in the electrical market to share power more fairly as well as improving customers' power, which formerly belonged mostly to electricity producers.

Because there are fewer risks associated with market prices (for how much the generated energy will be sold) and revenue streams (if there is little curtailment, it can be considered stable) in such an environment, where curtailment is low and market prices are (if not stable, at least) consistently positive, there are good reasons for a viable business plan and a favorable cost-benefit analysis (CBA). As a result, investors and creditors are more likely to support such projects. [26]

2.2.2 Demand Flexibility Providers

Consumers, or prosumers if they are Distributed Energy Resource (DER) owners, are the main source of demand flexibility. However, their involvement in flexibility projects becomes incredibly difficult and complex because of their few resources. Thus, the aggregator, a new market participant with the goal of facilitating their involvement in demand flexibility programs, developed. A more comprehensive view and description of the aggregator will be given further ahead. [34]

[39] states that, in Europe, there is a potential for 52.35 GW of demand flexibility in Europe, with roughly 31% coming from the industry, 27% from the tertiary, and 42% from households, with each sector dictating the customer's ability to participate in demand flexibility programs.

When it comes to the industrial sector, the sort of flexibility that can be acquired depends on the type of industry that is partaking in supplying flexibility. For instance, a number of energy-intensive factories, such those that produce steel or process copper, are only appropriate for load shedding or curtailable loads. The industrial sector has previously been cited in certain studies as a very promising source of demand flexibility. Like in [40], where it is examined the financial and technical feasibility of energy-intensive businesses as sources of demand flexibility.

In the sector of services, also known as tertiary, most demand flexibility comes from HVAC (air conditioning), heaters and ventilators which can be easily adjusted. The benefits of these loads are that they make up a sizable fraction of most commercial buildings' overall load and are typically managed by energy management systems (EMS), which facilitates the implementation of flexibility control measures [41]

Demand flexibility implementation may be significantly impacted by the shift in the domestic sector's residential consumers' passive to active behavior. Due to increasing technological improvements, most families now have a variety of loads with a wide range of controllable flexibility. Microwaves and ovens are common unmanageable loads in homes; they are unable to offer flexibility. Because they are regularly used during the day and their use may be disrupted, other loads like lights, TVs, and laptops are also not ideal for flexibility. Other loads, like Refrigeration, Cooling and Heating and Washing Appliances, serve as examples of additional loads suitable for flexibility. Units that are more frequent in the summer like refrigerators and freezers and HVAC units and water heater systems that are more commonly used in the winter, as well as, washing machines and dish washers can give flexibility in load shifting and load reduction while they are fully loaded. [42, 43].

Lastly, the existence of prosumers also needs consideration when talking about demand flexibility. More specifically, regarding the usage of the prosumer's Distributed Energy Resources (DERs), since they can have a significant impact on the grid with its ability for bidirectional flow of energy, from supply to demand sides and vice-versa. Assets like electric vehicles (EVs), battery storage systems (BSS), and distributed generation (DG), which can use either petrol-based or renewable energy, are examples of common DERs. Photovoltaic panels, which are more unpredictable since they depend on the weather, can also be a source for flexibility, when incorporated with smart inverters. The latter have made it possible for PV power to provide flexibility services due to its ability to potentiate PVs capacity for injection or withdrawal, on par with BSS and EVs. [44]

EV can even act as a generator, during discharging periods. As long as it can inject power into the grid, it can be compensated. This is a relative new concept as well, denominated vehicle-to-grid interactions [45]

2.2.3 Demand Flexibility Consumers

For some market actors, demand flexibility can be a useful asset. System operators like TSOs and DSOs typically benefit the most from demand flexibility. It can, however, also be advantageous to other market participants including retailers, BRPs, and owners of RES-based generators. [34]

At the transmission level of the grid, TSOs oversee the equilibrium between supply and demand on an hourly basis. At this level, flexibility is needed to control voltage and frequency changes, done during electricity markets.

Distribution system Operators (DSOs) are in charge of managing the distribution network and supplying power to customers. By exploiting the demand-flexibility side's, the DSO can use it as a method for congestion management and moving the bulk of demand from the hours when is at an all time high (peak hours) to times when there is a lack of energy (valley hours).

Both can, however, delay the requirement for additional investment in grid security by taking demand flexibility into account when planning for future action. By properly coordinating with each other, the DSO and TSO can ensure success on this approach of demand-side flexibility and prevent irrational flexibility requests, which might cause further grid issues. As such, cooperation and information sharing between the two parties is crucial.

Other participants, such as Balance Responsible Parties (BRPs) and Retailers, can also profit from taking part in the trade of demand-side flexibility. Retailers or balance responsible parties(BRPs) are other agents who can profit from obtaining demand flexibility. In day-ahead energy markets, for example, the process of purchasing energy often occurs prior to the actual operation.

So, there will inevitably be differences between the value present in the bid and the amount actually activated during real-time, which could result in significant penalty fees. Retailers and BRPs can benefit from demand flexibility to balance their consumption profiles and reduce costs as a result. So, variations between the bid amount and the actual real-time consumption amount are inevitable and may lead to large penalty charges. Thus, in order to minimize expenditures, BRPs and Retailers should make use of demand flexibility to optimize their profiles while profiting.

2.2.4 Barriers to Demand Flexibility

As seen, demand flexibility has great potential in solving many issues present in the grid. Why is it, that it still isn't widespread? Well, despite the apparent potential benefits of demand flexibility, which have been the focus of numerous recent studies, there are some difficulties and impediments to their implementation.

2.2.4.A Regulatory barriers

One of the key challenges is the lack of laws and regulations governing their involvement and penetration as a service in power markets [46, 47]. There are already work-in-progress regulatory policies in order to promote demand flexibility services throughout the whole spectrum; from balancing and reserve markets, to wholesale and retail markets, and also for providing ancilliary services. However, the IEA argues, there needs to be regulatory policies, as well, in order to promote demand flexibility in demand flexibility markets. [48] Regrettably, there's much work to be done regarding demand flexibility in the EU. Because demand flexibility services differ so much from country to country, the development isn't as straight-forward as hoped, hindering the development of policies.

2.2.4.B Economic barriers

Another challenge that is looked at the most when investing towards change is profitability. However, when it comes to providing flexibility, the financial rewards to be given, are still up for discussion and have not yet been agreed upon. [47]. Some argue that flexibility services ought to be compensated at standard energy market rates. This implies, however, that in addition to receiving payment for supplying flexibility, providers will also make significant financial savings on their bills by cutting back on their usage. As such, there are also those that argue that the payment for supplying flexibility should be paid differently from the rates on the energy market and in a large amount, making up for the the financial and environmental perks that flexibility services bring to the systems.

Others, like [49], argue still that the absence of clear business cases hinder customers from participating with demand flexibility. To enable demand flexibility, an investment in technical measuring as well as control equipment is required in many cases. This investment is expected to yield a return. That means uncertainty for customers, including industries and real estate companies, in making legitimate calculations and profitability assessments without clear price information.

2.2.4.C Technical barriers

To enable trading of demand flexibility, there are a couple of technical parameters that need to be met. It necessitates access to qualified information and communication technology, to provide data and correct electricity measurements. This data is then required for trades to take place between the actors involved. The providers need to have appropriate technology that can provide accurate metrics on an hourly (or even shorter) basis, to confirm the delivered flexibility. As an addition to this, the transfer of data accessible might cause problems regarding privacy and General Data Protection Regulation (GDPR) issues. [47]

2.2.4.D Organizational barriers

Other factors that need to be overcome are of the organizational area. The regulations set in place for entering the markets still aren't accomodating enough of the various aspects of flexibility supplied on the demand side. Minor concerns such as the minimum value for MW necessary for participating in the market continue to hamper the establishment of proper flexibility services, because the offers from the demand side are unquestionably smaller than those made on the generation side. [47]

In addition, the lack of an effective market structure that encourages and maximizes the use of demand flexibility is a significant element that is holding back its full potential. [50] In order to benefit all market participants, modern market designs must contain suitable price signals, shorter trading intervals that are close to real time, and improved bidding procedures.

3

Flexibility Markets

Flexibility markets are, a fairly new concept in academia and the energy industry. In recent years, a number of projects regarding flexibility markets have been initiated in Europe, which will be presented in more detail further ahead, at the end of this chapter. In fact, EU directives and policies, including the Clean Energy Package, responsibilizes TSOs and especially DSOs to procure market-based flexibility services, for example in the form of distributed electricity generation, demand flexibility and energy storage options, when these services are cheaper than investing in electricity network expansion [51,52].

As we can see, flexibility markets are emerging and it can be interesting to do an analysis to the various forms it can take. In the following chapter we will start by looking at the existant and possible models for flexibility usage in the market and what it entails for the relationship between TSO and DSOs. Then we will look at the typical players in a LFM, methods for clearing congestion and voltage control, the many architectures that the LFM can take as well as clearing methods.

3.1 Flexibility services models

Traditionally, the market structure was centralized. The TSO had a primary role and oversaw the wholesale markets where energy exchange took place. The traditional paradigm is disrupted by DERs with high penetration (most often connected to the distribution grid). Not only does generation no longer come from centralized producing units, but RES also adds a higher level of unpredictability, increasing the demand for flexibility services.

As a result, both TSO and DSO are pressured to deal with issues including unpredictability, bidirectional power flows, voltage limit issues, and distribution-level congestion. Previously, DSO was a passive body tasked with ensuring a secure and consistent power supply. This was mostly accomplished through network expansion investments. This entails considering the financial viability of such an expenditure as well as planning to increase grid extension based on the worst-case scenario, even if it is not very likely to occur.

The problem arose when the DSO started interfering with the TSO's role, on a lower level. The DSO became a more active player, solving their own problems at the distribution level by managing existing DERs to solve issue. Its crucial then that a coordination mechanism exists, so that when the DSO fixes one issue, it doesn't bring consequences to the transmission level.

All of the coordination mechanisms between TSO and DSO that will be mentioned in this chapter share comparable prequalification (verifying potential consequences of flexibility procurement by the TSO, at a distribution level), activation, and settlement of flexibility resources. In descending order of the mechanisms, the DSO becomes a more active participant. If the impact was unfavorable, the DSO would inform the appropriate TSO to change its plans.

These coordination mechanisms can be divided into five different types: [53]

- Centralized ancilliary services (AS) market model
- Local AS market model
- Shared balancing responsibility market model
- Common TSO-DSO AS market model
- Integrated flexibility market model

3.1.1 Centralized Ancilliary Services Market Model

The DSO plays a completely passive role in this approach, whereas the TSO plays the dominant role. Only the TSO, which is not required to take distribution grid limits into account, may activate resources connected at the transmission and distribution levels for flexibility. No local markets are envisioned for this approach because the TSO operates both the system and the market. DSOs are not permitted to use DERs to solve their issues. Prequalification is sometimes used in order to guarantee restrictions at the distribution level. While centralized markets remove the concern for low liquidity, its biggest drawback is that system operators cannot employ DERs to address issues with the distribution grid. The TSO and the DSO practically dont communicate, except for constraints that may show up in distribution level and that the TSO must take into acccount.

3.1.2 Local Ancilliary Services Market Model

The distribution level receives some control under this concept. There are local markets here as well, which contrast with the centralized market concept. DSOs run them, whereas TSOs continue to run the central market. Since the DSO is in control of the DERs on the distribution, it can use them to solve local congestion and control voltage levels. This makes it so that local markets are cleared before the centralized market. The central market then provides the remaining services provided in the local market. In this case, cooperation between the DSO and TSO is required to prevent the procurement of flexible services going in the wrong directions.

3.1.3 Shared Balancing Responsibility Model

Similar to the Local Ancilliary Services Market Model, in this case there are two markets as well. The local market, managed by DSO, and the central market, run by TSO. The main difference from the previous model is that the two markets are cleared at the same time and the DSO can obtain the necessary flexibility from the local market whereas the TSO can only obtain flexibility from the central market. Both system operators are responsible for the balance at the distribution grid and for resolving congestions. For such a paradigm to work, TSO and DSO must communicate in order to agree on predetermined schedules that forbid autonomous system operation by TSO and DSO. The schedules can be defined by using the energy market as a base or considering the interconnection between transmission and distribution. Due to the local markets' separation from the central market and its operation by local DSOs, this architecture may also experience issues with liquidity, higher prices for ancillary services, and greater operational expenses for DSOs (though lower for TSOs). If the DSO is unable to fulfill its balancing obligations for the relevant area, the entire system risks instability, which is the the biggest hazard.

3.1.4 Common TSO-DSO Ancilliary Services Market Model

The TSO and DSO jointly run a single market for ancilliary services. Since system equilibrium is the model's ultimate goal, neither system operator has precedence; instead, flexibility is given to the entity that needs it the most. There are two possible approaches to implement the model. The first option is a single central market run by TSO and DSO, which would be financially beneficial since it would make use of the existing DERs to efficiently manage the system but permitting also the inclusion of grid constraints in the market clearing. The con in this option is the fact that since both transmission and distribution are observed at the same time and the solution has to work for both at the same time, the optimization problem might be that much more difficult, especially for large systems. The second option would be more numerous and varied local markets which would result in increased operational costs and potential financial issues. The mathematical cost of large systems is lessened, however, because initially just local grid restrictions are taken into account, shared with TSO, and dealth with in a second optimization that also takes into account TSO limitations. Some contend that in order to maintain neutrality, both options require an impartial market participant.

3.1.5 Integrated Flexibility Market

In this approach, alongside system operators (TSO and DSO), deregulated participants may also procure flexibility. They may both purchase and sell supplementary services. To ensure neutrality and an even playing field for all market players in this market configuration, an independent market operator is a must, and the market clearing procedure should take distribution level restrictions into account. High market liquidity is ensured by this approach. Due to the fact that all services are offered on a single market, there will be more competition and cheaper pricing, but this could affect trade volumes in the day-ahead and intraday energy markets. Additionally, gained flexibility may be sold, and the cost of maintaining the market shouldn't worry anyone because it may be distributed among a large number of players. The likelihood that TSO might purchase ancillary services to preserve system stability outside of the market, if deregulated participants induce so with their market actions, is possibly the biggest drawback of this paradigm. In some cases, the rivalry may even force the activation of services in the reverse direction at the transmission and distribution levels, resulting in high costs for the end customers. On the other side, the cost may be a good indicator of how desperately TSO needs these services, and with the right safety measures, such tragic events may be averted.

This last one will be the focus here forward. This is the type of market, at the distribution level, that will be explored in this chapter as well as in this thesis.

