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Network Aware Local Flexibility Markets
–
Business Case Analysis

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A la meva mare i el meu germà

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Abstract

The power system is undergoing a period of transformation towards a cleaner, more resilient, and just paradigm based on renewable energy and distributed energy resources. The period of transition from a fossil-fuel based system towards a renewable-based one is full of opportunities, but also challenges. The role of distribution grids in this new paradigm will change due to an increased share of renewable generation assets connected to them, and less predictable load profiles. Active management of distribution grids is not an option anymore, but a necessity to maintain a safe and reliable power system.

This thesis work is focused on exploring on such method of active management of the distribution grids using the flexibility from multiple sources available via network aware flexibility market. The particular focus of the work is on exploring the business model of a network aware local flexibility market. Local flexibility markets are one of the options that distribution system operators are exploring to actively manage their grids. This thesis research the business model impact caused by the addition of network aware capabilities into (local) market clearing algorithms. Therefore, it studies through a business case analysis how this innovative solution influences market dynamics (and market participants), and it also studies the impact on the business model of the market operator.

Two complementary approaches have been used to evaluate the impact on market dynamics and the impact on the business model. First, for the market dynamics a business case study has been performed. On it, market clearing events have been simulated using the algorithms developed by DTU. Second, for the business model impact analysis the results of the business case have been combined with industry insights gained during discussions along the development of the thesis.

From the business case analysis, the main conclusions are that: with enough liquidity in the market the network aware algorithms can perform as good as their non-network aware counterparts. Therefore, on average, market participants will not be affected by the implementation of network aware algorithms. From the market operator perspective, it is true that the use of network aware algorithms requires higher computational power, but this could be expected since the algorithms have added features. When it comes to the business modelling work, interesting discoveries have been made. The implementation of network aware algorithms for market clearing has a direct impact on the market operator business model. The new network aware market operator will have to perform new tasks as: (confidential) data collection and storage, and possibly new roles and responsibilities will be attributed to it. One of the main uncertainties of the business model according to the industrial partners consulted is the liability over failed market clearings. Up until now if the security and quality of supply were bad, the system operator was responsible for that. With network aware local markets, such responsibility is blurred between the system operator and the market operator.

In this thesis the study of the business model for a network aware local flexibility market has been performed, giving relevant insights on the opportunities and challenges such business idea entails. Furthermore, during the development of the research work future topics for research have been presented to further explore new business models for local market operators.

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Acronym List

RES	Renewable Energy Source	**SaaS**	Software as a Service
DER	Distributed Energy Resources	**FMO**	Flexibility Market Operator
DSO	Distribution System Operator	**NEMO**	Nominated Electricity Market Operator
CEP	Clean Energy Package	**MO**	Market Operator
TSO	Transmission System Operator	**MTU**	Market Time Unit
BSP	Balancing Service Provider	**SoS**	Security of Supply
BRP	Balancing Responsible Party	**QoS**	Quality of Supply
vRES	Variable Renewable Energy Sources	**DA**	Day Ahead
LFM	Local Flexibility Market	**ESP**	Energy Service Provider
LEM	Local Energy Market	**SGAM**	Smart Grid Architecture Model
DLFM	Distributed Local Flexibility Market	**FSP**	Flexibility Service Provider
DLEM	Distributed Local Energy Market	**ESCO**	Energy Service Company
EC	European Commission	**DR**	Demand Response
PCR	Price Coupling of Regions	**DSF**	Demand Side Flexibility
PF	Power Flow	**OPF**	Optimal Power Flow
NDA	Non-disclosure Agreement	**FSP**	Flexibility Service Provider
BEIS	UK Government Department of Business, Energy & Industrial Strategy		

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1. Literature Review

1.1 Energy Transition in Power Systems

The content and structure of this section takes inspiration from the report *Future Role of Distribution System Operators – Innovation Landscape Brief* [1] published by IRENA. The report tackles the challenges of the ongoing energy transition and explores the opportunities arising for DSOs, which is aligned with the research questions of this thesis.

Environmental policies entered the orbit of European energy systems regulation with the publication of the Third Energy Package in 2009 [2]. In 2019, after the publication of the Clean Energy Package (**CEP**) it was clear that, among others, sustainability had become one of the building blocks of the European energy strategy. Furthermore, in the last three years due to the impact of the COVID pandemic and the recent events involving Russia, the EU is committing more and more funds to accelerate a sustainable, just, and beneficial energy transition. This is the case of the European Green Deal and its first outcome, the **'Fit for 55'** set of proposals. The fundings for this 6-year plan (2021 to 2027) amounts to a total of 2 trillion € of which around 35% will be committed to climate action [3]. On top of that, the European Commission presented the **REPowerEU Plan** as a measure to counteract the hardships caused by Russia's invasion of Ukraine and stabilize the energy market disruption caused by it. This plan adds 225 billion € to the European Green Deal budget - all of them focused on clean energy production, energy efficiency, and diversification of energy supplies [4]. Renewable energy targets are the warhorse when it comes to energy transition and in Figure 1 it is possible to see how the ambitions of the EC have ramped up in the recent years.

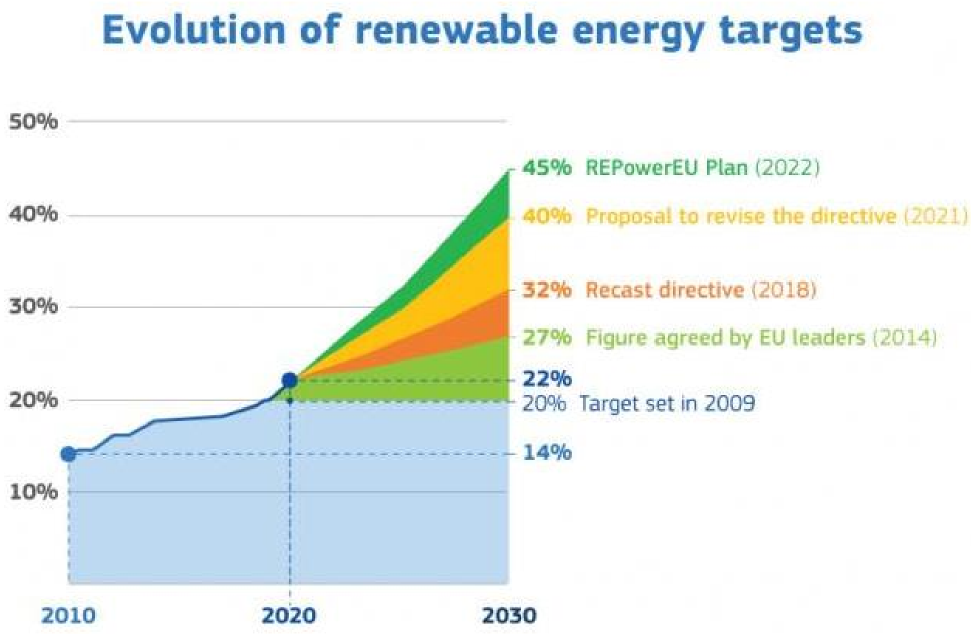

Figure 1. Evolution of Europe's RES targets [5].

The energy transition consists of the shift of energy sources from fossil fuel to renewable energy sources (**RES**). This shift has immense implications on today's energy systems and is promulgating a complex shift in almost every aspect of economy. From the power system standpoint during the recent decades distributed energy resources (**DER**[1]) have emerged thanks to their economic competitiveness, but their implementation is challenging the traditional operation of the power grid. The fact that most RES-based technologies allow for DER size installation is the main driver of this change. However, in recent years digitalization is taking over consumption assets too, creating an accessible pool of DERs at the consumption side.

DERs are connected at distribution grid level, and they are becoming active participants of the power system. Figure 2 depicts both the past and the future (if not present already) structure of the power system. On the Emerging Scenario part of Figure 2 the complexity of the system has increased particularly at the distribution side, showing from new generation parks to the emergence of what can be called smart-load paradigm[2].

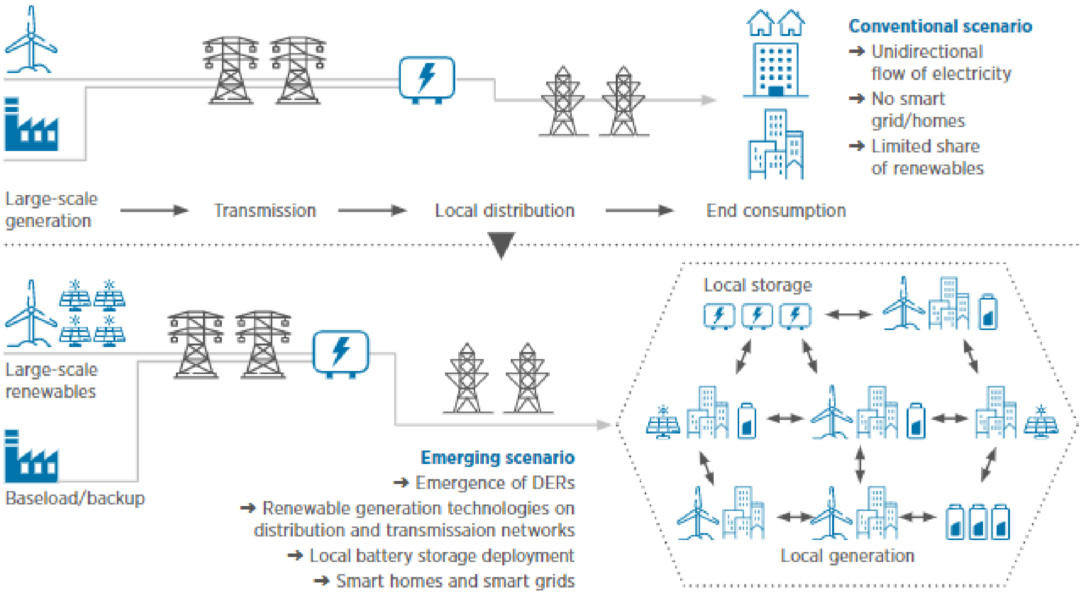

Figure 2. Power system structure present and future.

The connection of DER technologies poses new challenges to a power system that was originally designed to operate in a centralized manner from generation to consumption, through the transmission and distribution systems. DERs can be both generation and demand, and in both cases, they have the potential to change the operation of the system. From the generation side, the increased share of RES in the system will create new generation patterns (seasonal and locational) together with increased uncertainty of generation schedule. Ultimately, this can cause an increased need of balancing in the power system, the need to create new infrastructure to connect generation regions with consumption regions, and it can cause issues for distribution system operators (**DSOs**) whose grids are designed to operate with unidirectional flows from transmission to end-users. Additionally, from the distribution grid perspective the increase in capacity connected to distribution can also challenge the operational limits of the current infrastructure. From the load side, the main challenges are the expected increase of the load due to the electrification of new assets such as transportation or heat-related ones, together with a more variable, and therefore less predictable, behaviour of consumption (due to, for instance, battery storage and/or rooftop solar installations). With that said, DERs also create

[1] DER: Electricity-producing resources or controllable loads that are connected to a local distribution system or connected to a host facility within the local distribution system [7].

[2] Smart Load: It is a generic concept (defined by the author of the thesis) that aims to encompass all loads that have Internet of Things embedded and therefore allow for automated "smart" management. Examples of smart loads could be: domotic homes (smart homes), domestic EV charging points, IoT electric water heaters, etc.

new opportunities for asset owners and grid operators to improve the management of energy in a more cost-effective way. Concepts such as demand-side response and local flexibility[3] are now backed up by the right technology advancements, and an increased share of assets capable of providing such services.

As has been presented in the previous paragraphs the energy transition will impact the power system as a whole. However, the core of the transformation is happening in distribution grids, and it is there where the scope of this thesis is centred. According to IRENA [1]:

"… the increasing penetration of DERs could lead to a less predictable and reverse flow of power in the system, which can affect the traditional planning and operation of distribution and transmission networks. Further, ***increased deployment of DERs is expected to cause congestion in the distribution grid, which must be actively managed****. This raises the need for a change in the role of the DSOs that have conventionally planned, maintained, and managed networks and supply outages. To effectively benefit from the available flexibility of DERs connected to the distribution network,* ***DSOs could deepen their role as active system operators*** *…".*

The following figure, extracted from an IRENA's report [1], depicts the potential new roles and responsibilities of DSOs in a future power system.

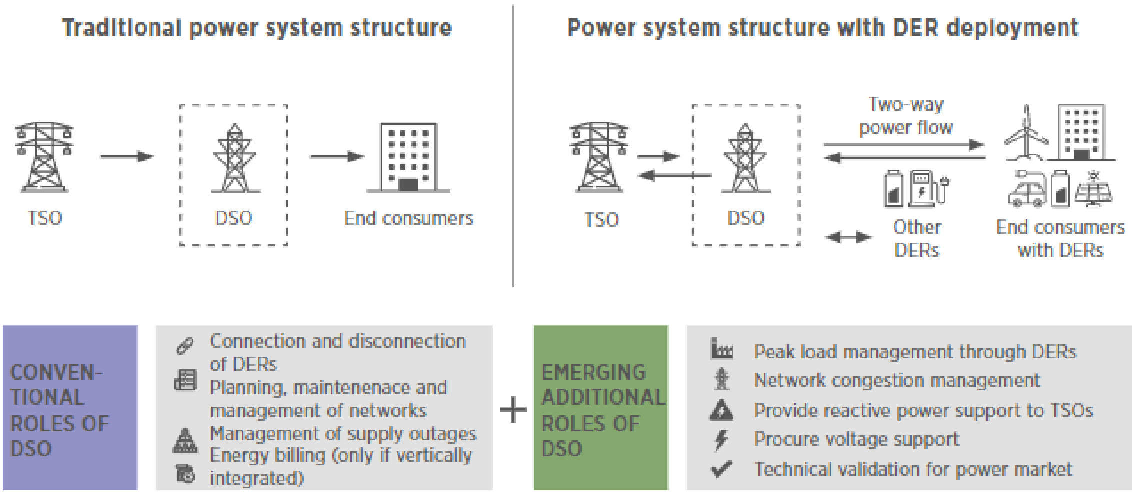

Figure 3. Conventional and emerging roles of DSOs in the power system.

To provide active management of the grid the DSO could either own assets that allow it to actively manage the grid or procure flexibility form market participants. The first of the options is restricted by Article 32 of the Directive 2019/944 of the CEP [6], which relegates it to those grids where flexibility procurement is proven not to be the cost-effective solution. When it comes to flexibility procurement, IRENA's report enumerates a representative list of options. The content of the list is also supported by a survey recently done by the Nordic Energy Research to DSOs from Norway, Sweden, Finland, and Denmark regarding their current and future use of flexibility [7]. The following are the options for flexibility procurement at DSO level:

- **Interruptible tariffs** – Reduced tariff to allow the DSO to reduce or interrupt the power supply of a customer in the case of need.

[3] Flexibility – Is the ability of generation, demand, and storage units, to modify their scheduled behaviour to provide (remunerated) ancillary and non-ancillary services to the power system, to assist with its QoS and SoS.

- **Conditional connections** – New assets are allowed to connect to the grid at a reduced price, but they have to constrain their power needs during a certain period of time (until grid expansion is available).
- **Bilateral flexibility agreements** – Generators/Loads reach an over-the-counter agreement with the DSO to operate according to the grid's needs. This supposes an active behaviour from the load/generator, and it can be used by the DSO to have local system services, such as voltage control, peak shaving, and congestion management.
- **Local flexibility markets** - This refers to local flexibility markets for distribution system services in which DERs could participate to support the distribution grid.

The following figures, extracted from [7] provide information on today's use of local flexibility and how it is procured in the Nordic countries.

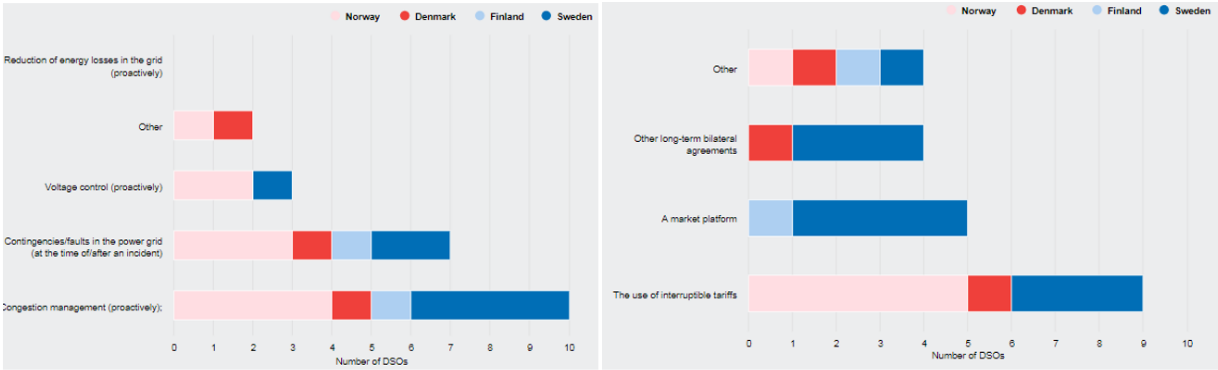

Figure 4. Nordic DSOs uses and procurement method of local flexibility.

The future of distribution grids does not only rely on active management though. According to a joint report between E.DSO, Eurelectric, and Deloitte [8], during the next decade EU DSOs will invest 35 to 39 bn€/year in their grids which supposes an increase of 50 to 70% compared to the last decade. From all these investments 90% are expected to be equipment costs, a.k.a grid upgrades, which is the traditional way for DSOs to adapt their grids to the increase of demand/generation. From this perspective, grid expansion periods are one of the main business cases for today's local flexibility markets. This is the case, for instance, of the sthlmflex market which is being used by regional DSOs in the Great Stockholm area to reduce the peak load in the grid during winter while a new transmission line is built in the region (expected to be finished by 2029) [9]. This project helps DSOs to reduce operational costs caused by exceeding their agreed power with the transmission system operator (**TSO**), and help the TSO keep the transmission system within its capacity limits.

This thesis' topic is related to innovative ways for DSOs to perform active management of their grids. To be more precise it is focused on studying the role of local flexibility markets (**LFM**) in future distribution grids. The following sections aim to give an overview of the power system from multiple angles and introduce the topic of flexibility.

1.2 Power System Layers

The scope of this thesis is focused on the business case analysis of a specific subset of innovative electricity markets. The context and business ecosystem where a business idea is developed is one of the most relevant factors for its success or its failure. From this perspective today's power system is one of the most complex but at the same time thrilling ecosystems to develop new businesses in.

To properly introduce the context where the business case will be analysed, this section gives a quick glance to today's power system structure, following the Smart Grid Architecture Model (**SGAM**) framework [10], and with special focus on its the business layer. The challenges of today's power system have been already introduced in the previous section, in this one a better understanding of the state-of-the-art actors, roles, and market players in the energy transition, together with their interactions within the electricity ecosystem will be presented.

Component Layer

The traditional electricity supply chain is integrated by three main components: generation, transmission, and distribution. At the "end" of the supply chain the loads use the electricity. The traditional power system structure follows a linear and unidirectional approach to the supply chain. It starts from the generation units producing electricity and injecting it to the transmission system. The transmission system is responsible of the transportation of the electricity at high voltages from the generation point closer to the consumption. Finally, the distribution grid, which operates at lower voltages, is the responsible to deliver the electricity to end users. This is an oversimplified explanation of the dynamics of the system, and both generation and demand can be connected at any voltage level, as it will be seen in coming sections. Figure 5 gives a schematic overview of the structure of traditional power systems. On it, different types of loads are represented. Note that generation is only connected at high voltage level.

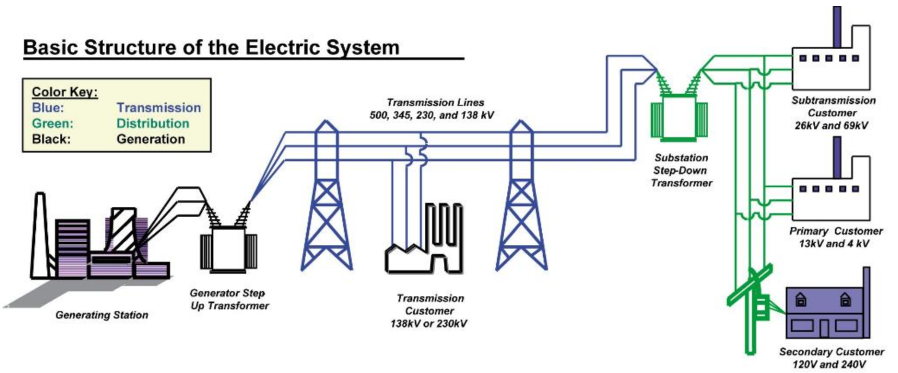

Figure 5. Power system physical structure.

Nowadays, the role of loads in the power system is becoming more and more relevant thanks to the adoption of new technologies such as battery storage systems and residential-sized generation units (PV). The figure of the Prosumer (active consumer) has been highlighted in the latest European energy regulation, and it is expected to see a higher adoption of such technologies in the coming years.

Communication and Information Layers

Within SGAM these layers refer to how assets interact between each other and the protocols to be used. The Communication layer represents the communication technologies (SCADA, GIS, DMS, etc) and how they interact among them (protocols and standards), whereas the Information layer is responsible of defining the information to be exchanged between the different devices. The following bullet points list provides some examples of relevant protocols and standards within the new smart grid paradigm, these have been extracted from Deliverable 4.1 of the **planet project** [11].

At substation level:

- **IEC 61850** [12]**:** This standard defines protocols for intelligent electronic devices (DERs) at electrical substations. Extensions of this standard are **IEC 61400-25** which follows the same methodology but specifically for wind turbines, and **IEC 61850-90-8/9** which respectively apply for electromobility and battery storage.

At asset level:

- **IEC 61970** [13]**:** Standard for program interfaces for energy management systems.
- **Zigbee** [14]**:** Standard to define a suite of communication protocols to create personal area networks. This standard is playing (and will play) a relevant role in the smart grid paradigm, since it is the backbone of most home automation systems.

Even though these are crucial parts of today's power systems and will increase in relevance with the increase of digitalization of assets. In this thesis both communication and information layers have been left out of the scope of the business case analysis. With that said, interoperability and therefore communication and information layer issues have been identified as one of the main challenges for the full deployment of the smart grid concept (see [15], and Art. 23 and 24 of the directive EU 2019/944)

Business Layer

Behind the physical structure of the power system there is a complex ecosystem of actors[4] whose roles, responsibilities, and business goals will be partially described in the following paragraphs. This complex ecosystem is a consequence of the liberalization of the EU power system. The physical assets connected to the grid have remained "unchanged" until recently, but the introduction of the market-based approach to the power system has fragmented the roles and responsibilities and it has given added market value some of their capabilities.

In 1996 the European Commission published the first legislative package aiming to liberalize the electricity sector (Directive 92/96/EC, [16]). Prior to that, the electricity industry was structured around vertically integrated, national monopolies, often owned by national or regional governments [17]. On the one hand, the pre-1996 approach might have hindered consumers by excluding competition from the electricity business ecosystem. But on the other hand, it limited the number of actors and communication layers in the system and thus made it easier[5] to operate (along this thesis the operational challenges of the power system will be extensively

[4] Following the SGAM framework.
Role represents the external intended behaviour of a party.
Actor represents a party that participates in a business transaction. Within a given business transaction an actor assumes a specific role or a set of roles.

[5] The physical operation should have been similar before and after the liberalization, but the change from a vertically integrated structure to multiple actors has increased the complexity of overall operation due to challenges at the communication level between power system actors.

discussed). The liberalization of the power system in Europe was (and still is) focused on both ends of the electricity supply chain: generators, and consumers. While it kept the transmission and distribution system as natural – regulated – monopolies.

As of now, **generators** are private entities that aim to maximize profit based on selling their energy or power in the electricity markets or via bilateral agreements. Whereas consumers have the possibility to choose from multiple electricity suppliers. These **suppliers** buy energy from generators through wholesale markets or bilateral agreements. These two actors can take multiple roles within the electricity business ecosystem, but the core of their business is related to energy generation and consumption. When it comes to the distribution and transmission grid, each of them has one or multiple actors responsible of their operation. To be more precise, the actors in charge of the transmission infrastructure are **Transmission System Operators**, and in Europe there is usually one per country – with some exceptions such as, Germany or Belgium. On the other hand, **Distribution System Operators** oversee the distribution grid infrastructure and there are multiple of them in each country. More detailed information is provided below.

Transmission system operators are the entities responsible of the security and quality of supply (**SoS** and **QoS**) of electricity flowing through transmission lines. They are also responsible of providing grid access to those players that are connected at high voltage lines. When it comes to reliability of the supply TSOs must consider two time-horizons. First, real-time linked to maintenance of the current infrastructure and active operation of the system (balancing and congestion management). Second, long-term which involves grid planning and extension. [18]

Distribution system operators are the entities responsible of the security and quality of supply of electricity flowing through distribution lines. They are also responsible of providing grid access to those players that are connected at medium and low voltage lines. Up until recently the task of the DSO was highly focused on long term planning and maintenance of its network, without any active management involved. For this reason, DSOs were also called distributed network operators. However, nowadays the role of DSOs is starting to change towards an active management of the girds.

