FlexiGrid

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Local market designs for energy exchange and grid services

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Authors

Surname	First Name	Beneficiary	e-mail address
Chobanov	Vesselin	TU/s	vesselin_chobanov@tu-sofia.bg
Fotouhi	Ali	CTH	ali.fotouhi@chalmers.se
Ivanova	Verzhinia	EE	verzhinia.ivanova@entra.energy
Koster	Daniel	LIST	daniel.koster@list.lu
Le	Anh Tuan	CTH	tuan.le@chalmers.se
Mirzaei Alavijeh	Nima	CTH	nima.mirzaei@chalmers.se
Mohandes	Baraa	LIST	baraa.mohandes@list.lu
Oana	Carmen	SIMAVI	Carmen.Oana@simavi.ro
Rumenova	Ralitsa	EE	ralitsa.rumenova@entra.energy
Sandhu	Amarina	IMCG	amarina.sandhu@imcginternational.com
Steen	David	CTH	david.steen@chalmers.se
Tobiasson	Wenche	RISE	wenche.tobiasson@ri.se
Vu Van	Thong	EMAX	thong.vuvan@emaxgroup.eu
Wahlström	Ulrika	IMCG	ulrika.wahlstrom@imcginternational.com

Reviewers

Surname	First Name	Beneficiary	e-mail address
Le	Anh Tuan	CTH	tuan.le@chalmers.se
Nguyen	Phuong	TU/e	P.Nguyen.Hong@tue.nl
Tobiasson	Wenche	RISE	wenche.tobiasson@ri.se

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List of abbreviations

Abbreviation	Definition
AC	Alternating current
B2B	Business-to-business
BRP	Balance responsible party
CL	Capacity-limit
DC	Direct current
DER	Distributed energy resources
DLT	Distributed ledger technology
DSO	Distribution system operator
EV	Electric vehicle
FED	Fossil-free Energy District
FED-EM	Fossil-free Energy district- Energy market
FlexiGrid	Enabling flexibility for future distribution grid – FlexiGrid
FS	Flexibility service
FSP	Flexibility service provider
GHG	Greenhouse gases
HP	Heat pump
HR	Human resources
ICT	Information and communication technology
IoT	Internet of things
LEM	Local energy market
LFM	Local flexibility market
LV	Low voltage
MO	Market operator
MV	Medium voltage
OLTC	On-load tap changer
P-2-G	Power-to-gas
P2P	Peer-to-peer
CPSPV	Cyber-Physical SystemsPhotovoltaic
RES	Renewable energy sources
TSO	Transmission system operator
UC	Use case
V2G	Vehicle-to-Grid
VCG	Vickrey-Clarke-Groves

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Executive Summary

The distribution networks are expected to face challenges in the coming years as the penetration of distributed energy resources and electrification of other sectors continue to increase. Two of these challenges are local congestions and voltage band violations. Different alternatives are suggested as solutions to these challenges such as grid reinforcements, market-based solutions, innovative tariff designs, active grid control, etc.

This report is **aiming** to explore the market-based solutions such as local energy and flexibility markets to address the distribution system operators' (DSOs) challenges. Different design considerations are discussed to be utilised for a better market mechanism design. Moreover, market designs are proposed for three market structures of peer-to-pool (centralized), peer-to-peer, and adaptive structures for local trade of energy and flexibility.

The **design considerations** include desirable market properties from economic theory and stakeholders' perspectives, different alternatives for market structure, value chain of local markets and potential cost and revenue streams for the DSOs, the role and functionality of IoT platform, and potential billing options and their pros and cons. The design considerations have been identified through reviewing literature and relevant projects beside conducting workshops with the different stakeholders involved in the project.

Four high-level **desirable properties** when designing a mechanism are efficiency, incentive compatibility, budget balance, and group rationality. An efficient mechanism should maximize social welfare of all the participants considering their revealed preferences. An incentive compatible mechanism incentivises participants to bid truthfully and reveal their true preferences. Moreover, a mechanism should be budget balance meaning that the market operator shall not end-up having neither deficit nor excess in the financial balance. A group rational mechanism is designed in a way to hinder separation of participants from the mechanism and leads to stability of the mechanism. These high-level properties can be translated into more practical properties such as standardized products, price-taking participants, freedom of entry and exit, symmetric information, inclusivity, and transparency.

There exist different alternative **structures for market design**. In this report we have explored peer-to-pool, peer-to-peer, and adaptive schemes. Peer-to-pool structure is a centralized mechanism aiming to maximize the social welfare for all the market participants according to their revealed preferences. The market operator is the advisory actor for managing the market, clearing the bids, and conduct the settlement. In peer-to-peer structures the trade is conducted in a decentralized and bilateral manner. Blockchain is one of the technologies that facilitate a transparent and decentralized payment and smart contracting between the buyers and sellers without the need for a centralized control. The adaptive scheme utilises both peer-to-pool and peer-to-peer structures and combine them into a larger framework. The adaptive structure adjusts these two different structures according to the need/state of the system through a list of controllable parameters.

The considered **actors** involved in the local markets are DSOs, aggregators, end-users, and market operator. There might be slight differences between the market structures in terms of the actors and their roles. However, from a general perspective, the DSO is the buyer of the flexibility products and is responsible for a reliable and secure operation of the distribution network. The aggregators are considered as the sellers of the energy or flexibility products. The end-users can participate directly in the

local markets or participate through an aggregator. The market operator is responsible for clearing the market to maximize the social welfare, and allocate the payments according to contribution of each market participant.

The **potential cost and revenue streams** in a local market for DSOs are further investigated. Potential cost streams are the costs related to measurements and ICT/IoT platforms, administrative and personnel for participation in the local markets, potential reduction in the revenues from power tariffs, and lower revenue caps due to postponing/avoiding CAPEX. Potential revenue (cost reduction revenues) are postponed/avoided investments, extending the lifetime of assets by not overloading them, lower connection fee payments to the upstream network owner, savings in avoiding costs related to operational actions, and potential savings by avoiding curtailment of distributed renewable energy sources.

The **IoT platform** is another important piece of the puzzle in having a functional local market. The IoT platform brings together different involved stakeholders and facilitate their communication in a secure and user-friendly manner. The FlexiGrid's IoT platform is designed based on the Federative System Space concept. This concept allows different demo sites and actors to have their own deployment. The platform facilitates the communication between the actors by offering common places for data storage and common functionalities while providing the opportunity for a certain degree of autonomy within the borders of the imposed rules.

The **billing** is an important step in the final stages of a market mechanism. The potential options for billing are currency (national vs. crypto currency), blockchain, separate billing and invoicing systems, and utilising an existing invoicing system between the market participants. To select an appropriate billing option, one needs to consider the size and number of transactions, the costs related to a transaction, payment currency, and legislations.

The **peer-to-pool market** designs are proposed for trading energy and flexibility locally in Chapter 3. The focus of the work though has been on the local flexibility markets due to potential complexity and challenges with implementing local energy markets in the current structure of the energy system. The design of the flexibility market is done considering the desirable market properties and identified common challenges mentioned in the literature regarding the design of local flexibility markets.

These common challenges are low market liquidity and its consequences, reliability concerns and security of supply/demand alongside a conservative culture in the energy industry, challenges regarding defining baselines for baseline-based products, forecast errors due to low aggregation levels, and high costs regarding the need for extra measurements and ICT/IoT infrastructure.

We have tried to address the low liquidity concern by utilising game theory payment allocation methods to hinder market power practices and untruthful bidding. We have introducing a long-term reservation market to facilitate decision making for DSOs and flexibility providers years ahead and thus increase the reliability of the market solution. Moreover, capacity-limit based products are introduced to avoid the challenges regarding the baseline, low aggregation level, and market manipulations. A continuous adjustment market is also considered to provide the opportunity for correcting the forecast errors. The proposed products are designed to require only measurements from the smart meters and thus not imposing extra implementation costs regarding the measurements.

In Chapter 3, the product design, clearing algorithm, payment allocation methods, and illustrative simulation case-studies are provided and it has been tried to provide the motivation behind each design decision.

The **peer-to-peer flexibility market** is an option when millions of flexibility assets are at the DSO network. Thanks to applicable concept from Blockchain for the peer-to-peer flexibility market, we have overviewed existing initiatives in the chapter, identified their innovative aspects and considered in the context for FlexiGrid project.

We highlight business use case, requirements of system architect, activation and process of trading flow, access right, data input, etc. These are important aspects to be considered for development of the trading platform.

An ultimate goal of the trading platform will not only support the trading activities to happen smoothly, but also provides great trading experiences for users. The key functionalities performed in the peer-to-peer Blockchain platform includes a) flexibility asset onboarding on Blockchain, b) Visibility of flexibility assets and needs, c) listing assets, requests and offers, d) validation of delivery using smart contracts, e) settlement using Blockchain-based smart contracts.

The outcomes of the chapter 4 on peer to peer will prepare necessary market design elements which will be implemented in WP7, in which DSO-consumer flexibility market platform for local grid imbalance, congestion and voltage management will be demonstrated.

Adaptive market structure design in Chapter 5 approaches the problem of grid congestions from an unconventional point of view. The right to use the grid is treated as a scarce commodity to be auctioned among grid users. The implications of this perception manifest themselves when the system is congested and the available flexibility is insufficient. Instead of aggregators selling a promise to the DSO to cap their load, the aggregators and other end-users buy the right to use the grid from the DSO. This operation paradigm is discussed from an economics point of view, and the rules of demand and supply.

A perfect mechanism design is almost impossible and therefore it is very important to be aware of the pros and cons of each element in the design, decide based on the most important desirable properties. In our **future work** the following items are going to be considered to reach a more mature and practical design:

- Improving of the market designs based on the pros and cons of different elements in the market design and improve the bidding strategies for the participants
- Exploring the pros and cons of including grid constraints in the market clearing and how it might impact alleviating distribution networks challenges
- Incorporating the market designs and the models into the IoT platform
- Demonstration of the solutions in the project demo sites
- Inclusion of different flexibility sources available at each of the demo sites

1 Introduction

Three main trends that can cause challenges in the future distribution networks are increasing penetration level of stochastic renewable energy sources (RES), electrification of other sectors such as transport and heating, and a more coordinated control of distributed energy resources (DERs) that can increase the load concurrency, potentially lead to congestions and voltage limit violations in the distribution networks.

Such trends can cause different challenges for the distribution grids, including congestions or voltage band violations. There are different potential solutions to address these challenges [1], [2] :

- Grid reinforcements,
- Market-based solutions (local markets for energy and flexibility)
- Innovative tariff designs
- Rule-based approaches
- Active network management
- Comprehensive methods including a mix of the above solutions

Article 32 of the Electricity Market Directive (2019/944) of the EU clean energy package [3] discusses the use of flexibility services in the distribution grids. In the Article 32 it is pointed out that distribution system operators (DSOs) "shall procure such services in accordance with transparent, non-discriminatory and market-based procedures unless the regulatory authorities have established that the procurement of such services is not economically efficient or that such procurement would lead to severe market distortions or to higher congestion". Accordingly, this report aims to assess such market-based solutions for solving the distribution networks' future challenges.

1.1 Objectives and scope

The scope of the report is limited to the markets and different aspects within the distribution grids. The explored market structures are peer-to-pool, peer-to-peer, and adaptive structure based on real-time grid conditions.

The objectives of this report are as follows:

- Developing local markets for energy (LEMs) and flexibility (LFMs) in three different mechanisms of peer-to-pool, peer-to-peer, and adaptive structure. The market designs include bidding, clearing, and settlements. The markets are designed considering the desirable market properties and stakeholders' perspectives.
- Exploring the roles and responsibilities of the market actors and potential cost and revenue streams of the DSOs in the context of local markets
- Exploring the role and the design of an IoT platform that enables the interactions between the DSOs and end-users
- Exploring the different billing and payment alternatives and providing recommendations for selection of the billing method

The work in this report can be used to connect the other activities in the project such as Deliverable 3.3 on process design for flexibility procurement and dispatch and Deliverable 3.4 on quantification of flexibility. Moreover, the market designs presented in this report would be used as the basis of the market mechanism which would be demonstrated in demonstration work packages.

1.2 Deliverable structure

Chapter 2 discusses different design considerations and alternatives. These considerations and alternatives are discussed in 5 different topics of 1) the potential use cases and product metrics in a local market, 2) the desirable market properties from an economic theory and stakeholders' perspectives, 3) different potential market structures such as peer-to-pool, peer-to-peer, and adaptive structures, 4) potential stakeholders and DSOs' related costs and revenues streams, 5) IoT platform, and 6) billing alternatives in local markets. Chapter 3 includes a market design for local peer-to-pool centralised flexibility and energy markets. Chapter 4 presents a market design for peer-to-peer structure. Chapter 5 proposes an adaptive market structure based on the grid status. Chapter 6 concludes the work and discusses potential future works.

2 Design considerations and alternatives

In this chapter, the differences between different market mechanisms are described. Moreover, shared design considerations between the market mechanisms are explained. The design considerations cover the desirable market properties from an economical perspective in addition to stakeholders' perspective. Furthermore, the potential local market actors are identified and the potential cost and revenue streams are elaborated with a focus on the DSOs. The overview of FlexiGrid's IoT platform is presented as it is one of the essential cores of the smart-grid solutions. The different billing alternatives are also outlined and the pros and cons for each alternative is discussed.

2.1 General use cases and product metrics in local markets

This section describes the general use case of local flexibility and energy markets and discusses the potential characteristics and metrics of the traded products in these markets.

2.1.1 Local energy markets use cases:

With increasing penetration of RES units in the distribution system, the payment from the DSO to prosumers, known as the feed-in tariff, is decreasing gradually. At the same time, the retail price of electricity, charged by the energy supplier, stays the same or increases due to carbon taxes. When the feed-in tariff falls below the retail price of electricity, a prosumer would make more profits by selling excess energy to other small consumers in their vicinity. Via peer2peer market, prosumers can advertise their surplus energy production and sell it to consumers interested in directly using electricity.

At the same time, a large consumer who pays the wholesale price of electricity can hedge against the price volatility by holding long-term agreements with small prosumers.

2.1.2 Local flexibility markets use cases:

Voltage Band Violations

As electric power flows from the MV to the LV level and towards the end of the feeder, the voltage decreases gradually over the length of a feeder due to line impedance. Often, the only tool to control voltage over the feeder is the on-load tap changer (OLTC) of the transformer at the beginning of the feeder. For long feeders, a large load located at the end of the feeder will cause a significant voltage drop, and the voltage at the end of the feeder falls below the minimum voltage level. If adjusting the transformer's OLTC is the only available option, it is possible that the voltage at the end of the feeder can only be restored to the minimum voltage level if the voltage at the beginning of the feeder exceeds its maximum limit.

The opposite effect can be caused by high renewable energy feed-in to the LV grid, e.g. by PV-systems, during times of low consumption. This energy injection causes a reverse power flow and the voltage gradually rises from the transformer location along the feeder, such that it reaches its maximum at the injection point. Consequently, in extreme cases of energy injection and low consumption, the prescribed voltage band may be violated.

Local Congestions (Overload) / Reverse Power Flow

Distribution feeders are radial, and the net energy consumption on a feeder passes through the transformer at the beginning of the feeder. If the demand of the total feeder reaches or exceeds the transformer maximum load, the transformer is subject to thermal stress. The primary effect of thermal stress is degradation of the insulation of the transformers' windings, which reduces the transformers' lifetime. Congestions can be also caused by large energy injections from RES units, such that power flows in reverse through the transformer, upstream.

(Deferral of grid investments)

Flexibility can benefit the distribution system even when the system is running without congestions or voltage deviations. System equipment must, theoretically, be large enough to supply the load requirements at all times. The load profile may exhibit a very rare spike which occurs once a year and lasts only for few minutes or hours. Theoretically, the system operator is still be required to procure the equipment necessary to supply this load, and expand the grid capacity accordingly. If the system operator is able to acquire flexibility to accommodate this rare event, the system operator can defer investments to expand the grid infrastructure.

Similarly, with the continuous growth of demand, certain components of the system, such as transformers, will soon require an upgrade. Acquisition of local flexibility can help defer this investment for some time.

2.1.3 Products characteristics and metrics:

As described earlier, flexibility can serve different goals such as resolving voltage deviations and relieving congestions. Each use case of flexibility requires the flexibility products to have certain technical characteristics.

The characteristics that determine the value and impact of a flexibility product on the system are:

- **Locational granularity:**
  The effect of flexibility on the voltage at a stressed node is dependent on the flexibility product's location with respect to the stressed node. The greatest healing effect comes from loads located further downstream of the stressed node. However, flexibility on a parallel branch also has a slight but observable effect. The IEEE 33-bus standard test system depicted in Figure 2-1 resembles a typical distribution system. An undervoltage at node 33 benefits significantly from up flexibility at any location between nodes 26 – 33. But the undervoltage can also benefit from up flexibility injections at any location between nodes 2 – 18, to different extents. This is because reduction of total over this branch of the system reduces the total current observed at node 2, and boosts, slightly, the voltage at node 2 itself. This voltage boost propagates to node 33.
  Locational granularity is even more critical in the case of congestions and overloads, in comparison with voltage deviations. Flexibility on an adjacent feeder has no effect on local congestions. In the case of an overload, only the flexibility strictly downstream of the congested point can have any healing effect on the problem.

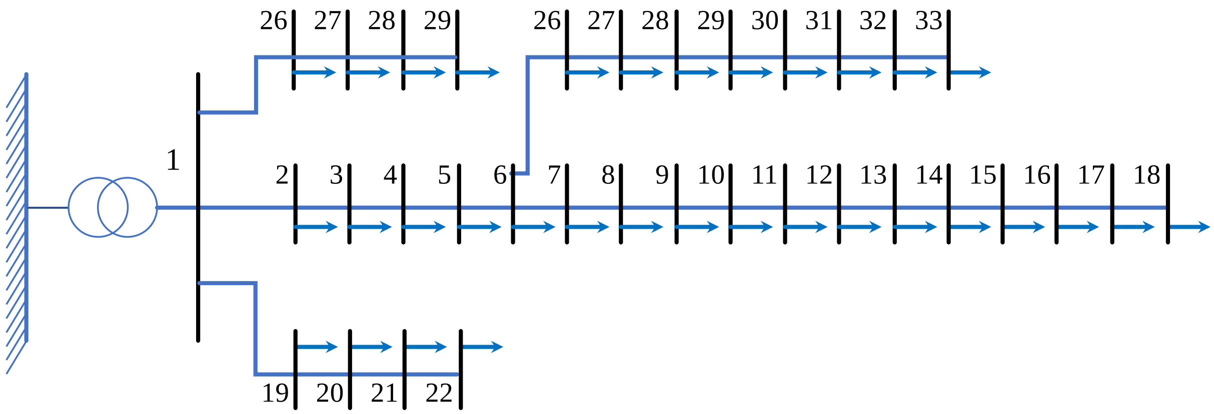

Figure 2-1. 33-Bus IEEE Standard Test System

- **Nature of curtailed load:**
  When the flexibility product comes in the form of load curtailment, two devices at the same location and with the same apparent power consumption may have different healing effect on the grid when each device is shut down. The further downstream a load is, the longer is the distance that the energy travels, and the larger is the voltage drop. Load characteristics which play a role in voltage drop are:

  - Load Power Factor (i.e. reactive power consumption): Due to the low X/R ratio on distribution lines, real power injection/withdrawal is strongly coupled with the voltage magnitude. Reactive power still has a mild effect on voltage magnitude. Up flexibility from loads that have a low lagging power factor (and large reactive power consumption) has a higher impact on the voltage. Voltage drop and large quantities of reactive power flowing over distribution lines also have an indirect effect on line losses, and consequently, a small impact on equipment overloading.
  - Voltage dependence factor: The nominal power consumption P_0 of a load, reported by device manufacturer, is based on supplying the device with the nominal voltage V_0. When the supply voltage deviates from the nominal voltage, within a permissible band, electric devices may respond to the voltage change in different ways. One way to model a device's actual power consumption as a function of the input voltage is given by (2-1).

$$\tilde{P} = P_0 \cdot \left(\frac{V}{V_0}\right)^{\gamma} \tag{2-1}$$

where: $\tilde{P}$*: effective power consumption by a device*

P_0*: the device's nominal power consumption at nominal voltage level* V_0.

