Local Flexibility Market for Congestion Management at the Distribution-Level

Tiago Daniel Alexandre Silva Felizardo
tiago.d.felizardo@tecnico.ulisboa.pt

Instituto Superior Técnico, Lisboa, Portugal

June 2023

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

1. Introduction

One of the concepts that's been popularized in power and energy industry is Flexibility. Flexibility, according to [13], 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 [7] 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.[5]

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. [7]

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 [12], a LFM can be defined as an electricity flexibility trading platform to trade flexibility in geographically limited areas such as neighbor-hoods, 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. Include relevant references [**?**].

2. Methodology

Here we delve into 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 earlier.

2.1. 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.

2.2. 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. 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 [3, 14, 11]

2.3. 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.

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 [14, 16] Fig. 1 illustrates this phenomenon.

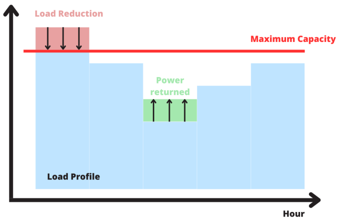


Figure 1: Load reduction flexibility

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**. [2, 4] which is represented in Fig. (2).

2.4. 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.

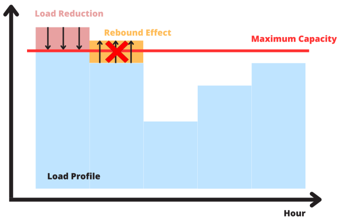


Figure 2: Rebound Effect

The rebound power conditions, are described as follows, in (1), based and adapted from [8], where R is the total rebound power, to be returned in a situation of load reduction, and in (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 (3). F^{red} and F^{inc} represent the total load reduction and load increase in a determined scenario where flexibility was activated.

$$R = \Theta_R \cdot \mathrm{F}^{red} \tag{1}$$

$$I = \Theta_I \cdot \mathrm{F}^{inc} \tag{2}$$

$$0 \leq \Theta_R, \Theta_I \leq 1 \tag{3}$$

2.5. 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 [14, 8]. (4), determines the total sum amount of activated flexibility, $F^{TOT}_{n,t}$, at each block b in the bid $\mathrm{F}_{n,b,t}$, at a specific node n and period t, restricted by (5), that set a limit maximum, $F^{MAX}_{n,b,t}$, and minimum value, $F^{MIN}_{n,b,t}$. (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, $C^F_{n,t}$.

$$\mathrm{F}^{TOT}_{n,t} = \sum_{b=1}^{N} \mathrm{F}_{n,b,t} \ , \qquad \forall n \tag{4}$$

$$\mathrm{F}^{MIN}_{n,b,t} \leq \mathrm{F}_{n,b,t} \leq \mathrm{F}^{MAX}_{n,b,t} \ , \qquad \forall n \tag{5}$$

$$\mathrm{C}^{F}_{n,t} = \mathrm{F}_{n,b,t}\mathrm{P}_{n,b,t} \ , \qquad \forall n \tag{6}$$

2.6. Market Operation

The structure for this market was based on the ones presented by [16, 14, 8]. 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 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. 3 illustrates the whole process.

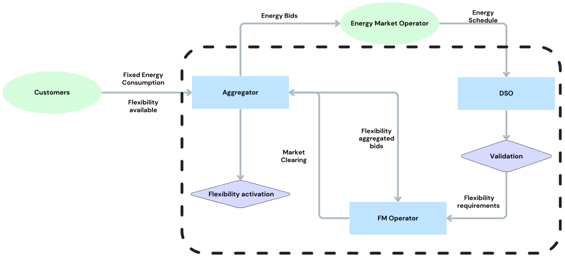


Figure 3: Structure of the Flexibility Market (only blocks inside the square are addressed in the case studies)

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 [15]. 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.

$$Pn = \sum_{m=1}^{N} |\mathrm{V}_n||\mathrm{V}_m||\mathrm{Y}_{n,m}|cos(\theta_{n,m}\delta_n{+}\delta_m){\cdot}\mathrm{S}_{base}, \tag{7}$$

$$Qn = \sum_{m=1}^{N} |\mathrm{V}_n||\mathrm{V}_m||\mathrm{Y}_{n,m}|sin(\theta_{n,m}\delta_n{+}{-}\delta_m){\cdot}\mathrm{S}_{base}, \tag{8}$$

$$Snm = Pnm + jQnm, \qquad \forall n, m, t \tag{9}$$

$$Snm \leq \mathrm{Snm}_{MAX}, \qquad \forall n, m \tag{10}$$

$$\mathrm{Vn}_{MIN} \leq Vn \leq \mathrm{Vn}_{MAX}, \qquad \forall n \tag{11}$$

In equation (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 (8), also for a certain node n, in a network composed by N nodes, with the same components as the previous equation.