Until now, the market actors behind the physical assets have been presented. However, one of the consequences of the liberalization of the power system in 1996 was the creation of the common internal market which has been expanding and redefining its scope throughout the years with each new EU energy package publication (1996, 2003, 2009, and 2019). Out of the liberalization of the power system different markets have been stablished at EU level (with different degree of interconnection). The reason behind the creation of different markets is that, as explained at the beginning of the section, even though electricity can be traded as a commodity, it has some physical characteristics that create the need for multiple markets. These characteristics make necessary the existence of multiple electricity markets to safely operate the power grid. Figure 6 presents an overview of the EU's electricity market structure.

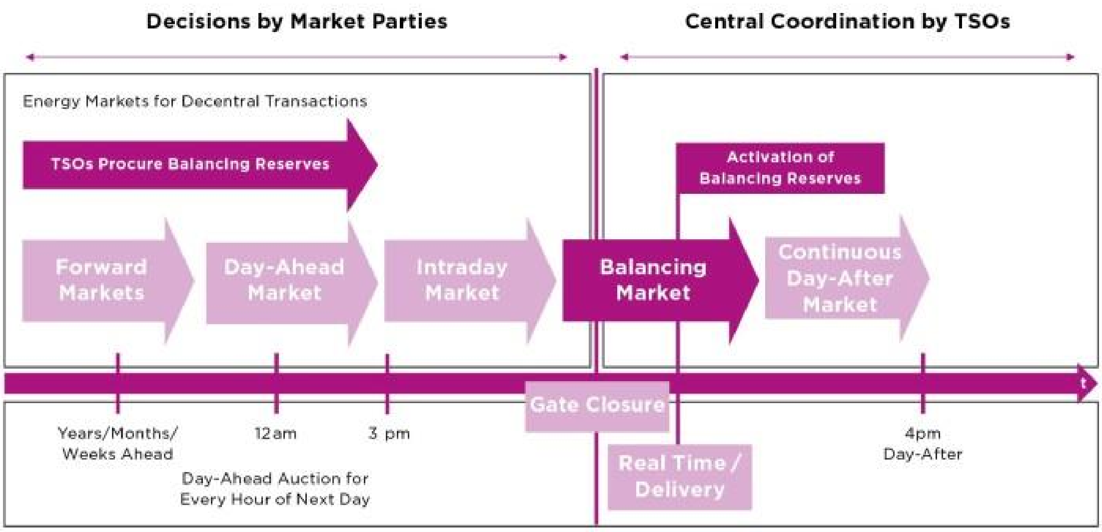

Figure 6. EU electricity market overview [19]

Without entering in much detail, and following temporary order, the electricity markets start with **Forward Markets**, which are purely financial markets that allow market participants (generation and consumption) to hedge themselves against short-term price uncertainties. Forward agreements tend to be over-the-counter/bilateral agreements between parties and can go from weeks to years ahead (e.g: To "secure" the return of investment in a new generation plant).

Then moving into markets that operate closer to delivery, the day before delivery is when the **Day-ahead Market** (DA Market) operates. This market, together with the intraday market, takes the role of adjusting the system forecasted needs to the real-time needs in term of demand and generation capacity. Based on the bids from generation units and retailers/loads, and after checking the physical feasibility of the agreed financial exchanges, a dispatch schedule is prepared. The **Intraday Market** follows a similar structure but instead of clearing the market for the following day, it is constantly clearing the market up to 45 minutes before delivery happens. When compared to forward markets, the day-ahead market does not only have the characteristics of **financial markets but also of physical markets**.

Up to this point the market is operating thanks to the exchange between generation and consumption. From 45 minutes before actual delivery onwards the markets related to real time operation of the grid start, these are the markets linked with QoS and SoS. As of today, these are called balancing markets and are a monopsony where the single buyer is the transmission system operator. In these markets power or capacity is traded, and they are mostly used to match demand and supply in real time, and therefore avoid frequency deviations. In some cases, TSOs use balancing markets to alleviate congestions by moving generation from one point of the grid to another [7, 20]. As can be seen in Figure 6, TSOs acting in the role of balancing market operators can procure flexibility in advanced in the balancing reserves markets.

This complex and interconnected market system was born with the liberalization of the power sector in Europe, and with-it new roles for the existent market actors appeared. The following definitions are useful to increase the understanding of electricity market related topics and therefore for this thesis. However, most of the roles that will be introduced in the next paragraphs are undertaken by traditional power system assets.

The first role arising from the new markets needed is the **market operator (MO)** role which is given to an entity that provides a service whereby the offers to sell electricity are matched with bids to buy electricity. Then for more particular cases there is the **nominated electricity market operator** (**NEMO**), which is a market operator designated by the competent authority of the European Union Member State to participate in single day ahead coupling and single intraday coupling (Article 2(8) of (EU) 2019/943, [21]).

The **balance responsible party** (**BRP**) is another role/actor that participates in the market. A BRP is a wholesale market participant or its chosen representative responsible for its imbalances ((EU) 2017/2195, [22]). The term imbalance is linked to the physical nature of electricity, and in generic terms means deviations between scheduled generation or consumption and the real value. This deviation can cause problems to the operation of the system and therefore is penalized by the TSO.

Linked to balancing services the role of the **balancing service provider** (**BSP**) also appeared. According to the ENTSO-E harmonised electricity market role model, a BSP is party with reserve-providing units or reserve-providing groups able to provide balancing services [23]. To put it in plain words, BSP is the role assumed by a load or generation or their representative BRPs when participating in balancing markets.

The BSP and BRP figures are crucial roles in today's electricity markets and will play a relevant role within the scope of this thesis. However, their role in the energy system and its business environment can be hard to frame. Further detail of the value of their services will be given in coming sections.

Finally, new actors are emerging on the energy consumption side. These actors are not necessarily involved with electricity markets, but at the same time can play an important role in the future of the system. There is a wide variety of new companies providing services related to active energy management, from energy optimization tools to active participation in electricity markets. These new companies are classified under the generic term **energy service providers** (ESPs) in FLEXGRID's business ecosystem. The following actors fall under the category of ESP, their definition has been extracted from the Universal Smart Energy Framework (USEF) [24]:

- **(Independent) Aggregator**: The role of the Aggregator is to accumulate flexibility from Active Customers and their flexible assets and sell it to the BRP, the DSO, or to the TSO. The Aggregator's goal is to maximize the value of that flexibility.
- **Supplier/Retailer**: The role of the Supplier is to source, supply, and invoice energy to its customers. The Supplier and its customers agree on commercial terms for the supply and procurement of energy.
- **Energy service company (ESCO)**: The ESCO offers auxiliary energy-related services to Active Customers. These services include insight services, energy optimization services, and services such as the remote maintenance of flexible assets.

One last key element to consider when defining the demand side of the power system is the role of end users. Nowadays, end-users of electricity are shifting from being passive loads towards being active players that can also generate and store energy. It is thanks to this change of paradigm that ESPs are now being put in the spotlight of the energy system. Based on this "trend" in the power system, the next logical step, as stated by the European Commission (CEP Art. 32 EU 2019/944 and Art. 59 EU 2019/943) in electricity market development should be the creation of **Distributed Local Flexibility Markets** (DLFMs) for DSOs to procure non-frequency ancillary services, such as congestion management, voltage control, etc. Nowadays, regulatory frameworks are being developed to foster the adoption of these new markets. For instance, ACER[6] has started developing guidelines for the future network codes for demand response, as requested by the EC [25]. However, within the research community more advanced solutions are proposed which are relevant to better understand the end-goal of local energy markets and see the limitations of today's approaches. The following paragraphs are an introduction to local flexibility market integration on the overall power market structure, and its content has been extracted from FLEGXGRID deliverables D5.2 and D5.3, and [26].

Today's electricity market structure has been presented in Figure 6. The main discussion (from the research perspective) is how to integrate DLFMs in the current market structure to maximize the benefit for the grid. FLEXGRID, considering the solutions developed - network aware local flexibility markets - proposes three approaches:

a) **Reactive-DLFM (R-DLFM,** Figure 7**)**: In the R-DLFM approach the local market operates right after the Day Ahead Market. At this stage, the assets connected to the grid have defined their expected consumption or generation for the following day, and therefore DSOs can make calculations of the feasibility of the expected power flows. In case there is unfeasible power flows the R-DLFM allows the DSO to correct the schedule of assets in their grid to solve the expected issues.

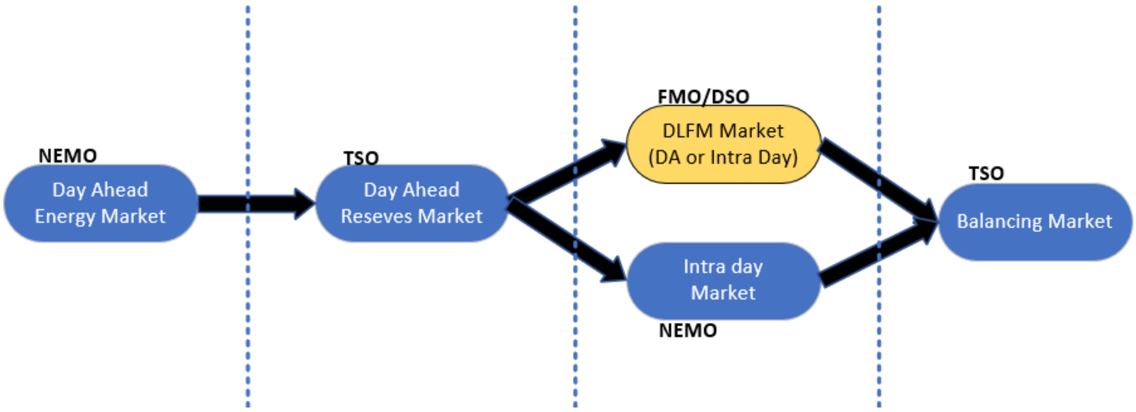

Figure 7. Scheme of the integration of R-DLFM in the electricity market structure.

b) **Proactive-DLFM (P-DLFM,** Figure 8**)**: The proactive approach proposes the inversion of roles in the market clearing order. P-DLFMs are not flexibility market anymore, but they become Distribution Level Energy Markets (**DLEMs**) that are executed before the clearing of the Day-Ahead market at TSO level. The main advantage of this approach is that if the DLEM can calculate power flows, it allows DSOs to ensure feasible dispatch within the limits of their grids. However, challenges arise when it comes to the coupling between both Day Ahead markets in terms of pricing.

[6] ACER: Agency for the Cooperation of Energy Regulators

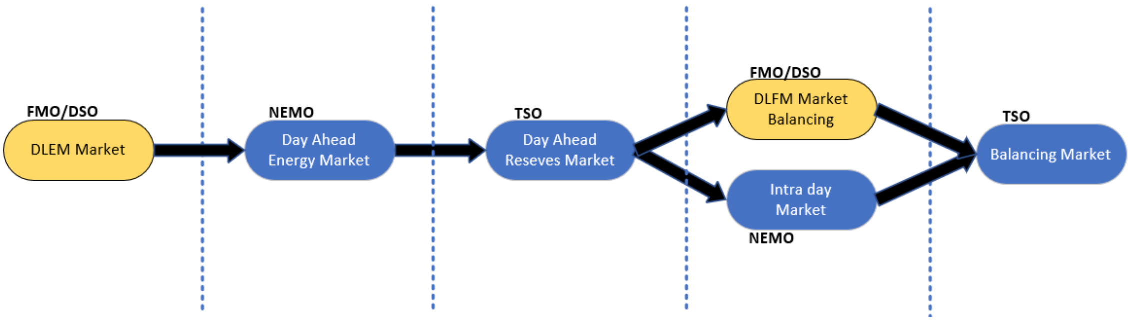

Figure 8. Scheme of the integration of P-DLFM in the electricity market structure.

c) **Interactive-DLEM (I-DLEM,** Figure 9**):** The interactive approach requires from constant interaction between different market operators. The I-DLEM operation consists of a process of Day-Ahead market clearing where TSO level and local level markets are cleared iteratively until they converge to an optimal dispatch schedule.

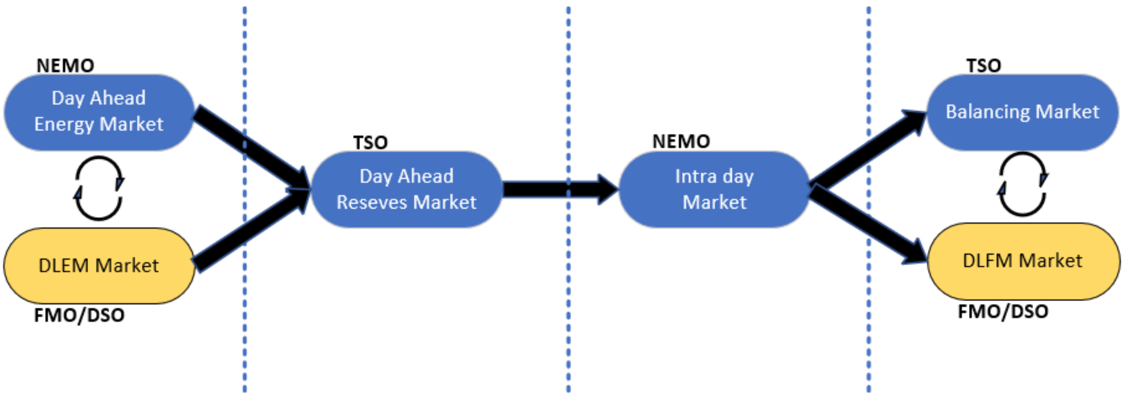

Figure 9. Scheme of the integration of I-DLFM in the electricity market structure.

In the case of DLFMs it is not clear yet who the market operator will be. Two are the possible options: a) to follow the balancing market approach, making the system operator (DSO) responsible of clearing the market, or b) create a new actor/role responsible of market operation (like the NEMO). In today's literature this new role is usually called **flexibility market operator** (**FMO**). The Directive EU 944/2019 promotes the second approach to keep unbundling the power system, therefore from now onwards this thesis will consider the FMO an independent actor in the power system.

Finally, two relevant considerations need to be made: a) the above presented state-of-the-art of DLFM research is only relevant if the local market clearing algorithms are network aware, and therefore can mimic (to a certain extent) the power flow calculation capabilities of the Day Ahead wholesale market algorithm (EUPHEMIA). Then, b) as of today all the existent DLFMs follow a reactive approach for two main reasons. First and foremost, because it is the only way to fit within today regulatory framework/market structure. Then, because as of today none of the relevant DLFM operators (FMO role) can calculate the physical state of the grid.

The following table presents the actors and their correspondent potential roles described in this section. This table follows the guidelines of the ENTSO-E Harmonized Electricity Market Role model, but it is simplified to better fit the scope of this thesis.

Table 1: High level list of actors and roles in flexibility markets.

Actor	Possible Roles
Transmission System Operator	System Operator and Market Operator
Distribution System Operator	System Operator
Flexibility Market Operator	Flexibility Market Operator and Market Operator
Generator	Balancing Responsible Party, Balancing Service Provider and Flexibility Service Provider.
Supplier/Retailer	Energy Service Provider, Balancing Responsible Party, Balancing Service Provider and Flexibility Service Provider.
Independent Aggregator	Energy Service Provider, Balancing Service Provider and Flexibility Service Provider.
Energy Service Company	Energy Service Provider. ESCOs do not actively participate in energy markets.

* Most of the actors in the table are quite generic, and therefore they could also be used as roles undertaken a party within the energy ecosystem.

The role of the new actors appearing on the demand side of the power system is one of the key components in this thesis, and the topic will be further developed in the coming sections.

1.3 Flexibility Characterization and Markets

The following section is devoted at defining what Flexibility means in the power system, how new flexibilities differ from traditional ones (ancillary services versus new DSO-oriented flexibility products), how different assets can give different types of flexibility, etc. Therefore, the starting point of this section is providing a wide definition of flexibility in the power system.

So, according to Eurelectric [27], flexibility is:

"[…] ***the ability*** *of a [electricity] market participant* ***to set the level of injection and/or consumption*** *of an individual asset or a set of aggregated assets* ***at a chosen value, to deliver a service*** *to a system operator and to facilitate daily network management and network development planning, mainly on the distribution system operator side*."

According to the German Federal Network Agency [28], flexibility can be defined as:

"[…] ***the change in feed-in or withdrawal in response to an external signal*** *(price signal or activation) with the aim of providing a service in the power system*".

Traditionally flexibility has been provided by adjusting generation assets to meet the load [29], but also from loads connected to high voltage levels. Nowadays, with the emerging role of prosumers, DERs, and the overall smart grid paradigm, more flexibility is available and easily accessible at distribution level than ever before. Usually, this flexibility is known as demand side flexibility (DSF)/ demand response (DR). The term explicitly refers to demand even though it can be provided by a mix of pure loads, loads combined with generation assets, or loads with generation and storage (all of them fitting under the prosumer definition). Untapping the potential of this new available flexibility is one of the current challenges not only for system operators, but also for regulatory bodies in the EU that foresee this new source of flexibility as crucial for the correct system operation, and a way to empower end-users.

For reference, Figure 10 shows the flexibility potential by technology in the UK during 2020. The main contributors are generation assets. The role of demand side response is not residual; however, it would be relevant to know which part of it comes from loads connected to HV lines.

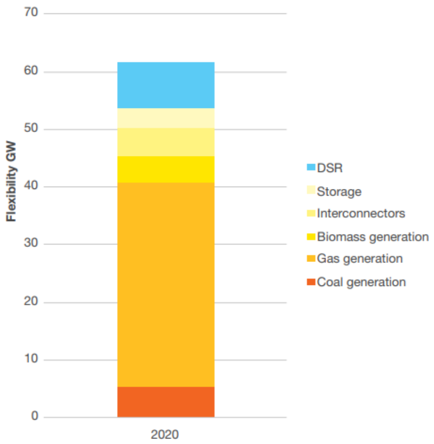

Figure 10. Flexibility potential by technology in UK's power system [28].

There are multiple possible classifications for flexibility. However, when flexibility is provided by loads the most relevant distinction is between:

Implicit flexibility – Reaction to market price signals.

Explicit flexibility – Loads offer flexibility markets to modify their expected electricity consumption in exchange of a remuneration.

From an overreaching perspective, it is relevant to mention that in a power system transitioning towards a high share of variable RES (**vRES**) the operation of the system will change from demand driven to supply driven. This radical change of paradigm opens the opportunity, and creates the need, for new types of flexible loads that generate value out of the excess energy. This kind of flexibility falls under the umbrella of the terms such as **sector coupling** or **sector integration**. IRENA classifies the flexibility coming from sector integration in different types [30]:

- **Power-to-heat**: It refers to the coupling of electricity and heat sectors. Assets such as heat pumps and electric boilers are more efficient than their gas counterparts and combined with thermal storage it allows to create shiftable loads even at residential scale. Thermovault™ and Klugit energy™ are residential applications of this kind of sector integration for flexibility purposes.
- **Power-to-hydrogen**: It is a particular case of **power-to-gas** technologies. However, according to IRENA hydrogen produced from vRES can be the potential missing link of the energy transition. Hydrogen can be generated by using electrolysers, which eventually could respond to power system needs (excess of generation mostly). It allows to transform electricity into a more flexible energy vector that has potential to be stored and used in multiple forms. For instance, as hydrogen, natural gas, and synthetic fuels.

Since the EU is promoting a transition to a vRES based system, sector coupling has been included as one of the pillars of the European energy strategy [31] Furthermore, aside to increase flexibility in the system it also allows to redefine the energy system structure. From a "silos-based" one to an interconnected one (see Figure 11). This makes it more resilient, and ultimately it can allow for more efficient decarbonization strategies.

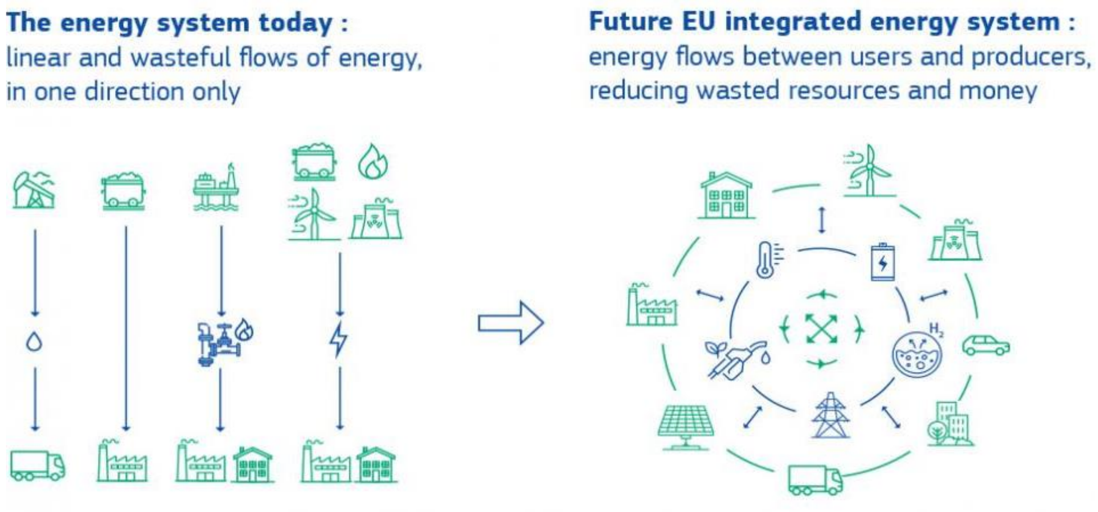

Figure 11. EU's envisioned integrated energy system [31].

Other technologies, such as electric vehicles, could be considered within the sector coupling concept. However, due to their nature from the flexibility perspective, this thesis restricts sector coupling flexibility to the options mentioned above. Finally, Figure 12 summarizes altogether the flexibility options and the role of sector coupling.

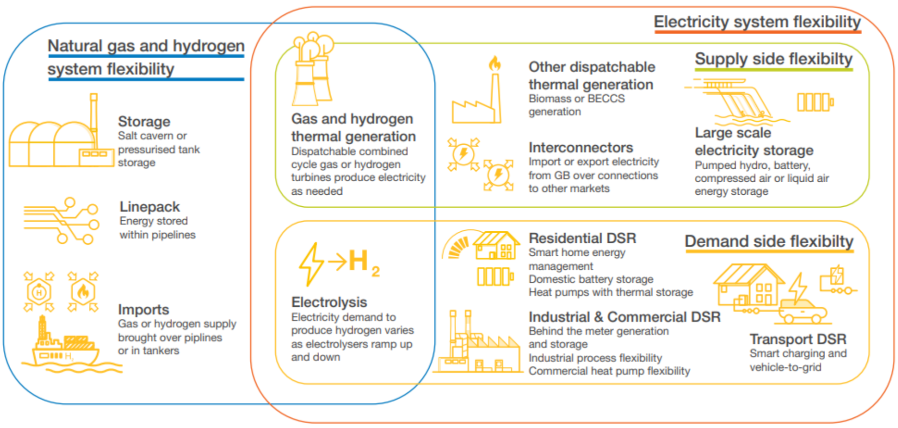

Figure 12. Energy systems' (potential) role of flexibility and reach of sector coupling strategies [32].

1.3.1 Current Role of Flexibility Markets

As of today, the only "official" flexibility markets accessible at European level are Balancing markets. These are markets are a monopsony, where the TSO is the market operator and at the same time the single buyer. ENTSO-E defines the function of balancing markets as "*markets ensuring the maintenance of system frequency within a predefined stability range, as well as compliance with the amount of reserves needed with respect to the required quality*". Additionally, some of the balancing markets are used by TSOs to perform different active management tasks such as congestion management, since they are the only way system operators can modify the real-time behaviour of assets connected to the grid in a market-based manner. Balancing markets are operated in real time as can be seen in Figure 13 which also shows the roles involved in the balancing market ecosystem.

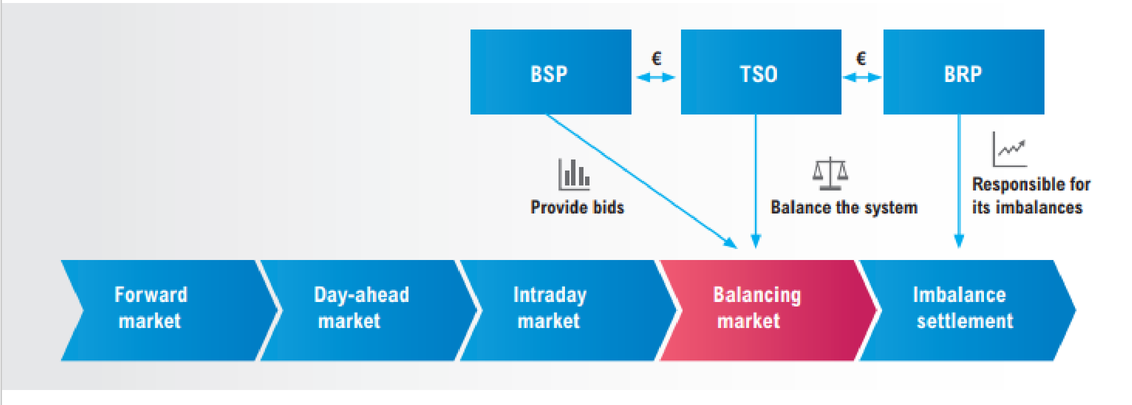

Figure 13. Schematic timeframe of electricity markets in the EU.