V_0*: The nominal voltage which the device is designed for*

V*: The actual voltage applied on the device*

γ*: the voltage dependence factor of the device*

Table 2-1 Voltage dependence factor of differnet loads		
$\gamma = 0$ $\tilde{P} = P_0$	$\gamma = 1$ $\tilde{P} = P_0 \times (V/V_0)$	$\gamma = 2$ $\tilde{P} = P_o \times (V/V_0)^2$

Constant Power (P) Load	Constant Current (I) Load	Constant Impedance (Z) load
Current is inversely proportional to voltage, to maintain power Real Power is fixed	Current magnitude is fixed Power factor drops Reactive power increases Real power decreases linearly	Current is directly proportional to voltage (Ohm's law) Real power decreases quadratically
○ Electronic Loads such as Data centers ○ Motors with electronic speed controllers (Variable speed drives) such as modern washing machines ○ Loads with automatic controllers	○ Induction motors in fixed-speed applications such as Fixed-speed compressors in old refrigerators, air conditioners. ○ Old washing machines, fans. ○ Fluorescent lamps (lighting fixtures with electronic components)	○ Old lighting fixtures such as: ○ Incandescent light bulbs ○ Old heaters ○ Old electric furnaces

$$\gamma = \begin{cases} 0 & \text{Constant Power Device} \\ 1 & \text{Constant Current Device} \\ 2 & \text{Constant Impedance Device} \end{cases}$$

Figure 2-2 illustrates how a constant-power device adjusts its consumption pattern to maintain total energy consumption at the same level over a period of time. In the case of an air-conditioning device, the timescale of the pattern in Figure 2-2 would be minutes to hours. The instantaneous power consumption drops, however, the total consumed energy over an interval of market operations may stay the same. In the case of an electronic device, the same pattern occurs on a timescale of micro-seconds to milli-seconds. From the perspective of market operators and measurement equipment, the instantaneous consumed power appears to remain the same.

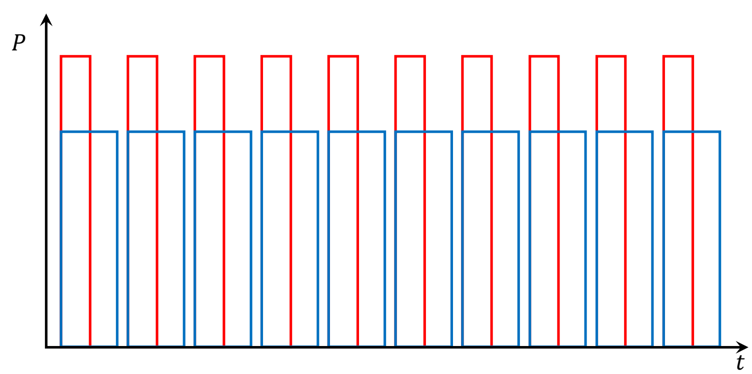

Figure 2-2 Constant power load's reaction to voltage drop

A device's voltage dependence level impacts line losses, and also the same device's reactive power consumption. Therefore, upwards flexibility from a constant-power (i.e. data center) device has a larger healing effect in any scenario of voltage deviation (up or down), than constant-current devices, and constant-impedance devices, respectively.

Interruptibility: Reference [4] highlights a fundamental difference between thermal generators and responsive demand units. Thermal generators status (i.e. switched on/off) is governed by a minimum-up-time, and minimum-down-time constraints. Thermal generators also have a start-up and a shutdown cost. These aspects are not necessarily applicable to responsive demand units. In contrast, the status (i.e. on/off) of responsive demand units is more likely bounded by the length of interruption or curtailment, and the number of interruptions per day. For example, a microprocessors manufacturing plant bears high losses each time the process line is halted. Such a demand unit prefers to provide flexibility for an extended period of time, however, only once per day or per week. Reference [5] provides an extensive survey of the duration of interruption vs. the maximum number of interruptions per day for different types of industrial processes. A few examples are provided in Table 2-2.

Table 2-2 Aptitude of different industrial processes for demand response

Industrial Premises	Process type	Min. Duration	Max. Duration	Max. # Interruptions
Food	Packaging	30 minutes	60 minutes	1-2 times per day
Food	Chilling	30 minutes	60 minutes	1-2 times per day
Textile	Wrapping/Weaving	60 minutes	60 minutes	1-2 times per day
Mills, Furniture	Sawing	30 minutes	60 minutes	1-2 times per day
Paper	Chipper	60 minutes	4 hours	1-2 times per day
Rubber & Plastics	Mixing / Milling	30 minutes	60 minutes	1-2 times per day
Stone/Glass/Concrete	Furnace	30 minutes	60 minutes	1-2 times per day
Stone/Glass/Concrete and Metal	Crushing	30 minutes	4 hours	1-2 times per day
Printing / Publishing	Compressor	60 minutes	3 hours	1-2 times per day

- **Power vs. Energy**

  Some electric appliances, such as lighting fixtures and electronics, have a constant consumption level over an extended period of time[1]. In contrast, intermittent loads, such as industrial scale motor drives, may switch on and off several times within a single period of market operations. Compensating a flexibility service based on the average or the maximum power level may not be fair, and may not attract potential flexibility providers. This also goes the other way; an intermittent load switched off to provide flexibility should not be compensated based on its maximum power level. In such cases, both the power and total consumed energy should be taken into account when calculating compensation and also analysing total load in the grid.

  On the other hand, there are load scenarios where the power level is the key characteristic of a flexibility product. A load spike which occurs few times over the whole year, lasting for few minutes

[1] The discussion here concerns the typical use of an electric device, and the consumer behaviour. The voltage dependence factor is irrelevant to this phenomenon. For example, lighting fixtures in an industrial facility stay on all night long. In contrast, a hoist, or an electric tram (intra-city train) may stop and re-accelerate every few minutes. This is the typical use of such devices, and this usage pattern is irrelevant to voltage level.

each time can be problematic to the power system. A sharp load spike (i.e. high-power level) lasting for a short time period, shorter than the length of an interval of operations, incurs a small amount of consumed energy. A flexibility product procured specifically to cope with this load spike should be compensated based on the power level it provides, rather than the energy component.

- **Duration:**
  For scarcity events that may extend over several intervals of operations, it makes sense to procure a flexibility service which covers the whole duration of the scarcity event. The duration of interruption in the case of responsive demand units was discussed earlier among the nature of load characteristics.

2.2 Desirable market properties

In this section, the desirable market properties are discussed from a theoretical and stakeholders' point of view.

2.2.1 Economic properties

Electricity markets are designed and have not appeared naturally as a result of goods or services being traded. Characteristics of electricity and its importance to society meant that the energy sector for a long time was monopolised, often state- or local government-owned and operated, followed by liberalisation, including privatisation of certain aspects, through a regulatory process. The segments of the sector that were considered to benefit from competition through efficiency improvements, i.e., generation and supply, were separated from those where competition were thought to lead to less efficient outcomes, i.e., transmission and distribution services.

Electricity wholesale market design is different across the world, however, the objective of regulators tends to be the same; reliable electricity at least cost to consumers. This is achieved through two key objectives: Short-run efficiency – making the best use of existing resources, and long-run efficiency – ensuring that the market provides the proper incentives for efficient long-run investment [6].

Efficiency in both the short-run and long-run is difficult to achieve and there are many aspects that will contribute. Knowledge of the aspects that will contribute towards an efficient market will aid the design process and help identify possible shortcomings and solutions. This section of the report will briefly outline the economic theory behind efficient market design and discuss its implications related to local markets for energy and flexibility exchange. Possible weaknesses and methods of overcoming these will be discussed.

Theory

In economics literature, there are various sources that discuss mechanism design and the desirable properties for a mechanism [7], [8]. Mechanism design can be used in different contexts such as agreements, voting, privatisation, and markets. Eric Maskin, the 2007 Nobel laureate and the professor of Economics and Mathematics at Harvard University, describes mechanism design as the "engineering part of the economics" in which the economists, instead of taking the economic institutes and predict the outcomes of such institutes, focus on starting from the outcomes and ask how economic institutions can be designed to achieve the suitable outcomes[2].

Some of these general suitable outcomes/properties, in the context of local markets, are presented in [9], [10],including:

- **Efficiency:** the mechanism should maximise the social welfare of the participants in the mechanism considering their revealed preferences. The mechanism should also guarantee that none of the participants would be willing to deviate unilaterally form its dispatch, meaning that the mechanism's outcomes should be aligned with each participant's profit maximisation algorithm.
- **Incentive compatibility:** The mechanism should be designed to incentivise the participants for submitting their true preferences (e.g., the true marginal cost/utility). In other words, the mechanism should motivate truthful bidding.
- **Budget balance:** the mechanism should be designed in a way that the market operator would not end-up in having neither deficit nor excess in its financial balance. Budget balance is also mentioned as the allocation efficiency.
- **Group rationality:** a desirable mechanism shall be designed in a way that no participant (or a group of participants) would be willing to separate from the game (i.e., the market) to obtain larger benefits. The result of such a property is the stability of the mechanism.

The above-mentioned are the general desirable properties of a market mechanism in the context of energy and flexibility markets. However, obtaining such properties are not straight-forward. More practical measures and criteria for a desirable market mechanism design are discussed further below.

In traditional economic theory, the law of supply (higher prices induce more production) and the law of demand (higher prices induce less demand) determine the equilibrium (efficient) price and level of output of goods and services. This is possible in perfectly competitive markets when four conditions are satisfied; sellers offer **standardised products**, sellers and buyers are **price takers** (unable to alone affect the market price), participants can **enter and exit the market freely**, and sellers and buyers have access to the same level of information (symmetric information or **prefect information**). In theory, this would constitute an efficient market where goods and services are traded at their fair value, demand meets supply. However, in practice, no industry strictly satisfies these four conditions and this is also true regarding electricity markets. Stock markets are sometimes referred to as markets close to perfect competition - they have many participants, close to perfect information and few entry/exit barriers.

Trading goods and services through markets that are not perfectly competitive will likely lead to inefficiencies, i.e., that the goods and services are traded at a value above their fair value leading to an inefficient outcome from a social-welfare point of view. The following sections will describe the four basic criteria for perfectly competitive markets in more detail and provide a discussion how these relate to local energy and flexibility markets.

Criteria for perfectly competitive markets

[2] Warwick Economics Summit 2014, https://youtu.be/XSVoeETsEcU (Accessed 2021-06-30).

The definition of a **standardised product** is that the products offered to consumers/buyers within the market are homogenous in the sense that consumers/buyers view them as interchangeable. Whilst this condition may hold in a wholesale electricity market, it is not necessarily the same in a local electricity market, particularly if the product traded is flexibility aimed at solving network operability issues. In those cases, the location of the flexibility provider will be important and although there may be several actors offering the same level and timing of flexibility, only one or a few may actually be able to deliver what is necessary.

Sellers are **price takers** when each individual seller lack market power and therefore must treat the market price as given. They are unable to affect the price by, for example, increasing or decreasing the quantity provided. Sellers are more likely to be price takers in markets with many sellers and small individual market shares. The extreme opposite of the price taker is the monopolist, who has market power and can therefore set the price above marginal cost, thus earning a positive profit. The loss to consumers from higher prices is greater than the profit gains to the monopolist. Society is therefore worse off compared to if the market was competitive. On the competitive market, prices are set equal to marginal cost as a result of competition among price taking firms.

If a local market is designed to solve issues related to network operation, for example, a local flexibility market, the market is a likely a monopsony market where there is only one buyer (as opposed to a monopoly where there is only one seller), in this case the DSO. This will put the DSO in a position of market power, which may be used to affect the price.

Moreover, for competition to be efficient, competitors must be able to **enter (and exit)** the market without barriers. Smooth entry puts a downward pressure on price because if a seller is making a profit, other firms will enter the market and increase competition. Barriers to enter (exit) can include high upfront investment (sunk) costs and burdensome rules and regulations.

Perfect information or symmetric information means that all market participants have access to the same level of information and perfect knowledge of prices, costs, and their own utility. Perfect or symmetric information is rarely achieved. It is likely that incumbents have access to more information and more knowledge about energy trading, technological solutions, other actors, etc. This is particularly true regarding DSOs due to its long-standing role connecting and supplying electricity to consumers. It will also have detailed knowledge about its own network that will not be available to other actors in the market due to its sensitive nature.

Overcoming or mitigating inefficiencies

One of the main reasons for inefficient outcomes in competitive markets is the concentration of market power to one or a few actors. Failure to meet one or more of the criteria for perfectly competitive markets will likely lead to inefficiencies because of this. The potential for abuse of market power should be recognised and mitigated at the design phase and when considering governance and regulatory structure. Five examples, in relation to local energy or flexibility markets, are highlighted below.

Market size - the market will be geographically limited due to spatial constraints of the technical solution. This means that the market size is limited also in terms of sellers and consumers that can participate, which may cause issues in relation to market liquidity, market power of a few actors, the ability of one or a few actors to affect the price and network effects. Market liquidity is high when supply and demand are high, i.e., there are many market participants. This results in a significant level of trading and increases the probability of a close match of buyers' willingness to pay and sellers' willingness to sell. The spread between bids and asks is tighter when market liquidity is high and wider when low. The market size must therefore be large enough to offset these issues yet small enough to solve location-specific issues where needed.

Information asymmetry - the energy market is complex and some actors will have an advantage in terms of knowhow and experience meaning that there is likely to be asymmetric information. This is an issue, particularly in the short run but less so in the long run as actors gain experience and know-how. The market design should cater for levelling the availability of information between market actors. For example, ensuring that well-informed aggregators can enter the market and act on behalf of small actors and households, which could help mitigate issues related to information asymmetry.

Transparency - the trading platform should be transparently managed by a neutral party and not for example by a firm that owns flexibility resources, as identified by [11]. Transparency will level the playing-field regarding, for example, information availability. However, even though information is available to all participants, it may be too complex for a household, houseowner or even industry to comprehend.

Market access - the local markets allow consumers to take a more active part on the energy market. Consumers can choose to participate or not, they can plan their consumption, and they can join the production side and become prosumers. However, the decision-making and investment costs lay with the household and other individual actors, which may be problematic from a fairness perspective. [12] account for three levels of necessary equipment requiring upfront investments. The first is a billing system that allows households and other producers and prosumers to sell, the second is the installation of a smart meter to support two-way power and information flow. The third, is the installation and activation of DER. While level one and two are investment decisions in most cases made by governments, the third lay with the households and other relevant stakeholders. The market design should (at least) ensure that no consumers are worse off after implementation or be able to adjust unfairness through compensation and thereby fulfilling Kaldor-Hicks efficiency (generates more benefits than costs).

Incentives - Local markets for electricity and flexibility are based and dependent on decisions made by households, property owners and industries. Owners of large properties and larger industries consume large amounts of electricity, often 24-hours, have access to large spaces (rooftops etc.) and access to capital. They are therefore expected to be able to invest and profit from taking part on these markets by adjusting their consumption and participate in trade when beneficial. Households are different. They make up almost one third of the final consumption of electricity in Europe and are therefore a key stakeholder. However, each household is, in itself, a very small entity with low levels of consumption and thereby low savings potential. Assuming that participation is voluntary, financial incentives are crucial to ensure that households join in. The challenge lies in obtaining a large enough compensation or cost saving, or a low enough investment cost. Given the relatively low cost of traded electricity and flexibility potential of individual actors, gains may not be large enough to incentivise participation [13].

Practical application and efforts to mitigate inefficiencies

Different measures to mitigate or reduce the inefficiencies are considered in our proposed market designs. Game theory payment allocation methods are explored to address the potential low liquidity of the local markets and mitigating untruthful bidding. Long-term reservation markets are introduced to increase the reliability, facilitate decision making, and provide incentives for participation. Moreover, in the local peer-to-pool flexibility market, the network constraints are excluded from the market clearing algorithm to increase the transparency and facilitating market participation. These measures are explained further in design Chapters 3,4, and 5.

2.2.2 Stakeholders' viewpoint for design principles

In addition to economic theory, we have looked at the recommended design principles from the viewpoint of different stakeholders such as the regulators, DSOs, and energy associations in Europe. This has been carried out by reviewing the literature and reports in the context of local markets, as well as an internal workshop with the project partners.

A number of high-level design principles for LFMs are suggested by Association of European Energy Exchanges [14]:

- **Transparent and accessible market platforms:** All market parties such as TSO, DSO, flexibility providers, etc., need to be able to compete freely for flexibility services via market platforms. Accurate and clear price signals reflecting the value for each participant should be included.
- **Operation of market platforms by independent, neutral third parties.**
- **Open to all technologies:** The market "shall be open to all generation technologies, all energy storage and all demand response unless technically not feasible" (Electricity Market Regulation (EU) 2019/943, Article 13)
- **Product design:** In line with the above principle, the product design is recommended to be done in a way that allow different technologies to compete fairly on the flexibility market.
- **Responsible to local needs:** The market shall be designed to address the local needs and pave the way for appropriate locational price signals.
- **Integration with the existing short-term power market:** Following the liberalisation of the energy sector with different market structures, it is suggested that the local flexibility markets are designed as a complement to the currently established structure. As a result, such local markets can be built upon the existing progress achieved by the wholesale markets. With establishing the right link between the local and wholesale markets, the need for redesigning of the already established markets can be mitigated and related costs of change can be avoided.
- **Clear unbundling rules for the operation of flexibility assets:** Considering the already existing unbundling logic to ensure that all the market participants have fair access to assets and mitigate the risk of system operators treating such assets differently. This can help to utilise the assets to their full capacity.
- **System operator incentives for cost effective system management:** The system operators shall be incentivised to utilise further the flexibility rather than grid expansions. Therefore, it is suggested that the incentive schemes to be designed in a more holistic way rather than focusing on CAPEX.

Furthermore, [15] has gathered the following guidelines from energy regulators and ENTSOE to be considered in the design of local markets:

- **Transparency and simplicity:** Simple and understandable product so that everyone feel comfortable trading it. It will facilitate the adoption by DSOs and flexibility providers.
- **Inclusive use of available flexibility:** Products should be designed in such a way that for example, low aggregation sizes (or small customers) should be able to participate efficiently in LFMs especially in low and medium voltage where the amount of flex per point can be small. Moreover,

if the service is provided by multiple aggregators, then the portfolio size is reduced even further per aggregator. Furthermore, in the transition phase it is likely that there will be few participants in the market. Therefore, the services must be designed considering this transition phase.