All five coordination mechanisms can be grouped in three big groups, a TSO managed model, TSO-DSO hybrid model and DSO managed model. The first model is closest to the actual situation in most countries and might be seen as a start in the right direction for a high percentage of DERs to be successfully integrated. Although it might take distribution-level restrictions into account, its major flaw is scalability. The DSO is given a less active role in the other two models. In the hybrid approach, the DSO validates the bids, whereas in the DSO controlled model, the DSO is in charge of both validation and dispatch. [54]

3.2 Local Flexibility Markets

As said before, Local Flexibility Markets (LFM) are the focus of this chapter and of the this thesis overall. Several parties can congregate in a market to facilitate the trade of goods and services. Typically, the parties engaged include market buyers, sellers, and retailers. Following this line of thought, [15] defines a LFM as a unique spatial place that serves a specific business purpose. A LFM can be described as an electricity flexibility trading platform to trade flexibility in geographically restricted areas such as neighborhoods, communities, towns, and small cities by analogy with the definitions of a market and a local market. As a result, a LFM consists of the goods or services that will be exchanged there, as well as a market operator, participants, and a clearing system.

3.2.1 Congestion Management and Voltage Control

At the distribution level, however, even though the DSO can use LFM for solving congestions and voltage violations, other methods, also extensively studied in the literature, can be used for similar purposes. The existing methods will be compared and summarized in this section. They can be categorized in Market-based methods, where LFMs are included, and Control-based methods.

Market-based methods mainly include, other than LFMs, Local Energy Markets (LEM), Price-based control and Transactive energy. Control-based methods, in turn, include virtual power-plants (VPPs) and active network management (ANM). [15]

- Local energy markets (LEM) were created and put into place to manage DERs with high penetration by promoting regional energy trading. They can be traded either peer-to-peer (P2P), under supervision of a mediator or a combination of the two. P2P allows prosumers to trade among themselves, however it may result on them having less negotiating power when exchanging with significant players.

- For price-based control, the DSO forecasts potential congestion during specific times and announces the congestion pricing in advance to the flexible demands. Most of the methods consist on the employment of different types of dynamic tariffs (DT), either day-ahead or closer to real time, to motivate players to shift the flexible demands from peak hours, in order to solve congestion problems.
- The transactive energy (TE) method is defined by the GridWise Architecture Council as ”a set of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter” [55]. It uses decentralized decision-making frameworks in order to manage the operation of DERs.

- A virtual power plant (VPP) is a cloud-based distributed power plant that aggregates the capacities DERs for the purposes of enhancing power generation, as well as trading or selling power on the electricity market. The DERs will have system visibility, controllability, and impact when they are combined in a VPP, much like a traditional generator would. Additionally, the enhanced utilization of existing assets made possible by VPP technologies might result in advantages for DSO, like improved network efficiency and cost saves in the distribution system.
- By using active network management (ANM), which is nothing more than control systems which manage generation and load for specific purposes, DSOs can solve congestion and voltage violations of distribution systems with high DER penetration, by controling said DERs, flexible demands and grid equipment in a centralized way.

3.2.2 Players in Local Flexibility Markets

Before exploring the designs and concepts of Local Flexibility Markets, it is interesting to understand who are the primary stakeholders and their objectives in markets for trading flexibility locally. Generally the key participants are [15, 26]:

3.2.2.A Prosumers

Lang defines prosumers as ”individuals who consume and produce value, either for self-consumption or consumption by others, and can receive implicit or explicit incentives from organizations involved in the exchange” [56]. They might have energy storage devices, other controlled and unpredictable units, and renewable energy sources like solar panels and wind turbines. They may act independently and even participate in peer-to-peer trade, but given their often tiny size (capacity and power), it makes sense to cluster them and then provide the flexibility of a clustered system. Then, between the prosumers and the flexibility procurers, there are the aggregators (explained in the following subsection).

3.2.2.B Aggregators

Aggregators are the newest players in this type of market structure. Aggregators have been defined as ”a company which acts as an intermediary between electricity end-users and DER owners and the power system participants who wish to serve these end-user or exploit the services provided by these DERs” [57]. In the context of this thesis, an aggregator will be seen as an enterprise that assists energy users in participating in demand flexibility programs, in order to curtail the broad scope of the aforemention definition. Due to their small quantities of flexibility, the individual DER or prosumer has little negotiating power in LFMs; therefore, in order to maximize their flexibility potential, the aggregators collect the individual flexibility to create multiple flexibility services and exchange it in LFMs.

Other than the limited negotiating position that the individual owner of DER or prosumer has when participating in a LFm, the other main reason for not participating individually is if every prosumer or owner of DERs decided to participate in these circumstances, they would end up overloading the market due to the large number of individuals, through communication and computation burden.

Aggregators are starting to be considered as the component needed in order for small-sized consumers to start exploiting their own assets as flexibility. There have been projects in Europe where aggregators have been put in place and tried in a local market. Energy Pool and Voltalis, for example, are aggregators focused on industrial and residential customers load reduction, in France and Great Britain, respectively [58]. There are however some challenges for aggregators to overcome. Consumers and prosumers, most of the times, are unaware of the problems that high loads can cause on networks. So, aggregators should be able to inform their customers in a simple way about their role in fixing the problem of peak loads. Customers should also need smart appliances and control systems in order for aggregators to gather the load data and better manage their flexibility. However, these technologies should require only minimal investment so to not alienate possible customers. [59]

3.2.2.C Distribution System Operator

Unlike aggregators, the Distribution System Operators (DSOs) have been mentioned in this thesis before and are the most well known of the participants in LFMs so its exploration will be a bit shorter. The DSO’s major responsibility is to provide customers with power in a way that is affordable, sustainable, and effective. It is also responsible for the distribution system’s safe operation as well as the caliber of power delivery services. Traditionally, this has involved planning, maintaining, and managing the distribution level grid, as well as supply interruptions and connecting and disconnecting DERs, which is where the DSO gets its flexibility in order to operate congestion management, loss control and voltage violations, to name a few.

3.2.2.D Balance Responsible Parties

Balance Responsible Parties (BRPs) trade in the energy markets on behalf of their clients, being exclusively responsible for balancing their portfolios. It is their duty to maintain a balance between energy supply and consumption over a specific period of time and incur imbalance fees if they fail to keep this balance. As a result, BRPs could have the flexibility they needed to maximize their portfolio and fulfill their energy commitments. Since BRPs are many times simultaneously generators, retailers, aggregators, DSOs or TSOs, they sometimes juggle the responsibilities of being a balance responsible party with other functions.

3.2.2.E Local Flexibility Market Operator

The Local Flexibilty Market Operator (LFMO) The Local Flexibility Market Operator is the entity charge of running the LFM's most crucial functions. It provides the flexibility trading platform for bidding, clearing and settlement of the market. Market clearing is the process that gathers flexibility offers and requests and determines trading outcomes (i.e., price and quantity of flexibility to be traded). There's many ways that this can be done and they will be explored also further ahead.

Many players can take over the responsibility of LFMO, such as the DSO, the aggregator or a BRP. It can also be a third party entity. There's been in the literature many pros and cons for the case where each of these players play the part of the LFMO, however the majority of the studies prefer a third party, preferably neutral, entity to take over the role. The DSO can become the LFMO since they are the entity most aware of the needs of the grid and are better fit for the solving of congestion issues. The current legal framework, however, forbids this from happening, the DSO from becoming the flexibility market operator. What if it is an aggregator? It could also work, but since the aggregator is an interested party in the market, there could potentially be a conflict of interest. If the aggregator becoming LFMO is to happen, there needs to be set first some network constraints. For these reasons, the preferred option for operating the market is a third party neutral entity.

3.2.3 Models of Local Flexibility Markets

When it comes to possible models for the proper functioning of LFMs, once again, there are many options under consideration and none are in clear position for the best solution. In deciding which model is better, its preferable to declare that there are different market models for different needs or purposes. Either being through peer-to-peer (P2P) trading, trading through a mediator, or a combination of both, not one should take precedence over the other without considering the specific characteristics of the system. Since the LFM involves interaction between different players, their behaviors should be predicted with mathematical formats. Different formulations can be classified into four categories and each category divides into small subcategories according to each model format [15,26].

3.2.3.A Centralized optimization methods

In centralized optimization models, there is usually a optimization problem when it comes to clearing the market. The optimization problem is tipically expressed as an objective function which needs to be optimized, while adhering to a number of technical and economic restrictions. The two main types of objective function are:

- **Social Welfare Optimization** - the term originating from economic standpoints, referring to to the satisfaction or benefit of numerous market participants, including consumers and producers, is calculated as a summation of the utility of all buyers minus the cost of all sellers (Revenue -(minus) Cost).
- **Operational Cost Minimization** - from each participant's perspective, it is preferrable to keep the operational cost of acquiring flexibility in the LFM as low as possible. This objective seeks that exactly, to minimize all the costs for a specific and different stakeholder (DSO, Aggregator, etc.).

The most important feature of this model is that it permits the optimization of an objective in order to find the best market clearing option. As easy it is to implement, the market clearing solution is also easy, solving headaches to the operator. However, the big cons of this system are the existant barriers for large-scale systems, since it is a model difficult to present in a scalable manner, due to limits of communication and computation, and the fact that it either focuses on minimizing the costs of only one specific player, or focuses on the social welfare present in the LFM.

3.2.3.B Game theory-based models

These models are based in game theory, the study of how interdependent decisions made by economic agents result in outcomes that are consistent with their preferences (or utilities) even when none of the agents may have intended the particular outcomes in question. The focus is usually the competition of all market participants in order to try to maximize profits:

- **Noncooperative Game Theory** - this models enters in action expecting players to decide their own strategies without consulting other players, is better suited for situations where participants may only have some of the information. It describes a competition among participants who have partially or completely conflicting interests. This is one of the most common markets in the literature, being used commonly even at the distribution level as [60–62] demonstrate.

- **Cooperative Game Theory** - it focuses on rational cooperative players that exhibit cooperative behavior. The method can be used in circumstances when it is possible, acceptable and desirable for individuals to provide information. The (usually) DSO is typically not willing (or even permitted) to disclose network information to other players in flexibility markets.

As the name indicates, game theory-based models look at the LFM as a game, wherein a player's ability to make decisions depends on those of the other players and mathematically record the game's players' behaviors. Its a scalable model and can be applied for markets with huge number of players, since its able to represent all the participants in the LFM with competence, however the model also assumes every player will act rationally, which sometimes doesn't happen in reality and it might generate situations where all influences are cancelled by another, effectively creating stable situations which isn't really the desired outcome of the model.

3.2.3.C Auction theory-based models

An auction, the base mechanism of this model, functions by allocating resources in such way that seeks to balance supply and demand through a competitive bidding procedure. In an auction market, multiple sellers and buyers can concurrently submit a number of orders for certain commodities to the mediator. This mediator in the process, the auctioneer, collects the bids and determines the clearing price. In a pay-as-cleared system, the nominated buyers, those who offered price higher or equal to the cleared price, are required to pay the same amount, and all nominated sellers, whose offered price is lower or equal to the cleared price, are required to pay the same commission. In a pay-as-bid system, the nominated sellers receive the price they requested.

Auction theory-based models can be then classified into single-side auction and double-side auction models. In the former, numerous buyers bid for an item being sold, while multiple sellers offer the item that the buyer requested. The latter, the double-side auction, works with multiple buyers bidding to buy goods from various sellers.

The double-sided auction model overcomes the single-sided one, being the most general type, and most appropriate in vast majority of occasions.

This model, inspired by stock exchange markets, which sees the LFM as an auction market, and where the auctioneer determines flexibility allocation as well as the clearing price of the market based on the participants' bidding strategies, has some pros and cons like the aforementioned models. This model, for one, is also scalable and can be applied even with the participation of many players and permits buyers and sellers to achieve market equilibrium quickly. There can be, at times, unviable auction price spikes, unreasonable and undesirable, due to excessive competition at the auctions.

3.2.3.D Simulation models

Last but not least, there are multiagent-based simulation models. Its a pretty flexible modelling framework, built to mimic the behavior of multiple participants. It captures the dynamics of the power market and is a good option for scenarios with several parties. Each party can be a single variable in a computer program or a smart item with an endless number of actions and decisions.

Even though the flexibility of the model in representing all the participants of the LFM regardless of the strategy, resources, private or public information permits a really solid representation of the LFM, it requires heavy computational power in order to consider every variable.

3.2.4 What's the best option?

In this section there will be an overall comparison of models. There isn't a clear winner between all of them, every model has its vantages and disadvantages. There should be a case-by-case study and decision and choose the model which suits best the situation at hand. Different circumstances require different architectures.

The centralized optimization model is the ideal option when just one player is the subject of interest. This streamlines the model but ignores other elements, such as the utility goals of the rest who is not being observed. This model also struggles to scale when there are many participants involved. On the other hand, alternative models can imitate market behaviors more accurately because they can include all market participants. Centralized optimization models are, therefore, simple to implement, however, because communication and computing have scalability restrictions, they face obstacles for large-scale systems. Market designs based on simulation models, auction theory models, and game theory models are a better option in situations with larger systems since they are definitely more scalable. The major benefit of the auction-theory based models is their capacity to swiftly establish equilibrium between the supply and demand curve with little computational work. The biggest disadvantage is that excessive competition may result in unintended auction price spikes. Since multiagent-based modeling is a simulation, its primary distinguishing feature is that it attempts to mimick potential human behavior and display it using mathematical models. One should keep in mind that game-theory models make the assumption that all players are rational, which is frequently not the case in real-life circumstances.

3.2.5 Local markets clearing methods

In this section, clearing methods for local flexibility markets are summarized and described. Its important to notice that the clearing methods and the market models are intrinsically connected so when opting for a model it is important to also choose a clearing method that matches the model and vice-versa [15, 26]. The clearing methods may be divided as follows:

3.2.5.A Centralized Optimization

As the name implies, this is the market clearing method used in the explored earlier centralized optimization model. It consists of an optimization program that searches for the ideal value to reduce or maximize the objective function using a specific algorithm over a given time horizon, and with a set of various constraints. Depending on the constraints, the optimization problem to solve may be considered by using lineal programming (LP), mixed integer linear and non-linear programming (MILP; MINLP), quadratic programming (QP) and mixed integer quadratic programming (MIQP). The centralized optimization methods can be solved by direct algorithms and indirect algorithms in accordance with the mathematical characteristics of the optimization programs.

Direct Algorithms classify the optimization problems that can be solved directly with commercial solvers like CPLEX and GUROBI [63, 64], while **Indirect Algorithms** need to be slightly altered and converted to a format that can play well with the existing solvers. In general, linear convex centralized optimization problems and those that are transformed into that format are solved by direct algorithms. On the other hand, when network limits are taken into consideration, the indirect approach is typically utilized. This rule should be followed so that congestion and voltage issues are taken into account.