But what is really traded in flexibility markets? The case of balancing markets can be used as the paradigm to define flexibility products: the nature of the grid forces grid operators to have assets ready to compensate possible mismatches between generation and demand, this is the real meaning of balancing. Therefore, the balancing needs are a stochastic variable, and TSOs buy balancing capacity (in the form of active power) that will be activated only if needed. So, in most cases flexibility is traded in the form of capacity or power, that may or may not be used. For this reason, in flexibility markets there can be two differentiated payments: capacity [€/MW] (power available) and activation [€/MWh] (power used/energy). Just for context, in the case of wholesale energy markets, the product traded is energy, and therefore the payment is only linked to the agreed volume [€/MWh]. Finally, it is relevant to mention that with new buyers in flexibility markets, such as DSOs, things can change. Balancing is a solely responsibility of TSOs, instead DSOs will use flexibility for other applications. For instance, to reduce congestions in their grids or optimize power flows. In these cases, since they are predictable events, DSOs could directly buy energy instead of capacity.

The constant increase of vRES capacity connected to the power system is one of the causes of the increased expenditure on balancing by system operators. For instance, TenneT's annual reports have been showing a trend of increased costs of *Maintenance of the energy balance* from 71 M€ in 2014 to 374 M€ in 2021 ([33] and [34]).

1.3.2 The Future of Flexibility Markets

Up to this point, DSOs are excluded from these markets even though some of the assets participating in them are connected at distribution level. However, as it has been shown in previous sections the needs of DSOs to actively manage their grids are increasing overtime. For this reason, the latest European energy regulation, the Clean Energy Package, set the basis to stablish local flexibility markets for DSOs in Articles 32 (1). During 2022 the implementation process of Articles 32 of the directive and Art. 59 of the regulation has started, and on the 1st of June 2022 the European Commission sent a letter to ACER that represented an invitation to submit framework guidelines for the creation of a network code for demand response [25].

DSOs uses of flexibility are different form the TSOs ones. The need of flexibility from DSOs mostly arises from wholesale markets unfeasible scheduled transactions at distribution level. This is due to the copper-plate assumption, where the grid physical constraints are only considered for the TSO's grid. Additionally, DSOs do not have balancing responsibilities, and therefore balancing is a responsibility restricted to TSOs as operators and electricity market participants as BRPs and BSPs. The following figure, extracted from [7], shows todays main uses of local flexibility by some Nordic DSOs surveyed.

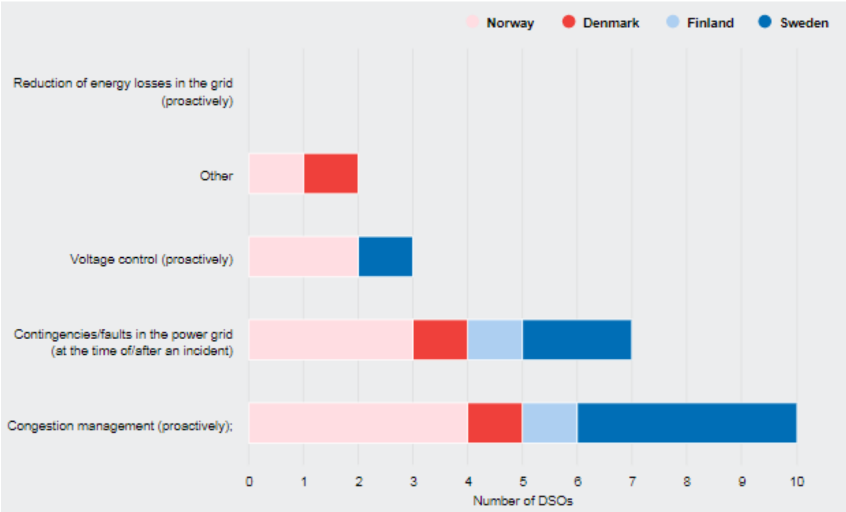

Figure 14. Uses of flexibility (2021) by Nordic DSOs.

DSOs have access to this flexibility trough some of the tools introduced in section 1.1, such as interruptible tariffs, conditional network connections and bilateral agreements. Therefore, in most countries the market-based approach promoted by the EU is not a reality yet. However, in some countries like the UK, and the Nordics the number of pilot projects testing local flexibility markets has started to increase in the recent years.

The research questions in this thesis are focused on this very specific subgroup of "flexibility" markets called Local Flexibility Markets. As of today, they are an idea that is mostly materializing in the form of pilot projects. However, in some countries (e.g UK) DSOs are already procuring flexibility to manage their needs through them and there is an emerging number of market operators offering their services to DSOs all around Europe.

1.4 Local Flexibility Markets

This section aims to give the big picture of local flexibility markets in Europe. It starts with a state-of-the-art review, where the latest events in the LFM ecosystem are presented. This section is highly focused on the business side of LEMs and presents the different companies developing them and what are their latest advancements in the business. Then, a brief introduction to LFM product definition is made. This is relevant to have a better understanding of what is/can be traded in LFMs, and which are the main targeted business actors. To conclude the section, one perspective of the LFM business actor's ecosystem is presented together with the alternatives for DSOs to manage their grids.

1.4.1 State-of-the-art of LFMs

Most of the content of this subsection is extracted from the report *Review of Flexibility Platforms* [35]. The first relevant differentiation done in the report is between the different types of platform models. Three are the main groups:

- Administrative flexibility scheme coordinators: On these flexibility platforms, flexibility is not allocated in a market-based manner, instead the platform facilitate a centralized system for the different stakeholders to exchange information and reach agreements. This type of platform represents the lowest level of integration of flexibility within the EU strategy.
- Market intermediaries: In this case the platform acts as an intermediary that is integrated with already existing marketplaces (e.g., EPEX SPOT and NordPool). The

platform offers stakeholders enabling services that facilitate procurement of flexibility, but the market clearing is done by someone else.

- Marketplaces: Finally, in this category fit all the platforms that perform functions of marketplaces, such as running the auctions and settling payments. In some cases, these platforms are connected to other markets (e.g., NODES) but they can operate independently.

From the above-mentioned categories, this thesis is focused on the last one: Marketplaces. However, local flexibility markets are at an early stage, and as it will be presented in the following paragraphs from the frontrunner platforms in Europe today, there is diversity of platform models. During the recent years, the literature in Europe regarding LEMs has been monopolized by a few LFM developers and their projects. These are the following ones:

- Piclo - UK
- NODES – Northern Europe
- GOPACS – Netherlands
- Enera/LocalFlex – Germany

Additionally, new commercial platforms (but not in the marketplace category) have started to be available during the recent years. This is the case of EQUIGY[7], a trans-European TSO endeavor to facilitate aggregators the access to ancillary services markets. EQUIGY has pilots in Switzerland and the Netherlands, and they are planning to start operating in Germany, Austria, and Italy. Then in Germany thanks to the implementation of the "Redispatch 2.0"[8], the DA/RE[9] ("Datenaustausch Redispatch" – data exchange redis-patch) has been implemented.

Focusing now on the marketplace category, a brief overview of the current commercial platform is given. The core information from this section has been extracted from the paper *Flexibility markets: Q&A with project pioneers* [36], together with other sources that will be mentioned when necessary during the coming paragraphs.

Piclo [10]

Piclo is one of today's most active LFMs in Europe. Their LFM service, Piclo Flex™ was launched in 2018 with funding from the Government Department of Business, Energy & Industrial Strategy (BEIS). The initial pilot had all the DSOs from the UK involved, today only Electricity Northwest has tenders activated (84). Piclo's approach to local flexibility is based on long term agreements, and the market is cleared through a price-based auction. Piclo's approach to LFMs through long term compromises is unique in the LFM ecosystem. It has its advantages and disadvantages. This capacity-market based approach might make some end-users think twice before joining a tender due to the "long-term" compromise. However, Piclo allows for both Availability (capacity) and Utilization payments. This double payment scheme is good to incentivize market participation. The following figure shows a real competition in Piclo's platform, with all the requirements stated by the DSO (Electricity Northwest). Figure 15 presents the user interface of a tender as flexibility suppliers see them.

[7] EQUIGY platform - Home - Equigy

[8] Redispatch 2.0 – New regulatory framework that lowers the threshold of redispatch obligation in the German grid from 50 MW, down to 100 Kw power plants (from October 2021). The lowered threshold has shifted the grid paradigm by including DSOs into the active management of the grids.

[9] DA/RE platform - DA RE – Eine Initiative von Netze BW und TransnetBW (dare-plattform.de)

[10] Piclo platform - Piclo — The UK's leading independent marketplace for flexible energy systems.

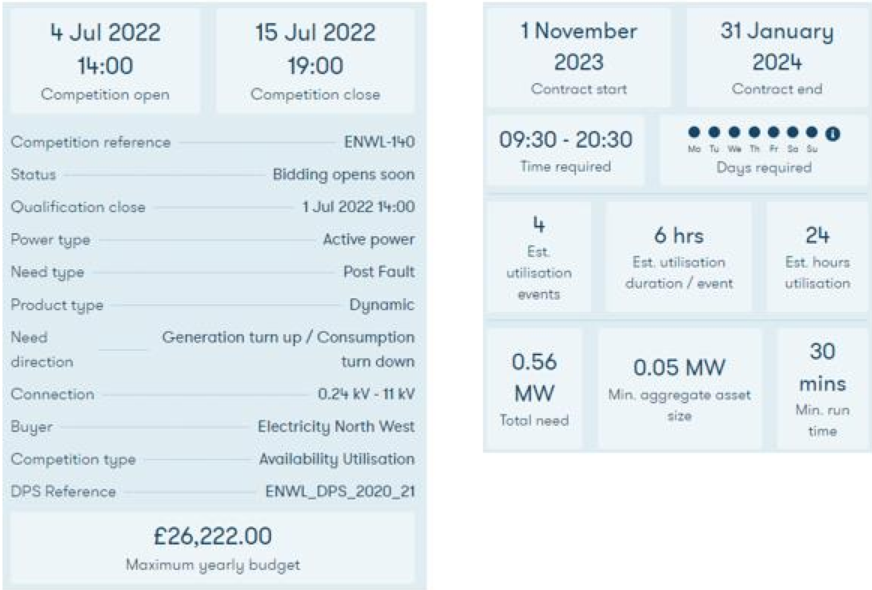

Figure 15. Piclo Flex platform real DSO buy offer.

Recently Piclo has signed an agreement Lithuania's ESO to start deploying its LFMs in the country. The platform is already active[11] and most of the tenders are targeted to Reinforcement Deferral products.

NODES[12]

NODES was launched in 2018 as a joint venture between Adger Energy and the market operator NordPool. Today NordPool does not have any stake of the company. NODES market is in the developing phase but has been implemented in different countries through multiple pilot projects. In Norway NORFLEX, SMARTSENJA, and Cineldi, in Sweeden sthlmflex, and Effekthandel Väst, in UK with INTRAFLEX, and in Germany with Mitnetz. NODE's offers a combination between long term capacity contracts (LongFlex) and short-term contracts (ShortFlex). LongFlex contracts can be considered a close product to what Piclo is offering (availability and utilization), whereas ShortFlex contracts are assigned through tendering in a continuous clearing manner. However, both LongFlex and ShortFlex flexibility must go through the market clearing process to decide which one will be activated on a cost basis.

GOPACS[13]

GOPACS, abbreviation for Grid Operators Platform for Congestion Solutions, was launched in 2019, and it is a project developed by TenneT and six Dutch DSOs. However, GOPACS is not a marketplace, instead it fits in the *market intermediaries* category. It aims to be an integration of local flexibility dispatch into existing market platforms. As of today, it is only available for ETPA, the Dutch intraday market platform. Since it is an integration within ETPA, GOPACS offers are like normal offers, but they have an additional locational tag that allows to locate the offer and dispatch it for grid management purposes. As of today, GOPACS is only operative in Intraday Trading, which means that the offers are cleared in a continuous manner.

Enera/LocalFlex

[11] Piclo Flex Lithuania - Dashboard - Piclo Flex
[12] Nodes platform - Home - NODES (nodesmarket.com)
[13] GOPACS platform - Home - GOPACS

Enera was a joint project developed in Germany by the market operator EPEX-SPOT, TenneT, EWE AG, Avacon Netz, and EWE Netz. It was operative from 2017 to 2020, and it aimed to provide DSOs and TSOs with additional tools to avoid curtailment of wind energy, which is a problem in Germany. Enera's Flexmarket solution was also focused on intraday trading of flexibility and therefore it was a continuous clearing market. Recently, after closing the Enera project EPEX SPOT has bought a local flexibility platform and has branded it with the name of LocalFlex [37]. The LocalFlex technology was developed by Centrica and N-SIDE during the Cornwall LEM project. One of the characteristics of the Cornwall LEM is that it was network-aware, meaning this that the market clearing algorithm performs power flow analysis before accepting an offer to ensure the physical feasibility of market clearing. The information about the acquisition of Centrica's platform by EPEX SPOT is scarce, but if the network aware capabilities have been maintained in the final product, this would be the first commercial platform to have such innovative technology.

The local flexibility market ecosystem is still at an incipient state, Figure 16 shows the capacity in MW of contracted-through LFMs of local flexibility by DSOs in the EU countries with highest use of flexibility.

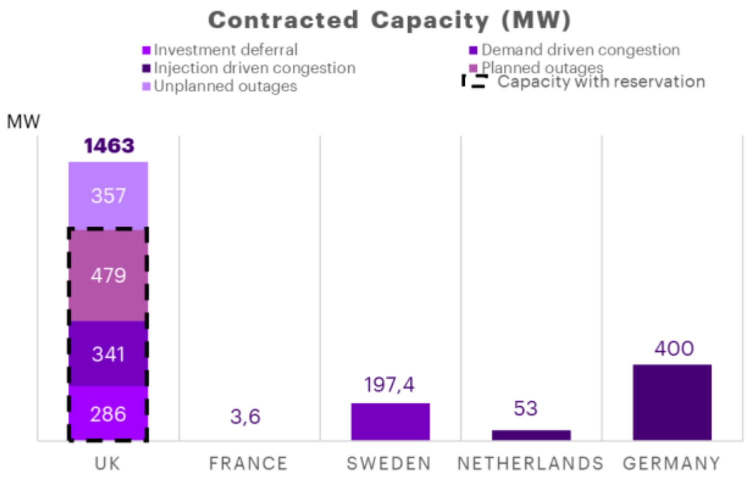

Figure 16. Contracted local flexible capacity in EU's best markets.

Furthermore, NODES and Piclo provide open access to information about their market clearing results which gives some insights to today's use of local flexibility by DSOs. With that said, it is relevant to mention that local flexibility is already in use for other purposes, for instance from 2012 France allows DERs to participate in balancing markets, since then the price of balancing has been reduced up to a 20%, and a total of 1.6 GW of balancing capacity is provided by DERs [38].

1.4.2 Local Flexibility Markets Characterization

The definition of market products influences which are the assets that can and cannot participate in flexibility markets (ancillary and non-ancillary), and therefore the business ecosystem of the market itself. The following paragraphs show the most relevant characteristics of flexibility market products as defined by ENTSO-E in the Electricity balancing guidelines. Even though local ancillary and non-ancillary services can be very different, this thesis follows Coordinet's approach. In that project LFM products are described using balancing product characterization rules, and some additional but necessary elements. This "standardization" should simplify the adoption of new market products to existing market players.

The following table, extracted from Coordinet's Deliverable 1.3 [39] shows the relevant product characteristics according to ENTSO-E together with their definition. A third column has been added to it. On this column it is given a qualitative assessment of how products should be designed to reduce market-entry barriers for DERs, particularly the smallest ones: Prosumers.

Table 2. Relevant characteristics to define a flexibility product.

Characteristic	Definition	LFM
Preparation period	The period between the request by the SO and the start of the ramping period.	The higher the better*
Ramping period	The period during which the input and/or output of power will be increased or decreased until the requested amount is reached.	The higher the better*
Full activation time	The period between the activation request by the SO and the corresponding full delivery of the concerned product.	The higher the better*
Quantity threshold	The maximum and minimum quantity of power for one bid.	Minimum quantity - as small as possible
Duration threshold	The minimum/maximum length of the period of delivery during which the service provider delivers the full requested change of power.	As short as possible: MTUs** of 15' are better than 1h for prosumers
Deactivation period	The period for ramping from full delivery to a set point, or from full withdrawal back to a set point.	--
Granularity	The smallest increment in volume of a bid.	As small as possible: 1 kW better than 0,1 MW
Validity period	Period during which the bid offered, if accepted, can be activated.	The shorter, the less uncertainty
Mode of activation	Manual or automatic.	--
Availability price	"Capacity" payment for flexibility [€/MW].	Yes
Activation price	Energy payment for flexibility [€/MWh].	Yes
Divisibility	The possibility for a system operator to use only part of the bids offered by the service provider.	--
Locational attribute		--
Recovery period	Minimum duration between the end of deactivation period and the following activation.	The larger the better. This is relevant for BSS
Pooling allowed	This attribute determines whether a grouped offering of power by covering several units via an aggregator is allowed.	Yes – Crucial for prosumers
Symmetry of the product	Up (generate more/consume less) and Down (generate less/consume more) are divided in two different products.	Yes – Crucial to reach technology neutrality

* Depending on the product this is not an option, e.g. FCR. However, the idea is to keep the requirements as relaxed as the product allows to.
** Market Time Unit (**MTU**)

None of the qualitative definitions of the LFM column in the previous table will have a negative impact to assets able to provide flexibility with higher technical standards, but they will ease participation of new actors, such as prosumers, in flexibility markets. Traditionally, balancing markets have restricted participation to big generation assets – over 1/5/10 MW- that were built to be an active part of the power system. One of the challenges with LFMs is participation/liquidity, because generation at distribution side tends to be vRES, hard to actively control, and on the demand side there are mostly prosumers and industries who use electricity as a commodity for a purpose, and therefore flexibility is "only" a side hustle.

Now that product characterization has been addressed, there are some additional characteristics of a flexibility market that are important to address. These are separated from the previous table because they are not directly linked with flexibility and the actors providing it. However, the following concepts are relevant for the thesis and will have a certain impact on the participation and outcomes of the LFM.

Market clearing strategies

Two are the main market clearing strategies Continuous Clearing and Auction. Continuous clearing refers to a market that as soon as an offer and a request are compatible, they are matched by the algorithm. This strategy tends to be used in close-to-real-time markets where market clearing is a priority. Continuous clearing mechanisms are not able to optimize market clearing neither form the price perspective nor from the system perspective, and they require the price settlement strategy to be price-as-bid. Auction-based market clearing is the strategy where the market has a market gate closure for one or multiple market time units, during the period before the market gate closure offers and requests are collected to be matched in an auction. This strategy is used in markets that are not close to real-time markets, such as the European day-ahead market, powered by the Euphemia algorithm [40]. The auction-based clearing allows for optimization of multiple parameters such as social welfare and power flows, together with flexibility in price settlement strategies. Either paid-as-bid or paid-as-cleared can be used.

Price settlement strategies

As with market clearing strategies two are the most recurrent pricing strategies in energy markets: paid-as-bid and paid-as-clear. Taking the definition from UK's Office of gas and electricity markets [41], under a paid-as-clear scheme market participants offers, if accepted, are awarded the price of the most expensive offer accepted. Instead, in a paid-as-bid scheme market participants offers, if accepted, are awarded the price they asked for[14]. Additionally, these strategies can be somehow linked to types of market clearing. Due to the "last-minute" nature of continuous clearing the only possible price settlement strategy is paid-as-bid. In the case of auction clearing both strategies can be used.

Market clearing algorithm/s

Finally, there is the capacity/extent of market clearing algorithms. This is the core motivation of the thesis and therefore it is important to clarify it before moving into the *Research Work* sections. As mentioned in previous sections there are multiple and very different electricity markets; however, in terms of market clearing one or two variables are considered to assign the cleared offers a) cost, and b) sometimes physical state of the network. Based on these two capabilities, there can be two types of market clearing algorithms:

[14] Paid-as-bid: There are multiple variations of this pricing scheme. However, the idea remains the same throughout all of them. In the algorithms used two different approaches have been taken due to the nature of the different algorithms. In the **continuous clearing** algorithm, the price is set buy the first bid in the market (only if price offer ≤ price request). In the **auction-based**, the accepted offer is paid at the asked price.

- Network aware algorithms: algorithms that (also) consider the physical state of the network while clearing the market.
- Non-network aware algorithms: algorithms that do not consider the physical state of the network while clearing the market.

As of today, the best representative of the Network aware market algorithms is the EUPHEMIA algorithm/s developed by N-SIDE and used in the Day Ahead market within the Price Coupling of Regions (**PCR**). To operate, EUPHEMIA needs information regarding the grid's topology (European HV grid), network data, and the DA market orders. As mentioned in the previous sections, EPEX SPOT has bought a LFM platform from Centrica (and N-SIDE) that originally was network aware. However, the information available regarding the purchase is scarce and the author of this thesis cannot guarantee that LocalFlex is a network-aware platform. The rest of the electricity markets from future markets to intra-day, and balancing to LFMs, are not network aware. This is the case of the LFM platforms mentioned previously [42], except for LocalFlex.

2. Methodology

2.1 Methodology of the Research Work

The research work to be developed during this thesis and presented in the Chapter 3 is a combination of business case and power system operation analysis. At this point it is relevant to mention that the core of this thesis is linked with innovative business model development in the power system. Therefore, even though the component layer of the power system is the core of any "electricity-based" business model in this thesis it takes a complementary role.

The methodology followed in the research work is the following one. First, the business ecosystem of local flexibility markets is analysed and defined, considering todays and future scenarios. Once the business actors, their business goals, and their interactions are clearly defined, the thesis moves into the more specific business case analysis. In the business case analysis this thesis aims to present a realistic use of local flexibility market to understand the impact of the innovative network aware market clearing for each of the business actors. It is during the business case that the developed algorithms are presented, together with the set-up used to analyse their performance. After introducing all the necessary elements, and justifying the relevant assumptions made, the results of the analysis are presented. Finally, moving back to the business side of the analysis, during the discussion the obtained results are analysed and discussed in the power system context, together with inputs from real stakeholders of LFM markets whose perspective complements the (limited) quantitative assessment performed during the results sections with their expertise on the field.

2.2 Open Research Questions

Up to this point the previous sections have schematically presented the structure and current situation in the European power system and have introduced the concept of local flexibility markets by showing their potential applications and the current market readiness level of the different alternatives. The EU is promoting the creation of regulations that eases the implementation of LFMs and incentivizes DSOs to use them to manage their grids. Therefore, LFM software can be a good business opportunity in the coming years. This thesis research questions aim to evaluate the business potential of innovative network aware market clearing algorithms, and how they impact the business model of the different business actors, with specific emphasis on the flexibility market operator.

So, the **research problem** to address can be summarized in the following sentence:

Can a network aware market clearing algorithm increase the value proposition of a local flexibility market platform?

The open **research questions** that this thesis will answer are:

1. Do network-aware market clearing algorithms have an impact on flexibility procurement costs for distribution system operators?

2. How does the complexity of the grid and the number of bids in the market affect the performance (execution time) of the market clearing algorithms?

3. Do network-aware market clearing algorithms have an impact on flexibility revenues for flexibility service providers?

4. Which are the differences for a flexibility market operator between operating a network aware and a non-network aware local flexibility market?

5. Can network aware algorithms increase/ease participation in the local flexibility market?

This thesis aims to answer the research questions presented above through algorithm testing in a simulated environment and interacting with market participants to understand their pains and needs.

3. Research Work

As presented in the previous sections the power grid is undergoing a process of transformation towards a greener and less centralized system. The role of RES and their “distributed-resource” nature is forcing distribution system operators to not only upgrade, but also to actively manage their grids. The EU, in the Clean Energy Package, has clearly stated that DSOs have to actively manage their grids through the use of flexibility, and that this flexibility has to be procured in a market-based manner – when cost-effective. The power system at the same time is undergoing a digitalization process and system operators are not the exception. However, from the business case perspective DSOs and TSOs are neither IT companies nor software developers, therefore the digitalization of the power grid is creating a new wave of business models to serve the new needs of the grid. One of these cases are Local Flexibility Markets, and this service (and subjacent business model) is the core of this thesis. As of today, FMOs offering is focused on being a software as a service (**SaaS**) platform where DSOs can procure flexibility products to solve grid issues, with sometimes additional features such as connection to TSOs markets (NODES is doing it in some of their pilots to maximize the value of flexibility for flexibility suppliers).

This section is devoted to understanding the business benefits and challenges of implementing network aware market clearing algorithms within an already existing FMO service. The first part of the work is focused on defining today’s business ecosystem of a local flexibility market and understand the potential business ecosystem of the future LFMs. Then a case study is performed to evaluate the quantitative and qualitative impact of implementing network aware market clearing algorithms for all business ecosystem stakeholders. Finally, the results obtained are discussed together with the inputs received from real flexibility market actors who have shared their view on the challenges and potential of such innovative development in the LFM field.

3.1 Business Ecosystem

The core objective of this thesis is to identify, study and quantify the value propositions of implementing network-aware market clearing algorithms for LFMs. Ideally, the use of network-aware algorithms should increase/ensure grid KPIs related to SoS and QoS. However, the use of these algorithms has implications on all the business actors that make relevant an analysis of the business case behind this innovation.

Before starting with the business case analysis, this thesis presents its conceptualization on how today’s LFM business ecosystem looks like, and how it could evolve in the coming years. Following the definition from EY [43]: “*A business ecosystem is a purposeful business arrangement between two or more entities (the members) to create and share in collective value for a common set of customers. Every business ecosystem has participants, and at least one member acts as the orchestrator of the participants. […]*”. Due to FLEXGRID extended scope (not only LFM operation) its business ecosystem is rich and complex in number of actors and roles. For clarity reasons the business ecosystem hereby described is simplified and contains the most relevant actors and the roles they undertake. Whenever it has been possible the roles defined by the ENTSO-E Harmonized Electricity Market Role Model have been used. The added ones are marked with an “*”.