- **Not prone to manipulations:** Local markets are considered to likely suffer from lack of liquidity and perfect competition, which can lead to market power abuse.
- **Compatibility with continuous control:** The DERs are changing from passive to active due to increase in controllability. The LFMs should not hinder aggregators to be able to freely participate in different markets. Moreover, LFMs must fit its purpose, i.e., an alternative to grid reinforcements. Therefore, considering that grid reinforcements have long lead times of at least several months or, more likely, a number of years depending on the type of the investment), the LFM design have to be compatible to this time frame.

FlexiGrid internal workshop

The most important aspects of local market design were discussed during an internal workshop with all project partners, including representatives from DSOs, service providers, platform developers and researchers. The aim was. In order to get practical insights and comments on the theory behind efficient market design and the workshop was therefore structured around the aspects and criteria drawn from economic theory, outlined above. However, the direction from the organisers was however limited to allow for an open and free discussion.

A key concern highlighted was the size of the market - it needs to be small enough to be able to solve location-specific and narrow issues yet big enough to include a sufficient number of actors to ensure market liquidity. Determining the ideal market size will be dependent on locational and contextual aspects and will therefore differ depending on where the market is established and the issues it will solve. The current levels of available supply, as well as demand, of flexibility services and products were raised as a barrier to achieving market liquidity and the appropriate market size. As a result, in addition to a lack of incentives and willingness to invest, this would make it difficult to establish a market in the first place. The issue is further amplified by the lack of accurate forecasting and the ability to accurately measure or quantify the available flexibility.

Moreover, aggregators were raised as an important part, both for market liquidity and access to accurate information. Workshop participants recognise that it will be difficult to ensure information asymmetry, however, indicate that it might not be necessary to ensure an efficient local market, as long as actors have access to the information necessary for their roles. Aggregators, acting on behalf of many smaller actors, would bridge the information-gap and open to increased participation and possibly, together with targeted regulation, reduce the need for symmetric or perfect information. As a result, aggregators could reduce the incentive requirements for households and other smaller actors to participate in the market by making it easier to access.

Finally, trust and transparency throughout the market will be important to guarantee that actors deliver what has been agreed and a new role for the DSO, yet to be defined, will be necessary and must function in tandem with current DSO safety and reliability requirements. This will all be reliant on the technical readiness and new technologies, from smart meters to the development of a suitable platform, which would allow for fast and frequent trades, possibly automated based on bids and offer availability.

2.3 Different market structures

In this report three different market structures are explored, peer-to-pool (centralised market), peer-to-peer, and adaptive market mechanism. The proposed market designs are based on the design considerations discussed in Chapter 2.

In a peer-to-pool (centralised) mechanism, all the buyers and sellers of the product submit their bids to a centralised pool and then the decision is made centrally regarding which bids are going to be cleared. The market operator is responsible for clearing the bids and settling the market according to the market regulations. The market clearing is done in a wholistic manner aiming at maximisation of the social welfare. In a peer-to-pool market, no peer-to-peer contract is made between two specific market participants, instead the bids are gathered in a centralised manner and they are cleared aiming to maximize the social welfare. This structure is further explained in Chapter 3.

In the peer-to-peer structure, the market participants trade in a decentralised manner without the need for a centralised advisory party. The blockchain technology is used for secure and transparent contracting and billing. The peer-to-peer structure is further explained in Chapter 4.

The adaptive market design utilises both the peer-to-peer and peer-to-pool structures , combining the existing designs to form a larger framework. The adaptive structure identifies a list of controllable parameters of the constituent markets and utilise them to adjust these markets according to the system's needs. The adaptive market design also comprises mechanisms which fall outside the peer-to-peer and peer-to-pool markets. The explored adaptive framework is presented in detail in Chapter 5.

2.4 Potential stakeholder and business models

There are different actors with different roles and responsibilities in the local markets. Understanding the roles and responsibilities of these actors and their business models play an important role in a better mechanism design and a more successful implementation. In this section, the potential stakeholders and their roles are presented. Moreover, to initiate the work on the business models, the potential related cost and revenue streams of the DSOs, as one of the main stakeholders in the local markets, are discussed.

These potential stakeholders in the local markets include DSOs, aggregators, market operator, balance responsible parties, and end-users (prosumers, passive, or responsive). The roles and responsibilities of these actors may be slightly different in different market designs. The roles and responsibilities of these are explained below.

- **Balance responsible party (BRP):** also known as *retailers* and *load-serving-entities*. A BRP is an entity which serves in the electricity market as a representative for a certain and predefined group of loads. The BRP forecasts the consumption size of its constituents, to be incorporated in the operation optimization plans. In the likely scenario where the actual consumption size deviates from the forecasted amount, the BRP is responsible to correct the deviation by filling the energy deficit / selling the energy surplus through bilateral agreements, or pay penalties to cover this deviation. The BRP can represent any type and number of customers, i.e., passive non-responsive consumers, responsive consumers, and prosumers. When BRPs detect a deviation between their load forecast and actual load, BRPs may procure flexibility from other BRPs, aggregators or small sized DERs.

- **Aggregators:** An entity which represents a large number of responsive consumers and/or prosumers. Aggregators acquire and consolidate flexibility from small consumers and prosumers to sell it in the electricity market. The aggregator negotiates on behalf of its constituents to trade flexibility or even energy. The aggregator issues commands to its subscribers (responsive consumers and prosumers) to adjust their energy levels exchange, such that the aggregated portfolio delivers the flexibility agreements held by the aggregator. Aggregators can act as BRPs for their clients.

- **Distribution system operator:** The authority which owns the distribution grid and holds the responsibility to preserve the grid by conducting the necessary maintenance, making expansion and reinforcement projects, and operating the grid components such as on load tap changers, line-drop compensators and capacitor banks. The DSO procures flexibility from other stakeholders for the purpose of resolving congestions and deferring network investments.

- **Market operator:** The entity which applies the market mechanisms, acting as the auctioneer in different auctions. In classical power systems, this role was assumed by the grid operator itself. However, future decentralized markets may allow for operators of different grid-levels or regions to compete for flexibility, therefore, it becomes necessary for a 3rd non-partisan entity to take this role.

From the entities defined above, the building-blocks and end-users in the distribution system can be classified into three types:

- **Prosumers**: end-users and customers who have generation sources in excess of their own consumption size, such that they are able to inject some energy into the grid. Prosumers may also own energy storage devices such that they can benefit from differences in electricity prices, or demand on flexibility. Prosumers can participate directly in the peer-to-peer market, or under the umbrella of an aggregator in any market.

- **Responsive consumers**: consumers who adjust their consumption level in response to price signals, or command signals to fulfil their commitment and subscription to an incentive program. Examples include rescheduling the charging of electric vehicles or rescheduling some intermittent loads such as washing machines and cookers. Such responsive consumers can participate in peer-to-peer markets as buyers of energy, or sellers of up-flexibility. They can also participate under the umbrella of an aggregator in any market.

- **Passive consumers**: classical end-users who neither react to any price signals, nor flexibility requests, or inject positive energy into the grid, either. Such consumers choose to forfeit the benefits of engaging in such market interactions, at the cost of paying a fixed above-average tariff. Passive consumers are treated as fixed or inelastic load, and do not engage in any trades.

The aim of a business model is to capture the value creation. This can be illustrated by different tools, such as the Business Model Canvas [16]. It follows the structure of the different elements of the business model canvas, a model created by Alexander Osterwalder and Yves Pigneur to visualise the business model in an accessible way. The purpose of the Business Model Canvas is to provide a framework with which we may collaborate to define the core sections of a working business model for the local markets in FlexiGrid. The structure directs focus to key areas which must be addressed, discussed and for which clear solutions are found. The questions and discussions will bring to light any areas which require further thought and definition.

Initially a brief review in related EU-projects has been conducted, such as FED [17], UNITED-GRID [18], COORDI-NET and SWITCH [19], and the business model initiative of BRIDGE [20], and have not found any conclusive business model canvas conducted for the local market. Therefore, the focus was to fill this gap in this project.

DSOs are one of the main actors in the local markets and will play an important role in the development, implementation, and operation of local energy and flexibility markets. As such, as a starting point in the work on actors' business models, this section focuses on the DSOs and more specifically their costs and revenues. The role that DSOs have in the traditional energy system and its business model is likely to change in the future and with the implementation of local markets. Other actors, including flexibility service providers and their business models, were not investigated as part of this report, however, will be considered at a later stage in the project.

This section outlines outcomes and analysis from the conducted meetings and workshops with IMCG, Chalmers, and the DSOs in the FlexiGrid project; that is, Göteborg Energi, OEDAS, Energo Pro, OIKEN. Also, these included actors Energo-Pro, a consultancy to DSOs, and SIMAVI, an IOT-provider. We found that the project DSOs had difficulty in the initial meetings to comment on the topic of business models, since it is a topic that is relatively novel, however they agreed it is important to consider further. It was agreed to initially focus on the areas Costs and Revenues of the business model canvas model andthe remaining areas will be further investigated as the project moves forward in Work Package 9, Task 9.4. A gross list of possible costs and revenues associated with local markets was developed by Chalmers, which was then iterated and checked with the project partner DSOs in workshops that were conducted on the topic together with IMCG.

- Costs:
    - Measurement and ICT/IoT related costs
    - Administrative costs for participation in the market
    - Lower revenue from power tariffs
    - Lower revenue cap

- Revenues:
    - Postponed/avoided investment costs
    - Extending the lifetime of assets by not overloading them
    - Lower connection fees paid to the upstream grid owner
    - Avoided costs related to operational actions
    - Avoided energy losses
    - Avoided emissions by not curtailing renewable energy sources (RES)

In the following sections, each cost and revenue are introduced with brief explanations in the context of a local flexibility market. These cost and revenues can be used as an initial point for quantifying the value of flexibility for the DSOs and utilised in developing business models.

2.4.1 Costs

Measurements and ICT/IoT related costs

To run the flexibility markets, different ICT and IoT technologies are required. These technologies are required for different purposes such as a high resolution and (close to) real-time measurements, sending signals, high quality inputs to forecasts algorithms, settlement, and payments in the flexibility market. Setting up such infrastructures, if not in place, requires investment and operational costs.

Administrative costs for participation in the market

DSOs, as the buyer of the flexibility in the market, are likely to require dedicated staff to work with forecasting, operation planning, and trading in the local markets. These costs can vary depending on the level of automation.

Lower revenue from power tariffs due to peak-shaving

By purchasing flexibility in peak hours, some consumers might reduce their peaks by valley filling or peak shaving. This means their largest peaks could be reduced. In case these consumers pay power-tariffs to the DSOs, the payments are likely to decrease, which would reduce the revenue that the DSOs can collect from power-tariffs.

Lower revenue cap

In the current regulations, DSOs revenue cap is regulated based on CAPEX determined by the DSOs asset base. In case the regulations do not change, and the DSOs want to purchase flexibility instead of investing in physical assets, their revenue cap would not increase as much as if they had gone with the latter option. This can potentially be seen as a cost to the DSOs.

2.4.2 Revenues

Postponed/avoided investment costs

Assume that a few years ahead, the DSOs have to decide whether to reserve flexibility or to reinforce their network. By purchasing flexibility, DSOs might be able to avoid or postpone investments in their grid. These investments can be, among other, building new lines, transformers, or any other asset in the grid.

The postponed/avoided investments can be counted as revenue or cost to DSOs depending on regulations and how broad the assessment is conducted. For example, if the revenue-cap of DSOs are regulated based on their CAPEX, utilising flexibility might lead to a lower revenue cap and thus be seen as a cost, rather than revenue, to the DSOs. On the other hand, even with CAPEX-based regulation of the revenue-cap, it might be challenging to transfer the cost of the new investments to the end-users. This is because it can increase the final price of electricity for the end-users, incentivise further proliferation of DERs, incentivise end-users to go off-grid, and set the DSOs on the path towards the so-called “death spiral” of the DSOs. Therefore, the costs or revenues from the postponed/avoided investments need to be carefully assessed in each case considering the regulations, the grid status, and the societal aspects in each case. Moreover, this discussion put an emphasis on understanding the new role of a DSO and the need for a more proactive communication with both its consumers and the regulators.

Extending the lifetime of assets by not overloading them

Assuming that a DSO had decided to use flexibility instead of investing in the reinforcement of its grid. Due to the forecast errors for loads and weather patterns, the reserved flexibility might not be enough. Thus, the DSO has to buy extra flexibility in the short-term/real-time market to avoid overloading its assets. By not overloading these assets (e.g. transformers, lines, etc) they can have longer lifetime and thus reduce the DSOs costs in the long run.

Lower connection fees paid to the upstream grid owner

In case DSOs pay any kind of connection fees to the upstream grid owners (TSOs or regional grid owners), these fees could potentially be lowered by utilising flexibility. For instance, if there is a power tariff or connection capacity fee that is paid to the upstream network owner, the DSOs could reduce this payment by utilising flexibility for peak reduction.

Avoided costs related to operational actions

With more volatile RES and demand in the system, operational costs of the DSOs might change in response to this volatility. Examples of these operational costs can be more frequent tap-changing in the transformers. Moreover, due to forecast errors, load curtailments might happen to maintain a safe grid operation. Calculating these costs can be part of the flexibility's value to the DSOs.

Avoided energy losses

Flexibility could be used to reduce the losses in the DSO's grid. The value of reducing energy losses will depend on how these are considered in the calculation of the revenue cap and is therefore different for different countries.

Avoided emissions by not curtailing renewable energy sources (RES)

Imagine the DSOs' network has a high penetration level of RES. This can cause excessive reverse power flows or congestions in hours with high generation levels. If the DSO does not utilise flexibility or reinforce its grid, the RES production may need to be curtailed. Also, it is also possible that the DSOs must pay a penalty for curtailing RES. This can be environmental penalties for curtailing renewables, or penalties to be paid to the RES owners by not being able to transfer their production. This will depend on the rules and regulations in each country.

2.5 IoT platform for local markets

The IoT platform is one of the essential cores of smart and digitalised solutions for the energy transition and market-based solutions for local trade of energy and flexibility. FlexiGrid's IoT platform is a fast and easy way for consumers, prosumers and electricity distributors to collaborate and exchange energy in a secured manner, on the strength of blockchain and smart contracts technology. Through the platform, a DSO can launch an auction in order to avoid congestion in a selected area and prosumers will be able to respond and sell the electricity surplus to the distribution grid. The DSOs will have a better overview of its grid according to several visualisation tools that will centralise all the data received from the IoT devices installed in the field.

In this section, an overview of FlexiGrid's IoT platform is provided. As the focus of this report is mainly the market design, the details of the IoT platform are not presented. Further details are available in the deliverables from work-package four of the project.

FlexiGrid's IoT platform is developed based on the Federative System Space concept. Federation refers to different computing entities adhering to a certain standard of operations in a collective manner to facilitate communication. In the federative system, each project's demonstration pilot will have its own deployment. This will be on site or on the central system. All the functionality is the responsibility of the subordinate pilot. Moreover, in this system, there will be a centralised system (Federation Authority) responsible for imposing rules, facilitating communications between subordinates, offering common places for data storage, offering common functionalities, and offering governance. The communication platform is responsible for all communications between subordinates and the central system.

The process of interaction with the IoT platform will be as simple and intuitive as possible. An authenticated user can access the main components from a fixed menu. The main sections are:

- Overview (Dashboard),
- Notifications,
- Profile,
- Invoices, and
- Homepage.

The Overview area will contain all the information related to the energy consumption, real-time data, history consumption, injected energy in the grid and types of devices, depending on the user role. All this data can be viewed as different charts and reports that can be exported as csv, xls and pdf.

The Notifications section will be the part in which the prosumers will receive requests to participate in auctions launched by the DSO. Also, this section can be managed in order to mark the notification as read/unread, archive or delete.

The Profile section will contain information about the user and some settings referring to the preferences. The related information about the user will be: first name, last name, phone, contact e-mail, registered address, post code, country for the consumers and source type, the amount of energy delivered, delivery period, supplied voltage and geographic position for the prosumers.

The Invoices section will contain the balance account and all the information about the history payments and invoices, that can be exported as pdf.

In the platform the main functionalities which will be developed are grouped as following:

• **Local market specific features** –which will provide information about the local market, community news/ dashboards, chat, blog.

• **Customers' specific functionalities** – related to customer account and his activity, notifications; custom search and navigation; reviews; booking, responsiveness, language (localisation) and SEO (if needed, Dashboards related to the information stored in the IoT Platform.

• **Market functionalities** –trading services.

All specific features will be implemented in the FLEXIGRID IOT Platform based on MoSCoW Prioritisation (Figure 2-3).

Figure 2-3 MoSCow prioritisation [21]

The main business flows which will be implemented are:

- User Authentication and Authorisation: In order to reach the platform the customer needs credentials – user name and password). After the authentication the user can receive the information about: TSO/DSO details like grid topology, contract ID/ smart meters details, invoices.
- Details about the forecasted energy will be displayed.
- Data logging will be implemented, this means that all the consumer actions will be logged in the system.
- Details about the consumption forecasts: after this action can see details about:
  - Generation: forecast data,
  - Consumption: forecast data,
  - Flexibility: forecast data.
- Set grid constraints: allow to set grid and see updated grid constraints information (date-time, grid node, max imported power, max exported power, price).
- Set emergency activation: allow to visualize the information about emergency limits (date-time, grid node, power).

The work on the IoT platform is mainly done in work-package four of the project. Further details of the IoT platform can be found in D4.3 Complete FlexiGrid IoT platform.

2.6 Recommendations for billing and payments

Receiving a payment in exchange for provided service is the key element behind any trading process and flexibility energy service exchange is not an exception. Trading parties get into a deal that would deliver a "fair" net value for each party. This means that if the transaction cost, that includes the payment transaction fee, the technology, administration and human resources (HR) cost for issuing, sending and handling invoices, is too high, the net deal value could be jeopardised and the total transaction value might be seen as marginal.

As flexibility services and markets are new concepts to all electricity market participants, thus an easy to understand and to use, as well as affordable, flawless and secure payment and billing process is critical for local flexibility market players' decision to participate and exchange flexibility services (FSs).

The aim of this section is to elaborate on the possible billing and payment scenarios that could be successfully applied to different flexibility market models.

2.6.1 Billing and payment as part of the market design chain

Payment and billing are two particularly important elements of the whole flexibility service trading and supply chain. Based on how the previous stages have progressed, the process for billing, payment and the following invoicing within the FlexiGrid project can be predicted.

Figure 2-4 represents a simplified flexibility service trading process chain, pointing at some elements of importance with regard to billing, invoicing and payment, at each step.