3.2.5.B Decomposition Methods

When dealing with a large number of participants its harder to escalate from small models to huge ones and brings a big computational burden, so an easier way to deal with it is break down these large models into small sub-problems. This is how Decomposition Methods work. Dividing and solving sub-problems brings down the burden in computational work, and decentralizes the efforts to each respective sub-problem. The first of these is the **Decomposition based on augmented Lagrangian relaxation** which works perfectly with scalability regardless of the number of constraints, however when the problem is non-convex and has a dual gap, it has a lot more trouble being efficient. When the problem has these circumstances, it is usually applied an augmented penalty function. Based on this technique, four decomposition methods were developed, namely the alternating direction method of multipliers (ADMM), the analytical target cascading (ATC), proximal message passing (PMP) and auxiliary problem principle (APP). The second is the **Decomposition based on Karush-Kuhn-Tucker (KKT) conditions** which, as the name implies, looks at first-order KKT optimality conditions that can be solved in the problem with its decomposition method in a decentralized fashion.

3.2.5.C Bi-Level Optimization

Bi-level optimization is a suitable solution for situations directed towards processes that require large-scale optimization and decision-making and are hierarchical with a leader in the top level and a follower in the lower level, whose actions directly affect the upper level leader. It is defined as a mathematical program, where an optimization problem is constrained by another optimization problem (in addition to the conventional constraints).

Bi-level problems are tackled either using single-level reduction techniques (with KKT conditions or KKT conditions and duality theory) or nested methods. KKT conditions are sufficient to reduce the problem to a single-level equivalent and solve it using readily accessible commercial solvers when both the upper- and lower-level problems are linear, however they cannot solve bi-level issues by themselves when the upper-level is non-linear. In this case, dual theory can help to linearize the upper-level before solving the problem. Then there are the nested methods. They are better applied in bi-level problems when the lower-level problem is non-linear. Depending on the mathematical properties, the nested technique works with each level using the suitable optimization procedure. It comes, however, at a high burden in mathematical work.

3.3 Market Platforms

There is a decent amount of literature referring to local flexibility markets initiatives pioneered in other European countries, their respective platforms and examples of other structures and models that can enhance network flexibility. Below are some of these initiatives and other analysis.

3.3.1 NODES Marketplace

The NODES Marketplace platform is one of four pioneering flexibility marketplace platforms. It is currently being implemented in a number of locations including Northern Europe and the Baltic region and emerged as a joint venture between energy market Nord Pool and Norwegian energy group Agder Energi. Its main function is to make flexibility trading easier while taking into account the location of available resources.

To achieve this goal, NODES, which acts as an independent market operator, locates the resource and introduces a tag with that location and then assigns another with a price determined according to the potential flexibility value of the analyzed resource. Thus, it manages to provide conditions for safe trading at transparent prices.

Flexibility providers - mostly BRPs, but aggregators, micro-grids and other individuals can also be considered - bid for sale on NODES, instead of the owners of flexibility resources, with a model defined by them and by the owners themselves and with the technology that allows the activation of flexibility on the part of the buyers. Bids can be differentiated, according to how they will be sold, either centrally or locally.Local sales are restricted to specific places in the network and, therefore, more risky, as only a few hundred hours are needed each year. Therefore, central selling is usually more advantageous, as it allows it to be used for necessary rebalancing on a larger scale. For this, each bid is included in a catalog that includes location, availability, time, profile and order parameters.

The last market entity is the flexibility buyer. This entity can range from system operators like TSOs, DSOs to also BRPs. They present bids through the NODES Marketplace platform to buy flexibility in a given location. They can also filter within the flexibility catalog available on the platform in order to choose those that best suit their needs. For example, DSOs can hire local flexibility to solve grid problems in the form of increased consumption rather than causing renewables to curtail. TSOs, on the other hand, gain the ability to contract flexibility that would otherwise be out of their reach in traditional markets, with preference given to activation times and ramping.

The way NODES works makes flexibility products non-standard. This means that, while there may be a better response to more specific flexibility needs, the fact that they may not be liquid enough for subsequent activities, due to their lack of standard. As such, they make it more difficult to build an order for competitive organization between products, price transparency and competition between providers. [1]

3.3.2 Enera and the EPEX SPOT Local Flexibility Market

Enera first appeared as part of SINTEG, a publicly funded program in northern Germany. The main objective was to develop and prove that there could be a solution for an energy supply that not also was scalable was also aware of ecological and environmental issues, safe and economical with a focus on the role and responsibility of the energy sector, regulatory framework, grid tariffs and local flexibility markets. Its structure was integrated in 2018 as part of the cooperation agreement between the European Power Exchange EPEX SPOT and an energy group EWE AG, with the aim of addressing the problem of grid congestion, establishing a demonstrable and scalable practical case (in the northeast of Germany).

The EPEX SPOT Local Market Platform is an open, voluntary, market-based network congestion control platform for flexibility providers that centralizes local flexibility offerings so that they can easily be used by TSOs and DSOs for the purpose of to alleviate congestion. EPEX SPOT acts neutrally as an intermediary between suppliers and buyers, overseeing the establishment of prices and ensuring transparency.

The platform is active during the operation period of the intraday market, separate from other existing markets and the access interface is universal, i.e. suppliers - aggregators, asset managers and exchanges - and buyers - medium and low voltage TSOs and DSOs - use the same medium. Suppliers can continuously submit bids in their respective order book and buyers can also continuously submit demand orders in the order book that correspond to the market area where flexibility is needed. The buying and selling process is then carried out in a similar way to that practiced in several intraday markets across Europe: offers in the same order book are automatically and continuously matched and remunerated according to the pay-as-bid pricing scheme. Flexibility products are defined and standardized by EPEX SPOT itself, in collaboration with network operators, taking into account ascending and descending blocks of energy, during a specific period and location.

The objective is to create conditions for coordination between system operators at the various levels of the electricity grid, depending on a high level of digitalization and automation. Thus, participants are able to add value to their assets, avoiding a potentially more expensive increase in the physical network and allowing for greater reliability, security and coordination. [1]

3.3.3 Piclo Flex Marketplace

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Piclo Flex emerged from a project funded by the UK government, but developed by an independent software company. The goal of the project, aimed at buyers and suppliers of flexibility in the UK, is to provide a smart, flexible and clean energy system, through the platform that allows flexibility providers to promote their services, as well as encourage new initiatives and models of business.

The pilot phase of the project revealed that both groups of flexibility suppliers and buyers that participated in the platform are quite diverse groups. The suppliers are mainly composed of aggregators, electricity providers and industrial and commercial users. Also included in this group, although to a lesser extent, are community participants and individual industrialists. But the biggest novelty that happened in terms of demography was the introduction of speculative users. More than 30% of Piclo users were potential investors in flexibility services.

Flexibility buyers included the six British DSOs - UKPN, Scottish and Southern Electricity Networks, Electricity North West Limited, Northern Powergrid, SP Networks and Western Power Distribution, each using the platform in a particular way. While some used the platform as an improvement of the processes of the existing markets, others used the platform in depth, making use of the auction's functionalities and seeking to satisfy their requirements in a standardized format. The major causes for the need for flexibility were because of reinforcement delays (deferral reinforcement), unplanned, pre- and post-failure network interruptions and also, albeit to a lesser extent, planned network maintenance.

During the pilot period, Piclo Flex saw demand for more than 456MW of flexibility spread across the six DSOs. The UKPN has in turn published the revenue ranges needed to keep up with competitors, requiring a budget of approximately £12 million.

In short, Piclo Flex was able to demonstrate that an online platform could be used by several DSOs in order to help maintain the electricity grid, using only distributed resources for deferral reinforcement, planned maintenance and unplanned interruptions. It appears however that Piclo Flex is used only by DSOs so far, with cooperation with the TSO being limited. [1]

3.3.4 IREMEL and the Iberian Electricity Market

The last of the four pioneering initiatives is IREMEL. It was launched by the Spanish electricity market operator, OMIE and IDEA, the Institute for the Diversification and Saving of Energy. Its main objective is to develop a local market model in order to facilitate the efficient integration of DERs such as renewables, prosumers and storage facilities. It also promotes the participation of DERs as a solution to localized congestion and other needs of DSOs. Other secondary objectives are the development of prototypes of local markets, identifying challenges and opportunities for the role of prosumers and consumers in the market, demonstrating the feasibility of new technologies to facilitate the management of distributed resources in participating in local markets.

Flexibility providers involved in IREMEL include DSOs, individual DERs, aggregators, proactive consumers, battery producers, etc. Two groups of products are considered, short-term (on order, only when necessary) and long-term for structural problems (long-term contracts, months or years). IREMEL currently has 5 pilot projects in different areas of the Spanish market, with different participants and under different conditions as well. However, they are still in the design phase. [1]

The conclusions drawn from these projects are interesting. NODES and Enera appear to be conceptually the most similar, with similar goals for both buyers and suppliers of flexibility. The biggest difference seems to be in the relationship of both platforms with the intraday market. Overall, however, all platforms have their similarities in that they are managed by an independent operator, which ties in with various DSOs to be the platform provider. The biggest differences are seen in the integration with other markets, in the use of reserve payments, in the use of standardized products and how the TSO and DSO cooperate with each other. . [1]

It is also worth noting that participation in the platforms is voluntary but involves a pre-qualification procedure. Suppliers can act as BRPs or instead of BRPs, as contractual responsibilities between aggregators, BRPs and suppliers are dependent on each regulatory framework. There are no measures to establish a base line, nor do any of the platforms specify any type of penalty if the proposals are not met. [1]

3.3.5 GOPACS

In January 2019, the Dutch TSO, TenneT, partnered with four DSOs to launch GOPACS, which stands for Grid Operators Platform for Congestion Solutions. Different from the other examples cited above, GOPACS is understood not as a market platform, but instead an intermediary between the needs of network operators and markets.

Connected to the ETPA, Energy Trading Platform Amsterdam, a national intraday platform operation in the Netherlands, GOPACS continuously procures standardized offers from flexibility providers on ETPA and sorts them from cheapest to most expensive to solve congestions. Each offer may have a locational tag, even though ETPA does not define static geographical zones. This allows providers to make multiple offers with the same flexibility at different prices, one as a portfolio offer and the other more specific to a location with proper locational information. However, it is the responsibility of the flexibility provider to avoid double activation, even though there aren't any penalties set in place for non-delivery. The participation in this market is voluntary, with no restrictions but requires a pre-qualification done by the system operator.

3.4 The Portuguese Case

The Portuguese scene is quite unique when it comes to the energy industry. A brief overview of the market will be discussed henceforth, and then an analysis of how the portuguese energy scene deals with congestion management.

3.4.1 Overview of the Portuguese energy market

The Iberian Electricity Market (MIBEL) arose from a joint initiative between Portugal and Spain, taking its first steps in 1998 and becoming fully operational in July 2007. The aim of the MIBEL was to create a regional electricity market, on an Iberian scale, which would allow Iberian consumers and producers to interact with each other in a transparent and equal manner. The MIBEL allowed a better integration of the electrical systems of the two countries, enabling a full exploitation of the existing interconnections. MIBEL integrates the derivatives exchange, managed by OMIP - *Operador do Mercado Ibérico de Energia (Pólo Português) S.G.M.R., S.A.* , and the spot electricity market, managed by OMIE - *Operador del Mercado Ibérico Polo Español, S.A.*.

3.4.2 Wholesale Markets

The wholesale markets follow a power exchange model composed by the day-ahead market, the intraday market and by bilateral contracts. The day-ahead market is where eletric energy is transacted for the following day through the presentation of sale and purchase orders by the market agents. These market agents can be either producers on the supply side, or distributors, retailers and customers on the demand side. Retailers buy electricity for resale to consumers or to other customers and customers have the option of purchasing all or part of the electricity they require from the market. Each bid is integrated from 1 to 25 blocks for each hour, sorted in descending order for the former and increasing order for the latter, and can be submitted to the session before to 12 noon in day d-1, which is when the market gates are closed. After that, the matching procedure is carried out and the marginal price will be determined by the point where the demand and supply curves intersect. Then, all the supply bids under and all the demand bids over the intersection will be attributed that same price.

This is how generally the day-ahead market works, however, if the global electricity exchange program between the Portuguese and Spanish electricity systems, resulting from the daily market matching process, exceeds the maximum capacity available in the corresponding transit direction transit direction, the market is separated into two zones with different prices. That is called *Market Splitting*

Intraday markets operate under the same concept as the day-ahead market but in different time periods. There are six sessions of intraday market per day, approximately every 3 to 4 hours, where the same market agents that participate in the day-ahead market can participate as well in order to correct their programs before real-time, giving them the opportunity to adjust their operation and optimize their portfolio. There is also one more session of the intraday market, called the continuous market, that, as the name implies, permits the continuous trading of energy between market agents.

Last but not least, when it comes to the wholesale markets, there is bilateral contracts. The celebration of these contracts means that two market agents can transact electric energy between themselves, where one of the parties commits to supply the grid with the energy contracted, and the other party commits to receive said energy, with conditions and price established between themselves, and letting each be responsible by the respective costs of their participation in this type of trade.

Forward markets are organized market that offers risk management instruments in the form of the form of derivatives. Organized by the OMIP, they can be classified between future contracts and forward or swap contracts and can be defined as standardized contracts (nominal volume and price) for the purchase or sale of energy for a given time horizon time horizon, in which the buyer commits to purchase electricity in the delivery period and the seller commits themselves to put this the same electricity at a price determined at the time of the at the time of the transaction. The big difference lays on the fact that in the first case, gains and losses resulting from price fluctuations during the trading phase are settled on a daily basis, while in the latter cases this only occurs during the contract delivery period and on a monthly basis. This type of markets mainly exist to cover the risk of price fluctuation. While, many times, the price of electricity can be really low, which could be really advantageous for consumers or retailers, price peaks are also common which is in itself disadvantageous. By making this kinds of contracts, retailers and consumers can agree with the producers a set determined price and commit to it.

There are additional markets offering supplementary services to maintain supply and demand equilibrium and boost reliability. These are called ancilliary services (AS) markets. They were conceived with the goal of maintaining a high degree of security in the electric system. In Portugal, they can be subdivided into Mandatory Services, which are not remunerated and which include voltage regulation, frequency regulation and stability maintenance and Complementary Services, such as synchronous and static compensation, reserve, secondary regulation, rapid interruptibility, autonomous startup and remote startup, which are remunerable.