Equation (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 (10) and (11), respectively.

2.7. Optimization Problem

The purpose of the market, when clearing, is minimizing the cost in acquiring flexibility for the distribution operator, $Min\ \mathrm{C}^F_{n,t}$[9, 14, 8]. As such, we can represent the objective function as (12), at block b, node n and time t with price $\mathrm{P}_{n,b,t}$ for each activated flexibility $\mathrm{F}_{n,b,t}$.

$$Min\ \mathrm{C}^F_{n,t} = \sum_{t=1}^{24}\sum_{n=1}^{Nn}\left[\sum_{Nb}^{b=1}\mathrm{F}_{n,b,t}\mathrm{P}_{n,b,t}\right] \tag{12}$$

$$\mathrm{F}_{n,b,t\ MIN} \leq \mathrm{F}_{n,b,t} \leq \mathrm{F}_{n,b,t\ MAX}, \qquad \forall n, t \tag{13}$$

$$\mathrm{R}_{n,t} = \sum_{b\in K}\sum_{b=1}^{N}\Theta_{Rn,b}\mathrm{F}^{red}_{n,b}, \qquad \forall n, t \tag{14}$$

$$\mathrm{I}_{n,t} = \sum_{b\in K}\sum_{b=1}^{N}\Theta_{In,b}\mathrm{F}^{inc}_{n,b}, \qquad \forall n, t \tag{15}$$

Since the DSO is acting as the operator of the flexibility market, it must clear the market in accordance with the constraints set in (7)-(11). Equations (13) and (14) and (15) set the maximum and minimum limits to existent flexibility and calculate $\forall n$ the rebound power, similarly to eqs. (1) and (2), as functions of either load reduction or load increase volumes with the respective coefficient $\Theta_{Rn,b}$ and $\Theta_I n, b \forall n$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 [8] 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.

3. 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.

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 network was simulated using Pandapower [17], an open source tool for power system modeling.

3.1. 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.

- Industrial Customers

  The available flexibility in the industry can be calculated using (16) and (17). 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.

$$\mathrm{F}^{red}_{ind,t} = \mathrm{Load}_{ind,t} - \mathrm{Load}^{min}_{ind,t} \tag{16}$$

$$\mathrm{F}^{inc}_{ind,t} = \mathrm{Load}^{MAX}_{ind,t} - \mathrm{Load}_{ind,t} \tag{17}$$

- 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 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 (18) and (19)

$$\mathrm{F}^{red}_{ind,t} = \sum_{res=1}^{Nres} \mathrm{Load}_{res,t} \cdot \mathrm{Percent}_{\mathrm{flex}_{res,t}} \tag{18}$$

$$\mathrm{F}^{inc}_{ind,t} = \sum_{res=1}^{Nres} (\mathrm{InstCap}_{res,t} - \mathrm{Load}_{res,t}) \cdot \mathrm{Percent}_{\mathrm{flex}_{res,t}} \tag{19}$$

3.2. Feeder Overload Management

Here, a distribution network feeder that is based on feeders in the north center of Portugal [6], is operating at 15 kV and consists of 24 buses with an annual demand of 140 GWh. The grid is represented in Fig. 4.

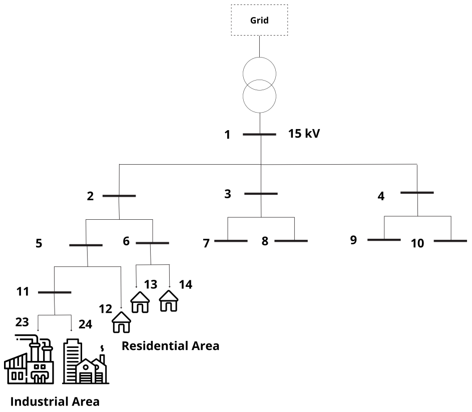


Figure 4: Representation of the distribution network for feeder overload management

Fig. 5 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.

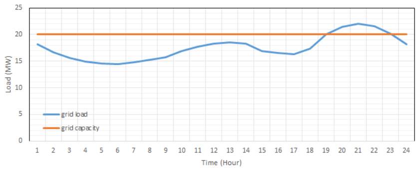


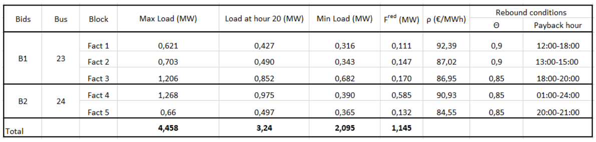
Figure 5: Load profile between nodes 1 and 2 and maximum line capacity (MW)

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 [10] as well as [1] and the Open Data made available by E-Redes [6]. 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 (16).

All the data in Table 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.