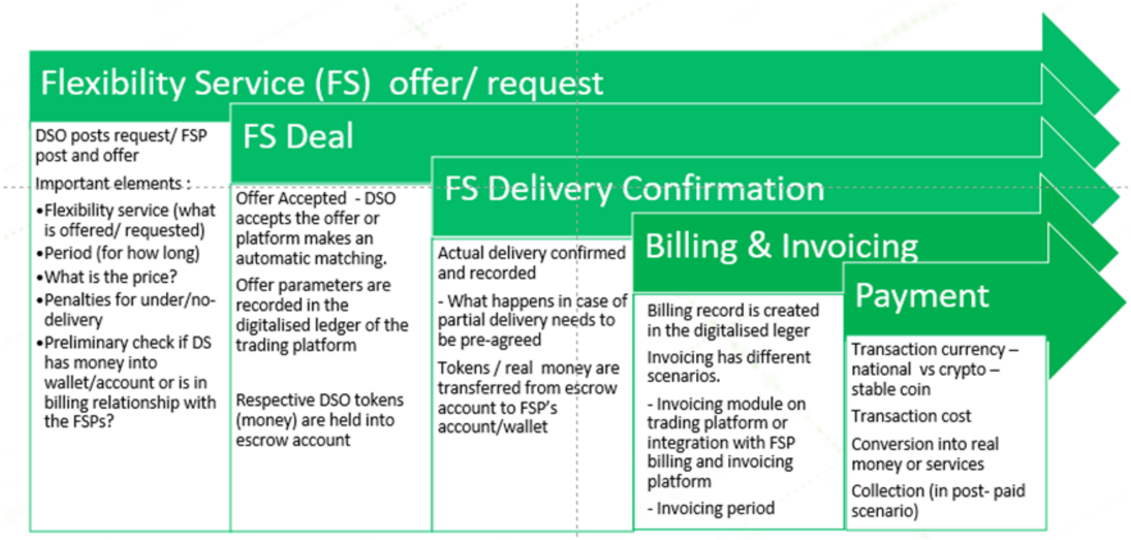

Figure 2-4 Flexibility services (FS) trading process

When talking about flexibility services and methods of their payment, it is important to note that the electrical industry is a strategic sector (critical infrastructure, sector of vital importance) for every country and as such it is highly regulated. In many European and none European countries, DSOs are not allowed to directly be involved in electricity trading, instead energy trading and contract with end-users are performed by third-party companies – either a DSO's daughter commercial companies or a completely separate company.

Legislation like this makes impossible for the DSOs who are the procuring party in the flexibility service exchange to be in direct (commercial) relationship with the FSPs. This makes some of the most obvious solutions for payment and billing currently impossible until the legislation frame is changed.

EU directives such as "Clean energy for all" will require the national low to include regulations forcing DSO's to consider flexibility solutions to network issues and enabling prosumers, consumers and producers to be more energy efficient, enabling the transformation towards smart grid and introducing new electricity market business opportunities.

Until the respective legislation is changed FlexiGrid needs to research solutions that are easy to implement and use, solutions that are not costly and that respect the local legislation at the same time.

On the other hand, flexibility is made possible due to the adoption and application of new technologies and the flexibility trading platform eFlex, developed in FlexiGrid is a good example of this. "With the emergence of crypto-assets (including so-called 'stable coins') they may soon be offering disruptive payment solutions based on encryption and distributed ledger technology (DLT)".[3] as stated in a recent document by the EU Commission on Retail Payments Strategy for the EU.

2.6.2 Billing and payment options

In this part of the deliverable, we will focus on the options that FlexiGrid has for billing and payment, highlighting what has been discussed between the partners, focusing on advantages and limitations for each option and their application to the different flexibility market models.

Potential options considered for the billing and payment are as follows:

- **Currency - National vs Crypto currency**
  - National
    - Pros - As a principle, flexibility services are exchanged on a local level aiming to relieve local grid issues. This makes the local/national currency an obvious solution for the local flexibility trading.
    - Cons - The size of a single transaction is especially important for the calculation of the related transaction costs. In case of micropayments the transaction cost might exceed the value of the payment.
  - Crypto currencies
    - Pros - Payments are made with very low (or none) transaction costs.
    - Cons - The challenge comes in converting crypto coins into real money. The process might seem complicated for many actors and high trading fees may apply.[4].

- **Blockchain – smart contracts for billing and crypto currency as a payment mechanism**
  - Pros:
    - Instant, simple – does not require additional steps, transparent for all players

[3] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS on a Retail Payments Strategy for the EU https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0592

[4] Trading fees cryptocurrencies List Of The Lowest Cryptocurrency Exchange Trading Fees [Updated] (bitcoinexchangeguide.com)

- Familiar/commonly used along with blockchain – the technology that peer-to-peer flexibility trading platform will be built on
- Scalable in big scale if needed – this makes it applicable to all market sizes - small and local or big scale and serving all possible flexibility market models including peer-to-pool, and peer-to-peer.

- Cons:
  - If applied today it needs to be connected to an existing billing/invoicing system of the FSP/DSO for invoicing purposes as the current fintech legislations does not allow smart contracts as official documents for accounting and tax purposes.
  - Blockchain is energy consuming and the net effect is still under discussion
  - Crypto currency value is highly volatile (Stablecoin could be a potential mitigation)
  - Crypto currency trading cost (the cost for converting crypto into real money) is currently high and this will reduce the total net FS exchange revenue/earning for the players that want to convert their earnings into local currency. In addition, the conversion process might seem unclear and too complex to many FSPs and that could be another reason for them not to participate the trading

- **Separate billing and invoicing system - connected/fed by the trading platform as transaction attributes input.**
  - Pros:
    - Familiar way of work
    - In line with current legislation and accounting practices
  - Cons:
    - Integration cost might be high and integration technically complicated
    - Potential administrative hassle (works slowly, many invoices for small amounts of money, efforts to send invoice to counterparty and follow through on payment)
    - Could prove to be a potential barrier for adoption

- **Including the bill in an existing invoice (if there are any) and deduct or surcharge the monthly bill with the respective FS value provided for the period.**
  - Pros:
    - The easiest and most familiar to the involved parties (in respect to the legacy relationship) method
    - No additional payment transaction fees for the FS provided during the period as one bill will include all services exchanged during the respective period – reduces the overall transaction cost
  - Cons:
    - Some FSPs may not be in relationship with the seller/buyer
    - The legislation currently prohibits this kind of transaction

- **The trading platform or a third party/commercial company to marketise and operate the FS exchange platform as trade platform manager acting as market operator – a selling and buying party to the other actors** - aggregates the offers, aggregates FS requests and acts as commercial intermediary to all players. In this scenario the buyer and the seller would be the trading platform and the platform will charge, bill, invoice and manage payments on a B2B basis with other FSM participants.

- Pros:
  - Familiar and easy to understand (similar model of work as Amazon, Google, etc.)
  - Scalable model
  - Accountability - general party that can facilitate the relationship between users, provide security of billing and payment and mediate when and if needed.
- Cons:
  - The third party needs to be recognisable and knowledgeable to inspire confidence and be able to coordinate market relations
  - The initial process might be slow and bumpy, before the right structure and way of work is found
  - Scalability might be costly

When considering a Peer-to-pool market, it can be imagined as something similar to a Google or Amazon platform. Outlined further:

- The Platform is the market operator (MO), aggregating multiple FSPs behind.
- The DSOs, aggregators and other FS Buyers will procure FS from the Platform and
- The Platform proceeds the payment and billing with the buyer and simultaneously re-pays to the actual supplier.

That would be a familiar way of working, both for the developers of the billing and payment mechanisms as well as the end-users, which simplify implementation. Consequently, using a third-party company around which the flexibility market will be centralised, is a possible solution.

2.6.3 Defining possible billing and payment solutions based on local market specifics

Based on the feedback from partners, adoption of FS is expected to be low at the beginning and, among other equally important factors, highly dependent on the easiness for taking part in the flexibility market. This may lead to some DSOs choosing to use such platforms only when legislation changes. A possible mitigation for that will be the flexibility platforms for different countries to allow or provide different solutions for payment and billing which are the most suitable for the respective local market.

Concrete aspects that need special attention when making the decision about the most appropriate payment and billing approach include:

- Size and number of transactions (per month)
- Transaction related cost:
  - payment transaction cost – in case of micro payments this cost could be equal of higher the transaction value
  - cost for issuing and handling invoices (tech, admin, human resource)
- Payment currency – prices and payment in national currency
  - currency trading cost (convert transaction currency into real money)
  - credit control, treasury and collection (in case of post paid services)
- Legislation – energy and financial legislation in the respective markets

- Technical and financial savviness of the players

2.6.4 Project usecases feedback and general summary

In respect of the billing and payment aspects mentioned above and in the process of research of the most suitable solution for billing and payment within the scope of FlexiGrid demo cases, Entra Energy performed interviews (a questionnaire and a following discussion) with use case (UC) leaders within FlexiGrid.

Each demo case in the project includes one or more demo area that would be tested on their premises. and different services, shown in the table below:

	UC1	UC2	UC3	UC4
Demo Areas Tested	1) Grid monitoring, control and flexibility intervention 2) Local energy market: exchange of energy/grid services	1) Grid monitoring, control and flexibility intervention 3) Blockchain & IoT based peer-to-peer demand side response management and energy trading 4) Flexibility measures from storage P-2-G an EVs	3) Blockchain & IoT based peer-to-peer demand side response management and energy trading 4) Flexibility measures from storage P-2-G an EVs	3) Blockchain & IoT based peer-to-peer demand side response management and energy trading

Figure 2-5 Use cases and demo areas demonstrated in each use case. To better understand each of the demos and how suitable and easy billing and payment processes can be incorporated Entra Energy collected and analysed information from the UC leaders in the following paragraphs:

UCs were asked what would be the usual FSPs in their testing as to better understand the typical users from which the DSO would procure flexibility. Most, if not all the UCs, included in their answer aggregators, individual end-users (generator, consumer or prosumer) as well as specifically in UC3 - V2G (vehicle to grid) station, EV (electrical vehicle) app and battery storage.

It is important to note, that most of the FSPs are connected/contracted to the DSO directly or indirectly. Due to legislative restrictions in some countries the companies have been separated so that the DSO provides grid services while the trading relationship is managed through the retail sister company of the DSO.

DSOs or their sister retail companies have sophisticated billing systems to handle the hundreds of thousands invoices they issue on a monthly basis to their clients. Conversely, many of the FSPs are SMEs (small and medium enterprises) that usually do not issue many invoices per month, and they would therefore prefer to use a manual process of issuing invoices for the flexibility provided. This would mean that if they have too big of an administrative hassle and cost, that could interfere with their desire to participate in the flexibility market. The administrative cost and effort may include time and human and financial resources to implement a regular process for checking the deal ledger issuing and handling invoices and reconcile versus revenues received. To make it easier to imagine, here is an example:

The FSP is a small hydro power plant that yearly generates less than 10 invoices. As to not have additional unnecessary expenses, it does not use a specialized invoicing software or procure such services from an accounting company. Instead, the owner has an invoicing book where he manually writes down an invoice if and when necessary. So, if he were to write down micro-transaction invoices and there were to many, the cost for their accounting and the efforts/time to write them down could exceed the marginal utility of the flexibility services.

In order to estimate the potential administration effort related to billing and payment, the average number of deals procured and their average size in euro was estimated. It is important to have in mind that the flexibility platform is still under development and some UCs are in the process of demo case preparations, not having started yet (as per FlexiGrid project schedule). In line with that, Entra Energy suggested to collect the expectations about the average number of FS deals per month in 3 scenarios: Pessimistic, Realistic and Optimistic to define the expected number of participants and monthly deals.

The project UC participants and leaders expect that between 0 and 100 deals might happen per month and about 10% of the registered FSPs would actually be active and make a deal.

The average deal size is thought to be in the microtransaction spectrum. Some partners speculated that the average deal size would be between 3 and 12 euros, while others thought that it would be in the ranges of 0.25 to 2 euros per one hour of flexibility provided. It is important to note that the price of the transaction will and can be dependent on time (how long) and size (MWh flexibility provided) for which flexibility will be procured, so a precise price cannot be provided.

Nevertheless, billing and payment needs to be made simple and easy to use as not to hinder users from taking part in the designed markets. Having in mind the usual billing and payment services of both DSO and FSP, the offered solutions and their price, different models may be needed in the different countries that would implement the solution. One universal solution could be billing and payment based on smart contracts and blockchain, however due to legislation and conservative nature of DSO/FSPs this solution also has its disadvantages.

In Table 2-3, the results from the questionnaire and discussion with UC participants and leaders on the mechanisms and important elements to consider when deciding the billing and payment model are summarised:

Demo Areas in the project:

1. Grid monitoring, control and flexibility intervention
2. Local energy market: exchange of energy/grid services
3. Blockchain & IoT based peer-to-peer demand side response management and energy trading
4. Flexibility measures form storage, P-2-G and EV

Table 2-3 Payment and Billing questionnaire feedback

	UC1	UC2	UC3	UC4
Demo Areas Tested in the UC	1,2	1,3,4	3,4	3
FSP	1) An individual end-user 2) Aggregator	1) Campus (End user/ Aggregator)	1)V2G station 2)EV (app) 3)Battery	1)Consumers 2)RES Producers 3)Prosumers
Service	1)Capacity-limit cap 2)Capacity-limit floor	1) Energy balancing for the local balancing group	1)Congestion relief 2)Peak shaving	1)Peak shaving 2)Load reduction 3)Curtailment
DSO Relationship	End-users directly connected to DSO	Connected to local DSO	Through retail company of the DSO	DSO clients for grid services
Deals per month (average)	Limited № during testing	1)Pessimistic: 0 2)Realistic: 20 3)Optimistic: 80	Limited № during testing	1)Pessimistic: 1 2)Realistic: 10 3)Optimistic: 100 10% of registr. will make a real deal
Average deal size in euro	Variable that depends on volume and time	50-200 kWh = intraday market ~60 euros/MWh -> Average deal size 3-12€	It would be simulated during testing, no real money due to legislation	between €0.25 - €2 per 1 hour flexibility provided
FSP financial savviness		No billing and invoicing system in place	Automatic billing system (DSO) -> manual	Manual billing and invoicing
Is it legally permitted to decrease electricity bill vs FS provided	Even if not, suggestions on how we think this can be handled more efficiently should be provided	The local authority would not be against testing new billing models in the framework of research projects	The local energy market regulatory authority does not permit this kind of regulations	If included into the General Terms and Conditions between the DSO and the end user

In each of the four Use Cases of the project, flexibility services that will be tested are different (with some small overlap between UC3 and UC4). The performed research and interviews identified variances within the UCs in the following areas:

- expected average monthly number of deals traded on the system,
- the monthly revenues/turnover that will need to be billed and paid between the parties
- the local legislation varies from more liberal to very strict when it comes to DSOs involvement in commercial relationships with end-users and allowance flexibility and electricity bills to be offset.

Thus, finding one ultimate billing and payment solution that serves all could be a challenge. It is likely that local and different billing and payment solutions for each use case will be applied, at least during the course of the project initial market adoption.

2.6.5 Billing and payment conclusions and recommendations

Billing, invoicing and payment for energy flexibility services are important elements of the FS exchange chain when discussing possible market designs and their potential for market adoption and penetration.

They must be addressed in a scalable, clear, secure, user friendly, risk free and profitable manner that abides by the relevant legislation. The different payment and billing approaches vary and their implementation could be contextual to the specific case, market, and local regulation (including fintech regulation).

The fast development of new technologies, like IoT, blockchain and fintech tools, combined with change and alignment of the EU regulations in energy and financial sectors might help new appropriate billing and payment solutions to emerge in the coming years.

When looking through the prism of peer-to-pool or peer-to-peer energy flexibility market some of these options seem more workable while others do not.

For the peer-to-peer market design (EFLEX), based on the fact that the trading platform is blockchain based and considering the limitations posed by the legislation in some of the UC markets, the best approach for payment and billing solution for the FlexiGrid Use cases to be demonstrated would be:

1) to use EFLEX digitalised ledger for recording the transactions and billing information and
2) to use crypto currency stable Etherium as a payment method.

As the transactions will be peer-to-peer, the actual invoicing will be done case by case/ for each transaction by the FSPs using their current invoicing systems, using the information recorded in the EFLEX ledger.

From DSOs perspective, FS will be procured from FSPs that will be different (in size, technical, financial and administrative savvily). In that respect, the simplest and the easiest way to manage (for all participants in the LFM) solution would be the trading platform to be integrated with the billing/accounting systems of the DSOs so that to exchange/feed with data from the digitalised transaction ledger that will be reconciled on the DSOs accounting/cost management system.

3 Peer-to-pool market

3.1 Introduction

As mentioned in Chapter 1, the future distribution networks could face challenges such as congestions and voltage limit violations. Local markets for trading energy and flexibility are suggested as a potential, direct or indirect, solution to these challenges.

The structure of local market can be categorised into three categories: peer-to-pool (centralised), peer-to-peer, or adaptive structures. The centralised local markets are a place in which the requests and offers are gathered and cleared centrally by the market operator to maximise social welfare. Moreover, the local markets are limited to a specific geographical area, such as neighbourhoods, small cities, or communities [22].

Local markets can be designed for trading different products such as energy in local energy markets, and flexibility in local flexibility markets. Energy can be traded in the form of different energy carriers such as electricity, district heating, district cooling, etc. A bought unit of energy is used to satisfy an energy demand. However, flexibility is the possibility for adjusting one's demand and generation levels according to a signal to provide services to a grid operator [1]. The flexibility product can be designed in different ways which are explained further in subsection 3.4.1.

Local energy markets can restructure the energy system and lead to active integration of small prosumers with intermittent renewable generation and small consumers [23], [24]. These markets can support in keeping the energy balance at local levels [23], [25] and thus reduce congestions indirectly and reduce the need for grid expansions. Moreover, local flexibility markets can unlock the potential to directly solve a specific grid challenge at a specific time and location by trading adjustments in the behaviour of the market participants.

Objective of the chapter

This chapter aims to discuss the potential roles of local markets in the future of the energy systems. Moreover, market designs for both local energy and flexibility markets are going to be proposed. The flexibility market is designed focusing on addressing congestion challenges in the distribution grids. Different elements of the proposed market design, such as the product design, actors, market timeline, clearing algorithm and payment allocation mechanisms are presented in detail. Finally, illustrative simulation case-studies are conducted for a better understanding of the market design.

Common design challenges and related work

In the past years, different market designs have been proposed and reviewed. Moreover, various discussions and workshops have been on going in the energy community. These sources have helped us to identify a set of common design challenges for local markets and try to address them accordingly for a more novel and contributing design.

Among the various design challenges, we can point out to the most common ones such as:

- Low market liquidity,
- Reliability concerns, security of supply/demand, and a conservative industry culture,

- Challenges regarding defining baselines for a baseline-based flexibility product,
- Forecast errors due to low aggregation levels, and
- The high costs concerning the need for extra measurements and ICT and IoT infrastructure

The challenge regarding the low levels of liquidity in the local markets has been, among others, mentioned in [26]–[30]. The low liquidity can be due to the geographical limit of the local markets, and also the lack of available resources in the transition phase. A market with lower liquidity is less competitive and therefore more prone to instability [31] and market manipulation [32]. Desirable market properties of efficiency and incentive compatibility can get affected in case the market is prone to manipulation.

As the DSOs' core responsibility is a reliable, secure, and efficient distribution network [3], the reliability of the market design and the security of supply is essential. This is especially important since the local markets are often presented as a substitute to grid reinforcements [33]. On the other hand, the flexibility service providers can be risk averse due to investments risk considering a lack of demand and uncertain revenue streams [28], [34]. Another reason for risk aversion of flexibility service providers, such as property managers and real estate owners, is that flexibility provision can be too risky as it might affect the comfort of their tenants in a negative manner, especially if the control of the assets are directly handed to the DSOs [33], [35]. The challenge with the reliability and the sensitivity of the commodity, can affect the efficiency property of the market and in addition is coupled with the question of whether or not there would sufficient incentives for the actors to participate in such local markets. this challenge can hinder the more risk averse actors to have a fair access to the market.