Among ancilliary services, those associated with frequency-power regulation are of special importance: primary regulation, secondary regulation and regulation reserve. Primary regulation, associated with genset droop, is an unpaid mandatory system service for all generators in service. The power variation resulting from its action must take place within 15 seconds for disturbances causing frequency deviations below 100 mHz and linearly between 15 and 30 seconds for frequency deviations between 100 and 200 mHz. Secondary regulation, associated with the teleregulation service of the generating sets, is an ancilliary service remunerated according to market mechanisms. The valuation is determined in two parts: the secondary regulation band, valued according to the maximum of the marginal prices of the secondary regulation band going down and going up each hour, and the secondary regulation energy, valued at the price of the last offer of regulation reserve energy mobilized each hour. Lastly, the regulation reserve is a complementary service, remunerated by market mechanisms, composed of two parts: minimum tertiary regulation reserve and additional reserve. The minimum tertiary regulation reserve is established by the System Manager (which in the case of portuguese markets, the responsibility befalls on the TSO, REN) for each programming period, taking as a reference the maximum production loss directly caused by the simple failure of an electric system element, increased by 2% of the foreseen consumption. The purpose of the additional regulation reserve is to guarantee consumption coverage and system operation in cases where the hourly consumption forecast by the System Manager exceeds, by more than 2%, the hourly consumption resulting from the production markets and when the forecast generation loss due to successive failures and/or delays in the connection or load raising of thermal groups is higher than the established tertiary regulation reserve.

3.4.3 Congestion Management in Portugal

In Portugal, congestion management is a responsibility very much allocated to the TSO, which is REN - Rede Elétrica Nacional, and is done mainly at the transmission level. It can be either internal congestion, which is when the congestions happens solely in one area inside the country borders, and inter-area congestion, which is when the congestion happens in the border between Portugal and Spain. In this case, there has to be a coordination between REN and RE - Red Eléctrica, the spanish TSO.

The mechanism for congestion management takes place after the day-ahead market. The system operator, that is, REN, starts by assessing the interconnection capacity and verifies if it exceeds their limit. It, then, can manage purchasing or selling bids to secure the interconnection. Even if after this action, a congestion is verified, the system operator can resort to Coordinated Remedial Actions, like countertrading, which are energy transactions provoked by the TSO in real-time and that overwrites the existing interconnection program. The resulting countertrading measures lead to speculative actions (of the same order of magnitude and in the opposite direction) in each system, as symmetric reserves are mobilized upwards or downwards, reserves provided by the respective ancilliary services markets.

3.4.4 Flexibility Services in Portugal: E-REDES and Piclo

In late 2022, E-REDES partnered with Piclo Flex to launch FIRMe, a local flexibility pilot project. It is being made as a proof of concept to test the approach of local flexibility markets and if the respective market has the due acceptance. While the market is going to be organized by E-REDES, which will act as the market operator, the platform for procuring flexibility will be the PICLO platform, as a market-base framework.

The operation of the local flexibility market in Portugal will be similar to the successful flexibility markets that PICLO has helped implement in the UK and Europe. This market allows companies, consumers, and prosumers to leverage their assets, such as distributed resources, renewables, and electric vehicles, to assist the Portuguese Distribution System Operator, E-REDES, in managing network stress. Participants will be compensated by E-REDES for modifying their generation or demand patterns to alleviate network stress, thereby providing an innovative way to balance supply and demand in the energy market.

4

Methodology

This Chapter delves into a the construction of a possible decentralized local market whose goal is the trade of flexibility in distribution networks. Specifically, the market designed will fit in the Integrated Flexibility Market model, with a Centralized optimization method, focused on the Operational Cost Minimzation. The innerworkings of all these were explained in earlier chapters.

In the context of a market being the space where buyers, sellers, and retailers can engage in the exchange of a specific product, the buyer will be the DSO and the sellers or retailers will be the aggregators; the product traded will be flexibility, either the ability to increase or decrease loads. Since the market will happen in the distribution level, the DSO will oversee and manage this ”local flexibility market”, since its going to take place within their own networks, as well as for simplicity’s sake.

4.1 Local Flexibility Market

For a local flexibility market to be efficient, it must have well-defined products, appropriate pricing mechanisms that benefit all participants, a high level of competition through increased participation, and trading intervals with effective bidding mechanisms. Furthermore, this market must also coordinate and not negatively impact other electricity markets and players.

4.1.1 Market Parameters

The proposed local flexibility market is set to operate during the day-ahead time period, parallel to the wholesale market, focused on the distribution level, since its main objective is solving congestions locally using consumer and prosumer assets.

In terms of contracts, they can take many forms. From the typical bilateral to power exchange or trading in a pool market. For this particular LFM, power exchange trading is deemed the most appropriate choice, since it permits the interaction of buyers and sellers of flexibility without the need for being tied down to one another. This decision has been made based on being the most applied form of trading in similar flexibility markets. The simplicity of the trading mechanism will make it easier for market players to participate, thus increasing market liquidity.

Regarding the method for price-clearing of the proposed market, the pay-as-bid approach is set to be employed. Market players who actively participate will earn compensation equal to their designated bids, providing a fair and transparent system. This approach will allow for a more efficient and effective market, providing benefits to both market players and consumers.

All of these are common approaches in establishing a flexibility market, as seen in [65–67]

4.1.2 Market Product

As the name suggests, the product traded in a flexibility market is going to be flexibility. This flexibility offered is shown in the market as **load reduction** and **load increase**. The DSO might make use of load reduction flexibility, to lessen network constraints caused by overloaded lines and with the right incentives and mechanisms, customers can provide this load decrease to the DSO in order to avoid congestions.

On the other hand, load increase flexibility, which entails raising the amount of load delivered by customers at a predetermined time, can be used to counteract overvoltages problems in the network. When the voltage levels exceed permitted thresholds, load increase flexibility can be applied to help solve this issue. It can be especially useful in networks with high penetration of RES as an alternative to curtailment, since RES can be intermittent and, thus, unpredictable when it comes to their behavior.

This type of adjustment in energy consumption by decreasing or increasing the load at a given time, may necessitate a shift in energy usage to another period. For this reason, it can also be referred to as shiftable power. Again, this type of product is very common in flexibility market proposals, such as [66, 68] Fig. 4.1 illustrates this phenomenon.

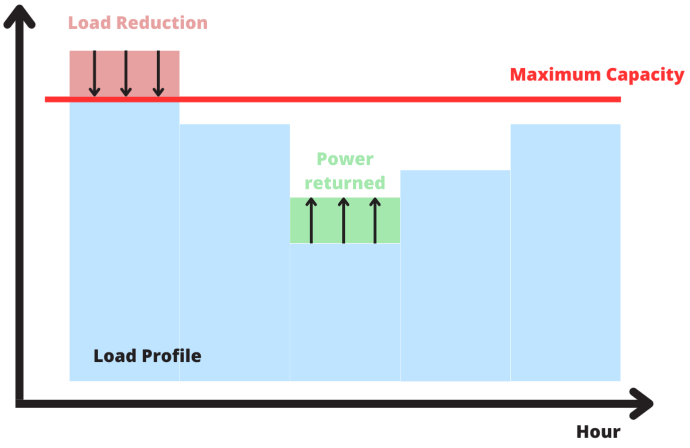


Figure 4.1: Load reduction flexibility

The reallocation of energy can result in additional challenges for the power grid, such as increased congestion if the energy saved through load reduction flexibility is used during peak load hours, or if the load is reduced at times where the voltage is still very high, a phenomenon known as the **energy rebound effect**. [69, 70] which is represented in Fig. (4.2).

4.1.3 Rebound Effect

While implementing demand flexibility mechanisms, the operator of the distribution system must take the rebound impact into account. Additionally, the flexibility supplier and the DSO should have a clear awareness of the circumstances in which the rebound effect occurs. To accomplish this, the DSO must have the information of which hour the client needs its power returned and what percentage of it is needed. These agreements are crucial in preventing network problems, although they also add complexity to the DSO's task.

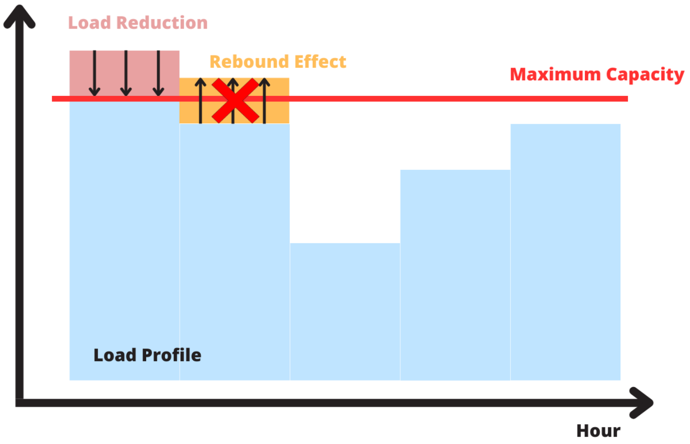


Figure 4.2: Rebound Effect

The rebound power conditions, are described as follows, in (4.1), based and adapted from [71], where R is the total rebound power, to be returned in a situation of load reduction, and in (4.2), where I is the total rebound power in a situation of load increase. The variable Θ_R represents the rebound coefficient for load reduction and Θ_I represents the coefficient for load increase. They determine the proportion of demand flexibility power that must be either returned or withdrawn by the customers, and are restricted by the equations in (4.3). F^{red} and F^{inc} represent the total load reduction and load increase in a determined scenario where flexibility was activated.

$$R = \Theta_R \cdot \mathrm{F}^{red} \tag{4.1}$$

$$I = \Theta_I \cdot \mathrm{F}^{inc} \tag{4.2}$$

$$0 \leq \Theta_R, \Theta_I \leq 1 \tag{4.3}$$

4.1.4 Aggregator Bids

The increased or decreased loads are then compiled and consolidated by an aggregator. This entity will then organize bids of flexibility, composed by various clients connected to a single feeder node, all composed. The next step is arranging the same flexibility bids, comprised of b blocks of available flexibility amounts $\mathrm{F}_{n,b,t}$ with respective prices $\mathrm{P}_{n,b,t}$, in as ascending order, for a specific node n, and period t.

The amount of power that is going to be paid back and the hour that it will be done so, need also consideration. These will be called rebound power and rebound hour, respectively. The first can be the total or just percentage of the flexibility and the latter can either be unrestricted, meaning it can occur at any time or be restricted to a time frame

The following equations represent the amount of flexibility activated and the respective cost, similarly to other approaches employed by authors like [66, 71]. (4.4), determines the total sum amount of activated flexibility, $F_{n,t}^{TOT}$, at each block b in the bid $\mathrm{F}_{n,b,t}$, at a specific node n and period t, restricted by (4.5), that set a limit maximum, $F_{n,b,t}^{MAX}$, and minimum value, $F_{n,b,t}^{MIN}$. (4.6), then determines that the total flexibility $\mathrm{F}_{n,b,t}$ multiplied by the corresponding price $\mathrm{P}_{n,b,t}$ gives the corresponding cost to activate the flexibility, $C_{n,t}^{F}$.

$$\mathrm{F}_{n,t}^{TOT} = \sum_{b=1}^{N} \mathrm{F}_{n,b,t} \ , \qquad \forall n \tag{4.4}$$

$$\mathrm{F}_{n,b,t}^{MIN} \leq \mathrm{F}_{n,b,t} \leq \mathrm{F}_{n,b,t}^{MAX} \ , \qquad \forall n \tag{4.5}$$

$$\mathrm{C}_{n,t}^{F} = \mathrm{F}_{n,b,t}\mathrm{P}_{n,b,t} \ , \qquad \forall n \tag{4.6}$$

4.1.5 Market Operation

The structure for this market was based on the ones presented by [66,68,71]. The key players for this market are customers (either consumers or prosumers), the aggregator, the day-ahead market operator, that as the name implies, operates the day-ahead market, the flexibility market operator (FMO), that will operate this market being elaborated and the DSO whose task is overseeing the distribution network. Fig 4.3 illustrates how the market plays out. In this structure, the FMO is assumed to also be the DSO, for simplicity's sake, and the role of the energy retailer and balancing responsible party (BRP) is taken on by the aggregator. The aggregator, acting as an energy retailer, engages in the day-ahead market to bid in the customer's stead, guaranteing their energy needs. when the market is cleared, the DSO will validate the resulting schedule for any technical concerns. The DSO then uses the schedule to forecast any potential grid contingencies for the next day, triggering a call to all aggregators, notifying the flexibility needs. Even though, realistically, any third party entity could be in charge of market clearing, to facilitate the process, in this case, that responsibility will fall on the DSO.

Finishing the bidding process, with every aggregator making all their submissions according to their own portfolio, the market is cleared and every aggregator will receive the impending result, which should include the accepted flexibility bids and the rebound energy schedule. As a result, the aggregator can modify their flexible loads in an appropriate manner. Fig. 4.3 illustrates the whole process.