- System Operator
    - Distribution System Operator*
    - Transmission System Operator*
- Market Operator
- Flexibility Market Operator*

- Balancing Responsible Party
- Flexibility Service Provider *
- Balancing Service Provider

In this business ecosystem some of the roles are clearly represented by a party with a single role assigned. This is the case of the DSO, TSO, MO and FMO. However, some roles can be performed by very different parties. This is the case of the BRP, BSP, and flexibility service provider (**FSP**). In Figure 17 it is further developed the type of power system actors that can undertake these roles within the scope of the thesis.

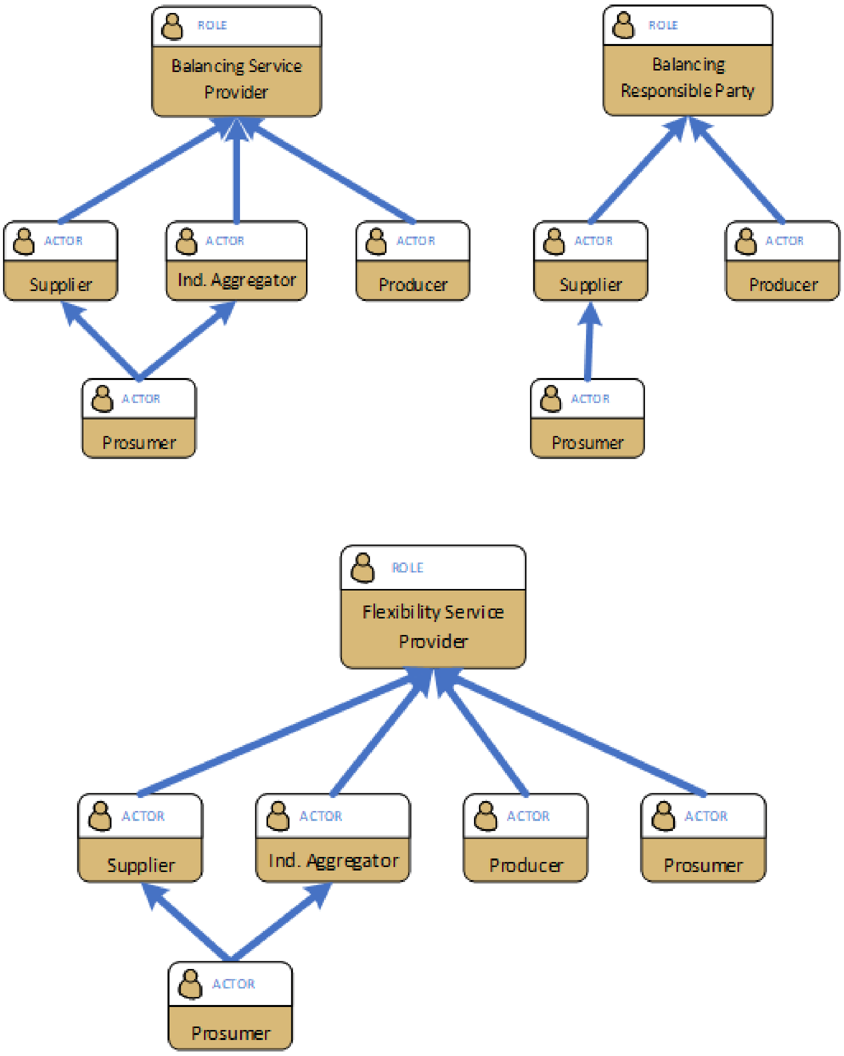

Figure 17. Local flexibility market actors mapped to roles in the context of this research.

So, the LFM business ecosystem considered in this thesis is the one presented in Figure 18. This business ecosystem contains the state of the art of today's operative flexibility market platforms (NODES and Piclo Flex). The interaction with Balancing Markets is something that can only be seen in some NODES pilots, whereas Piclo Flex is 100% focused on local flexibility trading. Since LFMs are still at an early-stage standardization is not a thing yet, therefore depending on the project/LFM implementation you consider the business ecosystem participants and interactions can slightly change.

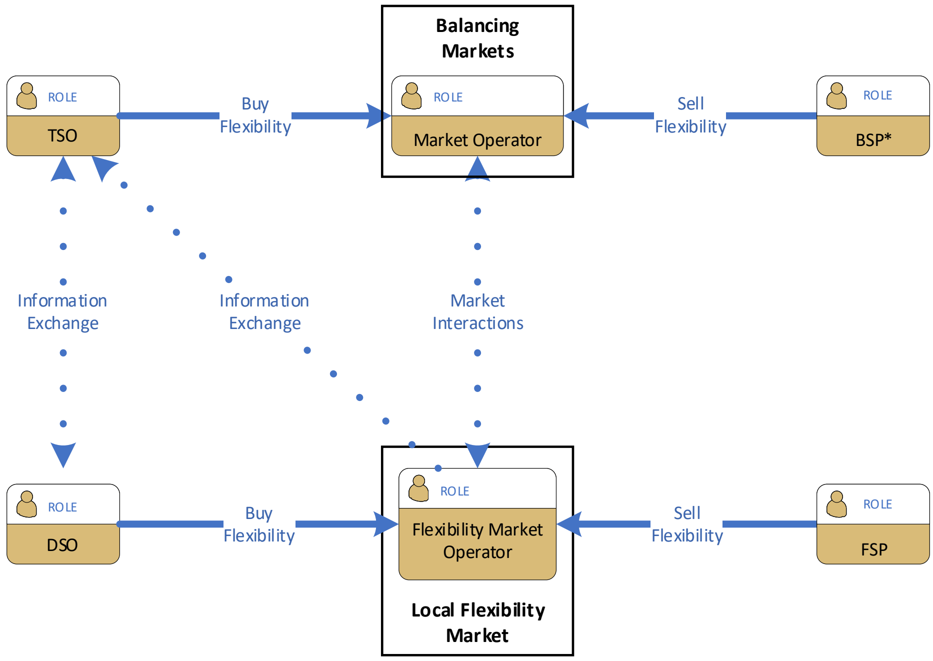

Figure 18. Local Flexibility Markets "short-term" business ecosystem

The business ecosystem presented in Figure 18 is already complex. However, FLEXGRID project works on the future of flexibility markets by proposing new services and innovative business models. Therefore, it not only aims to show today's business ecosystems, but also to investigate the potential of future innovations to create new and better solutions for flexibility provision. It is in this long-term scenario that a different LFM business ecosystem could be considered, Figure 19 presents a more futuristic approach to LFM participation.

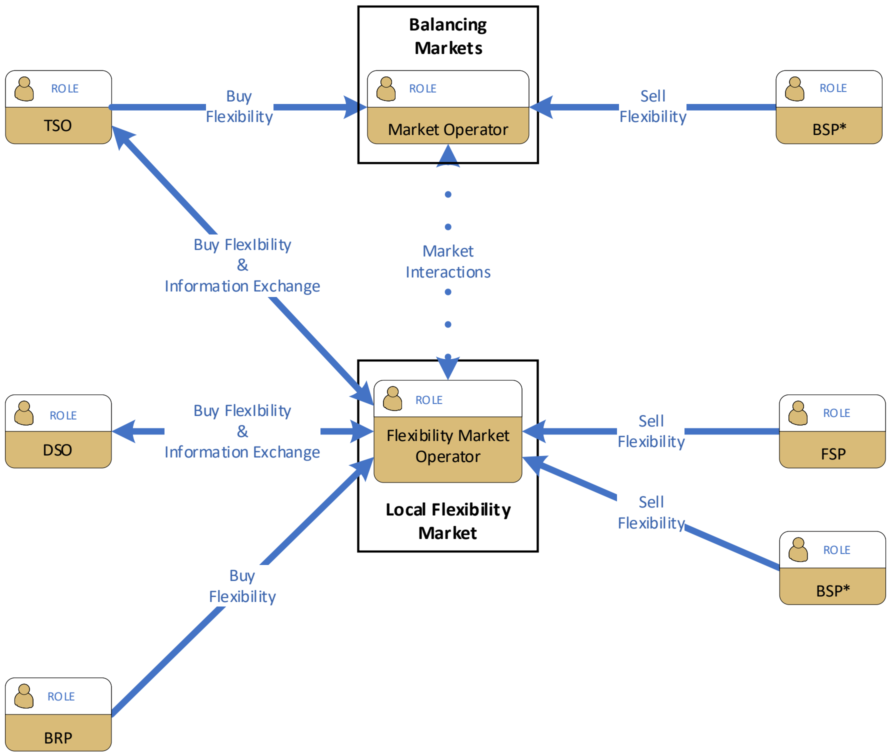

Figure 19. Local Flexibility Market "long-term" possible business ecosystem.

3.2 Case Study

The research problem of this thesis is focused on network aware LFMs business models. As of today, from all the LFM platforms in the market, only EPEX SPOT with their platform LocalFlex is offering network aware capabilities in their local markets. Based on the current LFM offering, being non-network aware is not a significant burden for the FMO's business model; however, in an envisioned future with higher number of flexible DERs connected to the distribution grid, not considering the grid limits in the market clearing process could lead to unfeasible transactions, and therefore more issues to the grid.

A business case analysis is one of the steps of the business model efforts made by companies to clearly define their business proposal by showing the value they give to the clients, identifying the key partners to reach the goals, etc. Figure 20 shows where the scope of this thesis is focused within the business development process.

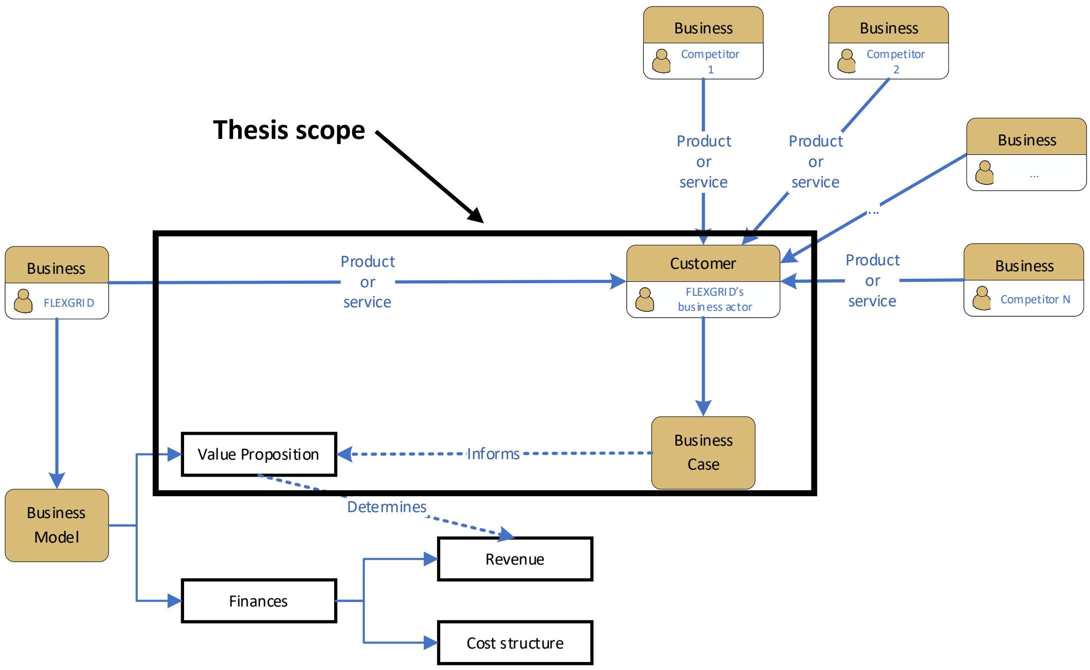

Figure 20. Business development process schematic

The main objective the business case analysis is to quantify up to which extent the innovative solution developed in the FLEXGRID project can help FMOs reach their business goals. The overreaching goal of FMOs consist of increasing the offering of services to system operators (SOs). So, the business ecosystem is complex because it consists on a dual sided market. The FMO offers a service to both system operators and flexibility providers. However, as of today DSOs are the ones who pay for the implementation of the system in their grids. In other words, LFMs solve problems to DSOs while creating extra value for flexibility providers. Therefore, the business ecosystem has to be divided hierarchically in two different levels:

- Flexibility market operators and DSOs: This level represents the seller and the buyer of the service.
- Market participants: In this level all the market participants are included. Flexibility suppliers and flexibility buyers are stakeholders in this business case and the impact of the proposed solution to their business objectives can determine the market viability of the proposed innovation

This business case is considering a fictional FMO who is already operating a local flexibility market - in a reactive manner[15]. In the business-as-usual scenario this LFM does not consider the physical constraints of the distribution grid when clearing the market. Whereas in the analysed case, it does. In both scenarios the DSO is the only buyer of flexibility (monopsony), and multiple FSPs offer their flexibility to the market. During the analysis, the market clearing algorithms are tested in different conditions of the grid and different levels of market participation (liquidity).

Two different market clearing algorithms are tested in this thesis: continuous clearing and auction based. Even though both algorithms serve a similar purpose their characteristics and capacities are different, for this reason they will be analysed as independent entities, and only compared in those aspects where they "compete" with each other.

3.2.1 Description of the Algorithms

This sub-section is based on FLEXGRID's Deliverable 5.3 [44], where DTU presented the results of the network aware market clearing algorithms development. On it, the logic behind the algorithms is presented together with parts of the code to show how the algorithms operate.

First, the main goal of a network aware market clearing algorithms is to stablish feasible operating points for all market players while matching buy and sell orders. The decision-making process of it can be the result of an optimization process trying to maximize, for instance, social welfare, or it can be the result of a more basic continuous market clearing process. In the case of auctions, Optimal Power Flow (**OPF**) algorithms have been used, since the auction format allow to optimize the market clearing. Instead, in the case of continuous markets Power Flow (**PF**) algorithms are used since the market clearing strategy does not allow for optimization. PF algorithms do not optimize the market clearing but oversee ensuring that the final operating points respect the network constraints

When compared to traditional non-network aware algorithms, in this case the FMO offers additional value/service by clearing the LFM while ensuring that the final operation point does not violate the distribution grid limits. For this reason, the inputs of the network aware algorithms are more extensive than in the non-network aware one. The additional inputs needed are:

- Grid topology data
- Grid day-ahead schedule
- Bids with location of the flexible assets in the grid

Grid Topology & Day-ahead Schedule

The grid topology data is a static input that needs to be provided by the DSO, and only updated when new infrastructure is built. The following list presents the necessary data to define the grid for the algorithms:

- Bus:
    - ID
    - Maximum voltage (p.u)
    - Minimum voltage (p.u)

[15] Reactive LFM: As mentioned in the Literature Review section, the main cause for the need of flexibility at a local level is the coper plate assumption done in the Day Ahead market. A reactive LFM, is a local flexibility market that following the current market clearing structure tries to correct these issues. The alternative is a proactive local energy market that is cleared before the day ahead market, allowing DSOs to control the feasibility of the DA market transactions, instead of correcting them afterwards.

- Branch:
    - ID
    - Buses connected
    - Resistance
    - Capacitance
    - Maximum power

The day-ahead schedule is a dynamic input that needs to be collected by the FMO for every market time unit. It serves as the base for the power flow calculations, to check if the activation of an asset is viable. The day-ahead schedule consists of the scheduled active and reactive power of each bus.

Bids

When market participants submit a bid, either offer or request, to the LFM it must follow a standardized structure specifying different characteristics of the bid. The following list presents them with the name used in the code:

- **Quantity**: Volume in MW/h
- **Price**: Price in €/MW
- **Direction**: Indicates the regulation direction, up or down. An up regulation offer means either increase of generation or reduction of load. From the algorithm perspective the setpoint of the node will increase. A down regulation offer means decrease of generation or increase of load. From the grid node perspective, the setpoint will decrease.
- **Bus**: Indicates which node of the grid is the bid located.
- **Time_target**: Indicates which time period is the bid valid for. For instance, time target t10, can mean that it is for the 10^{th} MTU cleared.
- **P_or_Q**: active (P)or reactive (Q) power
- **Type**: It is a request exclusive characteristic and indicates if it is Conditional or Unconditional.
- **Bid**: Indicates if it is an Offer or Request.

Then some attributes are specified by default:

- **ID**: It is an assigned unique bid ID identifier.
- **Time_stamp**: Indicates the day, hour, and minute the bid was submitted. It is an attribute relevant for the continuous clearing algorithm, but not used in the auction-based one.

Continuous market clearing

Continuous market clearing uses power flow algorithms to evaluate the physical feasibility of each potential market transaction. DTU has developed 3 algorithms, one for energy market clearing (1), another for active power reserve market clearing (2), and the last one for active and reactive power reserve market clearing (3). For algorithms 1 and 2, since they are focused on local energy markets (MWh) or active power reserves (MW), the algorithms simplify the network check by considering a DC-PF (Direct Current Power Flow) problem. However, in this thesis the algorithm tested is the one for active and reactive power reserves. In this case the LinDistFlow [45] simplification is used for the network check. LinDistFlow is a linearized approximation of the non-convex AC power flow calculation algorithm. The trade-offs of this simplified algorithm are that line losses are neglected to allow for linearization. Power flows and node voltage are calculated.

Operatively speaking a continuous market is cleared every time a new offer/request is submitted on a first-come-first-served basis. In this sense, the algorithm stores the non-matching bids in two shared orderbooks, one for offers and the other for requests. Each time a new bid arrives, the orderbook of "contrary" bids is checked. However, once a bid has entered the orderbook it is sorted on a price basis. For requests the highest in price goes first and for offers the lower-price bid goes first.

When it comes to matching, it is a multiple step process. First the price is evaluated. If the price of the offer is lower or equal to the price of the request the algorithm moves to the second criterion, physical feasibility. In this step the new state of the grid is calculated. The algorithms developed by DTU are able to perform partial execution of offers, and therefore the algorithm starts by checking the state of the grid considering full activation. If it is not feasible, the algorithm will reduce the size of the offer by epsilon[16] and calculate again the state of the grid until the market clearing is feasible, or the bid size reaches zero. The algorithm now does not allow to select the type of bid (e.g: Fit-or-Kill), and if a bid is not fully matched the rest of it will be stored in the shared orderbook.

Pricing-wise, the continuous clearing market implement a paid-as-bid methodology where each participant gets the price of the standing bid. This method is different from the implemented in the auction-based algorithm where the request sets the maximum price, but the offers get the price they have asked for.

Finally, moving to the network check part and how it works. It is based on a scheduled energy baseline (in the following sections called initial setpoints). This initial setpoint must be given to the algorithm to be able to do the power flow calculations. Then, once two bids are matched on a price basis the new setpoints are checked by the algorithm (see Annex II – Continuous Clearing LinDistFlow) if the bid is accepted the initial setpoint is "modified". One of the innovative characteristics added by DTU to the algorithm is the consideration of stochasticity in the clearing of power market reserves. To do so, the algorithm does not only check the feasibility of the latest clearing but tests the impact of all possible combination of activations. It does so to ensure that no matter which offers are activated there will not be any new congestion in the grid. This characteristic aside from innovative can be quite intensive in computational power therefore DTU allows to "turn it off". To do so the flexibility requests have to be defined as Unconditional, which means that any offer accepted will be activated with a 100% certainty. Unconditional requests are also a way to convert the algorithm form power reserve market to energy market.

Auction-based market clearing

Focusing the scope on OPF algorithms there are multiple possible implementations. From full AC-OPF which considers all the network qualities in its calculations, to simplified versions such as DC-OPF where few network qualities are considered. However, the more extensive and precise approach of a full AC-OPF algorithm comes at the cost of a non-convex problem (it is not guaranteed to find the global optimum).

The algorithms developed by DTU are based on AC-OPF algorithms simplified by using the LinDistFlow approximation. A linear approximation of the DistFlow [45] method, which is a method that uses a second order cone programming relaxation. Even if it is not the most

[16] Epsilon: This value can be defined by the user. The lower the epsilon, the higher the execution time of the algorithm.

complete and accurate market clearing method, DTU has considered that the LinDistFlow approximation is good to serve its purpose and at the same time allow for different implementations: from market clearing with different objective functions such as minimize procurement costs or maximize social welfare, to identification of congestions by a DSO.

Operatively speaking an auction-based market clears once for each market time unit, waiting until the market gate closure time for each MTU or multiple MTUs at the same time. The market clearing solution developed by DTU is formulated as a multi-period optimization problem. Therefore, it is capable of clearing multiple MTUs at the same time, and it will try to optimize the solution for the whole-time horizon of the given MTUs. In coding language this is implemented by using Pyomo's block object, each MTU is represented by a block and then Pyomo optimizes the whole sequence. This means that the final optimization problem, is built as a Mixed Integer Linear Program.

In the case of the auction-based algorithm, the network aware part is embedded in the code as part of the constraints of the optimization problem. This thesis uses the simplified version of the AC-OPF algorithm simplified through the LinDistFlow method. This algorithm allows for calculations considering active and reactive power, and its outputs are: power flow through lines and node voltages. With that said, the product traded in this thesis simulations (as it will be described in the coming sections) is for congestion management and therefore linked to active power.

All the solutions developed in FLEXGRID are open source, and you can find them at the Github repository: FLEXGRID [46]. There you can see in full detail how the algorithm has been implemented in Python's Pyomo library[17]. The most relevant lines of code can be also consulted in Annex III – Auction-based algorithm.

Finally, the payment method defined in the auction-based algorithm is the classic paid-as-bid. On it, market participants (if their bid is activated) get paid what they have asked for.

3.2.2 Experimental Setup

The case study hereby presented analyses the operation of a local flexibility market in a "real" distribution grid, during multiple market clearing events. Network aware market clearing behaviour and performance are directly linked to the specific conditions of each event. For this reason, the analysis is done under multiple grid states and with different types of market orderbooks, to capture the differences in behaviour in a "wide range" of situations. These cases used to evaluate the grid have been artificially created due to the lack of information regarding the grid daily load profile and flexibility potential of its connected assets. In the following paragraphs the set up created for the case study will be explained, together with the assumptions made and their correspondent justification.

Grid Topology & Assets

The distribution grid used the case study, is the only "real" piece of information given to the algorithm. It has been provided by bnNETZE, a German DSO, and is in the Freiburg area. The grid has 81 low voltage nodes connected through a radial topology (see Figure 21). The DSO has provided all the information needed to create the virtual model of the grid - line maximum power capacity, node voltage ranges, and line impedances. The information regarding the grid

[17] To find the block implementation read through P_and_Q_Market_Clearing.py, and to find the variables, constraints and objective function read through the Market_clearing.py file.

limits and impedances will be part of the inputs for the network aware algorithms; however, it cannot be disclosed any further since it was shared under a non-disclosure agreement (**NDA**).

Regarding the assets in the grid, as of today the main use of flexibility by DSOs is congestion management. Within FLEXGRID other business cases have been analysed which gave very relevant insights on the potential of congestion of DSOs grids. In FLEXGRID's Deliverable 8.3 [47] there is a business case analysis to evaluate the difference between grid investments (infrastructure upgrade) and the use of local flexibility markets to defer investments. In that business case the DSO uses another distribution grid from the same region. In that grid the yearly peak power is only reaching the 14% of the line total capacity. In under-utilized lines such as that one, the risk of internal congestion is low. Even though grid utilization is a grid-specific characteristic, according to the DSO nowadays in Germany DSOs' grids have very high security margins incentivized by regulation. As presented in the literature review sections, today's implementation of flexibility markets is focused on grids under high utilization levels to alleviate congestions while "waiting" for the grid expansion. In the future, the applications of local flexibility markets can be extended to include more actors and to cover more situations; however, the scope of this thesis is to evaluate the business case for network aware algorithms in today/near future scenarios. Therefore, it has been considered that the best environment to test the algorithms is in a grid with risk of congestions. For this reason, that environment has been synthetically created by replacing the assets connected to each node by synthetic assets (either generation or demand). To do so an iterative process has been used testing how each of the connections affect the system and avoiding any kind of configuration that would put the grid under immediate risk. Moving into the assets considered for the simulations, they have been classified in three categories:

- **Generation**: Within the generation category is included any generation facility over 50 kW. For clarity purposes this generation units have been defined as RES parks, either of wind power or PV farms. However, this differentiation is not relevant for the algorithm (technology agnostic) that only evaluates and optimizes power flows. The total of generation nodes is 6, with at total installed capacity of 1,34 MW.

- **Industrial Loads**: Within this category any load above 50 kW has been included. One more time, for clarity purposes on Table 3 they are identified as EV charging stations. The technology behind the load is not considered by the algorithm, but the author of the thesis has considered that since electrification of transportation is one of the challenges of today's power system it would be interesting to present the industrial loads as EV charging. The total of industrial loads nodes is 8, with an installed capacity of 1,25 MW.

- **Prosumers**: The rest of the nodes in the grid have been defined as prosumers. They represent residential loads with a peak power of 5,2 kW, that can include PV generation and EV charging.

All the nodes in the grid have been assumed to be capable of participating in the flexibility market from the technical perspective (some of them will other will not depending on the scenario evaluated).

Table 3: Characterization of assets connected to the test grid.