Two commonly reported challenges for local flexibility markets are forecasting a baseline, and coming to a consensus on a baseline for a baseline-based flexibility product. A baseline-based flexibility product can be seen in Figure 3-1. The potential challenges with baseline-based products are discussed extensively by Ziras et al. [15]. They assess different existing methods for defining baseline and argue why these are not suitable for LFMs. They mention that finding admissible days that can be used as a reference for defining the baseline is challenging as wholesale energy prices are becoming increasingly intermittent, whilst end-users and aggregators are becoming smarter, thus more reactive to price signals. Moreover, they argue that the local markets are different than wholesale and balancing markets since, at the local level, no schedule exists to be used as a method for defining the baseline. In case LEMs would exist, still the low aggregation level at the local level would cause large errors in schedules. Another challenge with baselines is the need for a consensus between the market participants on the baseline which can be further complicated by conflict of interests. They mention that a large focus of the research has been on improving the accuracy of baselines while still transparency and simplicity in the baseline calculation method are necessary. Therefore, even with better accuracy of baselines, simpler products are advocated. A more straightforward substitution for flexibility products is capacity-limit based products (Figure 3-1) [15], [36]. A capacity-limit (CL) product is a service that keeps the net exchange with the grid below or above a certain limit. This service is requested by the system operator and delivered by the flexibility service providers. Our suggested CL product is inspired from [15] and is further discussed in 3.4.1. Complex baseline calculation methods can cause transparency challenges which is one of the desirable market properties. The challenges with the baseline-based flexibility products can be also coupled with information asymmetry between the flexibility service providers and the system operator. This information asymmetry, that partially boils down to the product design, can impact the incentive compatibility property and risk the market design to be prone to market manipulations that could lead to an inefficient mechanism.

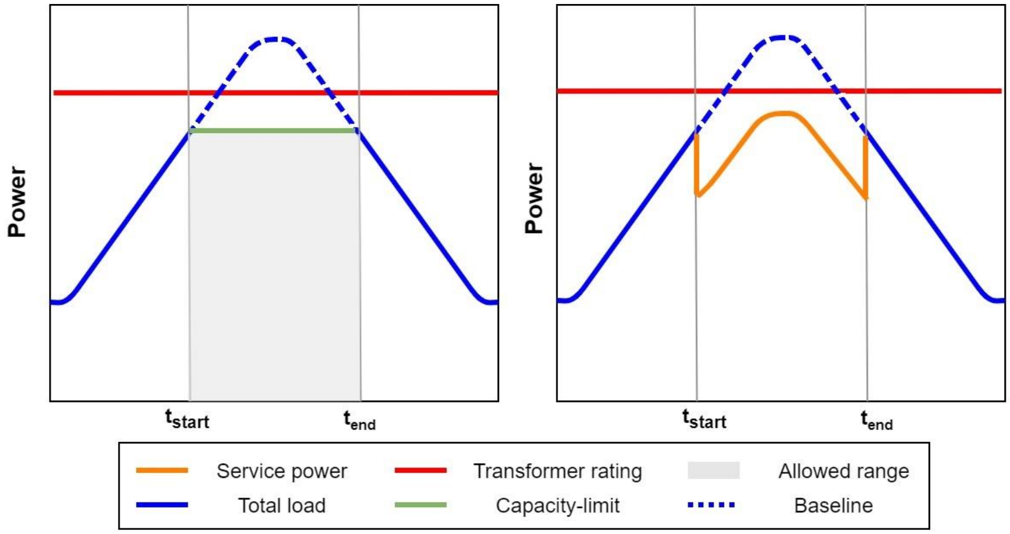

Figure 3-1 Baseline-based (on the right) and capacity-limit based (on the left) flexibility products [13]

The fourth challenge is forecast errors at low aggregations levels. As the aggregation level is becoming smaller at the local level, forecasting the load and generation levels would become more challenging [37]. The inaccuracy of forecasts can cause issues for defining baselines in an LFM [15], [38], or forecasting the behaviour of the end-users (especially residential end-users) to keep the schedules and balance in an LEM [39]. The forecast errors, if not handled properly, can potentially cause higher costs for all the stakeholders and reduce the efficiency of the designed mechanism.

The last common challenge is the need for extensive measurements and investments in ICT and IoT platforms. This challenge has been brought up in the discussions with the DSOs in the consortium concerning the possible cost and revenues that were discussed in subsection 2.4. Based on these discussions, a market design that requires fewer measurements is preferred.

Contributions and novelties

To the best of our knowledge, there have not been a proposed market design that has addressed all these challenges at the same time. Therefore, the novelty and contribution of our market design can be summarised as follows:

- Ensuring the incentive compatibility in a local market with low liquidity through game theory payment allocation methods at the settlement phase
- Introducing an integrated long-term reservation market aiming to facilitate decision making for the DSOs and FSPs years ahead and increase the reliability of the market solutions
- Using capacity-limit products for flexibility to avoid challenges regarding the baseline, the low aggregation level, and less prone to manipulation
- Including a continuous adjustment market to provide the opportunity for correcting the forecast errors
- Introducing a flexibility product that require no extra measurements beyond smart meters

Structure of the chapter

In the following sections, the potential roles of the local markets and their relationship with each other are discussed in 3.2. The design for the LEM is presented in 3.3. The proposed LFM design is explained in detail in 3.4 including an illustrative simulation case-study. The conclusions and suggestions for future work are provided in 3.5.

3.2 The potential roles of local markets in the energy system and their linkage

As mentioned in 3.1, local energy and flexibility markets are different. Their differences are, among others, the traded product i.e., energy vs. flexibility, and their approach for addressing the local grid challenges i.e., indirect vs. direct.

An important question when designing new markets is how such markets can potentially be integrated in the current structure of the energy system. This is especially important as energy is a strategic commodity and changes in the system would most probably be gradual and in a conservative manner. A few examples of such questions are:

- Does the designed market require substantial changes to the already established markets e.g., wholesale and balancing markets?
- Can the designed market be integrated in parallel to the existing structures or would they be a substitute to the current markets?
- If the designed market is going to be integrated in parallel to the existing markets, how is the interaction between the different markets?

The traded commodity on the local energy markets is similar to the good traded on the wholesale national energy markets. Therefore, there might be complications if the two markets co-exist at the same time. Some of these complications are:

- Which market would the generators/consumers prefer to sell/buy energy to/from?
- What is the added value for having a local and a wholesale market?
- How does having two parallel energy markets impact system operators, end-users, retailers, and other balance responsible parties?

Based on such complications for co-existence of wholesale and local energy markets, we see the local energy markets to potentially be a substitute of the wholesale markets. For example, instead of having four trading zones in Sweden, the trading zones can be increased to a couple of thousand zones for different areas. However, as mentioned before, such a large change in the structure of the system would most probably be costly and be gradual. This challenge can be especially important in the countries with already established national grids and functional wholesale markets. In such “brownfield” environments, the evaluation and implementation of such ideas can be more complicated compared to “greenfield” environments or the countries in which the national grid is not yet well-developed or national wholesale markets are not yet established. This challenge has been briefly pointed out in [40] as “interoperability” component of LEMs. Moreover, [41], [42] mention that most of the LEM projects are at the early stages of development. In addition, they highlight that the actual business models are yet widespread and unclear. Weinhardt et al. [41] point out further that a wide implementation of LEMs requires further analysis of the regulations and an active discussion of feasible adaptations.

On the other hand, the traded product on the local flexibility markets is different than the wholesale markets and therefore they would not be substitutes of each other. Therefore, they could probably co-exist if a functional coordination mechanism would be in place. As local flexibility markets are not substitute to the wholesale markets, they would probably not impose changes to the energy system's structure as large as local energy markets. Thus, implementation of flexibility markets might happen sooner than local energy markets.

With respect to the discussion above, the focus of the work in this chapter is on the design of local flexibility markets rather than local energy markets. However, a proposed design for a local energy market is also provided because in future work we see a potential that local energy and flexibility markets to co-exist and support each other. An example of their linkage can be utilisation of the schedules from the local energy market as the baseline for a baseline-based flexibility product that is traded in the local flexibility market. Analysing such connection between these two markets is in the scope of our future work and not explored in this report.

3.3 Local energy market

A local energy market can provide a solution for local stakeholders to share and exchange energy in a local energy community. It can be used to create incentives for customers within a local system to invest in renewable production and flexibility. It also opens up the possibilities for the aggregators to purchase flexibility from end users which could be offered to other stakeholders such as DSOs and TSOs. This section presents the framework and design of a local energy market. The framework is based on the local energy market developed in a previous EU project - Fossil Free Energy Districts (FED), where several energy carriers could be traded simultaneously. A more detailed information can be found in the report [17].

3.3.1 Local energy market framework

Figure 3-2 present the framework for the local energy market. The market is organised by a local market operator and different agents can place offers and bids on the market. The local agents represent different local resources e.g. building, PVs or batteries whereas the intermediate agents represent external stakeholders e.g. retailers, DSOs and aggregators, etc.

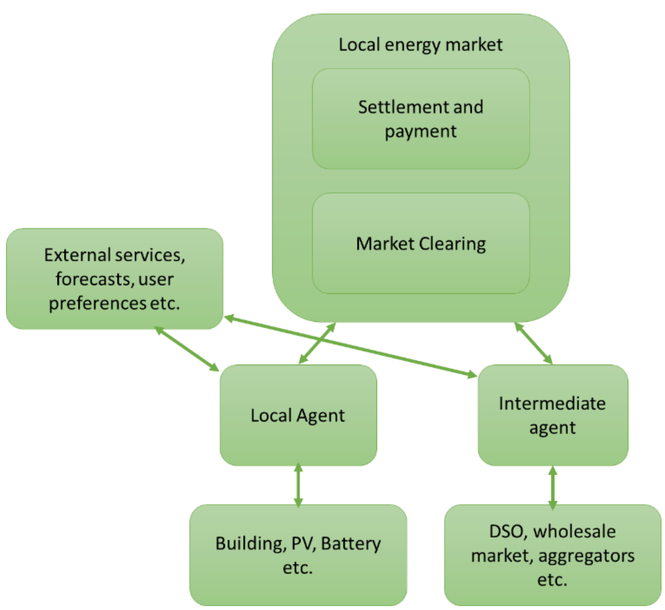

Figure 3-2 Framework of the local energy market

The market is designed as a peer to pool market based on a double-sided auction structure where both demand and supply asks/bids are organised in aggregated demand supply curves. This can be seen as a mix between centralised control and peer to peer trading.

The commodity traded on the local energy market is mainly energy and the trading takes place using a rolling horizon approach where the market is cleared for a specific trading horizon for a number of trading periods, as shown in Figure 3-3. However, it is only the first trading period that is binding whereas the remaining trading periods can be viewed as a forecast. Once the market is cleared the agents are informed of the winning bids and then dispatch their resources accordingly.

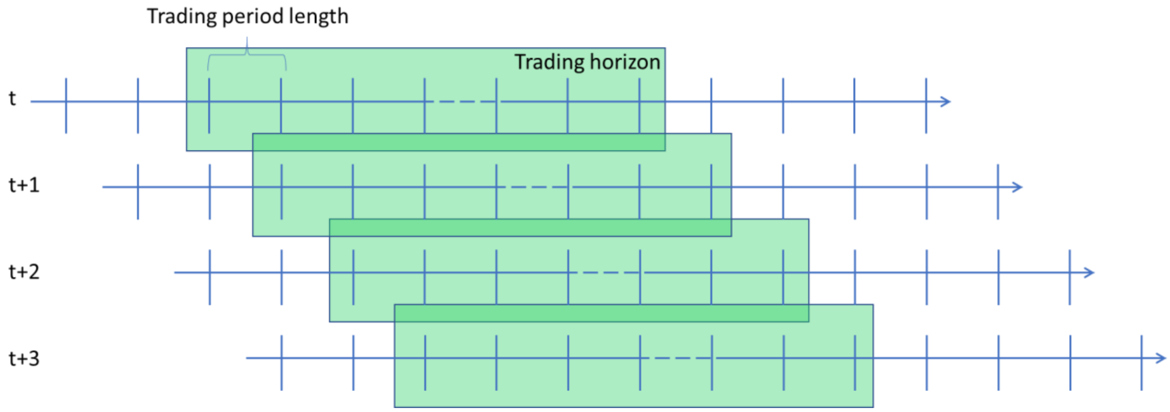

Figure 3-3 Illustration of the rolling horizon trading approach

3.3.2 Market clearing and bids

This section presents how the bids are structured and formulated and how the market is cleared.

Bid structure

The bids to the market are split into two parts, the first part involves price, volume and energy carrier, while the second part involves bid dependencies. This enables the agents to bid in flexibilities in the energy market, e.g., if the agent is flexible to when their EVs are being charged as long as they are fully charged at departure, they can specify a summation dependency to specify that over certain time horizon the total demand should be met. The dependency bids could also be used to specify dependencies between different energy carriers, e.g. an agent with a heat pump would have dependencies with electricity demand and heat/cooling supply. Table 3-1 and

Table 3-2 present the general structure of the bids and how they can be formulated.

Table 3-1 General bid structure, local energy market. Abbreviations: TP = Trading period ID, EC = Energy Carrier ID, Curr = Currency.

Parameter	Quantities included	Explanation/Comment
General	Agent ID Bid ID Bid type (Demand OR Supply) Trading period [TP] Energy carrier [EC]	General information for identification and scope of the bid.

Energy	Capacity [kWh] Price [Curr/kWh]	Reflect production and willingness to produce at a certain price level, or consumption and willingness to consume at a certain price level. For supply the price constitutes a minimum level, while for demand a maximum level.

Table 3-2 Bid dependencies for the local energy market

Dependency	Bids included	Operator	Quantity	Explanation/Comment
Discrete	Bid1 [Bid ID] Bid2 [Bid ID]	AND OR XOR	N/A	Using these dependencies, an agent can set conditions on the acceptance of bids in relation to other bids using logical operators.
Summation	Bid range [Bid ID, ...]	> < =	Capacity [kWh]	Using the summation dependency, an agent can set conditions on the sum of accepted energy quantities for a number of bids.

Market clearing algorithm

In order to determine the market price and energy volumes a market clearing must be performed. In the energy market the well-established microeconomic principle of maximisation of social welfare or total system benefit have been implemented in a market solver in order to clear the market. This section presents the general structure while a more detailed description can be found in [30].

The objective function of the market solver can be expressed as:

$$\max_{y_b} \sum_{b \in D} v_b \times y_b - \sum_{b \in S} v_b \times y_b \qquad (3-1)$$

where y_b is the optimisation variable denoting the cleared capacity of each bid, v_b is the valuation of the bid. Since the bid structure allows for bid dependencies, these dependencies are included as constraints in the optimisation model and are further described in [30].

Grid constraints

In the FED project, the market solver incorporated network transmission limitations by utilising a DC load flow model as presented in [30].The reason for using the DC load flow was to enable same notation for the different energy vectors traded on the platform. However, for distribution system, the DC load flow does not provide very accurate results. To increase the accuracy a linearized AC load flow model of the underlaying distribution system could be used. The reason for utilising linearized AC load flow is to keep the optimisation model linear while ensuring a more accurate representation compared to the DC load flow. The active and reactive net injection from the price/network locations are calculated according to the following two equations:

$$P_l = g_{ll} + \sum_{\substack{j=1 \\ j \neq l}}^{N} g_{lj}\left(|V_l| - |V_j|\right) - \sum_{\substack{j=1 \\ j \neq l}}^{N} b_{lj}\left(\theta_l - \theta_j\right)$$

$$Q_l = -\left(b_{ll} + \sum_{\substack{j=1 \\ j \neq l}}^{N} g_{lj}\left(\theta_l - \theta_j\right) - \sum_{\substack{j=1 \\ j \neq l}}^{N} b_{lj}\left(|V_l| - |V_j|\right) \right)$$

where g_{lj} and b_{lj} is the conductance and susceptance of the between node l and j. The active power is calculated from the cleared demand/supply bids according to:

$$P_{t,e,l} = \sum_{b \in S} y_{b,t,e,l} - \sum_{b \in D} y_{b,t,e,l}, \forall t \in T, e \in E, l \in L \qquad (3-2)$$

where the indexes T, E and L represents the time step, energy carrier and pricing locations. In addition, one of the buses must be defined as a slack-bus, the energy flow between two nodes must be within the transfer capacity limits and the injected power must be equal to the outflow of energy in each pricing location, i.e., power flow balance.

3.3.3 Market clearing prices and market settlement

From the market solver the cleared capacities can be obtained without introducing any price variables into the optimisation problem. The prices are instead obtained from the duality properties of the LP problems. By finding the shadow prices for the power balance constraints, the marginal cost of increasing the power in each node/location are obtained and would represent the market clearing price for each node.

As mentioned above, the market is cleared for the entire trading horizon but only the first trading period is binding. In this way the trading horizon can be viewed as a forecast of the coming hours. One drawback with this approach is that the market participants may not have financial incentives to bid truthfully for the full trading horizon. An alternative would be to have all trading periods financially settled. This would alleviate the risk of market manipulation but would also increase the complexity and financial risk for the participants.

3.4 Local flexibility market

In this section, the market design for a centralised local flexibility market is presented. First, the product design, market actors, and the different market horizons are explained in subsection 3.4.1. The bids and the market clearing algorithms are presented in subsection 3.4.2. The payment allocation mechanisms are presented in subsection 3.4.3. The simulation case-study is introduced in 3.4.4, the results are shown in Subsection 3.4.5 and discussed in Subsection 3.4.6.

3.4.1 Market framework

The market framework aims to provide a wholistic overview of the market design including the products that are traded, roles and responsibilities of the actors, and the different market horizons and the reasoning behind the existence of each market horizon.

Products

The original idea of the capacity-limit products are inspired by the products introduced in [15]. However, there are slight differences in how the product is defined in order to improve the design. This is further presented and discussed in this section.

As presented earlier in Subsection 3.1, two main products have been proposed which can be traded on FlexiGrid's LFM:

- capacity-limit cap, and
- capacity-limit (CL) floor

As an illustrative example, Figure 3-4 shows the average hourly loading of a transformer that is feeding only two end-users. The DSO's forecast for the coming year shows that in the winter months the loading of the transformer is getting close to its ratings and thus it might be better to keep the loading below the safety margins (the red line). In this case, the DSO can ask for a CL-cap service during winter days. The amount of the CL cap is calculated with respect to the sum of all the already sold connection capacity to the end-users connected to this transformer (i.e. CL-cap: 60-25 =35kW). Fuse levels have been considered as the already sold connection capacity in this example. By purchasing this product, the DSO would ask the end-users to keep the sum of their exchange with the grid below that level in the specified times. Each of the end-users can provide part of this reduction according to their connection capacity and capabilities.

Another similar product is CL floor that can be traded in the hours of the year with reversed power flows due to local generation units such as solar panels. By purchasing this product, the DSO asks the end-users to keep their exchange with the grid above the requested floor. Calculating the quantity of the CL floor is similar to CL cap with respect to the connection capacity.