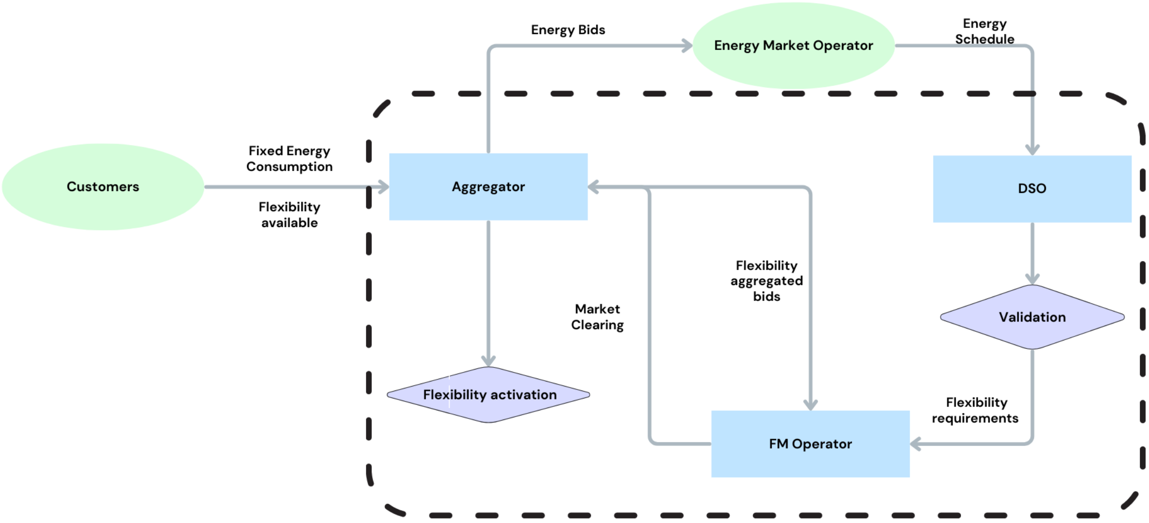


Figure 4.3: Structure of the Flexibility Market (only blocks inside the square are addressed in the case studies)

The DSO-led technical validation is integral to the functioning of an electricity market. It involves conducting a Power Flow (PF) analysis to guarantee the grid's secure operation in accordance with system and resource constraints [72]. The market operator, that is, within the suggested framework for flexibility, the DSO, has the objective of efficiently clearing the market while keeping the overall cost of acquiring flexibility to a minimum. This is accomplished by using an Optimal Power Flow (OPF) to guarantee that the system restrictions are not breached. The power flow equations are expressed ahead.

$$Pn = \sum_{m=1}^{N} |\mathrm{V}_n||\mathrm{V}_m||\mathrm{Y}_{n,m}|cos(\theta_{n,m} - \delta_n + \delta_m) \cdot \mathrm{S}_{base} \ , \qquad \forall n \tag{4.7}$$

$$Qn = \sum_{m=1}^{N} |\mathrm{V}_n||\mathrm{V}_m||\mathrm{Y}_{n,m}|sin(\theta_{n,m} - \delta_n + -\delta_m) \cdot \mathrm{S}_{base} \ , \qquad \forall n \tag{4.8}$$

$$Snm = Pnm + jQnm = |\mathrm{V}_{n,t}^2 \mathrm{Y}_{n,m} e^{-j\theta_{n,m}} - \mathrm{V}_{n,t}\mathrm{V}_{m,t} e^{-j(\delta_{n,t} - \delta_{m,t}\theta_{n,m})}| \cdot \mathrm{S}_{base} \ , \qquad \forall n, m, t \tag{4.9}$$

$$Snm \leq \mathrm{Snm}_{MAX} \ , \qquad\qquad \forall n, m \tag{4.10}$$

$$\mathrm{Vn}_{MIN} \leq Vn \leq \mathrm{Vn}_{MAX} \ , \qquad\qquad \forall n \tag{4.11}$$

In equation (4.7), Pn represents the injected active power at a node n with $Y_{n,m}$ being the bus admittance matrix, with n rows and m columns, $|V_n|$ being the voltage magnitude for the n_{th} bus and $|V_m|$ the voltage magnitude for the m_{th} bus, the $|\theta|_{n,m}$ being the difference between phase angles for the n_{th} bus and m_{th} bus and δ_n and δ_m being the voltage angle for the n_{th} bus and m_{th} bus, respectively. Lastly, S_{base} represents the system base power, a reference value in order to normalize power calculations.

Qn is similar, representing the injected reactive power in (4.8), also for a certain node n, in a network composed by N nodes, with the same components as the previous equation.

Equation (4.9), Snm represents the power between nodes n and m. These power flow equations are true for all points in time t within the considered period. The network's line capacity and voltage limits at each node are shown in equations (4.10) and (4.11), respectively.

4.2 Optimization Problem

The purpose of the market, when clearing, is minimizing the cost in acquiring flexibility for the distribution operator, $Min\ \mathrm{C}^F_{n,t}$ [66, 71, 73]. As such, we can represent the objective function as (4.12), at block b, node n and time t with price $\mathrm{P}_{n,b,t}$ for each activated flexibility $\mathrm{F}_{n,b,t}$.

$$Min\ \mathrm{C}^F_{n,t} = \sum_{t=1}^{24}\sum_{n=1}^{Nn}\left[\sum_{Nb}^{b=1}\mathrm{F}_{n,b,t}\mathrm{P}_{n,b,t}\right] \tag{4.12}$$

$$\mathrm{F}_{n,b,t\ MIN} \leq \mathrm{F}_{n,b,t} \leq \mathrm{F}_{n,b,t\ MAX} \ , \qquad\qquad \forall n, t \tag{4.13}$$

$$\mathrm{R}_{n,t} = \sum_{b\in K}\sum_{b=1}^{N}\Theta_{Rn,b}\mathrm{F}^{red}_{n,b} \ , \qquad\qquad \forall n, t \tag{4.14}$$

$$\mathrm{I}_{n,t} = \sum_{b\in K}\sum_{b=1}^{N}\Theta_{In,b}\mathrm{F}^{inc}_{n,b} \ , \qquad\qquad \forall n, t \tag{4.15}$$

Since the DSO is acting as the operator of the flexibility market, it must clear the market in accordance with the constraints set in (4.7)-(4.11). Equations (4.13) and (4.14) and (4.15) set the maximum and minimum limits to existent flexibility and calculate the rebound power, similarly to eqs. (4.1) and (4.2), as functions of either load reduction or load increase volumes with the respective coefficient $\Theta_{Rn,b}$ and $\Theta_{I}n, b$. The activated bids for the rebound at time t are represented by K.

This minimization can prove itself to be challenging issue. In large networks, the rebound effect can be complex and multi-faceted, and it can be difficult to accurately predict the change in energy consumption that occurs over time. When presented with a bid, the operator has to consider the rebound effect causing potential new congestions and in networks with many flexible customers, it becomes dramatically harder.

To tackle this issue, the approach employed is based on the one described in [71] and aims to manage the intertemporal complexities efficiently, while also ensuring that any activated flexibility bid is technically feasible and that the rebound effect is taken into consideration.

Firstly we should consider the number of combined bids. When deciding to solve a specific congestion, for a network with aggregators responsible for n bids, there are $2^n - 1$ possible combinations that may be utilized, each with a number of activated blocks that have specific characteristics and conditions. With this big of a number, there is a need to narrow down the search space and divide the problem into two stages, which would help in solving the optimization problem.

- **Feasibility Assessment -** In the first stage, the rebound conditions are ignored since the focus is on finding all the combinations that are feasible to relieve congestions. Of all the possible combinations, the feasible ones are filtered through. For large number of combinations, something like a genetic algorithm can be used to do the filtering and then, through the usage of an optimal power flow solver, the identification. This is done in order to save time, since the assessment of all the possible combinations for large networks would be highly time-inefficient.
- **Rebound Assessment -**The second stage of the optimization process involves registering if the rebound conditions are viable and determining what is the best hour to pay back the viable set of combinations found in the first phase. The DSO only considers technically possible combinations and selects the best combination with the lowest activation cost.

4.3 Power Flow Solver - Pandapower

In order to validate the feasibility of the network and the market results, there was a need for a Power Flow Solver. The settlement was on Pandapower [74], a Python-based program which offers a wide range of functionalities, that permit a proper power system analysis such as power flow calculations, optimization, state estimates, network assessments, topological graph searches, and short circuit design.

It employs a Newton-Raphson method as a solver for nonlinear equations, useful when doing network analysis and optimization for both distribution and transmission networks, providing a versatile platform to explore numerous scenarios related to future grid configurations and technologies. Notably, as well, it supports constant current loads, grids with multiple reference nodes, lines, 2 and 3-winding transformers, and provides a connectivity check for robust network modeling. Furthermore, the software provides visualization capabilities through integration with the matplotlib and plotly libraries, allowing the network to be plotted with or without geographical information.

In the context of this thesis, when the network was created, it needed a grid connection bus, loads and generators with steady active power and lines and transformers with proper parameters.

4.3.1 Network Structure

This function of Pandapower initializes the datastructure which will serve as the base for the construction of the distribution network. Each element can be added on top of the structure, designing a grid as one intends. The function isn't necessary to take inputs however there are some optional inputs one can add, such as the intended frequency, a name or reference power in per-unit.

At its most basic, the function appears as the example 4.16, with its only output being a set of empty tables where the information will be inserted.

$$net = create\_empty\_network() \tag{4.16}$$

4.3.2 External Grid

As the name implies, it creates an external grid connection, which represents the higher level power grid connection. It works as the slack bus in the power flow calculation, since it has the highest power capacity, with fixed voltage magnitude and angle. Its only required inputs are the pandapower network where the bus is inserted and which other bus it is connected to. It can also have other optional inputs like the voltage slack node in per units, the voltage angle at the slack node in degrees, among other. Equation 4.17 is a possible example of a created external grid.

$$create\_ext\_grid(net, 1, voltage = 1.03) \tag{4.17}$$

4.3.3 Bus

Busses are the nodes of the network that all other elements are connected to. Its required inputs are the network in which the element is created and its respective voltage level. It can have other optional inputs such as a name or coordinates if plotting a ultra realistic network. Equation 4.18 shows an example of the function.

$$create\_bus(net, vn\_kv = 15, name = "bus") \tag{4.18}$$

4.3.4 Load

In Pandapower, all loads are modeled in the consumer system. Every positive load is considered a load and negative active power is considered generation. Its required inputs are the net where the load is created and the bus id to which the load is connected, and other optional inputs are name or power. Equation 4.19 shows an example of the function.

$$create\_load(net, bus = 1, voltage = 1.03, p\_mw = 0.3, q\_mvar = 0.1) \tag{4.19}$$

4.3.5 PV generation

To simulate PV generation, it can be done with the static generation function. This element models generators with constant active and reactive power feed-in. The required inputs are the network, the bus to which it is connected and the active power of the generator. Optionally it can have reactive, nominal power as inputs as well. Equation 4.21 shows an example of the function.

$$create\_sgen(net, bus = 1, p\_mw = -6.6)) \tag{4.20}$$

4.3.6 Line

The line element is defined by means of a standard function. It requires the IDs of both buses to where the power line is connected, the power line length and the pre-defined standar line type from Pandapower. Optionally it can also have the temperature defined, thermal resistance, among others. Equation **??** shows an example of the function.

$$create\_line(net, name =' line1', from\_bus = 0, to\_bus = 1, length_k m = 0.1, std_t ype = "NAYY4x50SE") \tag{4.21}$$

4.3.7 Transformer

This element is also defined through the standard type library. It requires as inputs the network, the high and low voltage buses to which it will be connected and the standard transformer type chosen from the library. It can also have specific impedances, among other optional inputs. Equation 4.22 shows an example of the function.

$$create\_transformer(net, hv\_bus = 0, lv\_bus = 1, name = \backslash trafo1", std\_type = \backslash 0.4MVA10/0.4kV") \tag{4.22}$$

The figure 4.4 ahead shows the end result, the proposed distribution network as presented by the tool. It contains the aforementioned elements, one slack bus, transformers, power lines, buses, loads and generation from pv panels.

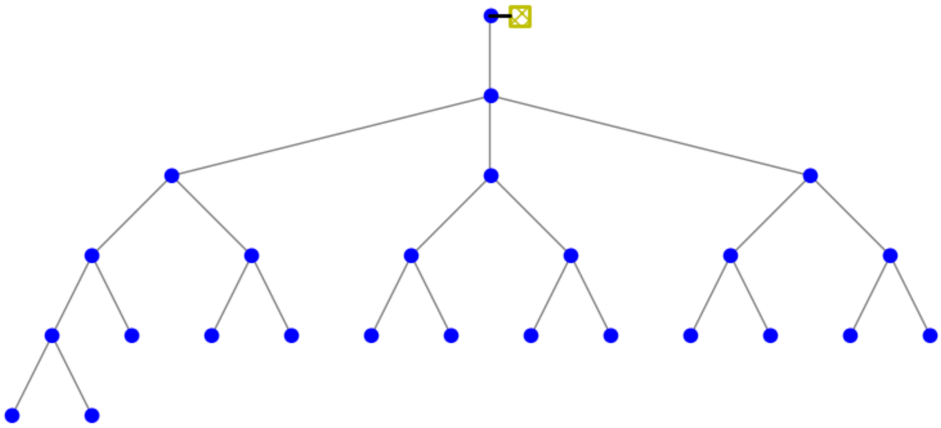


Figure 4.4: Representation of the distribution network on Pandapower

5

Case Study

This chapter focuses on showcasing the market planned until now and how flexibility can become useful in aiding the DSO in alleviating network congestions. To demonstrate the use of load reduction and load increase, two case studies are presented. However, obtaining information on the types of customers an their consumption is difficult, as it requires proper communication systems and data. As a result, assumptions regarding customer types, loads and rebound conditions were taken from [**?**, **?**, 75]

The objective is to show the capability of the aforementioned methodology in dealing with complexities brought on by numerous flexibility bids with various rebound conditions.

In order to prove the utility of this type of market, it is put to the test with a few medium voltage distribution feeders, in a grid similar to a typical portuguese distribution grid, based particulary in the city of Viseu, in the north center of Portugal. The data was collected from E-REDES Open Data Portal [**?**]. Factories and households are assumed to have curtailable disconnectable and shiftable loads and solar panels in their rooftops.

The network was simulated using Pandapower [74], an open source tool for power system modeling.

5.1 Flexibility Available

This subsection outlines the process used to calculate the total flexibility available from the industries and households. Since the calculations only consider the flexibility provided by each type of customer, the subscripts do not include the number of blocks b.

5.1.1 Industrial Customers

The available flexibility in the industry can be calculated using (5.1) and (5.2). The amount of flexibility resulting from load reduction can be determined as the load being utilized at the time t the flexibility is needed, minus the minimum exact load the customer needs for his endeavors. Similarly, flexibility resulting from load increase can be determined as the maximum load the customer has minus the load at the load at time t the service as activated.

$$\mathrm{F}^{red}_{ind,t} = \mathrm{Load}_{ind,t} - \mathrm{Load}^{min}_{ind,t} \tag{5.1}$$

$$\mathrm{F}^{inc}_{ind,t} = \mathrm{Load}^{MAX}_{ind,t} - \mathrm{Load}_{ind,t} \tag{5.2}$$

5.1.2 Residential Customers

The residential sector is a particularly difficult sector to quantify the available flexibility due to a variety of reasons. Firstly, the enormous amount of data needed for each flexible appliance, makes it so that by itself is already quite challenging to obtain and an obstacle to overcome, and secondly, the load profiles of the appliances must extracted from the residental agents' profile, particularly the total capacity in their households. The share of flexibility in household appliances correspond to a range between 13% to 50% [43], and the appliances considered as being present in the residential customers households are freezer/refrigerators, washing machines, tumble driers and dishwashers, ACs, electric water and space heaters and heat circulation pumps [**?**], even though not all households have these. As such, the share percentage of flexibility vary between customers.

This share percentage is defined as $\mathrm{Percent}_{\mathrm{flex}_{res,t}}$ and represents the portion of the flexible appliances load able to be decreased. By multiplying this share by the total load of the flexibile appliance, we can determine the amount of flexibile load that can be shifted.