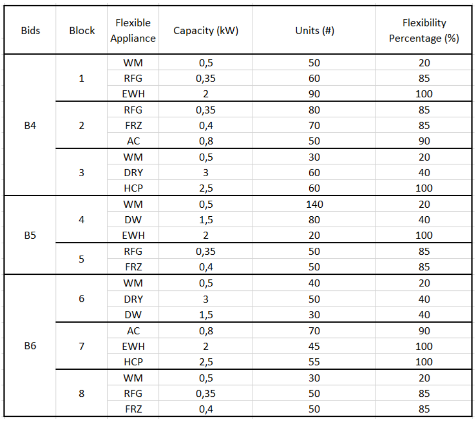


Bids	Bus	Block	Max Load (MW)	Load at hour 20 (MW)	Min Load (MW)	F^{red} (MW)	ρ (€/MWh)	Rebound conditions	
								Θ	Payback hour
B1	23	Fact 1	0,621	0,427	0,316	0,111	92,39	0,9	12:00-18:00
		Fact 2	0,703	0,490	0,343	0,147	87,02	0,9	13:00-15:00
		Fact 3	1,206	0,852	0,682	0,170	86,95	0,85	18:00-20:00
B2	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 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. The Table 2 illustrates the appliances present in each household, with assumptions based on the data from [10], 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 2: Curtailable or shiftable appliances by bid

The Table 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 [10] as well as [1] and the Open Data made available by E-Redes [6]. 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 3: Flexibility available in the residential sector at hour 20

3.3. 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. 6.

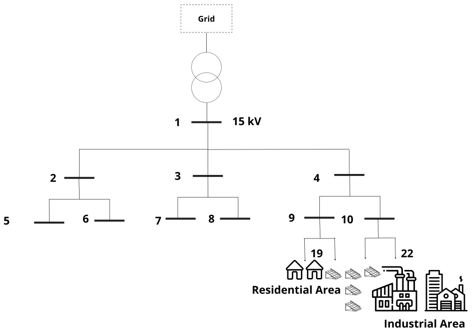


Figure 6: Representation of the distribution network

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. T

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 7 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.

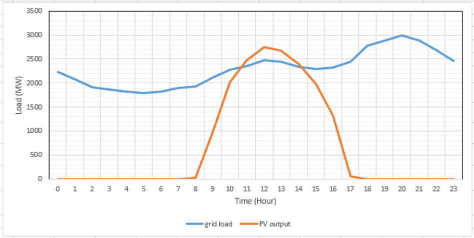


Figure 7: Forecasted load profile and PV solar production (MW)

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 [10], [1] and [6], 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 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 4: Flexibility available in the industrial sector at hour 12

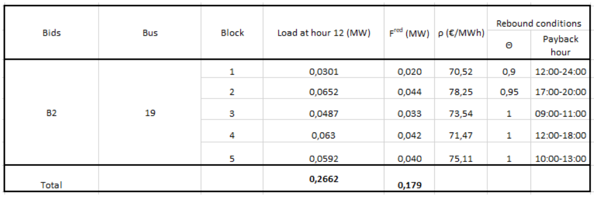
- **Residential customers**

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 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: Curtailable or shiftable appliances by bid

The Table **??** 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 6: Flexibility available in the residential sector at hour 12

3.4. 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.

3.5. 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.

.5

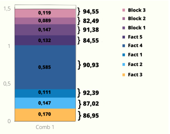


Figure 8: Bid 1

.5

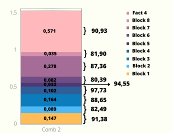


Figure 9: Bid 2

.5

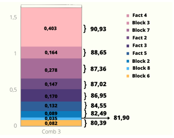


Figure 10: Bid 3

Figure 11: Three possible combinations of bids resulting from the first stage of optimization at hour 20

The following figure, figure 12, 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.

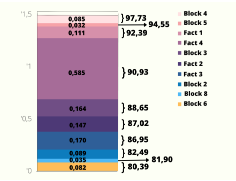
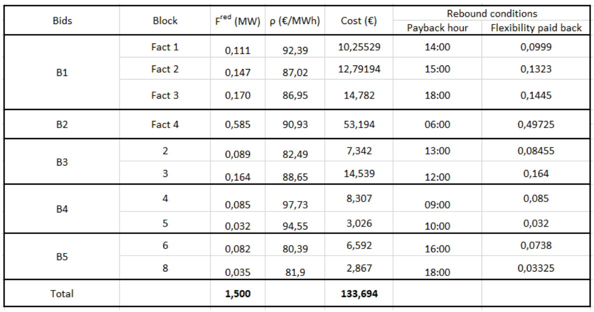


Figure 12: Activated blocks from industrial and residential bids at hour 20

Table 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**		

Table 7: Market results for hour 20

3.6. 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.