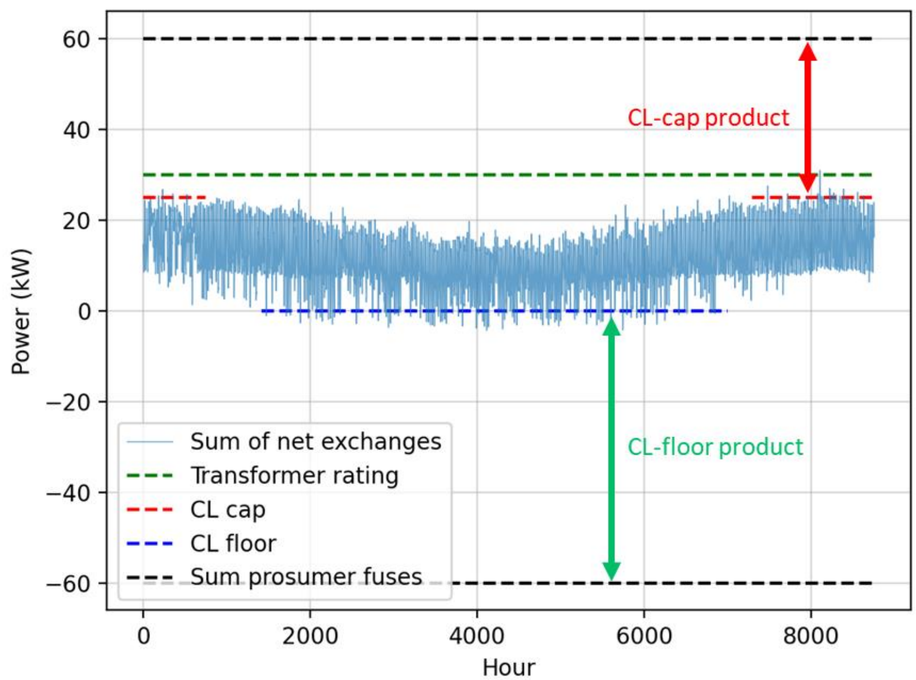

Figure 3-4 Capacity-limit cap, and capacity-limit floor products

The introduced products would not require any baseline and are calculated with respect to static and transparent values such as the connection capacities. The capacity-limit products introduced in [15] are with respect to the nominal capacity of the flexibility resource. This can cause potential market manipulations by misreporting or not reporting the capacity of the flexible assets. This risk has been also mentioned in their later work [43]. To hinder this risk, the FlexiGrid CL products are defined according to the connection capacity of the flexibility provider. This value is a static transparent quantity and cannot be manipulated by misreporting or addition of new flexibility assets behind the meter. Another benefit of the introduced CL products is that it does not need any extra measurements (e.g. measurements at each DER asset) than the values from the smart meter at the point of common coupling of the end-users. This would be beneficial due to the avoided costs from the extra measurement and additional extension of the ICT infrastructure.

Roles and responsibilities of the market players

The market players can be divided into the following groups:

- **DSOs**: The buyer of the products
- **Flexibility service providers:** Aggregators or the end-users who are the seller of the products
- **Market operator:** A neutral, independent party that is responsible for managing the market, receiving the bids, clearing, and settlement of the market

The flexibility service providers can be aggregators that aggregate flexible end-users and handle management of the end-users' assets and administrative works for participation in the market. End-users, especially large end-users, can participate directly in the market. We expect that it would be mainly aggregators who would provide flexibility services because of three main reasons. First, the cost of participation for small end-users would most likely be high and thus, their participation can be unprofitable [31], [44]. Second, Eid et al. [45] point out that the small end-users might not be able to fulfil the requirements the markets concerning for example the reliability and availability. Third, it might be preferable that small end-users would be gathered under an aggregator as the number of decision variables and constraints would increase to a large extent in the clearing algorithm and can cause computational challenges for the market operator [46]. The operation of market platforms is recommended to be done by independent, neutral third parties [14].

Market horizons and their linkage

To have a more comprehensive market design, three connected market horizons of long-term, short-term, and close-to-real real-time have been proposed for FlexiGrid flexibility market. This triple horizon structure is inspired by the work done by Bouloumpasis et al. [47] in the UNITED-GRID project.

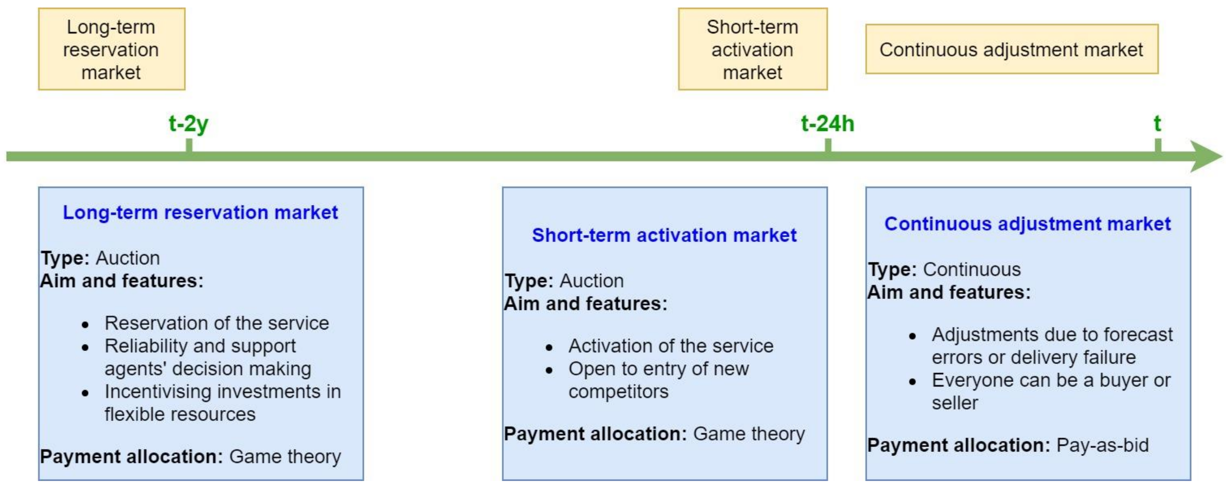

Figure 3-5 an overview of the market horizons

An overview of our proposed market horizons is presented in Figure 3-5. Each of the market horizons are designed to satisfy a specific purpose in the procurement procedure of a flexibility service. Long-term market is for reservation of the services, short-term for activation, and the continuous close-to-real real-time market is for adjustments due to forecast errors or delivery failures. In the long-term market, the DSO will send the expected date, time, quantity of the product that might be required, and the value that it is willing to pay for reserving such a service. The cleared FSPs in the long-term will be paid to be available for activation in the short-term activation market. The cleared FSPs are obliged to participate in the short-term market if the DSO request a service. The cleared activation values on the short-term market are binding and need to be delivered. All the participants can be buyer or seller of the service in the continuous close-to real-time adjustment markets in case they want to adjust the quantity of their request or offer. The payment allocation methods for the long and short-term markets are considered to be game theoric e.g., Vickrey Clarke Groves, or Shapley payments to achieve incentive compatibility in the local markets and address one of the consequences of the low liquidity. In the adjustment market, we have concluded that continuous markets would be more suitable based on the discussions that will be provided in this section. Due to the nature of bid-matching in the continuous markets, game theory payment allocation methods are not plausible and the payments need to be done on a pay-as-bid basis.

In our design, the long-term and short-term horizons are auctions (call-markets) while the adjustment market is a continuous market. A literature review has been carried out on the differences between call-markets and continuous markets to decide the suitable market type for the different horizons. Call markets and continuous markets are different from different point of views. These differences are presented in Table 3-3.

Table 3-3 Comparison of continuous markets with call-markets (auctions)

	Continuous market	Call market (auction)
Information efficiency [48], [49]	+	-
Suitability for risk-averse actors [48]	+	-
Liquidity	- ([49], [50]) + ([34], [51])	+ ([49], [50]) - ([34], [51])
Suitability for small actors [49], [50]	-	+
Market power resilience [49]	-	+
Cost of late scheduling [48]	+	-
Social welfare [48]–[50]	-	+
Modelling [48]	-	+
Computational burden [50]	-	+

Information efficiency is described as the possibility for transferring the arrival of new information instantaneously to the market [49], [52]. Continuous markets provide this possibility for the agents to correct and communicate the changes in their plan as soon as possible. This possibility for fast corrections can help market parties to have lower costs which is important for the efficiency of the market [49]. The continuous markets allow the participants to trade whenever they anticipate benefits [48] compared to auctions that are cleared only at a specific time and cause delay to transferring information and trading [49]. From this perspective, the continuous market is very suitable for our adjustment horizon as it matches the main purpose that is providing the possibility for an instantaneous adjustment.

Continuous markets are more suitability for risk-averse actors. Risk-averse actors can be the ones who want to minimise the risks related to imbalances as soon as possible [48]. Another risk-averse actor can be the DSO. As the DSOs' core business is to guarantee a reliable supply of power, they might prefer to procure adjustments as soon as possible.

Regarding the liquidity, there are different opinions for and against the two market types. Ocker et al. [49] argue that the auction markets can lead to higher liquidity as they collect all the bids and clear them once at the end of the trading session. A study done by Neuhoff et al. [50] on intraday market in Germany has shown that the addition of auctions has increased the liquidity and a higher market depth. On the other hand, Cheng et al. [51] argue that the liquidity can be higher in a continuous market as it offers a fast trade execution. Schittekatte et al. [34] also mention that "in case of low liquidity, there are also arguments in favour of continuous trade".

The auction markets are mentioned to be more suitable for small actors and more resilient to market power. In references [49] and [52], it is argued that the continuous markets give an advantage to the large actors as these actors have a "better return on information costs and thus create barriers to entry" and conclude that the continuous markets are more prone to market power. Moreover, the results from Neuhoff et al. [50] show that auctions provide obvious benefit for small players that do not have the capability for a continuous 24/7 trading.

The continuous markets can be more suitable for the actors that might face costs in the case of late rescheduling as they can communicate and trade corrections (adjustments) as soon as possible [49]. Examples of such actors in the context of flexibility markets can be storage units, or demand response, especially from large industrial flexible demands.

Social welfare is another aspect that has been discussed when comparing continuous markets with auctions. Auctions are mentioned to produce larger social welfare levels compared to continuous markets [48]–[50]. An explanation for this advantage is shown in Figure 3-6 where the possible loss of social welfare in a continuous market is illustrated.

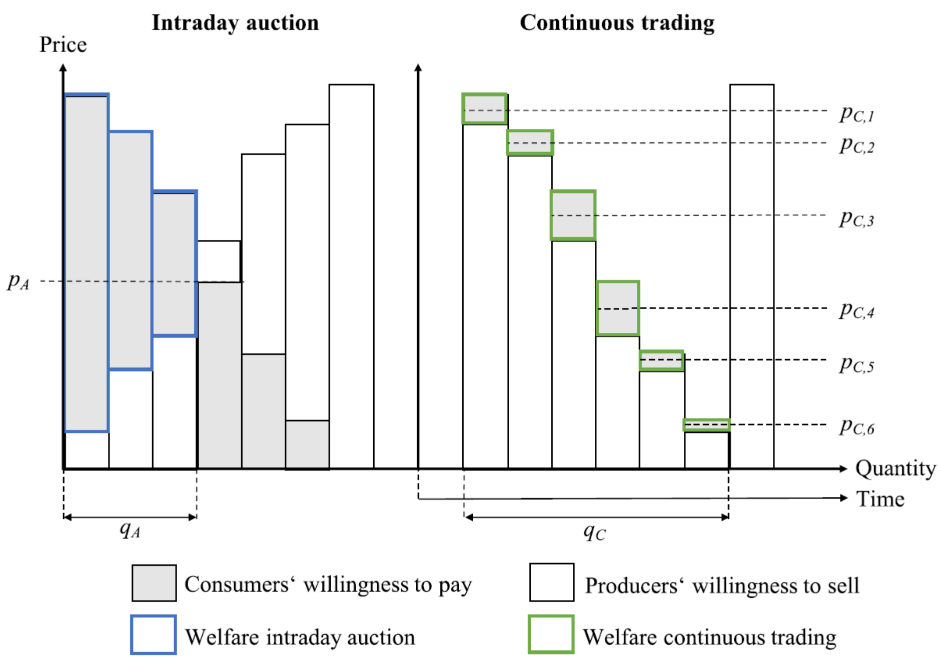

Figure 3-6 Possible loss in social welfare in continuous markets in comparison with an auction intraday market [49]

There are other aspects that differentiate auction and continuous markets, such as difficulties in modelling and the required computational resources. Reference [48] argues that continuous markets are more challenging to model since the trading behaviour on these markets are not straightforward as there might always be a more profitable trading opportunity at a later point in the same period of delivery. Moreover, Neuhoff et al. [50] argues that auctions are generally simpler to operate and the dedicated computers for market clearing can be allocated only for a certain period of time. On the other hand, continuous markets require a completely dedicated computer for the whole period of the adjustment market for computing and bid matching.

To summarise, we see many arguments in favour of auction markets and their suitability for local flexibility trading except for the adjustment horizon where the purpose is adjustments and thus information efficiency and minimising risks for the DSO is essential. Therefore, auction markets have been chosen for the long-term and short-term horizons and the continuous market for the adjustment horizon.

There are different advantages and disadvantages related to a three-level market structure, especially regarding the long-term reservation market and the linkage with the short-term market. An argument in favour of the long-term reservation markets is that it can provide reliability and support to the market participants in their decision-making process. One often mentioned benefit from procuring flexibility services is avoiding or postponing grid reinforcements. The planning horizon for most of DSOs is argued to be up to 10-20 years [53]. However, this time can be reduced to approximately 5 years to utilise the benefits of flexibility services [53]. As a result, making decisions about choosing flexibility options or traditional “poles-and-wires” alternative needs to be done well in advance. However, to be able to make such decisions, the DSOs require a certain guarantee regarding whether there would be enough flexibility when it is needed or not. This is essential for having a reliable supply of energy to the end-users which has been mentioned as a common challenge for adopting flexibility market solutions. On the other hand, the flexibility service providers might not be willing to invest in flexible assets if there is not a clear business case available. The long-term reservation market aims to provide this guarantee to the DSOs and FSPs to take decisions with lower risks. The reservation markets are specially required in the adoption phase of local flexibility markets when there are not enough flexible assets in the system and market actors might be extra conservative.

Some of the arguments against long-term markets are reduction of the efficiency in the short-term markets [34], entrance barriers for technologies with higher difficulties in long-term forecasts (e.g. demand response) [34], and possibilities for gaming in the short-term market by the reserved FSPs in the long-term market. In our suggested framework, the long-term market is solely for reservation and the activation payments are done in the short-term market. New actors have the possibility to enter the market in the short-term horizon. Therefore, more competitive FSPs can enter the short-term market and provide the service instead of the reserved FSPs and thus prevent a reduction of the efficiency. Moreover, a game-theory payment allocation mechanism in the short-term market can incentivise truthful bidding and therefore reduce the potential for inflation of prices in the activation market. Ausubel and Milgrom has discussed this imposed truthful bidding strategy for a Vickrey mechanism [54]. On the other hand, the technologies such as demand response can still face challenges for participating in the long-term market. However, as the short-term activation market is open to new actors, they can still provide the service in case they are competitive. This barrier to demand response technologies can lead to less investments in such technologies that might require more considerations by, for example, compensation through other mechanisms.

3.4.2 Market clearing and bids

In this section, the market clearing and the bids are explained in detail for different market horizons. We propose two different market clearing algorithms based on two different potential shapes for the demand curve of the DSO for a capacity-limit product.

The bids:

An example of a bid from an agent is shown in Table 3-4. A bid can be a request from a DSO or an offer from an FSP. The bids for an agent include the ID of the agent, the hour the bid is corresponding to (t), the granularity of the bid (g), the date, the locational code in which the service is required or the service provider is located in, the quantity of the capacity-limit product (q), and the valuation of the bid (u). In the proposed structure, the agents can submit multiple bids that represent their cost/utility curves. The multiple bidding can be represented through the granularity bids. The granularity bids can be accepted at the same time and are therefore not mutually exclusive. The valuation can represent the cost/utility for reservation or activation of the product depending on the market horizon.

Table 3-4 The bid attributes of an agent

ID	t	g	date	location	q (kW)	u (SEK/kW)
d0	**17:00:00**	**g0**	2021-01-06	Jb0, Jb1	281.11	0.3
		g1	2021-01-06	Jb0, Jb1	70.28	2
		g2	2021-01-06	Jb0, Jb1	24.70	9
		g3	2021-01-06	Jb0, Jb1	7.52	1
	18:00:00	**g0**	2021-01-06	Jb0, Jb1	295.89	0.3
		g1	2021-01-06	Jb0, Jb1	73.97	2
		g2	2021-01-06	Jb0, Jb1	6.22	9
		g3	2021-01-06	Jb0, Jb1	7.52	1
	19:00:00	**g0**	2021-01-06	Jb0, Jb1	276.50	0.3
		g1	2021-01-06	Jb0, Jb1	69.13	2
		g2	2021-01-06	Jb0, Jb1	30.46	9
		g3	2021-01-06	Jb0, Jb1	7.52	1

Multi-bids can support efficiency, a reliable market environment and the auctioneer's (the buyer) revenue according to the study done by Rosen et al. [55]. However, their results also suggest that the revenue of the bidders can decrease though become more stable. Their finding suggests that multiple bids should be preferred to single bids for divisible goods if possible. Moreover, Bouloumpasis et al. [47] suggest that submitting bid-curves can facilitate clearing larger quantities of flexibility in case the flexibility resources are limited.

DSOs' bidding curve:

The bidding curve of a DSO in a specific hour can be presented in two ways due to the special design of the capacity-limit product. The two demand curve shapes require different clearing algorithms. Figure 3-7 can be used as an example for explaining the two demand curves. In Figure 3-7, the forecasted loading of a transformer is shown for a period of 10 days. As can be seen in Figure 3-4, the sum of the sold connection capacities to the end-users are much larger than the maximum preferable threshold for the transformer loading (e.g., transformer's nominal rating). This is due to load coincident factors that are usually used when dimensioning the grid components as not all the end-users would use their capacity at the same time. The DSO wants to keep the transformer loading under the preferred threshold. Therefore, it would need to ask for a capacity-limit cap product in the hours the load forecast crosses the threshold (e.g., at 3rd of January 17:00).

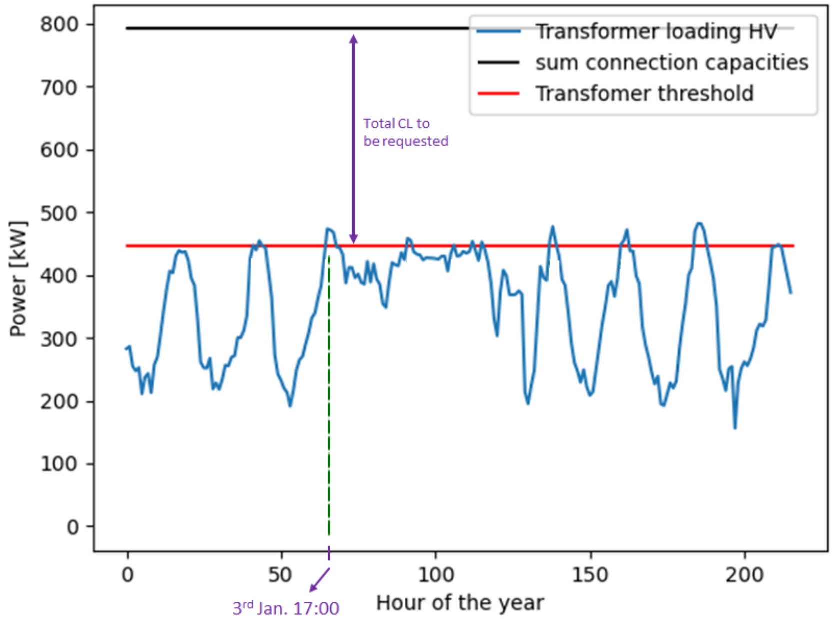

Figure 3-7 Transformer loading forecast for a period of 10 days. CL refers to the capacity-limit cap product to be requested.