The amount of load available to be increased is constrained by the installed capacity of each flexible appliance. As such, the flexibility percentage, in this case, is multiplied by the total capacity of the appliance that is not in use, which translates to being the total capacity of the appliance minus the load at the time the service is activated.

As a result, the load reduction and increase flexibility for a single customer of the residential sector can be calculated as (5.3) and (5.4)

$$\mathrm{F}_{ind,t}^{red} = \sum_{res=1}^{Nres} \mathrm{Load}_{res,t} \cdot \mathrm{Percent}_{\mathrm{flex}_{res,t}} \tag{5.3}$$

$$\mathrm{F}_{ind,t}^{inc} = \sum_{res=1}^{Nres} (\mathrm{InstCap}_{res,t} - \mathrm{Load}_{res,t}) \cdot \mathrm{Percent}_{\mathrm{flex}_{res,t}} \tag{5.4}$$

5.2 Feeder Overload Management

Here, a distribution network feeder that is based on feeders in the north center of Portugal [**?**], is operating at 15 kV and consists of 24 buses with an annual demand of 140 GWh. The grid is represented in Fig. 5.1.

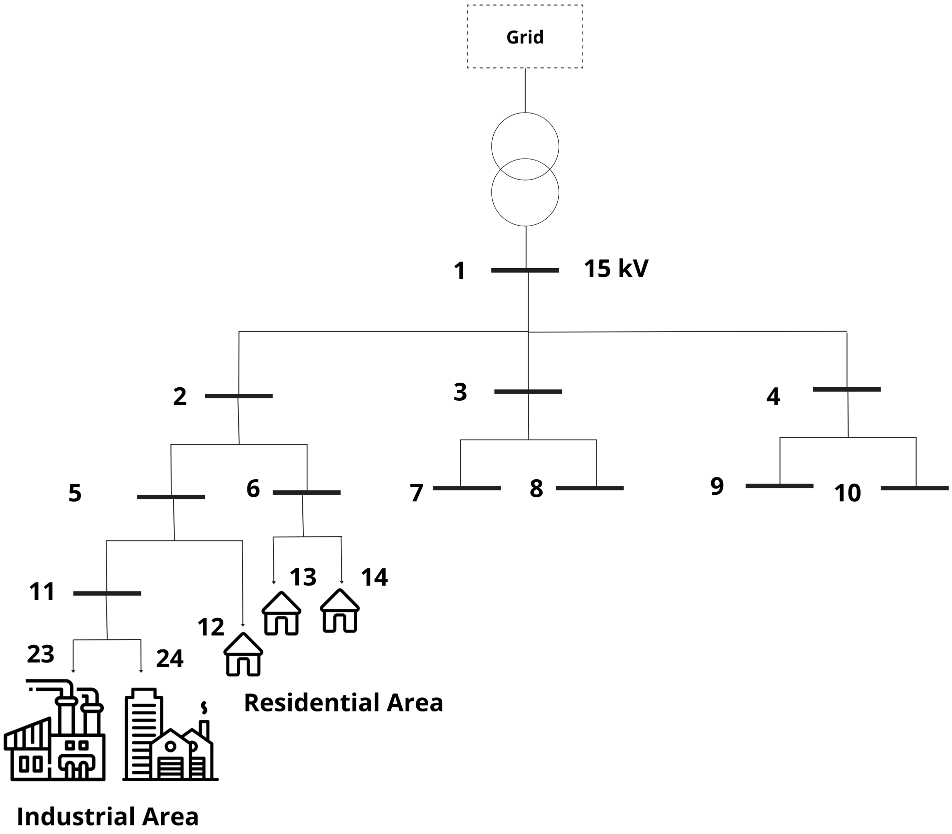


Figure 5.1: Representation of the distribution network for feeder overload management

Fig. 5.2 represents a determined load profile for the day-ahead, when it is exceeding the maximum grid capacity. As such, an overload congestion is expected to occur in line 1-2, between hour 19 and 23. Instead of upgrading the grid, to counter this congestion, the DSO can employ the use of load reduction flexibility to decrease load during the hours as a way of anticipating grid overload, when the load exceeds the existing capacity. The selected hour to exemplify the load reduction potential is hour 20.

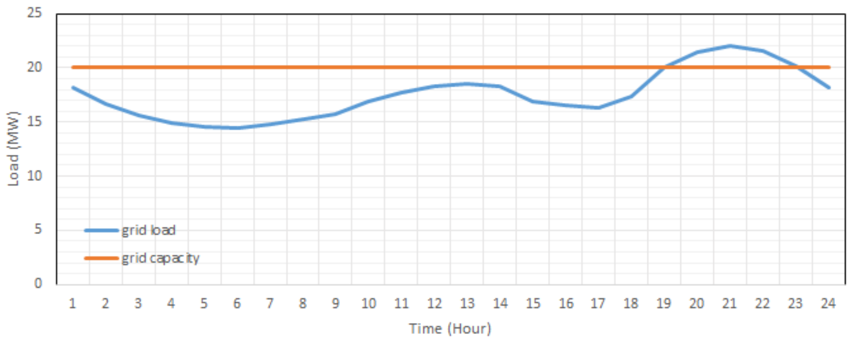


Figure 5.2: Load profile between nodes 1 and 2 and maximum line capacity (MW)

As seen earlier, clients in both residential or industrial area can contribute for the potential for load reduction flexibility. The flexibility bids are as follows.

- **Industrial customers**

The industrial sector is composed by several factories, that are supplied by 2 buses, bus 23 and bus 24. The data regarding these factories are based on the information available in [75] as well as [**?**] and the Open Data made available by E-Redes [**?**]. The rebound conditions are assumed for the single reason that specific data for industrial customers in a distribution network in these conditions is currently unavailable. The amount of load reduction offered by the processes in the industrial park is given by (5.1).

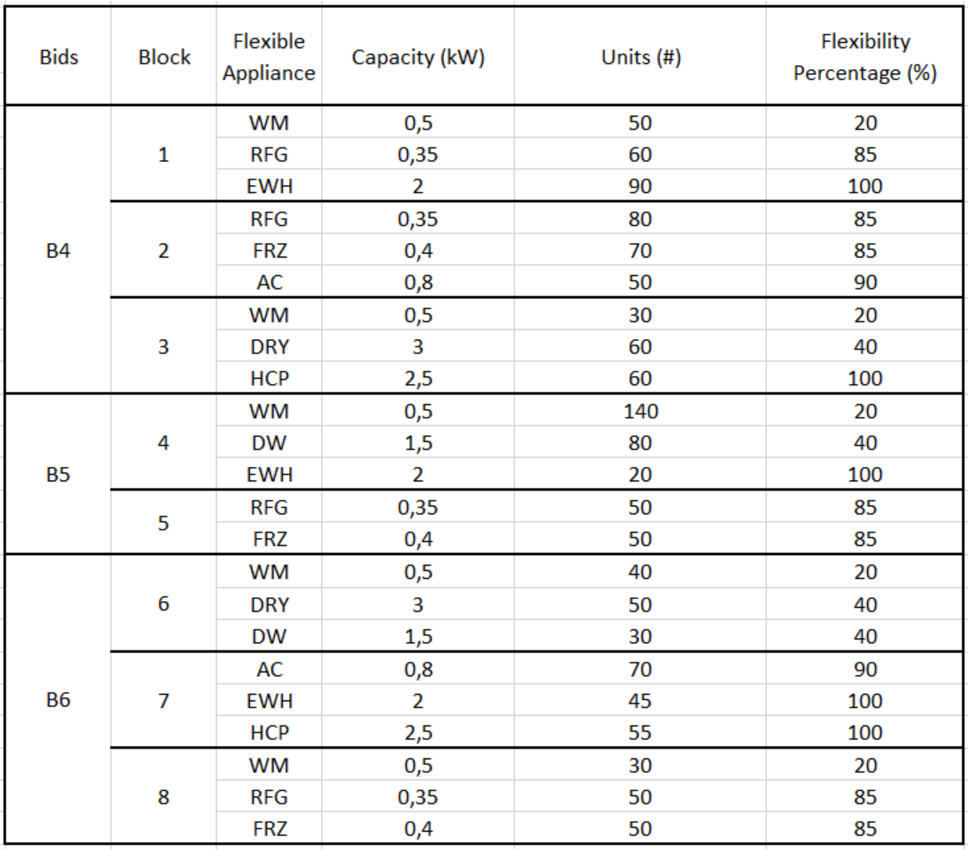
All the data in Table 5.1 represents the installed capacity for the factories and their respective loads for hour 20. It also shows the amount of load able to be reduced, the corresponding price and the conditions for it, with the rebound coefficient and the time intervals for the reposition of the reduced load. The difference in prices result from a measure of sensitivity to changes. The blocks offered at lower prices are blocks with less sensitive operations that permit the reduction without bigger problems.

Bids	Bus	Block	Max Load (MW)	Load at hour 20 (MW)	Min Load (MW)	F^{red} (MW)	ρ (€/MWh)	Rebound conditions	
								Θ	Payback hour
B1	23	Fact 1	0,621	0,427	0,316	0,111	92,39	0,9	12:00-18:00
		Fact 2	0,703	0,490	0,343	0,147	87,02	0,9	13:00-15:00
		Fact 3	1,206	0,852	0,682	0,170	86,95	0,85	18:00-20:00
B2	24	Fact 4	1,268	0,975	0,390	0,585	90,93	0,85	01:00-24:00
		Fact 5	0,66	0,497	0,365	0,132	84,55	0,85	20:00-21:00
Total			**4,458**	**3,24**	**2,095**	**1,145**			

Table 5.1: Flexibility available in the industrial sector at hour 20

- **Residential customers**

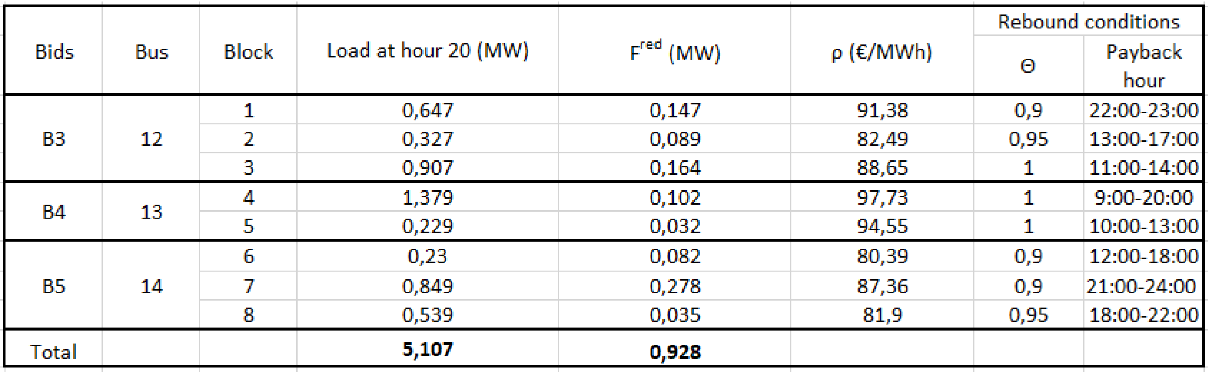
The residential area is connected to bus 12, 13 and 14, with a total of 290 households. It is presumed that the customers have proper control systems installed, so that the aggregators are able to manage the flexible loads. Every bus has a different flexibility bids with many blocks and each block is comprised by aggregated flexible appliances from consumers with similar comfort levels in their households with each bid consisting of multiple load types. Again, the difference in prices result from different ranges of operation sensitivity. Less expensive flexibility result in load that can be switched out without larger isssues. The Table 5.2 illustrates the appliances present in each household, with assumptions based on the data from [75], which states that the more common shiftable and curtailable loads in Portugal are washing machines (WM), refrigerators (RFG), electric water heaters (EWH), air conditioning (AC), dryers (DRY), dishwashers (DW) and heat circulation pumps (HCP). It also contains the installed capacity, the number of units and the percentage available for curtailment or shifting of each appliance by block which in turn compose different bids made by the aggregators.



Bids	Block	Flexible Appliance	Capacity (kW)	Units (#)	Flexibility Percentage (%)
B4	1	WM	0,5	50	20
		RFG	0,35	60	85
		EWH	2	90	100
	2	RFG	0,35	80	85
		FRZ	0,4	70	85
		AC	0,8	50	90
	3	WM	0,5	30	20
		DRY	3	60	40
		HCP	2,5	60	100
B5	4	WM	0,5	140	20
		DW	1,5	80	40
		EWH	2	20	100
	5	RFG	0,35	50	85
		FRZ	0,4	50	85
B6	6	WM	0,5	40	20
		DRY	3	50	40
		DW	1,5	30	40
	7	AC	0,8	70	90
		EWH	2	45	100
		HCP	2,5	55	100
	8	WM	0,5	30	20
		RFG	0,35	50	85
		FRZ	0,4	50	85

Table 5.2: Curtailable or shiftable appliances by bid

The Table 5.3 presents the load reduction flexibility bids in the residential sector. Similar to the industrial area, it shows the load , the percentage available to be reduced and the price at which the flexibility can be bought. This data is, once again, based on the information available in [75] as well as [**?**] and the Open Data made available by E-Redes [**?**]. The rebound conditions are also assumed, in order to be considered by the DSO while making a final decision.



Bids	Bus	Block	Load at hour 20 (MW)	F^{red} (MW)	ρ (€/MWh)	Rebound conditions	
						Θ	Payback hour
B3	12	1	0,647	0,147	91,38	0,9	22:00-23:00
		2	0,327	0,089	82,49	0,95	13:00-17:00
		3	0,907	0,164	88,65	1	11:00-14:00
B4	13	4	1,379	0,102	97,73	1	9:00-20:00
		5	0,229	0,032	94,55	1	10:00-13:00
B5	14	6	0,23	0,082	80,39	0,9	12:00-18:00
		7	0,849	0,278	87,36	0,9	21:00-24:00
		8	0,539	0,035	81,9	0,95	18:00-22:00
Total			**5,107**	**0,928**			

Table 5.3: Flexibility available in the residential sector at hour 20

5.3 Feeder Voltage Management

For this case, in the same network as seen before, we focus on the buses on the south-right side. The feeder is still operating at 15kV. The load buses are 19, 20, 21 and 22 and we are considering a situation where most households or buildings have PV panels for self-consumption, with a total installed capacity of 2.7 MW. Ahead is a representation of the grid in Fig. 5.3.