.5

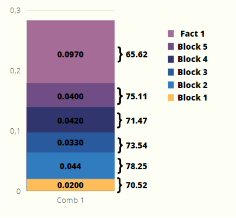


Figure 13: Bid 1

.5

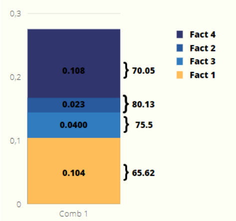


Figure 14: Bid 2

Figure 15: Three possible combinations of bids resulting from the first stage of optimization at hour 20

The following figure, figure 16, 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 8 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.

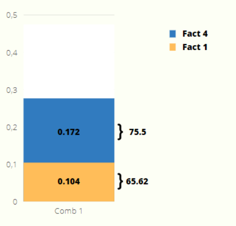
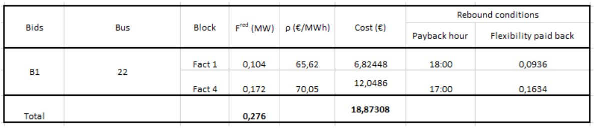


Figure 16: Activated blocks from industrial and residential bids at hour 20



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**		

Table 8: Market results for hour 20

4. Conclusions and future work

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 work 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.

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.

Since this work 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;
- 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.

References

[1] J. Anjo. Assessing the impact of demand response in the portuguese electric system. *IST - Instituto Superior Técnico*, 2017.

[2] C. Bergaentzlé, C. Clastres, and H. Khalfallah. Demand-side management and european environmental and energy goals: An optimal complementary approach. *Energy Policy*, 67:858–869, 2014.

[3] I. Bouloumpasis, N. M. Alavijeh, D. Steen, and A. T. Le. Local flexibility market framework for grid support services to distribution networks. *Electrical Engineering*, 104:401–419, 4 2022.

[4] J. M. Cansino, M. Ordóñez, and M. Prieto. Decomposition and measurement of the rebound effect: The case of energy efficiency improvements in spain. *Applied Energy*, 306, 1 2022.

[5] H. de Heer and W. van de Reek. Flexibility platforms, universal smart energy framework. *Universal Smart Energy Framework*, pages 1–29, 2018.

[6] E-REDES. Portal open data da E-REDES, 2023. (access date: January 2023).

[7] E. Ela, M. Milligan, A. Bloom, A. Botterud, A. Townsend, and T. Levin. Incentivizing flexibility in system operations. *Electricity Markets with Increasing Levels of Renewable Generation: Structure, Operation, Agent-based Simulation, and Emerging Designs*, 144:95–127, 2018.

[8] A. Esmat, P. Pinson, and J. Usaola. Decision support program for congestion management using demand side flexibility. *2017 IEEE Manchester PowerTech, Powertech 2017*, 7 2017.

[9] M. A. F. Ghazvini, G. Lipari, M. Pau, F. Ponci, A. Monti, J. Soares, R. Castro, and Z. Vale. Congestion management in active distribution networks through demand response implementation. *Sustainable Energy, Grids and Networks*, 17, 3 2019.

[10] H. C. Gils. Assessment of the theoretical demand response potential in europe. *Energy*, 67:1–18, 4 2014.

[11] C. Heinrich, C. Ziras, A. L. Syrri, and H. W. Bindner. Ecogrid 2.0: A large-scale field trial of a local flexibility market. *Applied Energy*, 261, 3 2020.

[12] X. Jin, Q. Wu, and H. Jia. Local flexibility markets: Literature review on concepts, models and clearing methods. *Applied Energy*, 261, 3 2020.

[13] J. Ma, V. Silva, R. Belhomme, D. S. Kirschen, and L. F. Ochoa. Evaluating and planning flexibility in sustainable power systems. *IEEE Transactions on Sustainable Energy*, 4:200–209, 2013.

[14] A. Masood, J. Hu, A. Xin, A. R. Sayed, and G. Yang. Transactive energy for aggregated electric vehicles to reduce system peak load considering network constraints. *IEEE Access*, 8:31519–31529, 2020.

[15] J. P. S. Paiva. *Redes de Energia Elétrica: Uma análise sistémica*. IST Press, 4 edition, 2015.

[16] F. Shen, Q. Wu, X. Jin, B. Zhou, C. Li, and Y. Xu. Admm-based market clearing and optimal flexibility bidding of distribution-level flexibility market for day-ahead congestion management of distribution networks. *International Journal of Electrical Power and Energy Systems*, 123, 12 2020.

[17] L. Thurner, A. Scheidler, F. Schafer, J. H. Menke, J. Dollichon, F. Meier, S. Meinecke, and M. Braun. Pandapower - an open-source python tool for convenient modeling, analysis, and optimization of electric power systems. *IEEE Transactions on Power Systems*, 33:6510–6521, 11 2018.