The question here is how the demand curve of the DSO can look like at this hour. In case of very high transformer loadings close to the sum of connection capacities, curtailing loads or serious damages to grid components might be expected. Such high levels of loading can cause high costs to the DSO and therefore the DSOs might be willing to pay large values for those levels of loadings. As shown in Figure 3-8, the demand curve of the DSOs can be represented in a descending manner where the expected utility from purchasing the first kWs of capacity-limit are very high and then decreases as more capacity-limit is purchased. We call this an "impact-based" representation of the demand curve where the valuations of the bids are equal to the impact ($u = impact$). The impact of the event can be calculated based on the various cost and revenue streams discussed in Section 2.4. However, one can argue that the forecast in Figure 3-7 does not have high probability for having such high loadings and therefore why a DSO should be willing to pay high values for a loading with a low probability of happening. This leads us to the second shape that a DSO's demand curve can look like. We call the second shape a "probability-based" demand curve for capacity-limits. An illustrative example of a "probability-based" demand curve is presented in Figure 3-9. The valuations in for this type are calculated by $u = \; impact \times probability$. In part (1) marked in Figure 3-9 (a), the loading of the transformer is much larger than its ratings. This loading can have very large impacts on the grid such as the need for curtailing loads and risks for component failure. However, the forecasts for that hour do not show high probability of occurrence for such a high loading. As a result, the value from purchasing the capacity limitation service for this part is expected to be very low. In part (2), the impact is lower than part (1) but the probability is higher which can result in for example a higher valuation for the demanding this level of capacity-limitation. Part (3), although having lower impact, has a rather high probability of happening according to the forecasts. This can lead to the DSO expecting high valuations for this part of the demand curve. Finally, in part (4), the probability of the loading level is almost certain, however, the expected impact is quite low as the loading is below the acceptable transformer's threshold. Therefore, the DSO might not see a high value in purchasing capacity-limitation services up to this level.

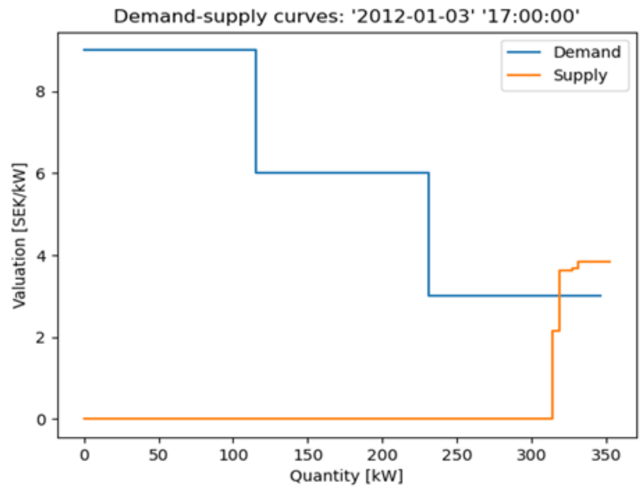

Figure 3-8 An "impact-based" demand curve for a capacity-limit cap product. The numbers for valuations are arbitrary values used only for illustration purposes.

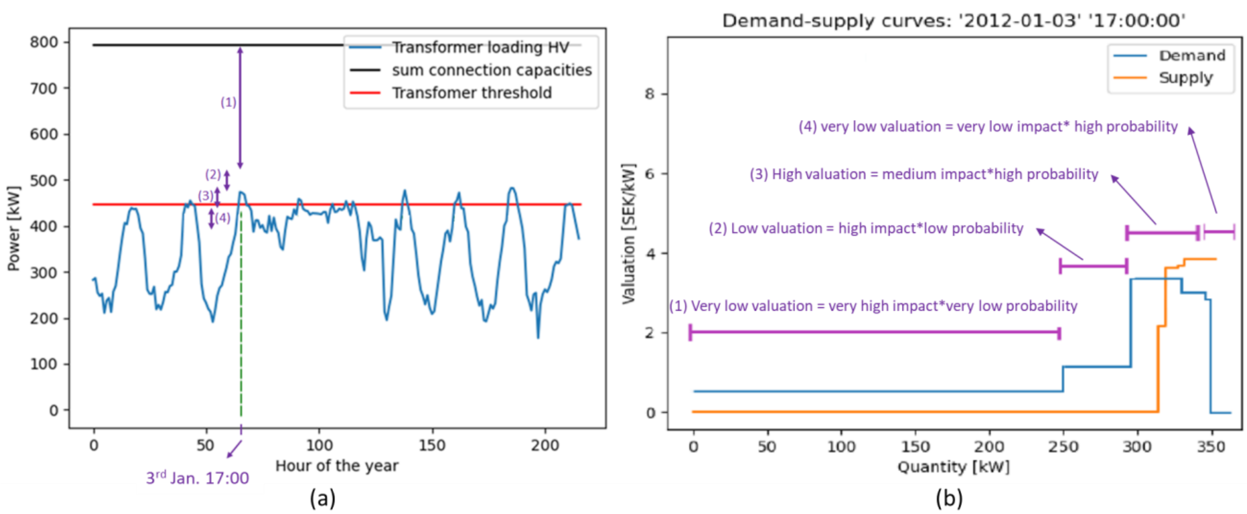

Figure 3-9 A "probability-based" demand curve of a capacity-limit cap product. (a) illustration of the different valuation parts of a demand curve on the loading forecast plot, (b) illustration of the different parts of a "probability-based" demand curve. The numbers for valuations are arbitrary values used only for illustration purposes.

The presented shapes for the demand curve require different clearing algorithms. The first demand curve can be cleared using a simple social welfare maximisation clearing, while the second demand curve requires an adjusted clearing algorithm to keep the order of the bid granularities into consideration. These clearing algorithms are presented further in the market clearing subsection.

FSPs' bidding curve:

The bidding curve of FSPs can be expected to look like an ascending supply curve. This because as the connection capacity of an FSP is limited at a specific hour, the FSP's optimal assets dispatch needs to be rescheduled deviating from the cost optimal plan. The further the connection capacity is limited, the more the deviation is from the cost optimal plan.

Market clearing algorithm for impact-based demand curves:

The clearing algorithms for long-term reservation and short-term activation markets are similar. The only difference is that in the long-term market, the valuations and quantities are for reservation while in the short-term market, they represent the activation (delivery) of the product.

The market clearing for an "impact-based" demand curve can be done by a standard social welfare maximisation formulation. The objective function for the market clearing is presented in (3-4).

$$\max_{\Xi} \sum_{i\in\mathcal{D}_t} \sum_{g\in\mathcal{G}_{t,i}} x_{t,i,g}u_{t,i,g} - \sum_{i\in\mathcal{S}_t} \sum_{g\in\mathcal{G}_{t,i}} x_{i,t,g}u_{i,t,g} \quad \forall t \in \mathcal{T} \qquad (3-4)$$

$s.t.:$

$$0 \le x_{t.i.g} \le q_{t.i.g} \quad \forall x \qquad (3-5)$$

$$\sum_{i\in\mathcal{D}_t} \sum_{g\in\mathcal{G}_{t,i}} x_{t.i.g} - \sum_{i\in\mathcal{S}_t} \sum_{g\in\mathcal{G}_{t,i}} x_{t.i.g} = 0 \quad : \mu_t \quad . \forall t \ \in \mathcal{T} \qquad (3-6)$$

The objective function aims to maximise the social welfare in each hour t by deducting the cost of supply from the utility of the demand side. The decision variables are $\Xi = \{x_{t,i,g} \mid \forall t \in \mathcal{T},\ i \in I_t,\ g \in \mathcal{G}_{t,i}\}$ in which $x_{t,i,g}$ is the cleared quantity at hour t for the granularity bid g of agent i. $\mathcal{D}_t$ and $\mathcal{S}_t$ are the sets of demand and supply agents at hour t. As mentioned in the bids section, each agent can submit multiple bids (granularity bids) at each hour t. $\mathcal{G}_{t,i}$ is the set that includes all the bids from agent i at hour t. $u_{t,i,g}$ is the valuation corresponding to the bid agent i has submitted at hour t and granularity of g.

Equations (3-5) is the constraint that ensures the cleared quantity x is less than the submitted quantity in the agent's bid. Equation (3-6) ensures that the sum of cleared quantities on the supply and demand sides are always equal at each hour t. The dual variable of constraint (3-6) is μ_t. This will be used later for uniform-pricing payments.

The adjustment market is based on a conventional bid matching in a continuous market scheme. Moreover, to increase the market transparency, the grid constraints are not included in the market clearing. These constraints need to be incorporated in the bidding strategy of the DSO and the DSO needs to consider these constraints through the location and quantity of its bid. This is further discussed in the discussion section.

At the delivery hour, the flexibility providers have to activate according to the cleared levels in the short-term market and the traded adjustments in the adjustment market. These values can be calculated by the market operator at the end of the adjustment period and be sent to the flexibility providers close to the delivery hour. Further research is required for deciding on the exact opening and closing time of each market horizon.

Market clearing algorithm for probability-based demand curves:

For "probability-based" demand curves, further constraints need to be incorporated into the market clearing problem explained in the previous section. These new constraints aim to keep the order of the granularity bids based on the previous discussion about the shape of a "probability-based" demand curve.

The objective function for clearing of “probability-based” demand curves is the same as “impact-based”. The decision variables are $\Xi = \{x_{t,i,g}, y_{t,i,g} | \forall t \in \mathcal{T},\ i \in I_t,\ g \in \mathcal{G}_{t,i}\}$ that are extended with introducing binary variables $y_{t,i,g}$. These binary variables aim to enforce keeping the order of granularity bids and they represent whether or not a bid is fully cleared or not (i.e. $x_{t,i,g} = q_{t.i.g}$).

The constraints of the market clearing for “probability-based” demand curves are presented in (3-7), (3-8), (3-9), and (3-10). Equation (3-7) is to limit variable y to be binary. For a granularity bid g, constraint (3-8) checks whether all the granularity bids before g are fully cleared or not. If the sum of x for the previous granularity bids is less than the sum of the bid quantities in that hour, y variable of that granularity bid is enforced to become zero. This zero value would enforce the cleared quantity (x) for that specific g to become zero through constraint (3-9). This way a granularity bid g is only cleared if granularity bids before are fully cleared and thus keeping the order of the submitted granularity bids. Constraint (3-10) is similar to (3-6) and ensures the balance of cleared values on supply and demand sides.

$$y_{t.i.g} \in \{0,1\} \qquad \forall y \qquad (3-7)$$

$$y_{t.i.g} \leq \frac{\sum_{g'} x_{t.i.g'}}{\sum_{g'} q_{t.i.g'}} \qquad \forall y,.\forall g' < g \qquad (3-8)$$

$$0 \leq x_{t.i.g} \leq y_{t.i.g}\, q_{t.i.g} \qquad \forall x \qquad (3-9)$$

$$\sum_{i\in\mathcal{D}_t} \sum_{g\in\mathcal{G}_{t,i}} x_{t.i.g} - \sum_{i\in\mathcal{S}_t} \sum_{g\in\mathcal{G}_{t,i}} x_{t.i.g} = 0 \quad \forall t\ \in \mathcal{T} \qquad (3-10)$$

The continuous market for adjustment is cleared similar to the adjustment market explained in the “impact-based” market clearing section. The grid constraints are also considered to be incorporated in the DSO’s bidding strategy similar to the “impact-based” market clearing.

3.4.3 Payment allocation mechanisms and market settlement

Different payment allocation mechanisms are explored for the market horizons in this study. The continuous adjustment market should be pay-as-bid. However, in the long-term and short-term markets uniform-pricing, VCG, and Shapley values are explored as the payment allocation methods. Uniform pricing is one of the common practices in market settlement beside pay-as-bid mechanism. The two latter ones are allocation mechanisms from game theory that have suitable properties such as incentive compatibility. Incentive compatibility or truthful bidding is an important property especially in local markets that might have low liquidity and are prone to manipulations. Due to the nature of the bid matching mechanism in the continuous markets, implementation of the social welfare-based payment allocation mechanisms is not plausible for these market types. The mentioned payment allocation methods are explained further in this section.

Vickrey-Clarke-Groves

To explain the VCG payment, new terms need to be introduced. The market at each hour is considered as our main game in which different players play. The set that includes all the demand and supply players is called grand coalition at that hour ($\mathcal{N}_t = \mathcal{D}_t \cup \mathcal{S}_t$). The value of the game $v_t(\mathcal{N}_t)$ with a set of players $\mathcal{N}_t$ is equal to the market clearing's objective at hour t which is the social welfare in this case. Another term is $v_t(\mathcal{N}_t \backslash \{i\})$ which represents the value of the game when player i is removed from the set of players $\mathcal{N}_t$. The VCG payment for agent i at hour t is calculated by (3-11). In (3-11), the marginal contribution of player i is calculated by subtracting the value of the game without the player in the game (i.e. $v_t(\mathcal{N}) - v_t(\mathcal{N}_t \backslash \{i\})$). The term $\omega_{t,i}^{\mathcal{N}_t^*}$ is the cost/utility of the seller/buyer i regarding its cleared quantity at hour t. This can be calculated as shown in (3-12) through multiplying the cleared quantities in the optimal solution ($x_{t,i,g}^{\mathcal{N}^*}$) to the corresponding valuation of its bid ($u_{t,i,g}$). $\omega_{t,i}^{\mathcal{N}_t^*}$ is positive for the buyers and negative for sellers.

$$VCG\ payment_{\ t,i} = v_t(\mathcal{N}) - v_t(\mathcal{N}_t \backslash \{i\}) - \omega_{t,i}^{\mathcal{N}_t^*} \quad \forall i \in \mathcal{N}_t \qquad (3-11)$$

$$\omega_{t,i}^{\mathcal{N}_t^*} = \pm \sum_{g \in \mathcal{G}_{t,i}} x_{t,i,g}^{\mathcal{N}^*} u_{t,i,g} \quad \forall i \in \mathcal{N}_t \qquad (3-12)$$

Shapley payment

The Shapley payments are calculated based on (3-13) which are the sum of the cost/utility of the player i plus the Shapley value ϕ_i. The Shapley value represents the average marginal contribution of player i to all the sub-coalitions to the grand coalition that contains player i. The cost/utility of each player is calculated by (3-12).

$$\text{Shapley payment}_{\ t,i} = -\omega_{t,i}^{\mathcal{N}_t^*} + \phi_i$$
$$= -\omega_{t,i}^{\mathcal{N}_t^*} + \sum_{\mathcal{M} \subseteq \mathcal{N}_t, i \in \mathcal{M}} \frac{(|\mathcal{M}|-1)!\,(|\mathcal{N}_t| - |\mathcal{M}|)!}{|\mathcal{N}_t|!} [v_t(\mathcal{M}) - v_t(\mathcal{M} \backslash \{i\})] \quad \forall i \in \mathcal{N}_t \quad (3-13)$$

After calculation of the Shapley values ϕ_i, the excess $e^{\mathcal{M}}$ of each coalition $\mathcal{M}$ is calculated based on (3-14) to check the stability of the game. The stability of game indicates whether the players would be better off in other sub-coalitions compared to the grand coalition or not. A positive excess value for a sub-coalition $\mathcal{M}$ indicates that members of $\mathcal{M}$ are better off to form their own coalition rather than take part in the grand coalition.

$$e^{\mathcal{M}} = v(\mathcal{M}) - \sum_{i \in \mathcal{M}} \phi_i \qquad \forall \mathcal{M} \subseteq \mathcal{N}_t \qquad (3-14)$$

Uniform pricing

Uniform pricing is one of the common practices in market settlement beside pay-as-bid mechanism. In uniform-pricing mechanism, there is a unique price that will be used for allocating payments to different market participants. This uniform price (also known as shadow price) can be obtained by extracting the dual variable of the balance equation (μ_t) in the market clearing algorithm.

In FlexiGrid flexibility market, uniform-pricing is used as a reference for comparison to other payment allocation mechanisms. Uniform-pricing is not investigated in "probability-based" market clearing as this market clearing includes integer variables. In addition, with the abnormal shape of the demand curve we might face multiple cross points of the supply and demand curves. The uniform pricing payments in the "impact-based" case are calculated by (3-15).

$$\text{Uniform payment}_{t,i} = \pm \sum_{g \in \mathcal{G}_{t,i}} \mu_t \, x_{t,i,g}^{\mathcal{N}^*} \quad \forall i \in \mathcal{N}_t, \forall t \in \mathcal{T} \qquad (3-15)$$

3.4.4 Illustrative simulation case-study

An illustrative case study is designed to show the how the market clearing and the payments allocation algorithms function. This simulation study is focusing only on short-term activation market because the long-term market clearing and payment allocation methods are very similar to the short-term activation market. The difference between the long and short-term markets is in their product types and the mindset for the bidding strategies. From the clearing and payment allocation point of view, these two markets are very similar as the attributes of the products, clearing, and payment allocation algorithms are the same. The only difference is that in the long-term market, the quantities and valuations need to be calculated from a long-term perspective and for reservation purposes, while in the short-term market the mindset for the bidding strategy is the activation of the product considering more accurate forecasts closer to the event. The adjustment market is not included in the simulations for two reasons, first, the clearing and settlement are more conventional and therefore considered to be less complicated compared to the short-term and long-term markets, and second, the adjustment market requires forecasts and deviation from forecasts which are not incorporated at this stage of the project. The adjustment market is planned to be demonstrated in the demonstration phase of the project.

A model has been developed in Python for conducting the case-study. The optimisation problems are solved with Gurobi [56]. The overview of the model's modules is presented in Figure 3-10. There are different modules in the model that further explained below.

In the "main" function, the simulation time-period, share of each end-user usage type, penetration levels of DERs (i.e., PV, and battery energy storage), the market clearing and market settlement methods are defined as input to the model. The district builder's aim is to assign electrical load, DER capacities, and historical weather to each individual end-user based on their usage type (e.g., single household, or multi-family dwellings), and the size of the building. District builder is a simplified version of the work done in [57]. The forecast module aims to be further developed later to include load and weather forecasts. However, it currently only estimates the import and export levels of each end-user based on a generalised energy management system optimisation problem which is run for each individual end-user.

The generalised energy management system of the flexibility provider is a simple cost optimisation algorithm with a rolling time horizon approach to decide the battery dispatch, import/export levels, and PV curtailment. The cost function includes the energy and power costs. The FSP agent module includes a bid generator module as well that provides the cost curve of the FSP for providing different levels of capacity-limit product. At the moment these modules are kept simple as the aim of the case-study is to illustrate the market design.