Generation: Wind and PV farms

Node	Maximum Power [MW]
117	0.3
130	0.2
138	0.3
154	0.3
172	0.12
181	0.12
Industrial loads: EV charging station	
Node	**Maximum Power [MW]**
116	0.2
121	0.2
132	0.15
137	0.2
168	0.1
177	0.1
182	0.1
183	0.2
Prosumers	
• The maximum power rating of the household is 5,2 kW. • Some households also have PV panels.	• Some households have additionally an active EV charger.

Figure 21 presents a visual representation of the topology of the grid together with the positioning of the synthetic loads described in the previous table.

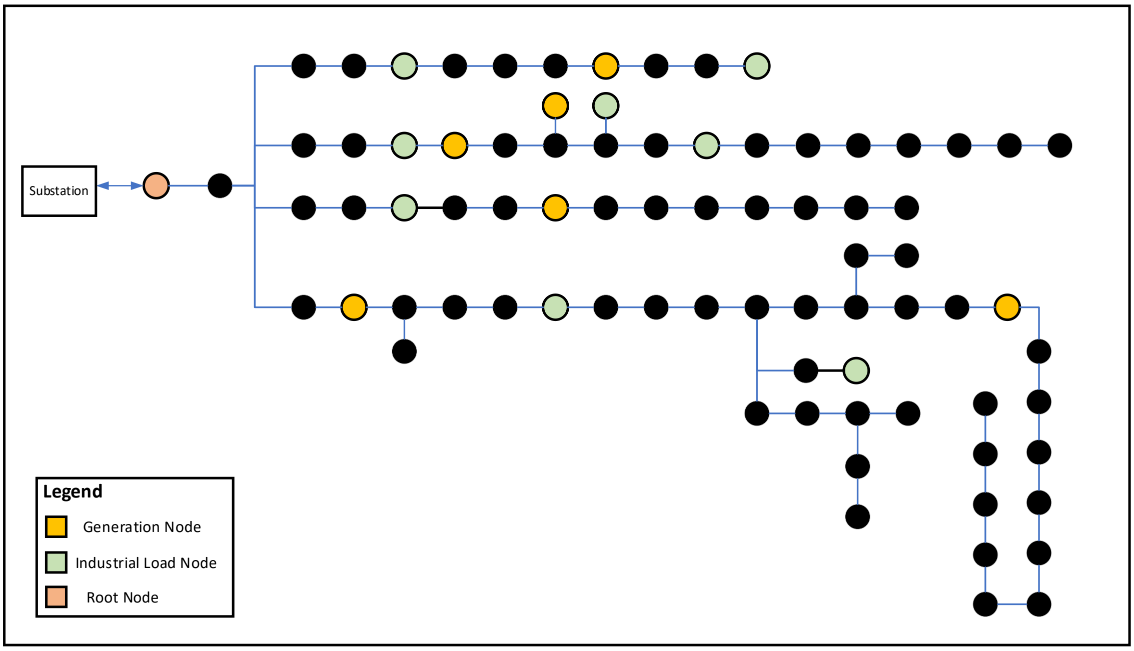

Figure 21. Topology of the grid used for the case study.

Schedule of the assets – Initial Setpoints

Based on the connected assets, the scheduled set points of the grid have been created. This set points represent the day-ahead scheduled load and generation, and in most of the cases studied represent the trigger for the use of the LFM. The setpoints have been created from scratch through an iterative process. First an initial setpoint is created considering the characteristics of the scenario and the assets in the system. Then using a modified version of the market clearing algorithm the physical feasibility of the setpoint was checked and modified to respect the grid capacity and voltage limits. On Annex V – Initial Setpoints Creation, the process and the code used to create the initial setpoints are explained step by step, together with the initial setpoints used.

Three are the initial setpoints created to evaluate the performance of the market clearing algorithms:

- **High generation:** This set point considers a single market time unit where the set point of the assets creates a congestion at the root node of the grid due to reverse power flows. The line capacity connecting to the root node is at 214%. Additionally, from the rest of the lines, three of them are at utilization rates over 60%. One operating at 97%, another at 75% and the third at 65%.

- **High demand:** This set point considers a single market time unit where the set point of the assets create a congestion at the root node due to high load. The line capacity connecting to the root node is at 212%. Additionally, from the rest of the lines, two of them are at utilization rates over 60%. One operating at 99%, and the other at 71%.

- **Normal operation:** This setpoint considers an initial setpoint of the grid where there is no congestion or voltage violations. The line connecting the root node with higher voltages is operating at 48% of its capacity, and the maximum usage of a line is at 71%.

The created setpoints (see Annex IV – Initial Setpoints) are the second necessary input, after the grid topology, for the market clearing algorithm to evaluate the physical feasibility of the flexibility market clearing. The last part of the puzzle is presented below, and it corresponds to how assets participate in the flexibility market.

Market behaviour of the assets – Market orderbook

With the initial states of the grid defined, the last necessary input for the case study is the flexibility market orderbook. Before explaining that, it is relevant to properly define the kind of flexibility product traded in this analysis. After a thorough literature review of the operative local flexibility markets in Europe, and talks with the consortium partner NODES, it was decided to evaluate the market algorithm through active-power-related products. The reason behind it is that nowadays LFMs products are used either for congestion management or in some cases are also participating in balancing activities, both of which are based on active power trading [35].

To improve the clarity of the analysis it has been decided to define in further detail the product exchanged in the LFM. To do so, the same product has been considered for continuous clearing markets (usually used in markets operating closer to delivery time) and auction-based markets (usually used in markets operating on a daily basis). Table 4 shows the definition of the product characteristics. It has been assumed that all market participants fulfil the technical requirements for participation.

Table 4. Continuous clearing market product definition.

Quantity Treshold	Validity Period	Duration Treshold	Max. Number of Activations	Symmetry
None	60’	15’	1	No
Energy/Power	**Utilization Payment [€/MWh]**	**Availability Payment [€/MW/h]**	**Tender Period**	

Energy	No	Yes	Continuous/ Day Ahead (MTU 1h)

Table 4 presents which have been considered the most relevant characteristics for local flexibility market participation from the FSP/prosumer perspective [48]. In the section Local Flexibility Market Characterization (page 29) an extensive list of characteristics defining flexibility market products (ancillary and non-ancillary) is presented. The ones related to technical requirements of the assets have been assumed to be “aggregator-friendly” and fulfilled by all market participants. For the rest of market product characteristics, this thesis has defined the products considering, as much as possible, the weakest link of the flexibility chain, the prosumers. With the product definition happens the same as with the asset categorization, the market clearing algorithms are technology agnostic and they are not affected by the type of product traded. From the product perspective, the only characteristic that will change the “behaviour” of the algorithm is the type of power traded: Active and/or Reactive.

For the High Demand and High Generation initial setpoints, two types of market orderbook have been created:

- **Reduced Liquidity**: This orderbook considers a short-term grid scenario where flexibility offers solely come from generation and industrial loads. This case mimics a “realistic” scenario that could already be found in pilot LFMs. In some cases, even nowadays, some assets already have the necessary IT infrastructure, and are interested in the potential revenue stream coming from flexibility provision as early adopters.
- **High Liquidity**: This orderbook aims to mimic a futuristic orderbook that includes the participation of aggregators in flexibility markets. The orderbook is composed of the bids from the Reduced Liquidity orderbook, plus includes participation from prosumers. This methodology was used to reduce the influence of the orderbook bids when studying the differences in performance of the algorithm based on the size of the orderbook.

To make the analysis closer to reality, the size and direction of the bids has been randomly created but based on the flexibility potential of each node, considering its initial setpoint and typology of asset. The market in this two orderbooks mimics a monopsony, meaning that there is a single buyer, the DSO, and therefore a single request per MTU. For more detailed information see Annex VI – Code to Create Bids. Last, it must be said that (on average) both orderbooks contained a large enough volume of flexibility offers to cover the needs, so in very few occasions the market couldn’t operate correctly due to the lack of liquidity.

Finally, there is the Normal operation orderbook. On it all the nodes of the grid bid in the market either offering or requesting flexibility. Since the orderbook is randomly created, it cannot be precisely described. However, when it comes to the ratio offer/request, on average 80% of the bids are offers whereas the rest are requests, and in a similar fashion the average Up/Down regulation ratio is 50%. This orderbook is less coherent with reality than the previous ones, its goal is to pave the floor to analyse the behaviour of the algorithm in a more complex future scenario where multiple flexibility buyers compete for flexibility. Its analysis is relevant to understand the performance of the algorithms, thanks to the increased complexity of the market clearing solution and the misalignment of interests between market participants that could lead to potential implications for the distribution grid.

Market prices

In this business case the performance of network aware versus non-network aware algorithms is evaluated under the same market conditions. As of today, one of the main challenges linked to demand side flexibility is to understand the potential and value of this flexibility in each market. Flexibility of generation assets, energy storage units, and profit-oriented loads can be predicted up to a certain point by considering that they are willing to provide flexibility at any price higher than the revenue created by the commercial activity they are performing. This is a very broad assumption; however, it serves to understand the logic behind traditional flexible assets. However, flexibility coming from the demand side is not as easy to price since the energy consumption of a residential load or an EV charging point usually is not linked to a commercial activity but the habits and wills of people.

After this very brief introduction to the challenges of local flexibility price forecasting, it is important to consider that this business case is evaluating the added value for an FMO of using network aware algorithms. In this case, when two algorithms are compared under the exact same conditions, the price of flexibility can be considered a secondary variable. For this reason, two of the main challenges of local flexibility – availability and pricing – do not affect that much the results of this analysis. The results can be presented through the relative (%) difference in Social Welfare, Procurement costs or any of the KPIs selected related to money, between clearings of the same orderbook. This % information is already able to show the different behaviour between algorithms. With that said, this thesis acknowledges that price and availability of flexible assets is a real challenge for DSOs, as this report - [49] - from Liander shows when evaluating the feasibility of implementing local flexibility markets (GOPACS-based) to reduce grid congestions while updating the grid.

Efforts have been made to use real data from local flexibility markets. Piclo Flex has all the information from closed tenders available, and NODES has provided information of one of their LFM projects, under an “NDA”. But after analysing the data it has not been possible to extract any relevant correlation between size of the bid and price, even in data from a single local market. Furthermore, when trying to calculate the average price of flexibility for size segments it has been observed a very small difference between sizes from 0.01 MW to 0.2 MW bids. These findings are hard to understand, since 10 kW loads have different interests and behaviours than 200 kW loads. In any case, the market clearing algorithms need price as one of the inputs to clear the market, and therefore an average price value, extracted from Piclo, has been used to create the bids:

- Industrial loads, generation, and request: 643 €/MW.
- Residential loads: 631 €/MW.

The only reason behind the selection of this value is its similarity with public data from NODES projects, while respecting the small difference observed between smaller and bigger loads.

Overall, the complete experimental set architecture of the business case evaluation can be found in Figure 22, where, through a tree diagram, al the scenarios evaluated are shown.

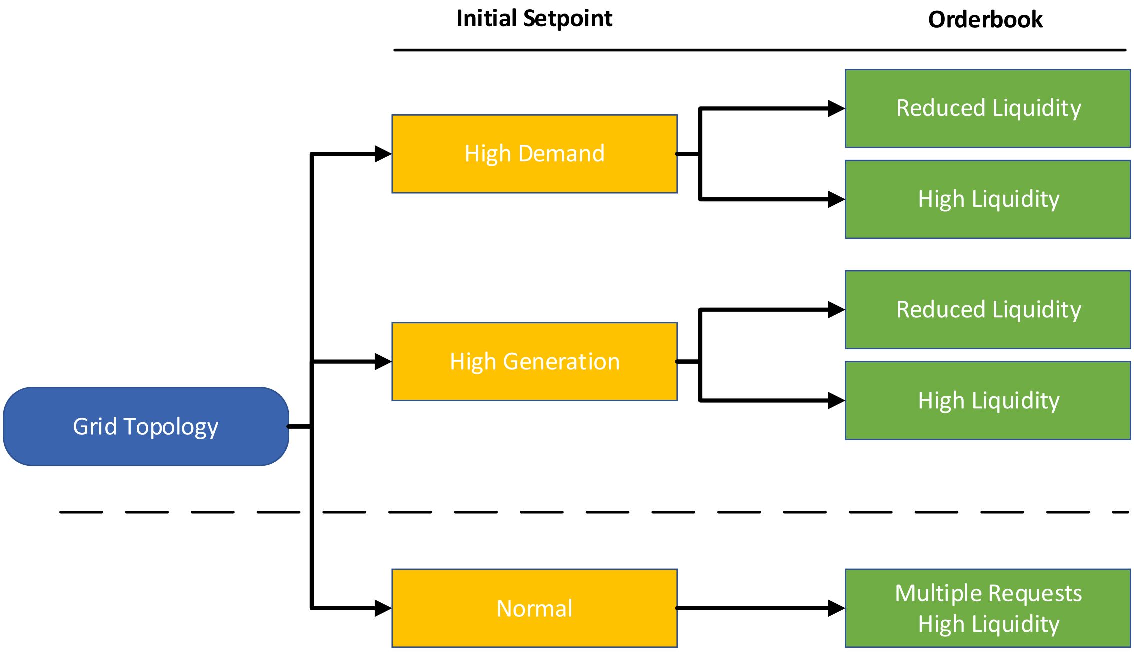

Figure 22. Tree diagram of the simulated market clearing scenarios.

Finally, regarding the simulation methodology: the market clearing events are simulated using both, network, and non-network aware algorithms. To reduce the influence of the assumptions made, 200 events have been simulated, half using the "reduced liquidity" orderbook and the other half using the "high liquidity" orderbook. Each new event is characterized by a randomized orderbook composition, while the rest of the inputs remain constant.

3.2.3 Key Performance Indicators

This section is focused on defining the KPIs that will be used in the Results to evaluate the performance of the market clearing algorithms. Since this thesis aims to evaluate the impact on the different business actors at two hierarchical/business interests levels, two categories of KPIs have been defined. Technical, related to the computational performance of the algorithms and therefore of interest for the FMO, and monetary, related to the results of the market clearing and therefore interesting for the market participants. Two types of market clearing algorithms will be evaluated: continuous clearing and market based, and each of them will be compared to the non-network aware version of themselves. As presented in the section *Description of the Algorithms* continuous and auction-based algorithms serve very different purposes and therefore some KPIs are more relevant for one or the other.

From the FMO perspective, after consulting with NODES the relevant KPIs identified are:

- **Execution time**: Time the algorithm needs to find the solution,
- **Execution time to find the first solution**: KPI that applies to auction-based algorithms only,
- **Difference between the optimum and the first solution**: KPI that applies to auction-based algorithms only.

From the market participant perspective (DSO and FSP), the identified relevant KPIs are:

- **Feasibility of the market clearing**: Binary KPI that indicates the physical feasibility of the cleared market transactions,

- **Energy not served**: Energy that cannot be served to end-users to respect the physical constraints of the grid,
- **Energy curtailed**: Energy that needs to be curtailed to respect the physical constraints of the grid,
- **Procurement Cost**: Total cost of flexibility procurement,
- **Social welfare**: Sum of the consumer surplus and the producer surplus. It does not consider additional costs linked to energy curtailment or energy not served.

3.2.4 Summary

Finally, before moving to the results section and to summarize and wrap up the Case Study section, the following tables present a summary of the inputs given to the algorithms in each of the created scenarios. First on Table 5 the type, number, and size of assets connected to the distribution grid is shown.

Table 5. Assets in the grid characterization.

	Number of Assets	Power Range
Generator	6	100 to 300 kW
Industrial Load	8	100 to 200 kW
Domestic Load	65	0 to 5.2 kW

Then, on Table 6 the initial state of the grid is presented for the High Generation, High Demand, and Normal Operation Cases.

Table 6. State of the grid based on the initial setpoint.

Scenario	Generation	Load	Flexibility Needed	Utilization of the grid
High Generation	0.81 MW	0.38 MW	0.23 MW Down Regulation	Three internal lines are over 60% capacity. One operating at 97%, another at 71%, and the last one at 66.
High Demand	0.44 MW	0.86 MW	0.23 MW Up Regulation	Two internal lines are over 60% capacity. One operating at 99%, and the other at 71%.
Normal Operation	0.77 MW	0.87 MW	0 MW	The root node is at 48% of its capacity, and the maximum usage of a line is 71%.

Finally, Table 7 summarizes the orderbooks used for the market clearing scenarios.

Table 7. Orderbook characterization.

Orderbook	Number of Offers	Description
Reduced Liquidity	14	Size of the offers are from 0 up to 0,2 MW. The average price is 643€/MW.
High Liquidity	72	Includes the previous 14 offers and adds 58 offers coming from prosumers. The size of the new offer ranges from 0 to 7 kW, and their average price is 631 €/MW.
Normal Operation	72	Mix of offers and requests, both for Up and Down regulation. The bid sizes go from 0,01 MW to 0,15MW, and the average price is 643€/MW. All the bids attributes are randomly created, but the offer/request ratio is 20/80.

3.3 Results

This section presents the outcomes of the event simulations. The results are given in the form of the KPIs previously defined. As presented in the business model, and shown in the KPIs definition, in this business case there are two types of actors with different business goals and interests, and therefore the algorithm can offer to them different value propositions. For this reason, the structure of the section will be the following. Each of the scenarios listed below will be presented independently. First the results will focus on the market clearing related KPIs (the ones that are of interest for DSOs and flexibility suppliers), in this part relevant insights of the behaviour of the algorithms will be shown. Then, the KPIs related to the computational performance of the algorithm (specifically relevant for the FMOs) will be presented and analysed.

- Continuous clearing – High generation
- Continuous clearing – High demand
- Continuous clearing – Normal Operation
- Auction based – High generation
- Auction based – High demand

3.3.1 Continuous Clearing Algorithm

High generation

The first and more important KPI to evaluate the difference in performance between a network and non-network aware algorithm is the amount of feasible and unfeasible market clearings. A feasible market clearing signifies that the activation of the accepted offers will not cause additional voltage or internal congestion problems. It can be seen in Table 8 that the network-aware algorithm is able to clear the market without causing new issues to the distribution grid almost in every simulated event. Both, in cases with reduced liquidity and high liquidity in the orderbooks. On the other hand, the non-network-aware algorithm presents a higher risk of unfeasible clearing.

Table 8. Market clearing results - High generation

	Algorithm	Feasible Market Clearing	Unfeasible Market Clearing
Reduced Liquidity	Network Aware	97	3
	Non-network Aware	36	64
High Liquidity	Network Aware	100	0
	Non-network Aware	66	34

On Table 8 there are only two columns: Feasible and Unfeasible clearing. If the results are studied in detail, it can be seen the reason behind the unfeasible clearings of the network aware algorithms. They are (mostly) caused by the lack of liquidity in the market. The first sign of this can be seen in the table itself, where the high liquidity scenario has zero unfeasible clearings caused by the network aware algorithm. Furthermore, if the 3 unfeasible events from the reduced liquidity scenario are studied more in depth (see Table 9) it can be seen how the failed clearings are due to curtailed power (initial problem in the grid, see also Table 6), whereas in 2 out of 3 of the clearings the non-network aware algorithm causes new issues to the grid

Table 9. Detailed behaviour of the algorithms in events with unfeasible market clearing.

	Event	Power Not Served [MW]	Power Curtailed [MW]
Network Aware	**5**	0	0.039
Non-network Aware		0	0.039
Network Aware	**33**	0	0.044
Non-network Aware		0.028	0.044

Network Aware	**93**	0	0.056
Non-network Aware		0.027	0.024
Initial State of the grid		0	0.23

Focusing the scope now on the impact of this market clearings to the Social Welfare and Procurement Costs, Figure 23 and Figure 24[18] show the obtained values for both high and low liquidity orderbooks respectively.

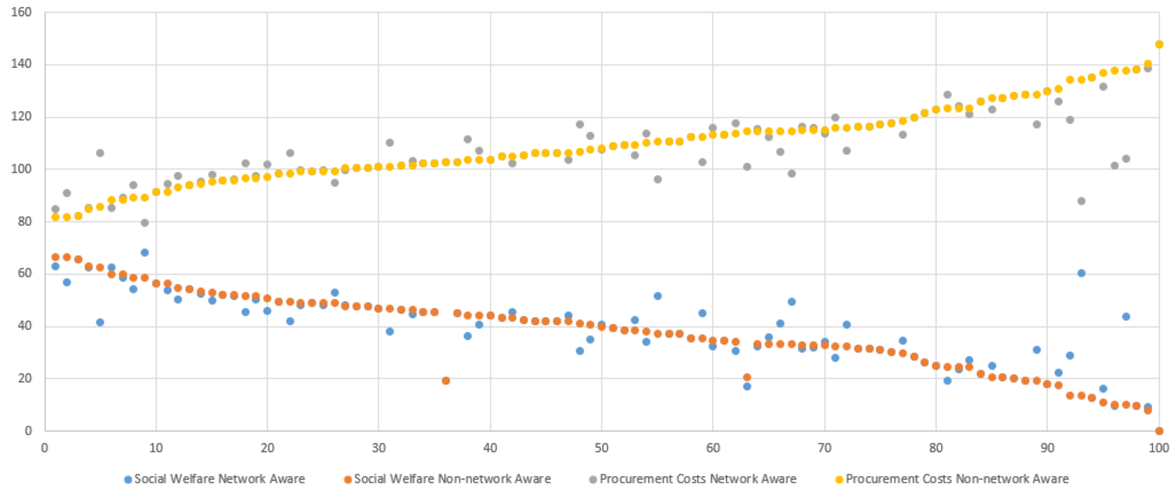

Figure 23. Visual representation of market clearing events - Reduced Liquidity

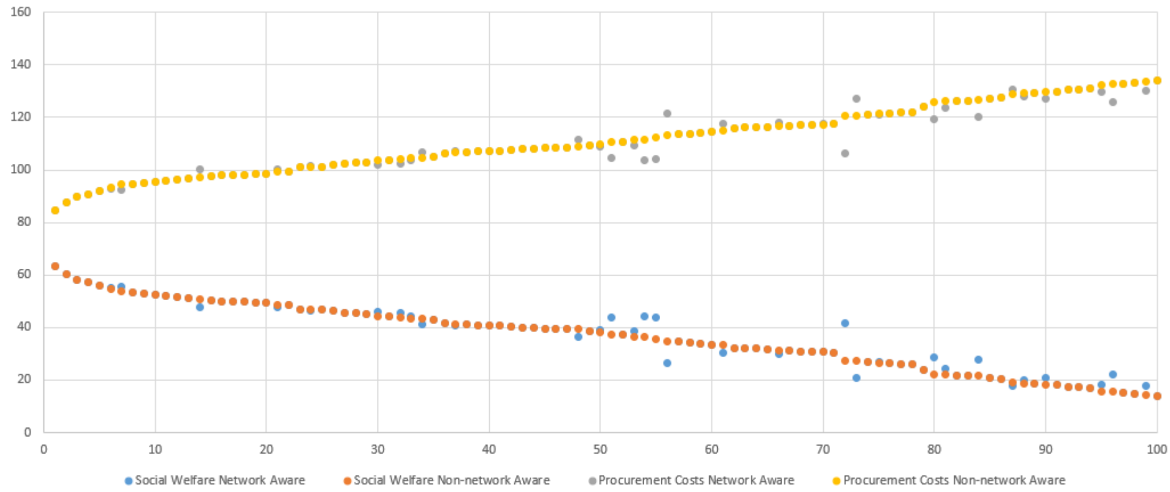

Figure 24. Visual representation of market clearing events - High Liquidity

The impact of being network-aware in both procurement costs and social welfare, is highly dependent on the specific event and state of the grid. However, focusing on the case analysed the average difference after 100 market clearings between network and non-network aware algorithms is:

- Low Liquidity events: The network aware algorithm has a **2%** higher social welfare and a **1%** lower procurement costs.

[18] The figures contain all the market clearings and have been sorted using the procurement costs results from the non-network aware algorithm.

- High Liquidity events: The network aware algorithm has a **1%** higher social welfare and a **0.5%** lower procurement costs.

If the scope of the analysis is pointed towards differences between scenarios, the results are quite interesting. In the Low Liquidity case the number of events where there is a significative difference between network and non-network aware results is higher. One possible explanation for this can be found in the market orderbook. In the low liquidity case, there are a few offers (14), and their average size is much bigger. This causes market clearing with lower number of transactions but bigger bid sizes. On the other hand, the high liquidity scenario has these 14 "bigger" bids, but also 58 bids from smaller assets, which are less prone to cause new problems, thanks to their smaller volume. This is also the reason why the amplitude of the discrepancy in social welfare and procurement cost is bigger in the Low liquidity scenario.

From the market participants perspective, the results from the figures above show that the implementation of network aware algorithms in most continuous clearing markets will not impose a significant change neither on the costs nor on the revenue from flexibility, except for very particular cases and events. It must be mentioned that continuous clearing algorithms by nature cannot be optimization algorithms, and therefore the information that we aim to extract from this analysis points towards the potential "negative" impact of the algorithm over the market participants' business model.

Until now the results of the market clearing have been shown but not their potential consequences. The following paragraphs present the impact to the grid of the non-feasible market clearing scenarios. This information is quite scenario specific, but it can show the potential consequences of not being network aware. The results are presented in Power not served and Power curtailed. To evaluate the final "congested" setpoints and identify the lines where power needs to be curtailed or cannot be served, a modified version of the auction-based network aware algorithm has been used.