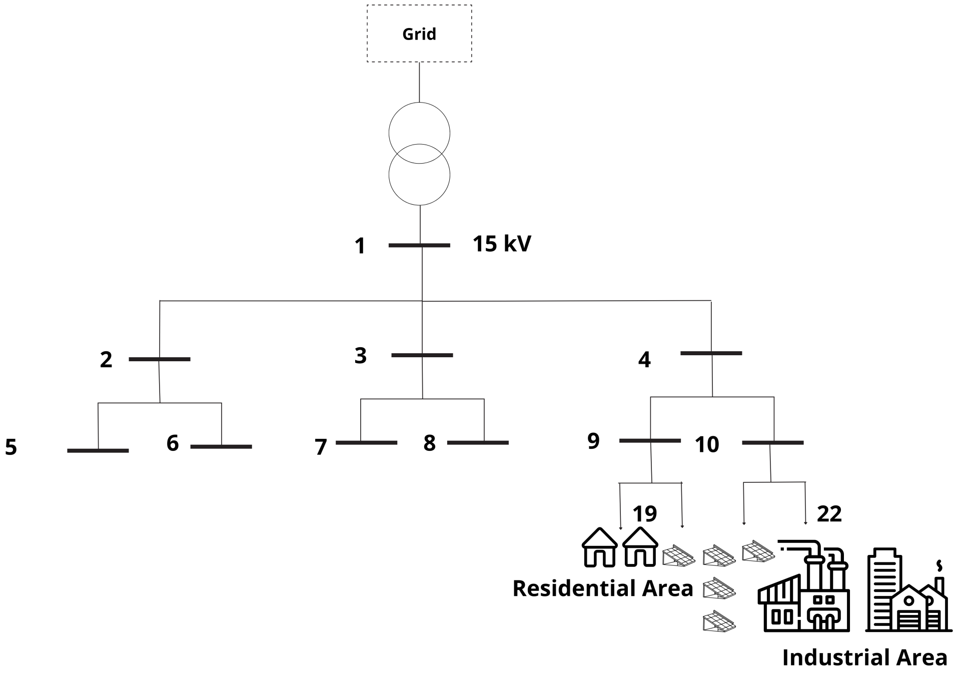


Figure 5.3: Representation of the distribution network

In times where there's less load and higher solar output production, overvoltages are prone to happen in the grid. To solve this issue the DSO may try to control the voltage levels by installing extra equipments that are rather expensive in order to prevent PV curtailment or as a last option, it may even resort to PV curtailment. This isn't the ideal resolution and its one of the things that are avoided in Portugal, since there is a priority for renewable generation for the injection of output power.

The alternative suggested here is simply to increase the load in order to match renewable production, at times where overvoltages may happen. In other words, increase flexibility may be resorted to in order to keep voltage levels in a permisible limit.

Bus 19 is connected to a residential area and bus 22 is connected to an industrial park. The load profile is shown in 5.4 as well as the PV output during a typical day of February. The voltage limits for the system are 1 ± 0.05 p.u. As such, an overvoltage is expected to occur between hour 11 and 14. The selected hour used to exemplify the potential in load reduction is hour 12.

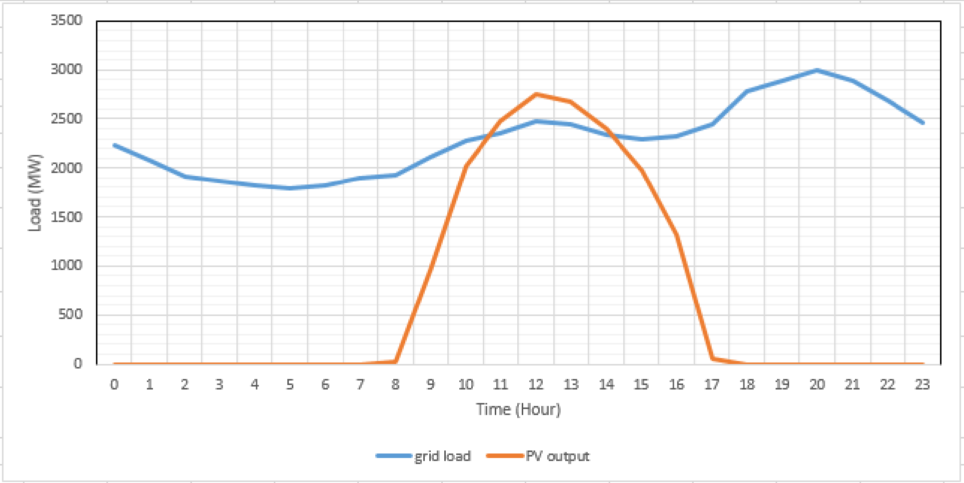
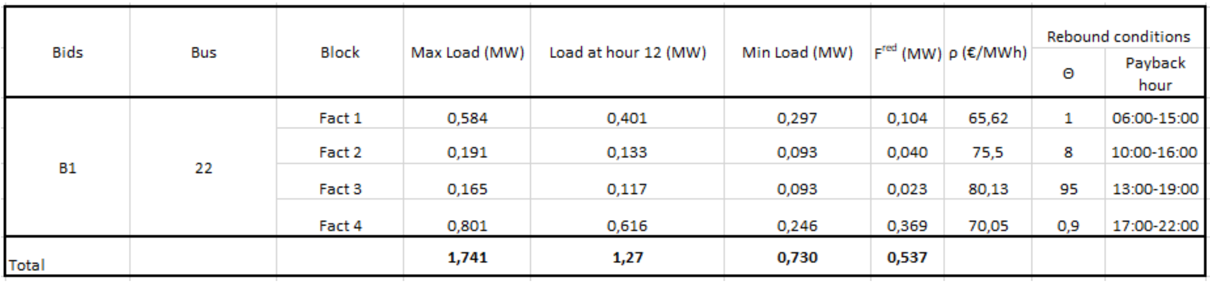


Figure 5.4: Forecasted load profile and PV solar production (MW)

The flexibility bids are as follows.

- **Industrial customers**

The industrial sector is composed by several factories, that are supplied by 1 bus, bus 22. Again, the data regarding these factories is based on the information available in [75], [**?**] and [**?**], and the rebound conditions are assumed since the specific data for industrial customers in a distribution network in these conditions is unavailable. All the data is represented in Table 5.4.

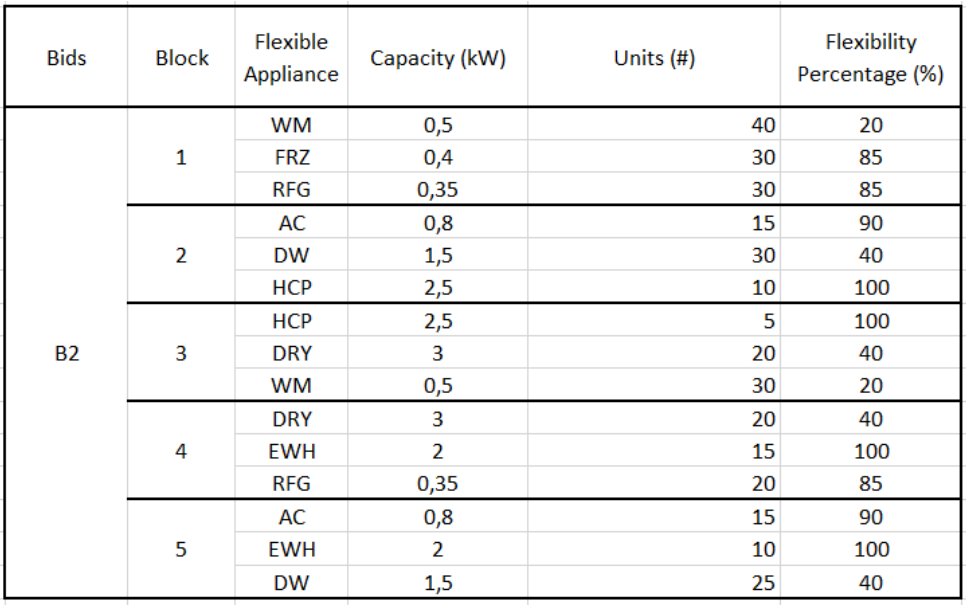


Bids	Bus	Block	Max Load (MW)	Load at hour 12 (MW)	Min Load (MW)	F^{red} (MW)	ρ (€/MWh)	Rebound conditions	
								Θ	Payback hour
B1	22	Fact 1	0,584	0,401	0,297	0,104	65,62	1	06:00-15:00
		Fact 2	0,191	0,133	0,093	0,040	75,5	8	10:00-16:00
		Fact 3	0,165	0,117	0,093	0,023	80,13	95	13:00-19:00
		Fact 4	0,801	0,616	0,246	0,369	70,05	0,9	17:00-22:00
Total			**1,741**	**1,27**	**0,730**	**0,537**			

Table 5.4: Flexibility available in the industrial sector at hour 12

- **Residential customers**

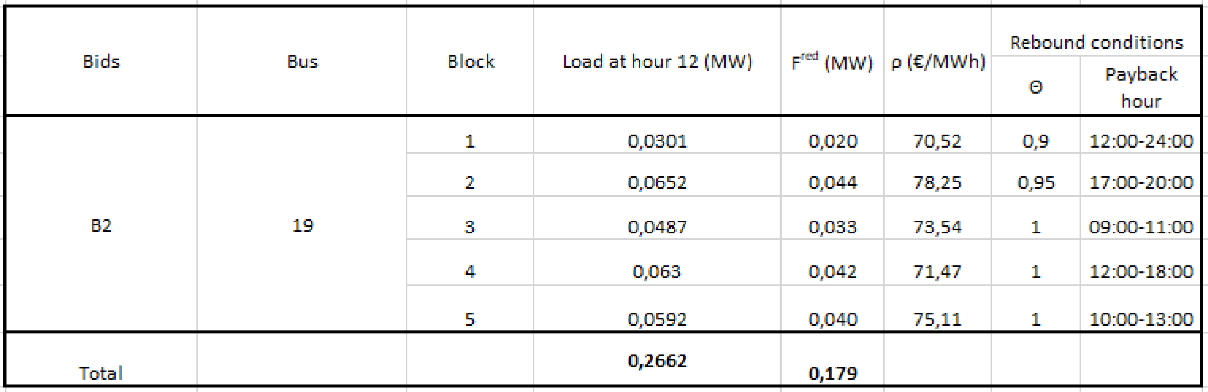
The residential area is connected to bus 19, totalling 72 households. Each of these buses has aggregated flexibility bids with different number of blocks and each block is comprised by a number of aggregated flexible appliances from consumers with similar comfort levels in their households with each bid consisting of multiple load types. The Table 5.2 contains the type of appliance, the installed capacity, the number of units and the percentage of the appliances composing each block which in turn compose different bids.



Bids	Block	Flexible Appliance	Capacity (kW)	Units (#)	Flexibility Percentage (%)
B2	1	WM	0,5	40	20
		FRZ	0,4	30	85
		RFG	0,35	30	85
	2	AC	0,8	15	90
		DW	1,5	30	40
		HCP	2,5	10	100
	3	HCP	2,5	5	100
		DRY	3	20	40
		WM	0,5	30	20
	4	DRY	3	20	40
		EWH	2	15	100
		RFG	0,35	20	85
	5	AC	0,8	15	90
		EWH	2	10	100
		DW	1,5	25	40

Table 5.5: Curtailable or shiftable appliances by bid

The Table 5.6 presents the load reduction flexibility bids in the residential sector. Similar to the industrial area, it shows the load , the flexibility percentage available and the price at which the flexibility can be bought. The rebound conditions are also assumed but in a way that assumes the diversity from different appliances and to show the impact it may have on the DSO's final decision.



Bids	Bus	Block	Load at hour 12 (MW)	F^{red} (MW)	ρ (€/MWh)	Rebound conditions	
						Θ	Payback hour
B2	19	1	0,0301	0,020	70,52	0,9	12:00-24:00
		2	0,0652	0,044	78,25	0,95	17:00-20:00
		3	0,0487	0,033	73,54	1	09:00-11:00
		4	0,063	0,042	71,47	1	12:00-18:00
		5	0,0592	0,040	75,11	1	10:00-13:00
Total			**0,2662**	**0,179**			

Table 5.6: Flexibility available in the residential sector at hour 12

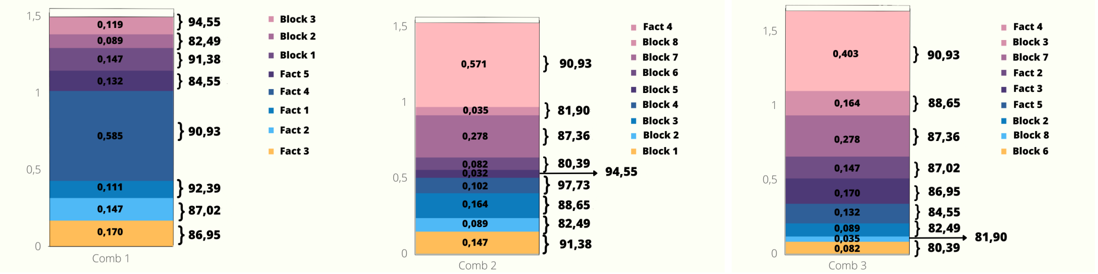
5.4 Market Clearing

With all the flexibility bids set, all there is to do is check the results, following the method previously mentioned. It starts with the feasibility assessment, checking which bid combinations are feasible, that is, are enough to satisfy the flexibility needs, and procceeds to the rebound assessment, to verify if the rebound conditions attached to the flexibility bid are possible to fulfill without causing further congestions.

5.4.1 Feeder Overload Management

For the first type, the amount of flexibility needed is 1.503 MW and we need this load reduced for hour 20. As such, we start by filtering all the combinations available, for the ones that fit the need for reducing the load more or equal than 1.503 MW.

Ahead are shown examples of these bids. Bid 1 is a bid comprised by the total of industrial flexibility summed by some of residential flexibility, bid 2 is the opposite, almost totally comprised by residential flexibility but it ends up being topped by the flexibility available in one factory and Bid 3 is the available flexibility that makes up the 1.503 MW reduction needed but ordered from the cheapest to the most expensive bids.



(a) Bid 1 **(b)** Bid 2 **(c)** Bid 3

Figure 5.5: Three possible combinations of bids resulting from the first stage of optimization at hour 20

The following figure, figure 5.6, shows the ideal set of bids for which the rebound criteria were feasible, as in determined to be possible, sorted from the least expensive to the most expensive. This combination activates every industrial bid, except for one, from factory 5, resulting in a load reduction of 1,013 MW and most of the residential bids, excluding the flexibility from blocks 1 and 7, equating to a total of 0.487 MW.