Figure 25 presents the evaluation of the congested events for the non-network aware algorithm with the low liquidity case (the results have been sorted to ease the reading of the information). It is relevant to consider the initial setpoint was causing a congestion in the root node due to an excess of generation of 230 kW (power curtailed). To solve the congestion the DSO could curtail 230 kW or more of generation capacity. In the presented it is relevant to show how in all the cases the initial congestion has been significantly reduced; however, the market clearing has created internal congestions due to excessive power through the lines.

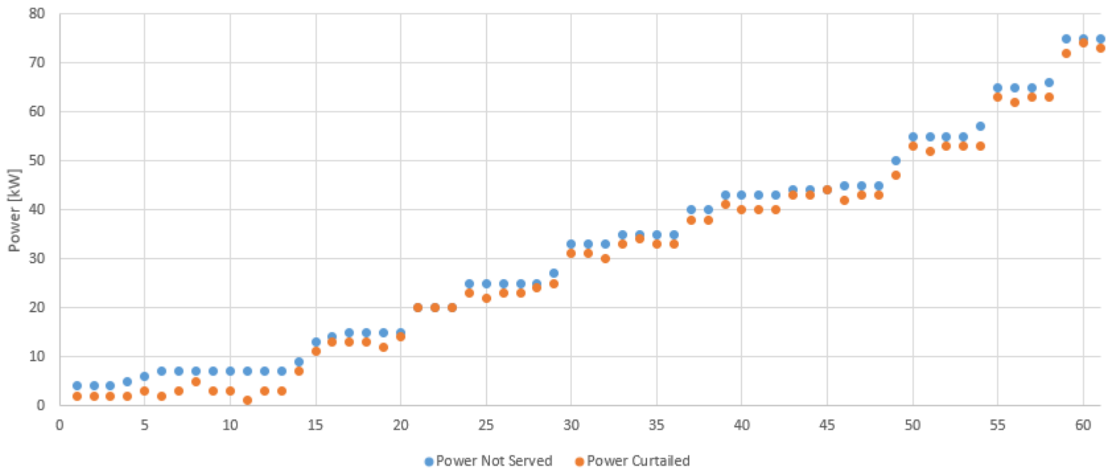

Figure 25. Curtailment and energy not served in the unfeasible market clearings – Reduced Liquidity.

Neither the cost for the DSO of curtailing a generator, nor the cost of not serving a load are included in this analysis. The reason is that, on the one hand whereas curtailment costs tend to be regulated, they are country specific. Furthermore, their calculation is complex since they account not only for the value of the energy curtailed but also for the opportunity costs and other operational expenses related to the technology. On the other hand, the scenario of dispatching a load without its previous consent is not a feasible scenario for most of low voltage connected loads and there is not available information regarding its costs.

In Figure 26 the same results but for the high liquidity scenario are presented. First, the number of unfeasible market clearings is almost half of the previous case. Like in the previous figure the initial problem is partially solved, but now internal congestions due to high load in the lines forces the DSO either to curtail power served to loads or expose its infrastructure to higher wear and tear.

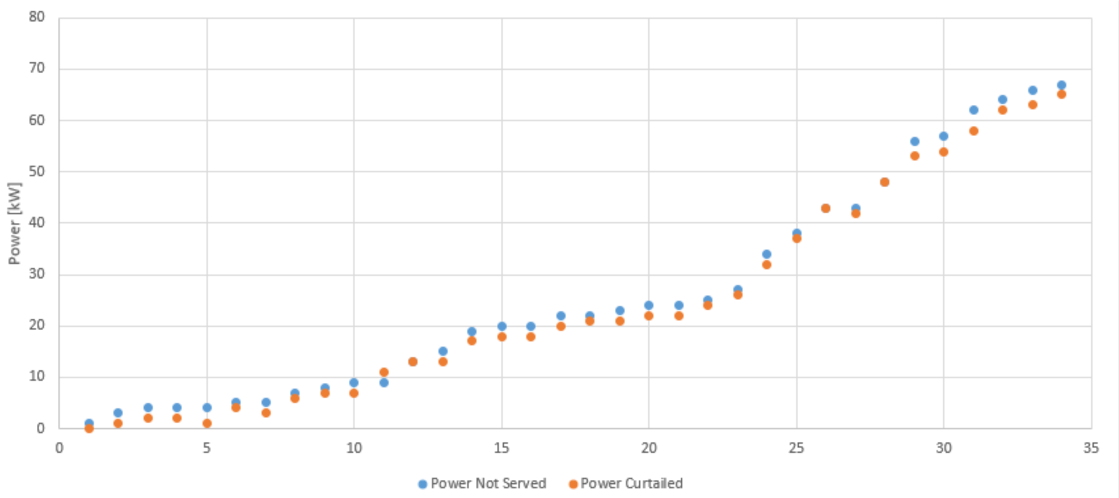

Figure 26. Curtailment and energy not served in the unfeasible market clearings – High Liquidity.

High Load

The behaviour of the algorithm in the high load scenario when it comes to feasibility of market clearing is aligned with the behaviour seen in the previous scenario. The differences in results, seen in Table 10 can be attributed to the different state of the grid and behaviour of the connected assets.

Table 10. Market clearing results – High Load

	Algorithm	Feasible Market Clearing	Unfeasible Market Clearing
Reduced Liquidity	Network Aware	95	5
	Non-network Aware	26	74
High Liquidity	Network Aware	100	0
	Non-network Aware	54	46

There is one relevant event from the unfeasible market clearing results that needs further consideration. Out of the total 400 simulated events (considering both scenarios) only one of them turned out to be feasible for the non-network aware algorithm and unfeasible for the network aware. The main characteristics of the event are presented in Table 11.

Table 11. Special unfeasible market clearing event.

Algorithm	Social Welfare	Procurement Cost	Congested	Power Not Served [MW]	Power Curtailed [MW]	Liquidity [MW]	Execution Time
Network Aware	0	0	Yes	0.226	0	0.9	45.74s
Non-network Aware	15.83 €	134.11 €	No	0	0	0.9	0.17s

The analysis of this event is a good opportunity to a) understand the logic and challenges behind the algorithm, and b) touch on the topic of liability of a failed market clearing results. In Table 11 it can be observed how the network aware algorithm has not accepted a single offer. This is shown in the zero result for procurement costs, together with the power not served KPI that is the same as before clearing the market. However, on the other hand the execution time is the longest of the documented in the 400 simulated events. This means that the algorithm has checked one by one each of the received offers but none of them respected the grid limits. One of the disadvantages of the analysed continuous clearing algorithm is that it evaluates the offers one at a time always following the same order, this implies that if a combination of bids leads to a feasible market clearing but those bids arrive in the wrong order there is the risk of not accepting them. This is what happened in this specific event.

Even if this kind of events are rare, they need to be considered. NODES, particularly when considering the auction-based algorithm, has raised awareness of the liability challenges of network-aware market clearings. A more detailed consideration of these challenges will be done in the discussion part.

Moving to the procurement and social welfare costs results, they can be seen in Figure 27 and Figure 28.

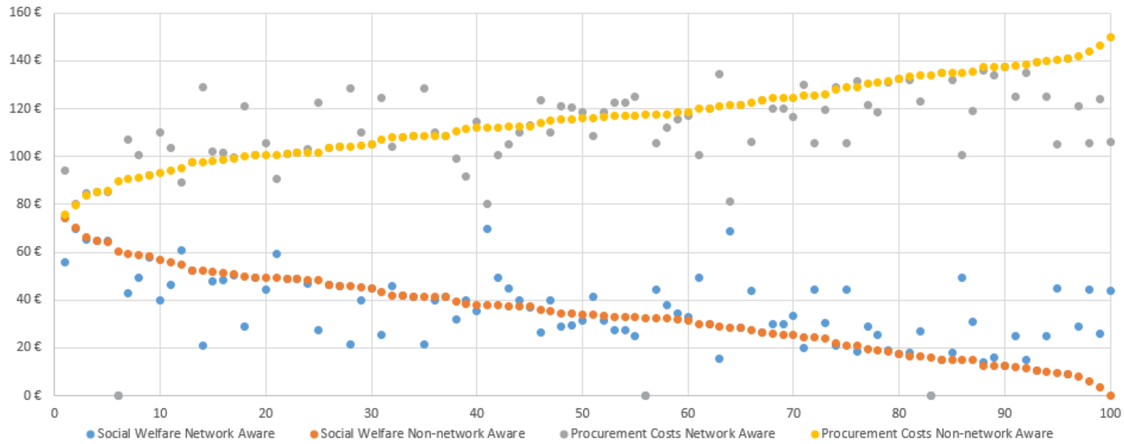

Figure 27. Visual representation of market clearing events - Reduced Liquidity

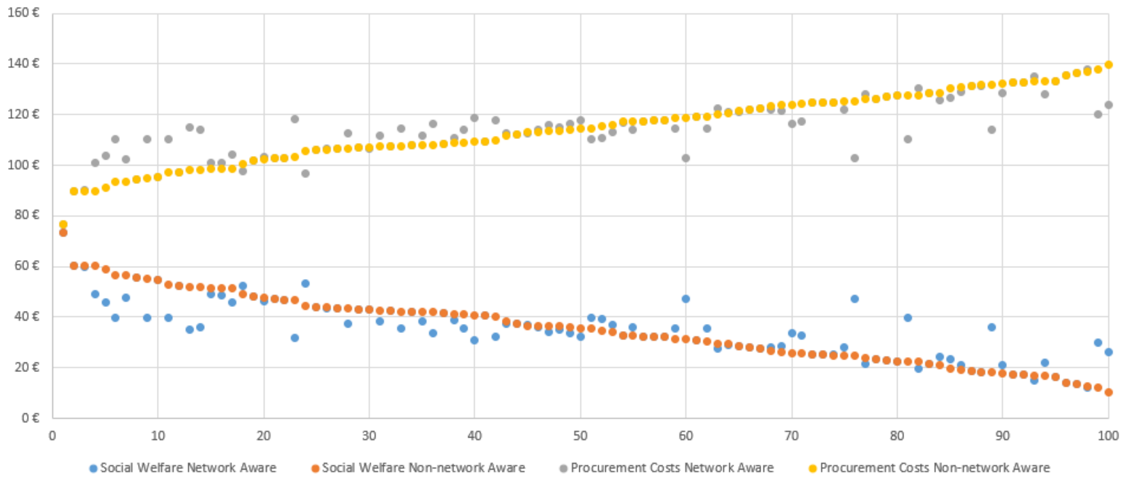

Figure 28. Visual representation of market clearing events - High Liquidity

The behaviour observed is very similar to the one of the previous scenarios. First, if the average of the KPIs is considered, the discrepancy of results between network-aware and non-network aware is small. The following list present the percentual difference depending on the type of orderbook:

- Low Liquidity events: The network aware algorithm has a **4%** higher social welfare and a **5%** lower procurement costs.
- High Liquidity events: The network aware algorithm has a **1%** higher social welfare and a **0%** lower procurement costs.

Furthermore, when it comes to the variability of each individual event the behaviour observed is very similar to the observed in the previous scenario, where in the reduced liquidity orderbook clearings the variability was significantly higher than in the high liquidity (and smaller bids) scenario.

Figure 29 and Figure 30 present the impact evaluation of the congested events for the non-network aware algorithm with the reduced and high liquidity cases, respectively. It is relevant to consider the initial setpoint was causing a congestion in the root node due to an excess of load of 230 kW (power not served). Due to the initial setpoint of the grid, in this scenario the impacts of "failed" market clearings are higher, reaching up to 130 kW of power not served and power curtailed, which means a higher "curtailment" needs in the system.

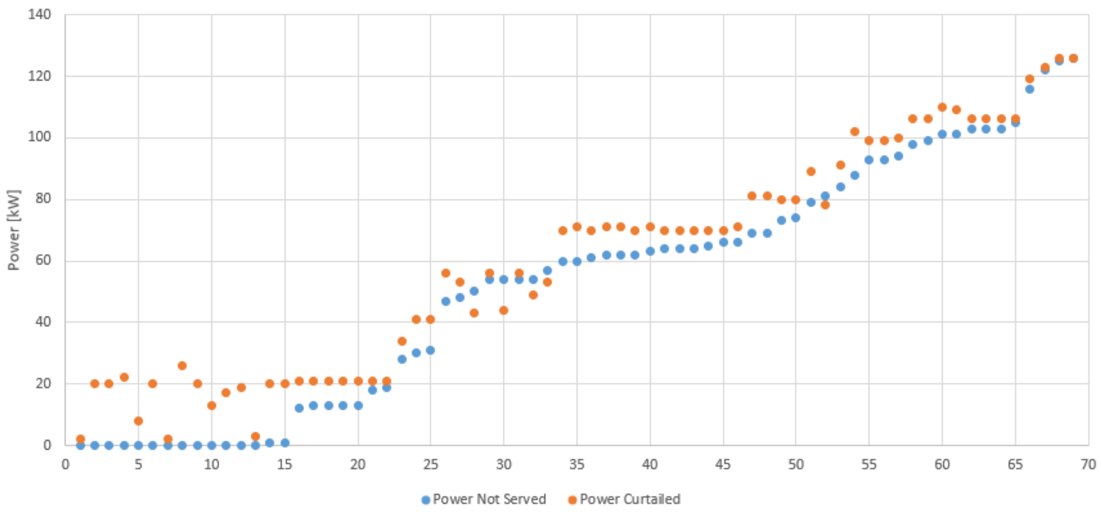

Figure 29. Curtailment and power not served in the unfeasible market clearings – Low Liquidity.

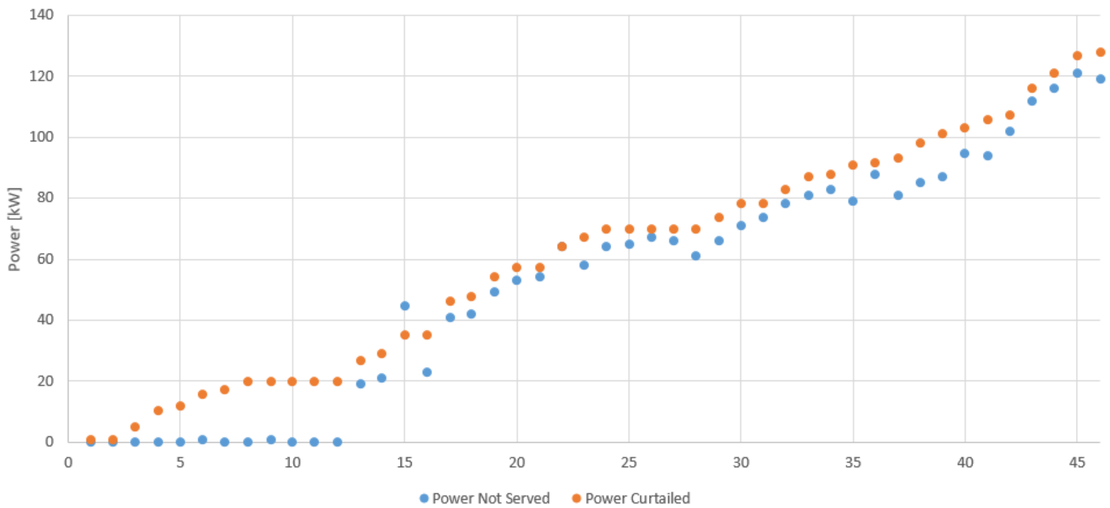

Figure 30.Curtailment and power not served in the unfeasible market clearings – High Liquidity.

The information that can be extracted from this graph is very specific to the current analysis. With that said, it can show the potential impacts of non-network aware market clearing in future grids with higher utilization rates.

Normal Operation

The results presented below have a slightly different objective when compared to the previous scenarios. Here the analysis points towards long-term scenarios where multiple FlexBuyers participate in the market competing for flexibility. Therefore, the analysis points towards understanding how this more complex orderbooks affect network and non-network aware market clearing algorithms' performance.

The first KPI presented is the number of feasible market clearings. As can be seen in Table 12, with a higher complexity of requests the risk of creating issues internal issues at the distribution level increases.

Table 12: Market clearing results – Normal Operation

Algorithm	Feasible Market Clearing	Unfeasible Market Clearing
Network Aware	100	0
Non-network Aware	14	86

The procurement cost and social welfare results can be seen in Figure 31. As expected with a higher volume of requests, a higher number of transactions were made. Therefore, the procurement costs when compared to the previous analysis, are higher. With that said, the observed behaviour from the algorithms is similar as the previous one. Even though in this specific set of simulations the network aware procurement cost tends to be lower than the non-network aware.

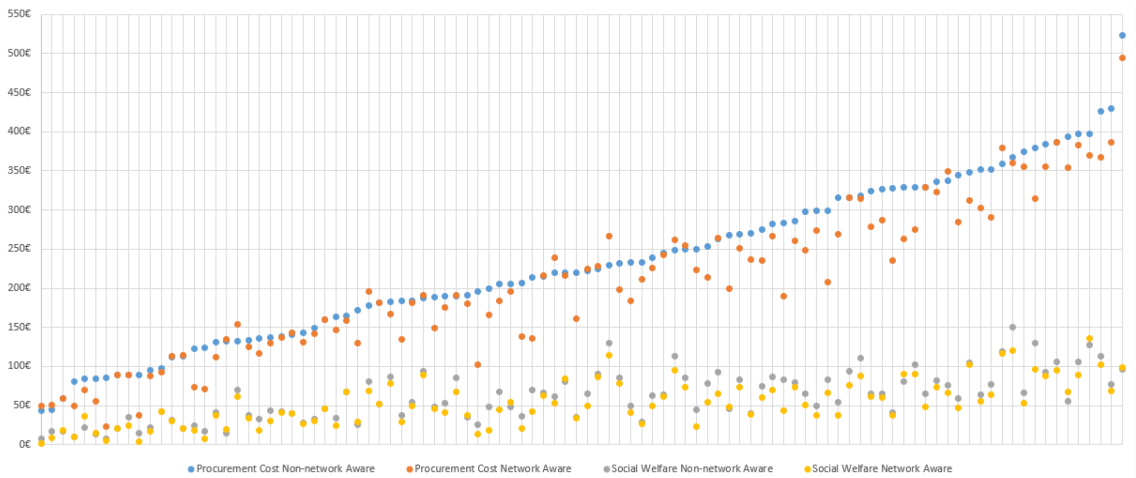

Figure 31: Visual representation of market clearing events - Normal Operation

On the other hand, there is the behaviour of social welfare. Since it is not dependent on the total number of transactions it stays relatively flat and in the same value range as the previous scenarios (this can be attributed to the use of the same price creation strategy). Due to the variability of the requests (and their price) per orderbook there is a much higher variability in the observed social welfare results.

Moving towards the real impact on the grid users of the unfeasible market clearing events, Figure 32 shows a new behaviour. In this scenario, multiple requests compete and there is not a common objective between them. This leads, in the studied orderbook to higher risk of curtailment and risk of not serving power, but also there seems to be a higher detachment between both variables. One more time, it is hard to extract generic information from a very specific simulation scenario, but it seems that in more complex orderbooks, the unfeasible clearings also present more complex to solve issues.

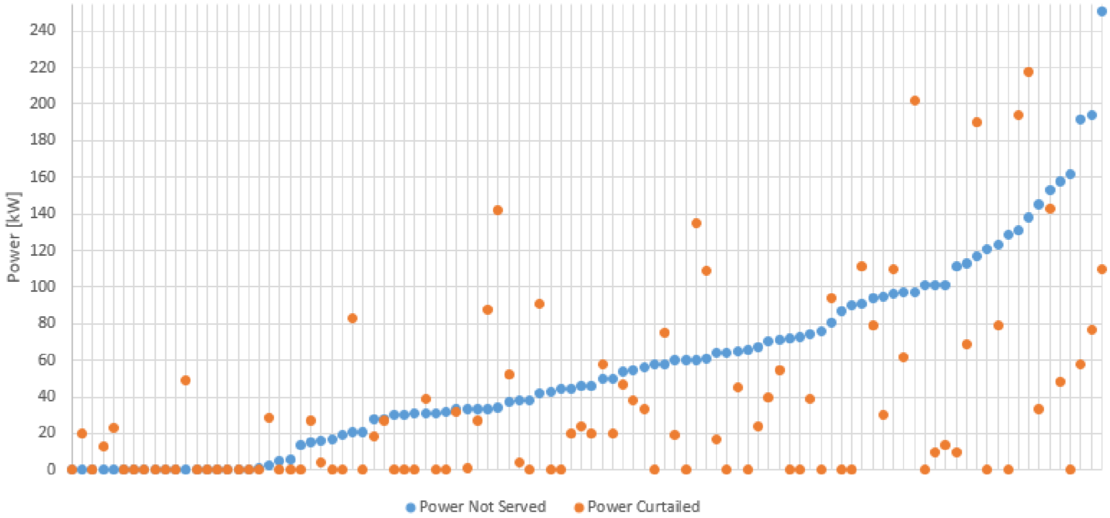

Figure 32: Curtailment and power not served in the unfeasible market clearings – Normal Operation

Flexibility Market Operator KPIs

Moving to the KPIs that are relevant for the FMO. In the case of the continuous clearing algorithm from the KPIs defined in section *Key Performance Indicators* only one is relevant or can be evaluated. It is the *execution time*. The rest of the KPIs defined in collaboration with NODES either cannot be evaluated in this algorithm or due to its nature would not make sense to evaluate them. This is the case of the KPIs *time to find the optimal solution* and *number of requests the algorithm can handle*, respectively.

The evaluation of the execution time serves as an indicator of the efficiency in the market clearing. Due to the nature of the algorithm, it is expected to see a significant impact on the time performance between the network-aware and not network aware case. Table 13 and Table 14 present the average results for the Reduced liquidity and High liquidity scenarios, respectively.

Table 13: Continuous clearing algorithm average execution time per scenario - Reduced Liquidity

	Algorithm	Both Feasible	Network Aware Feasible	Not Feasible
High Load	**Network Aware**	3.04s	4.32s	5.49s
	Non-network Aware	0.18s	0.18s	0.20s
High Generation	**Network Aware**	5.89s	11.42s	8.11s
	Non-network Aware	0.35s	0.35s	0.34s

The first thing that can be observed is the difference in performance between network aware and non-network aware. There is an order of magnitude of difference between the network aware and non-network aware clearing. Furthermore, the impact of the power flow calculations can be observed a) in the execution times of the network aware algorithms, and b) in how the network aware algorithm has larger execution times with those orderbooks that have higher risk of creating congestions and/or voltage issues.

Table 14: Continuous clearing algorithm average execution time per scenario - High liquidity

	Algorithm	Both Feasible	Network Aware Feasible	Not Feasible
High Load	Network Aware	9.42s	17.36s	--
	Non-network Aware	0.80s	0.74s	--
High Generation	Network Aware	8.58s	22.25s	--
	Non-network Aware	1.55s	1.46s	--

It is also interesting to see that the typology of orderbook has a relevant impact on the performance of both algorithms. No conclusions should be extracted from this observation, since there are multiple variables that could have caused this execution time difference (e.g % of CPU used by other loads during the simulations). The technical performance of the algorithm has already been evaluated in FLEXGRID's deliverable 5.3. However, from the FMO perspective, NODES indicated other parameters that FMOs want to know to understand the real value proposition. These indicators (for continuous clearing) are:

- Complexity of the grid – Maximum number of nodes the algorithm can handle, and the impact of higher number of nodes in the market clearing performance.
- Complexity of the orders – Type of orders that the algorithm can operate with, and how the number of orders and their size impact the execution time of the algorithm.

During the experimental part of the thesis an attempt to evaluate the abovementioned indicators has been done. Due to limitations in time and resources the analysis did not proceed further. However, the simulations of the Normal operation setpoint can show some very preliminary results regarding the impact of complex scenarios to the algorithm performance.

Table 15: Continuous clearing algorithm average execution time per scenario - Normal Operation

Algorithm	Both Feasible	Network Aware Feasible	Not Feasible
Network Aware	25.19s	43.49s	--
Non-network Aware	1.37s	1.42s	--

From the results it can be seen how a more complex orderbook results in longer execution times. This is a trend that can be already observed when comparing the reduced liquidity and the high liquidity scenarios execution times. In this case, with higher liquidity in the market and multiple requests the execution times are higher than in the other cases.

3.3.2 Auction-based Algorithm

The auction-based algorithm expected market clearing results were to clear the market respecting the upper and lower voltage limits of each node, and the power flows in the lines.

Additionally, thanks to its optimization nature it was expected to see a reduction of procurement costs and/or an increase in overall social welfare. However, during the events simulation it was observed that the results observed were not entirely as per expectation since the algorithm was occasionally omitting the voltage boundaries, leading to unfeasible market clearings. Therefore, the following mitigation actions were applied to solve the malfunction:

1. **Check-up of the mathematical model**:

A deep understanding of both algorithms was gained during the development of the thesis. However, when the issue was identified the first action done was to check the code for missing boundaries or potential "weak points". The explicit boundaries for voltage (Voltage Squared[19]) are properly defined within the voltage squared variable.

```
model.V_sq = pyo.variable_dict()
for i in node_data.index:
   model.V_sq[node_data.loc[i, 'Bus']] = pyo.variable(lb=node_data.loc[i, 'Vmin']**2, ub=node_data.loc[i,
'Vmax']**2,value=1)
```

The lb and ub in the code above stand for *lower* and *upper boundary* respectively, and they are defined by the given information of the network. To be fully transparent, the following figure shows the output of the solver after clearing the market.

```
Problem
  Name                   :
  Objective sense        : min
  Type                   : CONIC (conic optimization problem)
  Constraints            : 570
  Cones                  : 80
  Scalar variables       : 717
  Matrix variables       : 0
  Integer variables      : 0

Optimizer  - threads                : 4
Optimizer  - solved problem         : the primal
Optimizer  - Constraints            : 1
Optimizer  - Cones                  : 0
Optimizer  - Scalar variables       : 7                 conic                  : 0
Optimizer  - Semi-definite variables: 0                 scalarized             : 0
Factor     - setup time             : 0.00              dense det. time        : 0.00
Factor     - ML order time          : 0.00              GP order time          : 0.00
Factor     - nonzeros before factor : 1                 after factor           : 1
Factor     - dense dim.             : 0                 flops                  : 1.50e+01
ITE PFEAS    DFEAS    GFEAS    PRSTATUS   POBJ              DOBJ              MU       TIME
0   2.2e+00  9.7e+01  1.0e+00  0.00e+00   -2.059210000e+01  -2.059210000e+01  1.0e+00  0.00
1   4.3e-01  1.9e+01  4.0e-01  -9.62e-01  -7.002552778e+01  -6.662000124e+01  1.9e-01  0.00
2   1.7e-01  7.7e+00  1.3e-01  -1.54e-01  -6.081774462e+01  -5.850412398e+01  7.9e-02  0.00
3   3.8e-02  1.7e+00  1.6e-02  3.94e-01   -6.297012536e+01  -6.217442961e+01  1.7e-02  0.00
4   4.2e-03  1.8e-01  5.8e-04  8.91e-01   -6.372021138e+01  -6.363994385e+01  1.9e-03  0.00
5   2.8e-04  1.2e-02  9.3e-06  1.08e+00   -6.369713910e+01  -6.369259713e+01  1.3e-04  0.00
6   1.2e-07  5.4e-06  8.7e-11  1.00e+00   -6.370659488e+01  -6.370659284e+01  5.5e-08  0.00
7   2.0e-13  8.9e-12  1.4e-16  1.00e+00   -6.370660000e+01  -6.370660000e+01  9.2e-14  0.00
Optimizer terminated. Time: 0.01
```

Figure 33. Solver output for an unfeasible market clearing event - Normal Operation

2. **Define "redundant" model constraints:**

[19] The use of V^2 is a variable change done to avoid having a non-linear optimization problem (see Equation 1).

The reasoning behind this strategy was based on the fact that the boundaries of the voltage were not defined as model constraints, but variable boundaries. Therefore, maybe the issue was there. The first, attempt tried to define a redundant constraint setting upper and lower boundaries for the voltage squared:

```
# Node voltage limit
model.Volt_up_lim = pyo.constraint_dict()
model.Volt_down_lim = pyo.constraint_dict()
for k in node_data.index:
   model.Volt_up_lim[k] = pyo.constraint(expr= model.V_sq[node_data.loc[k, 'Bus']]<=model.Vmax_sq[node_data.loc[k,
'Bus']])
   model.Volt_down_lim[k] = pyo.constraint(expr=model.V_sq[node_data.loc[k, 'Bus']]>=model.Vmin_sq[node_data.loc[k,
'Bus']])
```

The second approach taken was trying to "simplify" the model by avoiding the change of variable from voltage squared to voltage. However, this poses a major challenge since as can be seen in Equation 1 and the correspondent pyomo implementation below, the voltage appears squared in the calculation (and constraint) of voltage drop between nodes.

```
#Voltage Drop
model.voltage_drop = pyo.constraint_dict()
for i,j in model.B:
   Lhs = model.V_sq[j]
   Rhs = model.V_sq[i] - 2 * (model.R[i, j] * model.P_lin[i, j] + model.X[i, j] * model.Q_lin[i, j])
   model.voltage_drop[i,j] = pyo.constraint(body=Lhs-Rhs,rhs=0)
```

Equation 1, forces to use voltage squared as a variable to avoid having to solve a non-Linear optimization problem. In fact, one of the proposed solution was removing the power flow constraint (S), since it was implemented as a conic.quadratic constraint, which is a type of constraint that even if it represents a nonlinear constraint, the solver can linearize it by default.

```
# Line flow limit
model.Lin_lim = pyo.constraint_dict()
for i,j in model.B:
   x = [model.P_lin[i,j],model.Q_lin[i,j]]
   model.Lin_lim[i,j] = pyo.conic.quadratic(model.Smax[i,j],x)

# This is equivalent to: S = √(P_i,j^2 + Q_i,j^2)
```

The removal of this constraint supposes a major issue for the model (not respecting line flow limits) that needs to be somehow addressed. For instance, through simplification of the model to only consider active power. However, even with a fully linear model the solver kept omitting some of the boundaries imposed.

The rest of the attempts have been challenged (among other issues) by the use of a very specific set of pyomo libraries and types of models, which reduced the compatibility of the code with most of the documentation used. More specifically, the use of the library pyomo.kernel[20] still in development phase is a challenge since to test the model in other implementations of pyomo (e.g., pyomo.environ) all the model variables and constraints need to be re-written in a different way. Then the secondary challenge, has been the use of the pyomo.block model, which allows for multi-period optimization by defining each time-period as a block of a bigger optimization

[20] Pyomo. Kernel: is an experimental modeling interface designed to provide a better experience for users doing concrete modeling and advanced application development with Pyomo. (The Kernel Library — Pyomo 6.4.2 documentation)

problem. This characteristic of the model has not been used during the simulations of this thesis, and therefore a “normal” model could have been used, allowing for more code flexibility.

After sharing the issue with the algorithm developer and testing alternative ways to define the constraint or even modifying the model, it was not possible to identify the issue (within the time frame of this thesis). The software developer has suggested that it might be caused by issues with the solver configuration. The scope of this thesis is focused on the business side of LFMs, therefore from now onwards the obtained results with the auction-based algorithm will be shown but their validity has to be taken from the qualitative perspective of the business analysis instead of the quantitative approach that has been presented in the continuous clearing case The research work for the business case analysis using an auction based algorithm results need further work to make overcome the challenges identified.

High generation & High load

The first and more important KPI to evaluate the difference in performance between a network and non-network aware algorithm is the amount of feasible and unfeasible market clearings. Here the issues this thesis has faced during the test period of the algorithm can be seen.

Table 16: Market clearing results - High generation

	Algorithm	Feasible Market Clearing	Unfeasible Market Clearing
Reduced Liquidity	Network Aware	55	45
	Non-network Aware	54	46
High Liquidity	Network Aware	55	45
	Non-network Aware	55	45

Table 17: Market clearing results - High load

	Algorithm	Feasible Market Clearing	Unfeasible Market Clearing
Reduced Liquidity	Network Aware	24	76
	Non-network Aware	23	77
High Liquidity	Network Aware	24	76
	Non-network Aware	24	76

The results from Table 16 and Table 17, show a worse performance in feasible-clearing ratio (an order of magnitude higher) than with the continuous clearing algorithm. To avoid dealing with failed market clearings (due to solver malfunction), it has been decided to focus the analysis on the Feasible market clearing results. On the one hand this allows to see the trend in operation of the algorithm when the solver works. On the other hand, information is lost when discarding all the unfeasible market clearings since it is impossible to differentiate between algorithm failures and lack of liquidity. This last example hinders the possibility to compare auction-based and continuous clearing performance in the same scenarios.

Moving to the Social Welfare and Procurement Costs, the results (in the feasible market clearing events) are quite interesting. Since the analysis for the auction-based has changed towards a qualitative one, the following paragraphs focus on the results of the High Generation initial setpoint. There is a very small difference in both Social Welfare and Procurement costs between network and non-network aware algorithms. On the one hand, these results show that also with auction-based algorithms market participants should not notice a significant difference between network aware and non-network aware optimization. In this case this affirmation can be done not only considering the average, but also considering each event (as seen in Figure 34 and Figure 35).

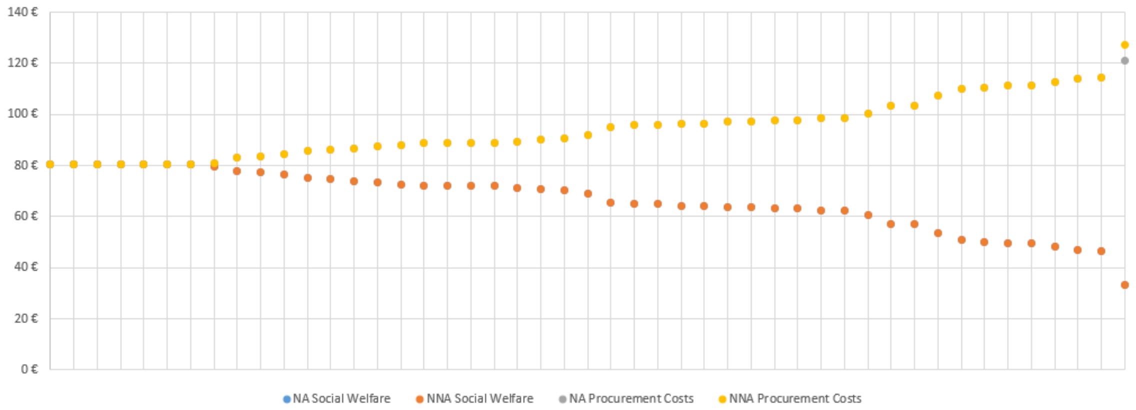

Figure 34: Visual representation of market clearing events - Reduced Liquidity

On the other hand, more interesting (but also expected) results can be seen when comparing the continuous and auction-based market clearing results. The auction-based algorithm, which by default maximizes social welfare, has an average social welfare noticeably higher than the continuous clearing algorithm (see Figure 27 and Figure 28). It is also interesting to see the reduced variability of the market clearing results for the auction-based algorithm, which has an almost linear trend with very soft slope. This effect can be further noticed in the High Liquidity market orderbook, where with higher number of offers and volume in the market the optimization can reach higher social welfare.

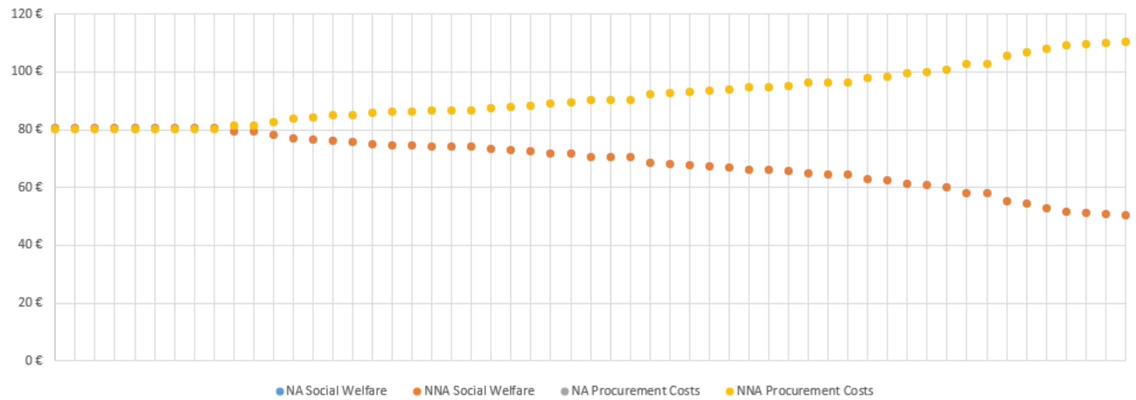

Figure 35: Visual representation of market clearing events - High Liquidity

Flexibility Market Operator KPIs

Moving to the KPIs that are relevant for the FMO. The industrial partners provided a set of KPIs that would be of their interest to understand the performance and capabilities of the algorithm. However, as mentioned previously most of them are KPIs that are defined to evaluate the performance of optimization algorithms, which therefore could not be evaluated for the continuous clearing algorithm. The KPIs initially to be analysed were:

- Execution time
- Time the algorithm uses to find 1st solution
- Time the algorithm uses to find optimal solution
- What is the delta in social surplus between the solution the algorithm found, and a theoretical optimal solution?

Due to the challenges faced with the auction-based algorithm, most of this KPIs could not be evaluated quantitatively in a trustworthy manner. However, for the ones that no numbers have been obtained a consultation process with the algorithm developer DTU has given some insights of the expected performance.

So, starting with the first KPI *Execution Time,* in Table 18 the average result for the feasible market clearings can be seen. An increased complexity of the orderbook causes higher optimization times; however, when compared to the continuous clearing algorithm, the auction-based has an average execution time one order of magnitude smaller.

Table 18: Average execution times for network aware and non-network aware feasible market clearings

	High Generation		High Load	
Algorithm	**Reduced Liquidity**	**High Liquidity**	**High Liquidity**	**Reduced Liquidity**
Network Aware	0.30s	0.74s	0.30s	0.96s
Non-network Aware	0.25s	0.69s	0.26s	0.89s

Another interesting observation is difference between network aware and non-network aware algorithms. In this case, the execution time difference ranges from 7% to 20%, whereas with the continuous clearing algorithm the difference was up to 1600%. This was predictable, since the nature of both algorithms is very different, and it would not be fair to compare them from this perspective. However, it is a relevant insight to consider when analysing the future implementation of network aware LFMs.

Finally, addressing the rest of KPIs. After consultation with DTU, they pointed out that the difference between 1^{st} solution and optimum solution, both in terms of execution time and difference in social welfare is almost negligible. Their justification is based on the fact that the model is a Linear Optimization problem, and therefore it does not suppose a relevant challenges for the solver. With that said, it would be interesting to test the model in more complex environments such as bigger grids (e.g., 1e3 nodes) to study these KPIs in more detail.

3.4 Discussion

After the analysis of the results this thesis proceeds to discuss the relevant findings from both, the analytical calculations, and the interaction with some business actors within the business case ecosystem.

The performance evaluation of the algorithms has shown that the implementation of network aware market clearing algorithms in the analysed cases had from none to positive impact for the market participants as a group. In the case of continuous clearing algorithms, the results showed that for most market participants there would not be a substantial difference if a network aware algorithm were to be implemented. However, the impact of the algorithm at an individual level can be much bigger. Assets connected to more robust parts of the grid will be more prone to activation than those connected to weaker parts. With that said, nowadays this filter/limit to flexibility provision is applied at the prequalification stage, the use of network aware algorithms would allow to limit the flexibility potential of the assets in a dynamic manner, allowing them to bid their maximum potential, but just activating (if activated) the maximum allowed according to the state of the grid. When it comes to the execution time, the analysis performed showed a significant difference in market clearing times. However, as the name suggests, continuous clearing algorithms clear the market every time a new bid enters the orderbook. The average execution times presented in this thesis were for fulfilling a whole request instead to clear one bid. If the clearing of an individual bid is considered the execution time would go from milliseconds to seconds. When it comes to the auction-based algorithm, this thesis acknowledges the limitations encountered during the experimental process, nevertheless the obtained results can give a qualitative idea of the business implementation of network aware auction-based algorithms. From the observed results, auction-based algorithms have the same advantages as their continuous clearing counterparts, with the added benefit of being able to optimize the clearing towards goals such as social welfare or minimization of procurement cost. Furthermore, the nature of linear optimization algorithms allows them to clear the market in shorter execution times, and to optimize for multiple periods. That said, not all LFMs nowadays operate using auction-based algorithms, in fact NODES does not. The reason behind that decision has to do with market participation dynamics, as explained in [42] in the initial stages of LFMs continuous clearing can be the best option to deal with potential low liquidity. In a future where regulation has prompted the creation of LFMs and the role of the Aggregator is already settled, auction-based algorithms have potential.

Moving to the more generic discussion between network and non-network aware algorithms, the following findings are considered relevant to understand the business case and the potential implications for the business model of FMOs. The most relevant element for discussion is the **liability over the final state of the grid**. As of today, DSOs (and TSOs) are responsible for the QoS and SoS in the power system, whereas flexibility market operators undertake the solely responsibility of market clearing. In the case of balancing markets, the TSOs are operating as MOs, but in the case of LFMs DSOs are not the market operator. All existing LFM products in the market are operated by independent companies such as NODES, Piclo Flex, or EPEX SPOT. Therefore, is the responsibility of DSOs to a) analyse their grids and create flexibility requests to manage their needs, and b) prequalify the assets to participate in the LFM (this second option depends on the flexibility platform). The implementation of a network aware market clearing mechanism clashes with today's electricity system role model, blurring the responsibilities of the different business actors, particularly DSOs and FMOs. This can be seen as a hinderer for the implementation of network aware LFMs, but at the same time creates the opportunity for FMOs/Software developers to offer non-network aware LFMs as one service, and power flow simulation software on the other, maybe even facilitating the integration of both services to ease the flexibility procurement process.

If the network aware LFM business model is pursued, then the big challenge to face is the liability over market clearings and the final state of the grid. From this perspective, optimization algorithms (auction-based) are the ones with a more complex scenario since they have a proactive role on choosing bids to reach the desired optimum. From the business model perspective, if an FMO accepts this liability, this would imply a clear shift on today's FMO business model, but also for the roles in the electricity market, where the DSO would not be anymore the only one in charge of the QoS and SoS of the grid. After discussing with NODES - the ones that showed their concern about the topic - it is quite clear that the **adoption of network aware or non-network aware LFM algorithms create two very different business model for market operators.**

Another of the challenges posed to the network aware LFM business model, when implementing network aware algorithms has to do with data. First and foremost, to operate a network aware market clearing algorithm the DSOs must provide a) technical information regarding their infrastructure, and b) initial setpoints of the grid per each market time unit. This presents challenges from both the DSO and FMO perspective. First, there is the risk (for the business model) to find **DSOs reluctant to share confidential information** regarding their grids. This is a critical point for the deployment of network aware algorithms and can hinder their implementation. Take for instance the analysis performed in this thesis, the technical information regarding the 81 nodes grid used was disclosed under NDA in the frame of an R&D project. Furthermore, the collection of grid data at distribution level cannot be taken for granted. Nowadays, DSOs are starting to digitalize their grids but, close to **real time information about the distribution grid is not widely available yet**. Another challenge is, whereas TSOs and NEMOs have information about the scheduled generation/loads of the system (this is a responsibility of the power market/system actors), this is not always the case for the DSOs. Some of the bigger assets can have DA schedules, but that is not the case, for instance of residential loads. This leads to the discussion of, if network aware LFMs were to be implemented, which is the minimum voltage level that would be feasible such implementation? The simulated events considered a known/scheduled forecast of loads as small as 5.2 kW. As of today, this is not feasible, and it probably will not be for a long time (even though new suppliers/aggregators are starting to become data collecting and processing companies to enhance their business model). Finally, assuming that all the information is available and can be collected daily. It must be considered that the current business model for FMOs do not involve neither the **storage of confidential data** nor the **daily collection of data**. This additional layer of “complexity” also implies a change in the business model of FMOs where confidential data storage and collection becomes an operation that has to be performed every day.

Network aware LFMs are, up to a certain extent, a disruptive innovation that would force flexibility market participants to adapt to a new paradigm. Without discussing if they should be the model to follow in the future power system, if they are to be implemented, they will need a proper regulatory framework. As of today, the European Commission is starting the consultation process to develop the network code for Demand Response [50], which will help to create a framework for LFMs by defining standardized LFM products, but also promoting the creation of regulation linked to congestion management from DSOs, and setting rules for data exchange between system operators, as well as between system operators and providers.

Until now, only the challenges of the business model have been presented. However, thanks to their network awareness, network aware LFMs can extend the value propositions of non-network aware LFMs. The following paragraphs present the direct value propositions, identified during the analysis of the results, together with other value propositions that cannot be directly evaluated in the analysis but can be interesting to explore.

First and foremost, the use of network aware algorithms create value for DSOs because it ensures them that the operation of a LFM will not create any internal congestion on their grids. This thesis has already acknowledged that, on today’s LFMs, this is not a real issue; however, in future grids with an increased penetration of RES, energy storage systems, and overall higher line utilization factors, this can be a very relevant value proposition for DSOs. Furthermore, network aware algorithms value proposition increases when the complexity of the LFM ecosystem increases. For instance, in LFMs where multiple buyers compete for flexibility. In these cases, the fact that the market clearing algorithm can keep the grid within its boundaries would be crucial, particularly for DSOs.

Another identified potential value proposition from network aware LFMs is the capacity to simplify the prequalification process of assets, and the implementation of a dynamic flexibility potential per asset. Even though the asset prequalification process is out of the scope of this thesis, it is also one of the relevant tasks of any local flexibility platform. Particularly flexibility market platforms aim to streamline the process to reduce the costs FSPs [35] and therefore increase liquidity in the market. However, nowadays the assets are once prequalified checking if they fulfil the technical requirements to provide flexibility, and the impact of their flexibility for the grid. With the use of network aware algorithms, the technical prequalification would be the same, but the grid impact assessment could be performed dynamically, since the algorithm would check the impact of the asset in the network in each market clearing event.

4. Conclusion and Future Work

In this thesis the business case of local flexibility markets using network aware algorithms has been explored. The business ecosystem of local flexibility markets has been studied together with the technical performance of market clearing algorithms. The analysis started with a literature review of the state-of-the-art of electricity markets as this was the framework where the business case analysis would be executed, followed by the Methodology chapter where the research rationale is presented. Then the Research Work chapter develops the business case for network aware local flexibility markets and finds quantitative and qualitative results, relevant for the business model. Finally, there is a discussion about the value proposition and business models of network aware market clearing algorithms, and next steps are defined to continue the research work. As presented in the Literature Review chapter currently the local flexibility market segment has few players, and except for the Localflex platform from EPEX SPOT none of them has network aware capabilities. Therefore, the novelty of the research lies on understanding not only the performance of network aware local markets, but also the business implications behind such innovative proposal. The quantification of impact work has shown, at a reduced scale, that network aware algorithms:

a) Have no impact, on average, for the market participants. Maintaining procurement costs and social welfare at a similar level than their non-network aware counterparts,
b) Require higher computational power, particularly for continuous clearing market architectures.

These results prove that. with enough liquidity available, the implementation of network aware local markets has the same value propositions than their non-network aware counterparts, with the added attribute to ensure viability of market clearing (which can be very relevant for DSOs). However, business model viability is not only limited to product or service performance, but also to the regulatory framework and implications for the company trying to launch the new service. From this perspective, in this thesis some relevant barriers have been identified, most of them through conversation with industry stakeholders:

a) Data availability regarding load and generation schedules at distributed level can be limited,
b) Access to network data can be a challenge for the business model. DSOs might be reluctant to share confidential information regarding their grids,
c) Data collection and storage is an additional task that the flexibility market operator will have to undertake if it operates a network aware flexibility market,
d) Responsibility over the final state of the grid. The implementation of network aware local flexibility markets blurs the roles between DSO and market operator. This rises significant uncertainties regarding who would be liable of issues in the grid.

The most relevant challenge identified above is the liability over the final state of the grid. This could be solved by the definition of a proper regulatory framework. In the short term, data availability and reluctancy of DSOs to share confidential information are seen from this thesis perspective as the main stoppers to implement the business model.

During the development of the thesis new research threads have been identified that could build up on the findings of the current work and evolve to other topics. First, the work done can be extended by expanding the analysis to include different distribution grid layouts, assets, and type of market orderbooks. This analysis would serve to validate the prospective results found during this thesis work. Then, further research on the use of optimization algorithms for network aware local flexibility markets should be developed. This would help to gain insights on their technical capabilities and the business challenges they face. Finally, based on the identified challenges of the business model researchers should consider analysing the integration of network aware algorithms for distribution grid in the electricity market operation. This topic has been briefly introduced in this thesis (Power System Layers), but it will become more and more relevant in the coming years.