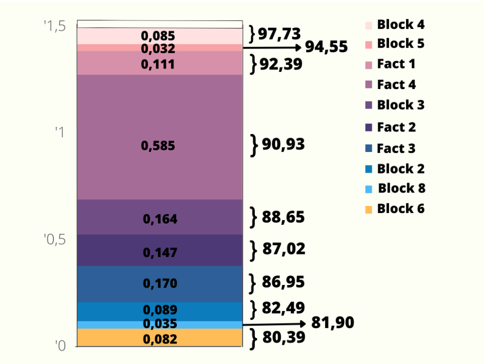
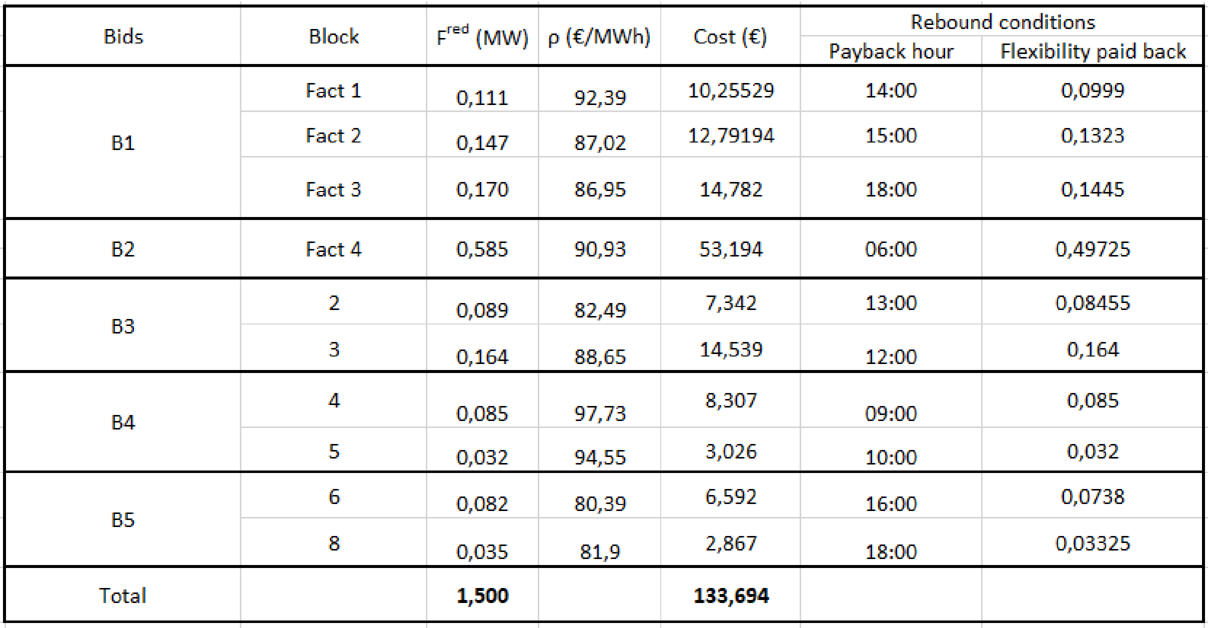


Figure 5.6: Activated blocks from industrial and residential bids at hour 20

Table 5.7 summarizes the previous figure and organizes the market results for hour 20 in a clear manner. It displays the amount of load reduction flexibility traded from each activated bid together with its associated cost to the DSO and the best payback hour.



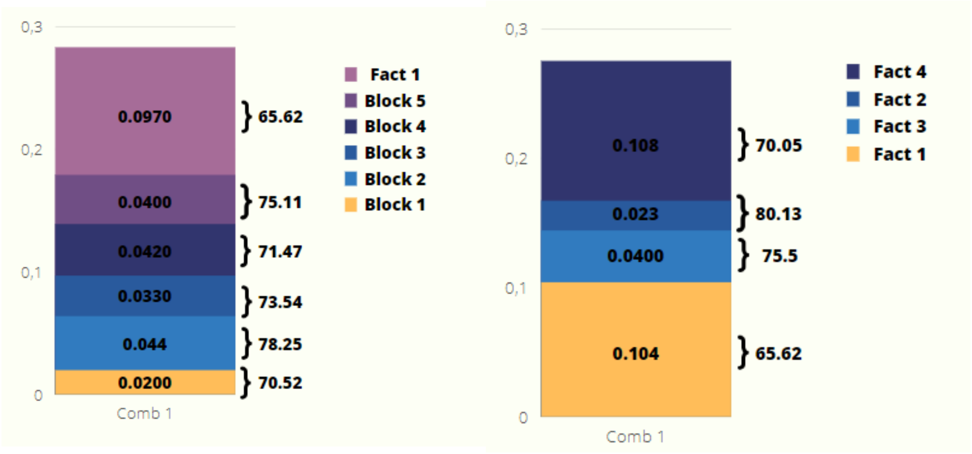
Bids	Block	F^{red} (MW)	ρ (€/MWh)	Cost (€)	Rebound conditions	
					Payback hour	Flexibility paid back
B1	Fact 1	0,111	92,39	10,25529	14:00	0,0999
	Fact 2	0,147	87,02	12,79194	15:00	0,1323
	Fact 3	0,170	86,95	14,782	18:00	0,1445
B2	Fact 4	0,585	90,93	53,194	06:00	0,49725
B3	2	0,089	82,49	7,342	13:00	0,08455
	3	0,164	88,65	14,539	12:00	0,164
B4	4	0,085	97,73	8,307	09:00	0,085
	5	0,032	94,55	3,026	10:00	0,032
B5	6	0,082	80,39	6,592	16:00	0,0738
	8	0,035	81,9	2,867	18:00	0,03325
Total		**1,500**		**133,694**		

Figure 5.7: Market results for hour 20

5.4.2 Feeder Voltage Management

In the second case, the flexibility needed is a load increase of 0.276 MW during the 12th hour. As such, by the aforementioned methodology, the bids are ran through a feasibility filter for the ones that fit the needs. The output then returns the 0.276 MW of load increase necessary spread through the prosumers.

Ahead are shown 2 examples of possible combinations. Bid 1 5.8a provided mostly by residential flexibility where every bid from that sector was activated. It needed to be supplemented with extra flexibility from a factory, since the total flexibility from the residential sector wasn't enough to fulfill the flexibility increase needs. The second bid shown, Bid 2 5.8b was made exclusively through flexibility offered from the industrial sector with no supplementation from the residential sector.



(a) Bid 1

(b) Bid 2

Figure 5.8: Three possible combinations of bids resulting from the first stage of optimization at hour 20

The following figure, figure 5.9, similarly to the one seen earlier, shows the ideal set of bids for which the rebound criteria were feasible, as in determined to be possible, sorted from the least expensive to the most expensive. This combination activates two industrial bids, from factory 1 and factory 4, even though the latter wasn't activated in its totality, resulting in a load reduction of 0.276 MW, with no need from more flexibility activation. Table 5.10 summarizes the market results for hour 12. It displays the amount of load increase flexibility traded from each activated bid together with its associated cost to the DSO and the best payback hour.

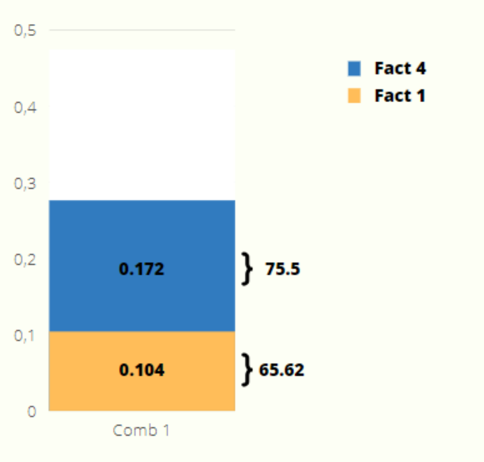
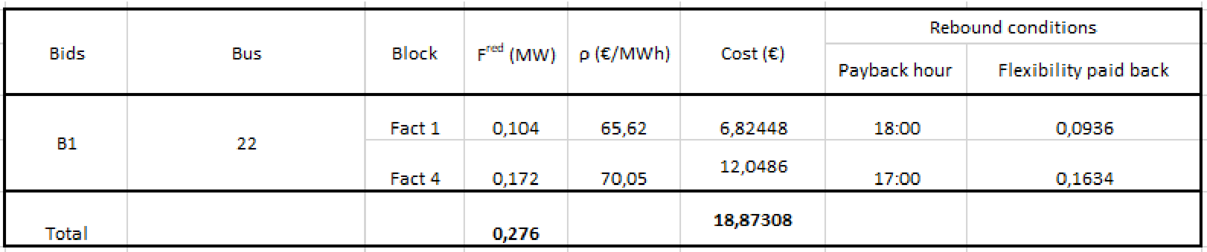


Figure 5.9: Activated blocks from industrial and residential bids at hour 20



Bids	Bus	Block	F^{red} (MW)	ρ (€/MWh)	Cost (€)	Rebound conditions	
						Payback hour	Flexibility paid back
B1	22	Fact 1	0,104	65,62	6,82448	18:00	0,0936
		Fact 4	0,172	70,05	12,0486	17:00	0,1634
Total			**0,276**		**18,87308**		

Figure 5.10: Market results for hour 20

6

Conclusion

As prosumers grow the necessity for independence in energy-usage as well as the difficulty electricity markets have been having in order to integrate their Distributed Energy Resources, new ideas are manifesting in how to rethink the structure of the electricity markets and take these same prosumers' preferences into account. By implementing a type of market similar to the one suggested in the previous chapters could be a solution towards a path of integration of DER.

The implementation of a bidding marketplace at the distribution level is evaluated in this work, and it is suggested that specific procedures be added to the market to ensure the viability of grid operations and validate the outcomes of the market clearing. It is crucial to note that these markets can only be integrated with the existing power markets if they prove feasible within the framework.

6.1 Main conclusions

All in all, it can be observed that the work of this thesis delves first into a theoretical analysis of the concept of flexibility and its implications in a broader context, ranging from its definition, to its role in power systems and ending locally in how its applied in the portuguese case, and then a practical analysis where the construction of a simple yet effective example of a flexibility market as a possible future was developed, complete with its players, intervenients and inner mechanisms.

The theoretical analysis starts by defining flexibility, which is succintly, the ability of a power system to respond to and manage the variability of demand and supply in a determined timescale, then, emphasizing the distinctions within the four categories of flexibility, namely, power, energy, transfer capacity and voltage flexibility. It also classifies as being provided from the demand and supply sides, with a bigger focus on the former since its the most appropriate in the context, pointing out Distributed Energy Resources (DERs) as a strong example of this. In addition, makes a point in clarifying what are demand flexibility providers and consumers, why isn't this kind of flexibility more widespread and the main barriers to its implementation, namely regulations, economy setbacks, technical shortcomings and organizational faults.

The Flexibility Markets are then explored, first in their concept, then in the many types of known flexibility markets ranging from models in which the TSO has the most control on the flexibility, with the DSO being a mere spectator or supportive entity, to models where this control is ceased in the benefit of the DSO, which becomes much more independent as a result. The exploration then continues further, closer to the latter models, with Local Flexibility Markets put on the forefront, as a method of solving congestions mainly with load and voltage control. Its key players are identified, namely Prosumers and Aggregators, as relatively new power system's adjacent ideas, the Distribution System Operator (DSO), the Balance Responsible Parties (BRPs) and the Local Flexibility Market Operator (LFMO). LFMs can be subdivided into many models, depending on how they are distributed and optimized. Some examples of local flexibility market platforms that are either as pilots or full-fledged ideas, are then explored throughout Europe, NODES, Enera, Piclo Flex, IREMEL and GOPACS explaining their inner workings, their pros and cons, and ending with a reflection on the portuguese power system, how flexibility is handled there, and a small note on the pilot project being developed by the portuguese DSO in a partnership with the aforementioned Piclo Flex.

The thesis then suggests a market for flexibility transactions that enables trading between DSOs and aggregators, who are placing bids on behalf of their clients, in a flexibility transaction platform. It defines demand flexibility, focusing on both load reduction and load increase, which correspond to lowering and increasing load volumes, respectively. When attempting to alleviate network restrictions at the distribution level, the DSO may find it to be useful a tool. Furthermore defined and explained is the rebound effect, which is connected to that form of flexibility.

Along with being recognized, the key participants in the flexibility transactions are also described, along with their respective roles and duties. The market for flexibility suggested trades in the day-ahead timeframe after the primary wholesale market is cleared, in order to assure efficient trading for flexibility.

Two case studies are then proposed in order to demonstrate the methodology. Stemming from a similar situation, a distribution feeder network with characteristics based on those of the north-centre portuguese city of Viseu, the first case study focuses on managing the feeder's overloads when the predicted consumption pattern exceeds line capacity. Flexibility in the form of load reduction is offered by customers, through aggregators to the DSO in order to avoid these kinds of congestions. The second case study focuses on managing overvoltages. High solar PV penetration causes overvoltages and instead of curtailing these PV panels, customers offer flexibility in the form of load increase in order to maintain adequate voltage levels.

The optimization approach is effective in solving these kinds of issues without overcomplications, managing to stick to a simple and understandable method where every party is benefitted without many inconveniences or costs for either side, which the market results prove.

The proposed market offers a practical plan for what flexibility markets might look like in the future. Moreover, it does not involve the DSO in energy trading and emphasizes the critical role of the aggregator in exploiting the potential of demand flexibility. The aggregator is given the job of balancing the discrepancies between the market solutions before and after flexibility activations, whereas the DSO is just given the task of market clearing. Additionally, the operation scheme emphasizes the notion that demand flexibility trading should be viewed as the trade of a service rather than energy.

6.2 Future work

Since this dissertation has a basis on a market that is simple, straight-forward but effective, there's many points where to improve:

- A real-time approach to the market. The market presented only looks at the day-ahead so it could be interesting to study the interactions between the DSO and the aggregators (and in turn the prosumers/consumers), via the market operator, in case a congestion happens;
- Utilization of a case study of a real life location in Portugal. Even though the presented case studies were based using information available from the real life location of Viseu, since the information is limited, its not a mirror-image.
- A non-deterministic approach to the methodology where, instead of setting in stone the amount of the load and the certainty of flexibility delivery, there is an uncertainty of the amount of load needed, with forecasting errors and if the prosumers will deliver or not.
- Equating costs and benefits to the DSO of adhering to a market where flexibility is traded locally to solve congestions, instead of investing in grid expansion.
- Mechanisms for coordination between the TSO and DSO and how acquiring flexibility and solving congestions locally at the distribution, impact the transmission level.

These recommendations would facilitate a more comprehensive examination of the application of this type of markets in the portuguese context, and how to make them competitive and an actual solution to the ever-growing renewable energy paradigm shift.

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