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Annexes

Annex I – Conference Publications

A Business Case for Flexibility Market Operators Using Algorithms for Improved Market Efficiency

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Abstract— The expected high penetration of distributed energy resources (DERs) in distribution systems is already challenging distribution system operators' (DSOs) management of their grids. Flexibility markets are a promising tool for DSOs to ensure the security and quality of supply in a cost-effective manner. However, most of the existing local flexibility market (LFM) platforms do not explicitly consider network constraints in market clearing, which could aggravate the local network problems in future scenarios. In this paper the business case for a network-aware continuous clearing algorithm for LFMs is presented through the quantitative analysis of the algorithm performance in different scenarios. The focus of the paper is on the quantitative performance of the algorithm and how it can affect the different business actors involved. Index Terms—Business Model, Distribution System Operator, Energy flexibility, Local Flexibility Markets, Network-aware procurement

Annex II – Continuous Clearing LinDistFlow

```
"""
Created on Mon Jan 18 22:09:55 2021

@author: Rahul N
"""

import pandas as pd
import numpy as np
def LinDistFlow_check(SetpointGP, SetpointGQ,Quantity,offer_bus,request_bus,direction,new_offer_PQ):

    epsilon=0.0005 # Tolerance of the steps
    lines_data = pd.read_excel(open(r"C:\Users\...\network_test_bench.xlsx", 'rb'),
sheet_name='Branch', index_col=0)
    lines = list(lines_data.index)  # index for lines
    lines_data.columns = ['From','To','R','X','Lim']
    bus_data = pd.read_excel(open(r"C:\Users\...\network_test_bench.xlsx", 'rb'), sheet_name='Bus')
    bus_data.columns = ['Bus', 'type', 'Vmax', 'Vmin', 'P', 'Q']
    ref_index = bus_data[bus_data['type'] == 3].index[0]
    bus_data.set_index("Bus", inplace=True)
    nodes = list(bus_data.index)    # index for nodes
    Vmax=bus_data['Vmax'].to_numpy()
    Vmin=bus_data['Vmin'].to_numpy()
    baseMVA = 0.1
    Quantity = Quantity / baseMVA
    epsilon = epsilon / baseMVA

    no_of_nodes = len(nodes)
    no_of_lines = len(lines)

    # %% Generating Incident matrix
    IM_pd = pd.DataFrame(np.zeros((no_of_lines, no_of_nodes)), columns=nodes, index=lines)
    r = np.zeros((no_of_lines, 1))
    x = np.zeros((no_of_lines, 1))
    i = 0

    for l in lines:
        IM_pd[lines_data.loc[l, 'From']][l] = 1
        IM_pd[lines_data.loc[l, 'To']][l] = -1
        r[i] = lines_data.loc[l, 'R']
        x[i] = lines_data.loc[l, 'X']
        i += 1

    IM = IM_pd.to_numpy()

    # %% Line capacity
    LC_pd = pd.DataFrame(np.zeros((1, no_of_lines)), columns=lines)
    for l in lines:
        LC_pd[l] = lines_data.loc[l, 'Lim']

    Line_Cap = LC_pd.to_numpy()

    # %% Getting load at each node
    P_pd = pd.DataFrame(np.zeros((1, no_of_nodes)), columns=nodes)
    Q_pd = pd.DataFrame(np.zeros((1, no_of_nodes)), columns=nodes)

    i = 0
    for n in nodes:
        P_pd[n] = SetpointGP[i] / baseMVA
        Q_pd[n] = SetpointGQ[i] / baseMVA
        i += 1
    if direction == 'Up':
        k = nodes[offer_bus]
        m = nodes[request_bus]
    if direction == 'Down':
        m = nodes[offer_bus]
        k = nodes[request_bus]

    congestion = True
    while congestion:
        if new_offer_PQ == 'P':
            P_pd[k] = P_pd[k] + Quantity
            P_pd[m] = P_pd[m] - Quantity
        elif new_offer_PQ == 'Q':
            Q_pd[k] = Q_pd[k] + Quantity
            Q_pd[m] = Q_pd[m] - Quantity
        P = P_pd.to_numpy()
        Q = Q_pd.to_numpy()

        A = np.delete(np.transpose(IM), 1, 0)
        Bp = np.delete(np.transpose(P), 1, 0)
        Line_P = np.linalg.solve(A, Bp)
        Bq = np.delete(np.transpose(Q), 1, 0)
        Line_Q = np.linalg.solve(A, Bq)

        Line_S = np.sqrt(np.square(Line_P) + np.square(Line_Q))
```

```
        # %% Finding Voltage

        Av = np.append(np.zeros((1, no_of_nodes)), IM, axis=0)
        Av[0][ref_index] = 1
        Bv = np.append(1, 2 * (np.multiply(r, Line_P) + np.multiply(x, Line_Q)))
        Node_V = np.linalg.solve(Av, Bv)**0.5

        if (np.greater_equal(Line_Cap / baseMVA, np.transpose(np.absolute(Line_P))).all() == True)
and (np.greater_equal(Vmax, Node_V).all() == True) and (np.greater_equal(Node_V, Vmin).all() ==
True):
            congestion = False
        else:
            if new_offer_PQ == 'P':
                P_pd[k] = P_pd[k] - Quantity
                P_pd[m] = P_pd[m] + Quantity
            elif new_offer_PQ == 'Q':
                Q_pd[k] = Q_pd[k] - Quantity
                Q_pd[m] = Q_pd[m] + Quantity
            Quantity = Quantity - epsilon
            if (Quantity <= 0):
                Quantity = 0
                congestion = False
    return Quantity * baseMVA
```

Annex III – Auction-based algorithm

In this annex the core of the auction-based algorithm is presented. To do so, the annex is divided in variables, constraints, and optimization function. This structure aims to show with clarity how the optimization problem works and how the grid power flows are modelled in the FLEXGRID approach. Consequently, the variables and constraints related to market clearing and bid matching will be omitted from this annex.

Starting with the variables, the lines of code below show the definition of the variables related to:

- Voltage
- Active Power flows
- Reactive Power flows

```
# Voltage
model.V_sq = pyo.variable_dict()
for i in node_data.index:
    model.V_sq[node_data.loc[i, 'Bus']] = pyo.variable(lb=node_data.loc[i, 'Vmin']**2,
ub=node_data.loc[i, 'Vmax']**2,value=1)

# Lines
model.Smax = pyo.variable_dict()
for i in branch_data.index:
    model.Smax[branch_data.loc[i, 'From'], branch_data.loc[i, 'To']] =
pyo.variable(lb=branch_data.loc[i, 'Lim']/baseMVA, ub=branch_data.loc[i, 'Lim']/baseMVA)

model.P_lin = pyo.variable_dict()
for i,j in model.B:
    model.P_lin[i,j] = pyo.variable()

model.Q_lin = pyo.variable_dict()
for i,j in model.B:
    model.Q_lin[i,j] = pyo.variable()

# Change in power injection
model.P_del = pyo.variable_dict()
for i in node_data.index:
    model.P_del[node_data.loc[i, 'Bus']] = pyo.variable(value=0)

model.Q_del = pyo.variable_dict()
for i in node_data.index:
    model.Q_del[node_data.loc[i, 'Bus']] = pyo.variable(value=0)

# Energy Not Served
model.Q_ENS = pyo.variable_dict()
for i in node_data.index:
    model.Q_ENS[node_data.loc[i, 'Bus']] = pyo.variable()

model.P_ENS = pyo.variable_dict()
for i in node_data.index:
    model.P_ENS[node_data.loc[i, 'Bus']] = pyo.variable()
```

As can be seen the variable defined for the voltage is the voltage squared, and its boundaries are the maximum and minimum voltage allowed per node (squared too). The reason to not define this variable as the voltage, has to do with the formulas to calculate the voltage drop (see in the constraints), where the voltage of each node is squared. Therefore, if the voltage is defined as a variable, the problem becomes non-linear.

The following line of code represent the system constraints, and therefore how the power flows and voltages are calculated. The constraints for P and Q flows represent a sort of Kirchoff's law also including the initial power, the power deleted (from bids), and the energy not served (this is a last minute addition from DTU to improve the performance of the algorithm).

```
#%% Constraints

# Active and reactive powerflows
model.active_power_flow = pyo.constraint_dict()
for k in model.N:
    Lhs = sum(model.P_lin[j, i] for j, i in model.B if i == k) - sum(
        model.P_lin[i, j] for i, j in model.B if i == k) + \
          model.P_init[k] + model.P_del[k] + model.P_ENS[k]
    model.active_power_flow[k] = pyo.constraint(body=Lhs, rhs=0)

model.reactive_power_flow = pyo.constraint_dict()
for k in model.N:
    Lhs = sum(model.Q_lin[j, i] for j, i in model.B if i == k) - sum(
        model.Q_lin[i, j] for i, j in model.B if i == k) + \
          model.Q_init[k] + model.Q_del[k] + model.Q_ENS[k]
    model.reactive_power_flow[k] = pyo.constraint(body=Lhs, rhs=0)

# Line flow limit
model.Lin_lim = pyo.constraint_dict()
for i,j in model.B:
    x = [model.P_lin[i,j],model.Q_lin[i,j]]
    model.Lin_lim[i,j] = pyo.conic.quadratic(model.Smax[i,j], x)

#Voltage Drop
model.voltage_drop = pyo.constraint_dict()
for i,j in model.B:
    Lhs = model.V_sq[j]
    Rhs = model.V_sq[i] - 2 * (model.R[i, j] * model.P_lin[i, j] + model.X[i, j] * model.Q_lin[i, j])
    model.voltage_drop[i,j] = pyo.constraint(body=Lhs-Rhs,rhs=0)
```

For the line flow limit constraint, a specific set of constraints in pyomo is used: conic.quadratic constraints. The set of conic constraints allow to use some nonlinear constraints into linear models. Finally, there is the voltage drop constraint that represents mathematically the voltage drop between nodes. The formula used is:

$$V_i{}^2 - \left(V_{i-1}{}^2 - 2(R_l P_{12} - X_l Q_{12})\right) = 0$$

Equation 1

Lastly, the objective function used in the analysis is presented below. In this case, it aims to maximize social welfare (see the "– "sign at the beginning of the formula). All the variables are multiplied by the parameter *baseMVA*, which is used to convert units from p.u back to absolute values, since the whole model inputs are given in p.u and therefore the model optimizes in p.u basis.

```
#%% Objective function

model.min_costs = pyo.objective(-(sum(model.Req_P[o] * baseMVA * Bid.loc[o, 'Price'] for o in
model.R_P) +sum(model.Req_Q[o] * baseMVA * Bid.loc[o, 'Price'] for o in model.R_Q) sum(model.off_P[o]
* baseMVA * Bid.loc[o, 'Price'] for o in model.O_P) - sum(model.off_Q[o] * baseMVA * Bid.loc[o,
'Price'] for o in model.O_Q)) + sum(model.P_ENS[k] * baseMVA * 200 for k in model.N))

#%% Specify solver settings and solve model
solver = pyo.SolverFactory('mosek')

display_results =True
if display_results == True:
    solver.solve(model, tee=True)
else:
    solver.solve(model)
```

Annex IV – Initial Setpoints

- High Demand Scenario

Bus	Setpoint – Active Power [MW]	Bus	Setpoint – Active Power [MW]
104	-0,000954	151	-0,0037106
105	-0,0023294	152	-0,0009538
108	-0,0021735	153	-0,0062918
110	-0,0015228	154	0,1562398
114	0,0091818	155	-0,0016223
115	0,0006265	156	-0,0053485
116	-0,0996439	157	0,0011518
117	0,1529829	158	-0,0128004
118	-0,0053646	159	-0,0024444
119	-0,0052212	160	-0,003069
120	-0,0003855	161	-0,0063433
121	0,0012661	162	-0,002288
122	0,0010023	163	-0,0042168
123	0,0021172	164	-0,001496
124	-0,0018313	165	-0,0043441
125	0,0006869	166	-0,0066737
126	-0,0018597	167	-0,0003063
127	-0,0024279	168	0,0026417
128	0,0027661	169	0,0034984
129	-0,0029102	170	0,0015057
130	0,1497558	171	-0,0026657
131	0	172	0,1452201
132	-0,0071275	173	-0,0035658
133	0,003226	174	0,0008446
134	-0,002196	175	-0,4282426
135	-0,0027062	176	0
136	0,0015425	177	0
137	-0,1053435	178	0,0030838
138	0,0663744	179	0,0018342
139	0	180	-0,0017327
140	-0,011	181	0,1
141	-0,0012984	182	-0,0023575
142	-0,0011748	183	-0,0089893
143	-0,0009252	184	-0,0062711
144	0,0000488	185	-0,0052807
145	-0,0007168	186	-0,0035271
146	0,0003159	187	-0,0027002
147	-0,0037111	188	-0,0026594
148	0,0030853	189	-0,0155078
149	-0,0027661	190	0
150	0		

- High Load Scenario

Bus	Setpoint – Active Power [MW]	Bus	Setpoint – Active Power [MW]
104	0	151	-0,0015521
105	-0,0018623	152	-0,0042778
108	-0,000822	153	-0,0033302
110	-0,0031636	154	0,0971653
114	-0,0031308	155	0,002529
115	-0,0001904	156	-0,0090937
116	-0,1002658	157	-0,0001651
117	0,05	158	-0,0020847
118	-0,000483	159	0,0013704
119	-0,0012435	160	-0,0036441
120	-0,0038815	161	-0,001926
121	-0,0978245	162	0,0008858
122	0,0002466	163	-0,0006158
123	0,0066127	164	-0,0023165
124	-0,0040685	165	-0,0017969
125	0,0101255	166	-0,0013788
126	0,0087091	167	-0,001825
127	0,0092723	168	-0,1022416
128	-0,001307	169	-0,0051389
129	-0,0082942	170	-0,0126161
130	-0,0365454	171	-0,0042281
131	-0,0036294	172	0,0017777
132	-0,1500052	173	-0,0011807
133	-0,0041254	174	-0,0027253
134	0,0027193	175	0,4258106
135	-0,00525	176	0
136	0,0031858	177	-0,0220884
137	-0,099529	178	-0,0017295
138	0,0981826	179	-0,0073206
139	-0,0001943	180	0,0130147
140	0,0046919	181	0,1
141	0,0005177	182	-0,0982457
142	0,0020954	183	-0,011
143	-0,0144544	184	-0,0038484
144	0,00692	185	-0,0122287
145	0,0000598	186	-0,0001703
146	-0,0012182	187	0,0006655
147	-0,001736	188	0,0038418
148	0,0034464	189	0,0025104
149	0,0023814	190	0
150	0,0032559		

- Normal Operation

Bus	Setpoint – Active Power [MW]	Bus	Setpoint – Active Power [MW]
104	-0,004163	151	0,0096821
105	0,0106179	152	0,0048764
108	-0,0014966	153	-0,0010622
110	0,008977	154	0,0966017
114	0	155	-0,0032294
115	0,0056605	156	0,0063417
116	-0,1022979	157	0
117	0,0586376	158	-0,0023428
118	0,0060021	159	-0,0113811
119	-0,003657	160	0,0108009
120	-0,0035146	161	0,0059132
121	-0,0651387	162	-0,0023266
122	-0,0007846	163	-0,0038099
123	-0,0024515	164	-0,0040702
124	-0,0049595	165	-0,0003313
125	-0,014537	166	-0,0051914
126	0,0090337	167	-0,0044681
127	0,0097639	168	-0,1041724
128	0,0040243	169	0,0080956
129	0	170	-0,0037332
130	0,097057	171	0,0062364
131	0,0036385	172	0,106493
132	-0,1560194	173	-0,0020242
133	-0,001923	174	-0,0059965
134	0,0101183	175	0,0975181
135	-0,005158	176	0
136	0,0068586	177	-0,1
137	-0,1024729	178	-0,0041993
138	0,1077985	179	0,0071384
139	-0,0030513	180	0,0099376
140	-0,0070805	181	0,1
141	0,0102438	182	-0,0947816
142	0,010432	183	0
143	-0,0061362	184	-0,0041576
144	-0,0029418	185	-0,0030475
145	-0,0059851	186	0,0058133
146	-0,0020265	187	0,0100101
147	0,0105019	188	0,0088161
148	-0,0054214	189	-0,0028776
149	-0,0045768	190	0
150	0,0053565		

Annex V – Initial Setpoints Creation

This annex aims to explain the process of creation of the initial setpoints in the grid. Due to the nature and complexity of the process, an iterative methodology has been implemented:

1. Create a setpoint using the Setpoint_Generator.xlsx file.
2. Test the setpoint created using the continuous clearing LinDistFlow check.
3. Test the setpoint created using the auction-based algorithm, with a modified optimization function to reduce curtailment and power not served.
4. Take the new initial setpoint created by 3 and repeat process 2 and 3.
5. If the power flows and voltage values are the same, and within the grid's limits → That is a valid setpoint.

Most of the code/software used to carry out this process is presented within the other annexes of this thesis. The only one that is specific to this process is the Setpoint_Generator.xlsx file. It has been created to automate the process of creating setpoints, and it has the following structure. First the loads are generated, to do so there are three excel sheets. The first one defines the "base load" which represent the residential loads and their consumption, the load is generated randomly per each node after defining: maximum value of the load (5,2 kW used in this thesis), and the parameters of a normal distribution (Mean and standard deviation). Then, there is another excel sheet to create the load from active domestic EV chargers. The only variable in this sheet is the % of active chargers. If one node has an active charger, the power of the charger is randomly selected from a list containing the maximum AC charging capacity of the best-selling EV cars in Germany (see Annex Table 1).

Annex Table 1: Top selling EVs Germany (February 2022).

Model	Maximum AC charging
Tesla Model 3	11 kW
Tesla Model Y	11 kW
Fiat 500e	11 kW
Hyundai Kona	7,2 kW
Renault Zoe	22 kW
ID.3	11 kW
ID.4	11 kW

Finally, on the last sheet the "special" loads are manually defined. This is where the industrial loads from the analysis are included in the load profile. If a node contains an industrial load, the previously created values (as residential loads) are modified to zero.

Then the same process is performed for the generation units. The first sheet contains the residential PV installations. Here the variables are the average capacity installed, the % of rooftop PV installed, capacity factor and standard deviation to create a normal distribution. The second excel sheet is for generation units, and these generation profiles have to be inputted manually.

Once this initial setpoint has been created. It is evaluated using the continuous clearing algorithm and a modified version of the auction based one, to get a feasible initial setpoint. The main modification performed on the auction-based algorithm - that can be seen in Annex III – Auction-based algorithm - is in the objective function:

```
#%% Objective function
model.min_costs = pyo.objective(baseMVA * (sum(model.P_CUR[i]*cost_cur for i in model.N) -
model.P_CUR[ref]*cost_cur+\
                                           sum(model.P_ENS[i]*cost_ens for i in model.N) -
model.P_ENS[ref]*cost_ens))
```

What this function does is, it optimizes the power flows to respect the grid limits at the lower cost possible. Therefore, modifying the bare minimum the given setpoint to make it feasible.

Annex VI – Code to Create Bids

The code to formulate the bid orderbook of each simulation has been created on purpose for this thesis and it allows to automate and randomize the market clearing events.

The code hereby presented aims to show the structure and logic behind the "random bid generator". Since this thesis aims to be as close to the reality as possible each asset flexibility is limited by the initial setpoint of itself. For this reason two bids_generator() functions have been created.

High generation and High load

Explaining the code line by line, it starts by creating the single flexibility request that the DSO needs to solve the existing congestion. On the initial lines, the volume needed, the maximum price of flexibility, together with the type of power, the direction of the flexibility needed, and the location of the request are defined. Additionally, the time stamp and time target are also added to the first row of the pandas DataFrame called all bids. The request is the only bid that is not randomized since the needs of the DSO are the starting point of this analysis.

```
import pandas as pd
import random

#Case 1 - Normal

def bids_generator():
    req=0.23
    price_req = 643.5
    Time_stamp = '11/04/2022 12.00' #+ str(random.randrange(10, 59, 1))
    all_bids = pd.DataFrame({'ID': ['r1'], 'Bid': ['Request'], 'Type': ['Unconditional'], 'Bus':
[176], 'P_or_Q': ['P'],
                             'Direction': ['Down'], 'Quantity': [req], 'Price': [price_req],
'Time_target': ['t1'],
                             'Time_stamp': [Time_stamp]})
```

Then two lists are created containing the Generators and Industrial loads maximum available flexibility. This is calculated by comparing the initial setpoint of the asset with either its maximum power capacity or its minimum power capacity. This maximum value will serve as a upper boundary for the randomized volume of flexibility.Then a *for loop* is used to go through each of the lists and create bids for each of the nodes. In this for loop the quantity, price and time stamp are created "randomly" based on: the maximum flexibility available on the node (lower or equal), the price requested by the DSO (can be lower or higher), and random values from 10 to 59, respectively. Finally, the new bid is added to the all_bids DataFrame.

```
    Chargers = [(116,0.1), (121,0.2), (132,0.15), (137,0.1), (168,0.1), (177,0.1), (182,0.1), (183,
0.2)]
    Generators = [(117,0.15), (138,0.065), (130,0.14), (154,0.15), (172,0.14), (181,0.1)]

    z=1

    for i in Chargers:
        name='o'+str(z)
        quantity = random.randrange(0,int(i[1]*100),1)/100
        price= (price_req)*random.randrange(5,13,1)/10
        Time_stamp= '11/04/2022 12.'+str(random.randrange(10,59,1))
        z+=1
        bid = pd.DataFrame( {'ID':[name],'Bid': ['Offer'], 'Type': ['NaN'], 'Bus': [i[0]], 'P_or_Q':
['P'], 'Direction': ['Down'], 'Quantity': [quantity],'Price': [price], 'Time_target': ['t1'],
'Time_stamp': [Time_stamp]})
        all_bids=pd.concat([all_bids,bid])


    for i in Generators:
        name='o'+str(z)
        quantity = random.randrange(0,int(i[1]*100),1)/100
        price= (price_req)*random.randrange(5,13,1)/10
        Time_stamp= '11/04/2022 12.'+str(random.randrange(10,59,1))
        z+=1
```

```
        bid = pd.DataFrame({'ID':[name],'Bid': ['Offer'], 'Type': ['NaN'], 'Bus': [i[0]], 'P_or_Q':
['P'], 'Direction': ['Down'],
                            'Quantity': [quantity], 'Price': [price], 'Time_target': ['t1'],
'Time_stamp': [Time_stamp]})
        all_bids = pd.concat([all_bids, bid])
    all_bids=all_bids.set_index('ID')
    return all_bids,z
```

Up until here the code presented is the one that has been used in the events of: High Generation and Reduced Liquidity. To move from the Reduced to the High liquidity orderbooks the same process has to be followed but now with the rest of the nodes in the grid.

```
def bids_generator_DER(z):
    req = 0.23
    price_req = 631.8
    Time_stamp = '11/04/2022 12.' + str(random.randrange(10, 59, 1))
    all_bids = pd.DataFrame({'ID': [], 'Bid': [], 'Type': [], 'Bus': [], 'P_or_Q': [],
'Direction': [], 'Quantity': [], 'Price': [], 'Time_target': [],'Time_stamp': []})

    Aggregated = [104, 105, 108, 110, 114, 118, 119, 120, 122, 123, 124, 126, 127, 128, 129, 131,
133, 135, 136, 139, 140, 142, 143, 144, 145, 146, 147, 149, 150, 151, 152, 154, 155, 156,
                  157, 158, 160, 161, 162, 163, 165, 166, 167, 169, 170, 171, 173, 174, 178, 179,
180, 184, 185,
                  186, 187, 188, 189, 190]
    for i in Aggregated:
        name = 'o' + str(z)
        Time_stamp = '11/04/2022 12.' + str(random.randrange(10, 59, 1))
        price = price_req * random.randrange(5, 13, 1) / 10 # Check this how to manage it;
        quantity = random.randrange(0, 7, 1) / 1000
        z+=1
        bid = pd.DataFrame({'ID': [name], 'Bid': ['Offer'], 'Type': ['NaN'], 'Bus': [i], 'P_or_Q':
['P'], 'Direction': ['Down'],'Quantity': [quantity], 'Price': [price], 'Time_target': ['t1'],
'Time_stamp': [Time_stamp]})
        all_bids = pd.concat([all_bids, bid])
    all_bids = all_bids.set_index('ID')
    return all_bids
```

Finally, is important to mention that for simplification purposes all the offers created are aligned with the direction of the request. This has been done because this is the first thing the algorithms filter even before the price, and therefore it has been considered not relevant to add this kind of bids in the orderbook.

Normal Operation

The following is the code that created the bids for the Normal Operation scenario. It differs from the previous ones, because both the direction (up/down) and type of bid (request/offer) are randomly created in this case, not considering the physical reality of the grid.

```
def multiple_req():
    price_req = 643.5
    all_bids = pd.DataFrame({'ID': [], 'Bid': [], 'Type': [], 'Bus': [], 'P_or_Q': [],
                             'Direction': [], 'Quantity': [], 'Price': [], 'Time_target': [],
                             'Time_stamp': []})
    All_nodes = [116, 121, 132, 137, 168, 177, 182, 183, 117, 138, 130, 154, 172, 181, 104, 105, 108,
110, 114, 118,
                 119, 120, 122, 123, 124, 126, 127, 128, 129, 131,
                 133, 135, 136, 139, 140, 142, 143, 144, 145, 146, 147, 149, 150, 151, 152, 154, 155,
156,
                 157, 158, 160, 161, 162, 163, 165, 166, 167, 169, 170, 171, 173, 174, 178, 179, 180,
184, 185,
                 186, 187, 188, 189, 190]
    z = 1
    for i in All_nodes:
        aux=random.randrange(0,10,1)
        if aux > 8: #Request creator
            name = 'r' + str(z)
            Direction = random.choice(['Up','Down'])
            quantity= random.randrange(10, 150, 10) / 1000
            price= price_req * random.randrange(5, 11, 1) / 10  # Check this how to manage it;
            Time_stamp = '11/04/2022 12.' + str(random.randrange(1, 59, 1))
            bid = pd.DataFrame( {'ID': [name], 'Bid': ['Request'], 'Type': ['Unconditional'], 'Bus':
[i], 'P_or_Q': ['P'], 'Direction': [Direction],
                 'Quantity': [quantity], 'Price': [price], 'Time_target': ['t1'], 'Time_stamp':
[Time_stamp]})
            all_bids = pd.concat([all_bids, bid])
```

```
            z+=1
        else:
            name = 'o' + str(z)
            Direction = random.choice(['Up', 'Down'])
            quantity = random.randrange(5, 100, 5) / 1000
            price = price_req * random.randrange(5, 13, 1) / 10  # Check this how to manage it;
            Time_stamp = '11/04/2022 12.' + str(random.randrange(1, 59, 1))
            bid = pd.DataFrame(
                {'ID': [name], 'Bid': ['Offer'], 'Type': ['NaN'], 'Bus': [i], 'P_or_Q': ['P'],
                 'Direction': [Direction],'Quantity': [quantity], 'Price': [price], 'Time_target':
['t1'], 'Time_stamp': [Time_stamp]})
            all_bids = pd.concat([all_bids, bid])
            z += 1
    all_bids = all_bids.set_index('ID')
    return all_bids
```