The DSO agent includes a flexibility need finder module that runs power flow calculations based on the results from the forecast module and finds how much capacity limit is required and at what hours. The test-system used for running power flows is CIGRE Low Voltage Distribution System [58] (Figure 3-11). This test-system is chosen due to limitations in data availability, and due to the potential for conducting comparable studies and benchmarking. In the demonstration phase of the project test-systems from DSOs in the consortium will be used for both the simulations and demonstrations of relatively more realistic cases. In our case-study the loads at the residential feeder are modified with the import/export values from the forecast module. Therefore, the flexibility providers are considered to be the six loads at buses R0, R11, R15, R16, R17, and R18. Panda Power [59] has been used for running the DC power flows.

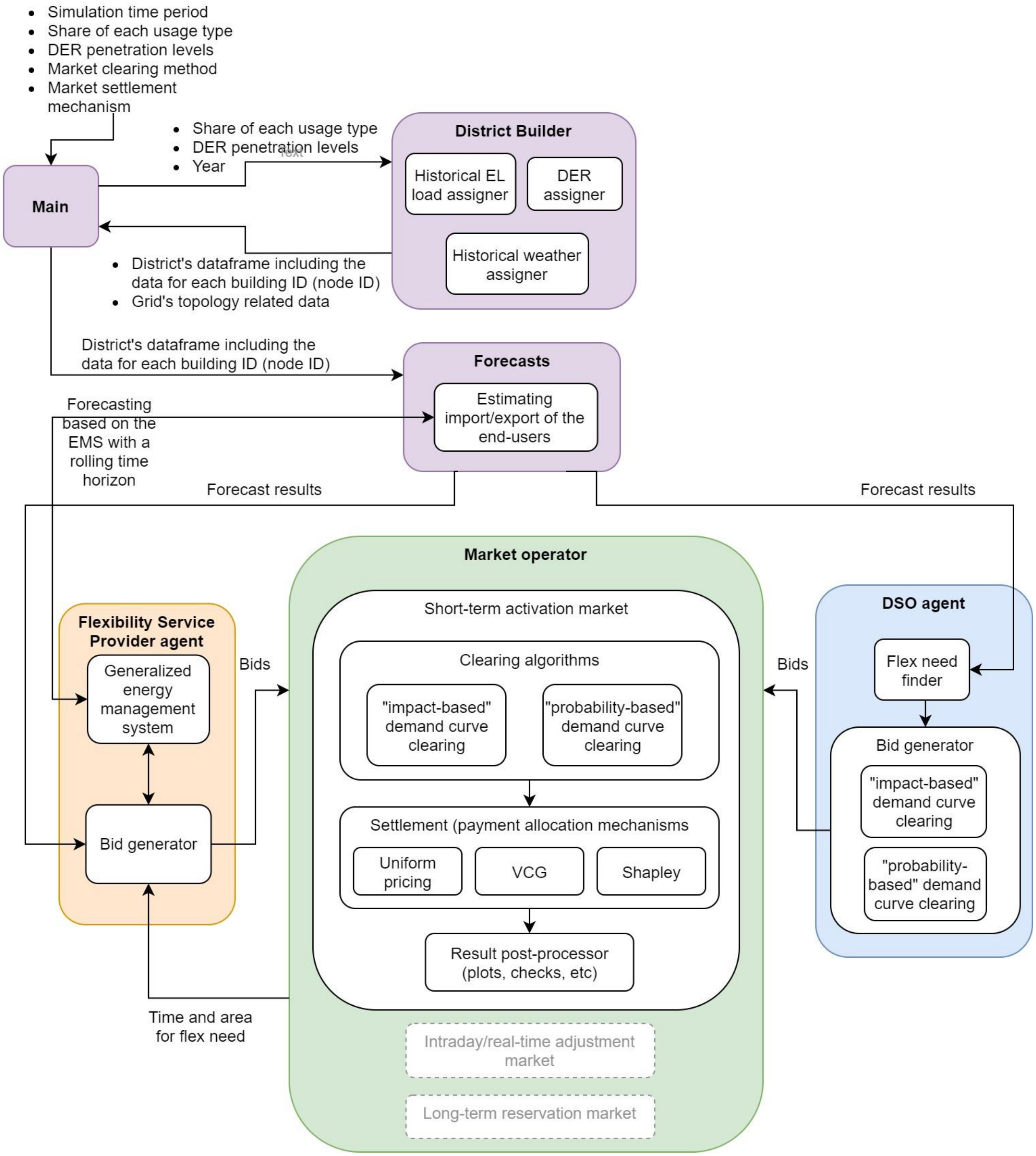

Figure 3-10 Overview of the model modules

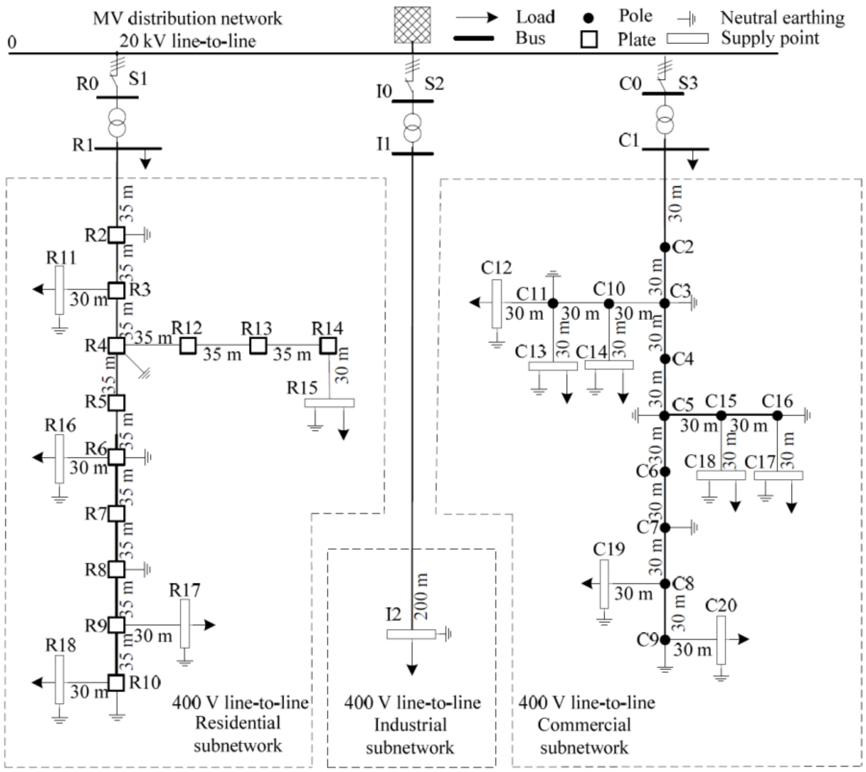

Figure 3-11 CIGRE European LV distribution network [58]

Finally, the market operator module receives the bids from the agents, clear the market, and calculate payments in the settlement modules. The results are afterwards sent back to the FSPs for activation, and to a module for post-analysis and generating plots.

3.4.5 Results

To illustrate how the market works, the six first days of January has been simulated for power flows, biddings, clearing mechanisms, and payment calculations. As mentioned in section 3.4.4, the illustrative simulations have been done only for the short-term activation market.

The active loading of transformer at bus R0 is presented in Figure 3-12. The threshold for an "overloading" is set to 95% of the transformer's ratings and from now on "overloading" refers to transformer loadings over 95% of the rated capacity. The results for the two different market clearing and demand curve shapes are presented in this section for both the of the market clearings.

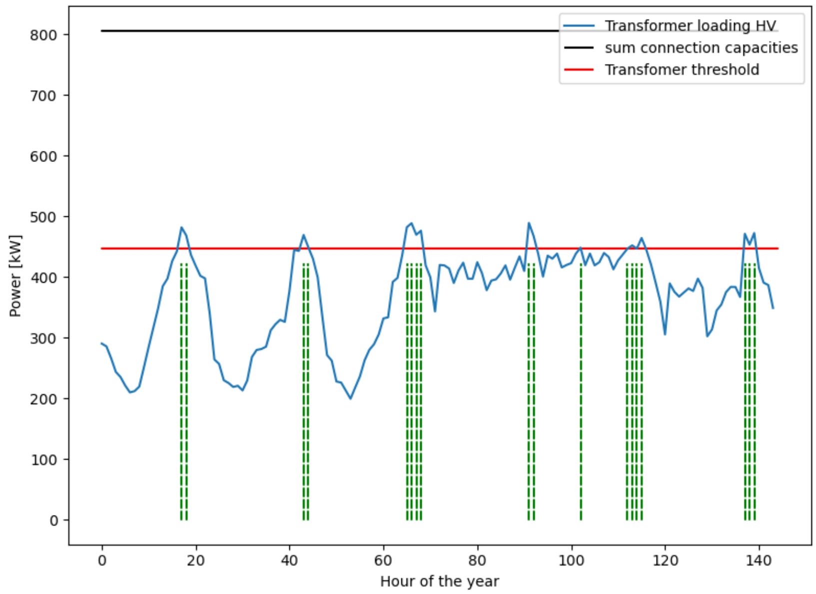

Figure 3-12 The loading of the transformer at bus R0. The green dashed lines represent the hours with loading over the transformer threshold. The threshold is assumed to be 95% of the transformer's rating.

Results for the "Impact-based" demand curve market clearing

The hours that the transformer is overloaded are presented in Table 3-5. The table includes the overloading for both before and after the market clearing. As can be seen, the transformer is congested at different hours during this week. The market is activated through the DSO's bids for the days that procuring capacity-limit cap product was needed.

Table 3-5 The hours that the transformer is overloaded before and after activating the market- "impact-based" demand curve market clearing

Hour of year	Date	Time	Transformer loading-before [%]	Transformer loading-after [%]
16	2012-01-01	16:00:00	Not overloaded	95.11
17	2012-01-01	17:00:00	102.65	Not overloaded
18	2012-01-01	18:00:00	99.75	Not overloaded
41	2012-01-02	17:00:00	Not overloaded	95.52
42	2012-01-02	18:00:00	Not overloaded	95.11
43	2012-01-02	19:00:00	99.93	Not overloaded
44	2012-01-02	20:00:00	95.59	Not overloaded
65	2012-01-03	17:00:00	102.70	Not overloaded
66	2012-01-03	18:00:00	104.12	Not overloaded
67	2012-01-03	19:00:00	100.02	Not overloaded
68	2012-01-03	20:00:00	101.44	Not overloaded
91	2012-01-04	19:00:00	104.22	Not overloaded
92	2012-01-04	20:00:00	99.56	Not overloaded

93	2012-01-04	21:00:00	Not overloaded	95.41
97	2012-01-05	01:00:00	Not overloaded	95.63
101	2012-01-05	05:00:00	Not overloaded	95.60
102	2012-01-05	06:00:00	95.43	Not overloaded
104	2012-01-05	08:00:00	Not overloaded	95.63
107	2012-01-05	11:00:00	Not overloaded	95.85
111	2012-01-05	15:00:00	Not overloaded	95.32
112	2012-01-05	16:00:00	95.08	Not overloaded
113	2012-01-05	17:00:00	96.23	Not overloaded
114	2012-01-05	18:00:00	95.08	Not overloaded
115	2012-01-05	19:00:00	98.85	Not overloaded
116	2012-01-05	20:00:00	Not overloaded	95.45
137	2012-01-06	17:00:00	100.34	Not overloaded
138	2012-01-06	18:00:00	96.50	Not overloaded
139	2012-01-06	19:00:00	100.a61	Not overloaded

The supply and demand curves and the cleared quantities in the case of having "impact-based" demand curve and market clearing is presented in Figure 3-13.

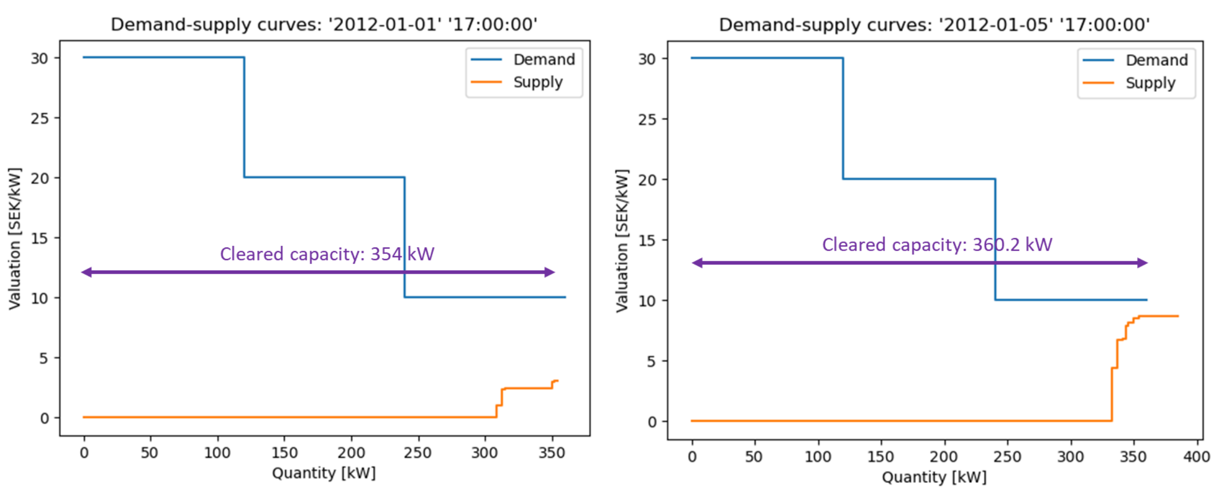

Figure 3-13 Two hours as examples for the supply-demand curves and the cleared capacities- "impact-based" demand curve market clearing

The transformer's loadings before and after the market activation are presented in Figure 3-14. Moreover, the loading levels can be seen in Table 3-5. As can be seen, the loading has been reduced in 68% of the congestion occasions. It is also worth mentioning that rebound effects can occur as a result in other hours which highlights the importance of the DSOs bidding strategy (e.g., procuring flexibility for a broader period including the hours that rebound effects can be expected), or consideration of such effects in the future improving the market design.

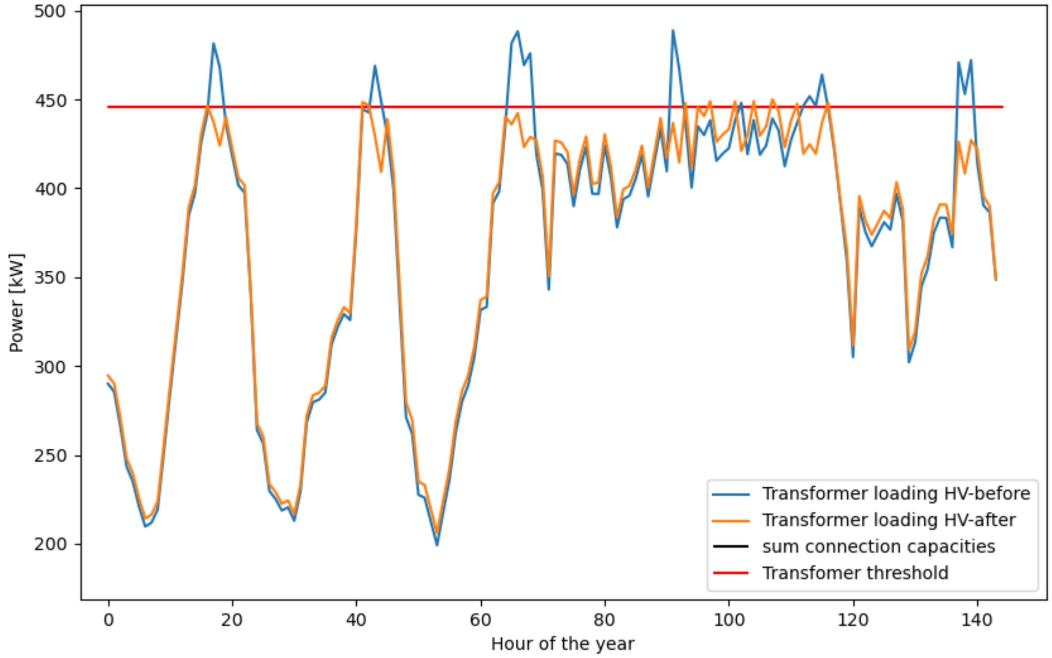

Figure 3-14 Transformer loading at R0 before and after market activation- "impact-based" demand curve market clearing

The payment allocations for different market participants are presented in Table 3-6. For a faster runtime, the objective function of the market clearing has been defined as the sum of all the hours within the day. Therefore, the results of the payment allocation are the aggregated payments for each day. It can be seen that the VCG is not budget balanced compared to the other two payment allocation mechanism that have a balance of zero.

Table 3-6 Shapley, VCG, and uniform-pricing payments for the "impact-based" demand curve clearing

	Shapley			VCG payment	Uniform-pricing payment
	Shapley value	Cost/utility	Shapley payment		
Date: 2012-01-01					
DSO	8072.0	-14282.8	-6210.8	-215.4	-7079.9
FSP 1 (R16)	150.1	0.0	150.1	183.4	183.4
FSP 2 (R17)	216.3	0.0	216.3	264.5	264.5
FSP 3 (R18)	593.4	32.6	626.0	738.3	738.3
FSP 4 (R1)	3177.5	0.0	3177.5	4806.5	3542.2
FSP 5 (R11)	1300.4	182.8	1483.2	1674.5	1674.5
FSP 6 (R15)	557.8	0.0	557.8	677.0	677.0
Sum (budget balance)			**0.0**	**8128.8**	**0.0**
Date: 2012-01-05					
DSO	20297.7	-36014.6	-15717.0	-1008.1	-15649.8
FSP 1 (R16)	295.4	0.0	295.4	337.2	337.2

FSP 2 (R17)	447.5	0.0	447.5	510.8	510.8
FSP 3 (R18)	1368.2	142.9	1511.1	1682.1	1604.1
FSP 4 (R1)	8746.7	0.0	8746.7	13246.8	8978.9
FSP 5 (R11)	2356.9	865.2	3222.1	2936.1	2551.7
FSP 6 (R15)	1494.0	0.0	1494.0	1754.6	1667.1
Sum (budget balance)			**0.0**	**19459.5**	**0.0**

The excess parameter of the Shapley payments has also been calculated for all the subsets of the grand coalition. Positive values have been observed for the 5th of January for the presented subsets in Table 3-7. The reason behind this instability in the game needs to be further investigated in our future work.

Table 3-7 Excess parameter for the Shapley payments- "impact-based" demand curve market clearing

Subset $\mathcal{M}$	Excess ($e^{\mathcal{M}}$)
(DSO, FSP1, FSP2, FSP3, FSP4, FSP6)	285.97
(DSO, FSP2, FSP3, FSP4, FSP6)	193.45
(DSO, FSP1, FSP3, FSP4, FSP6)	145.81
(DSO, FSP3, FSP4, FSP6)	53.29

Results for the "probability-based" demand curve market clearing

The hours that the transformer is overloaded are presented in Table 3-8. The table includes the overloading for both before and after the market clearing.

Table 3-8 The hours that the transformer is overloaded before and after activating the market- "probability-based" demand curve market clearing

Hour of year	Date	Time	Transformer loading-before [%]	Transformer loading-after [%]
16	2012-01-01	16:00:00	Not overloaded	95.11
17	2012-01-01	17:00:00	102.65	Not overloaded
18	2012-01-01	18:00:00	99.75	Not overloaded
41	2012-01-02	17:00:00	Not overloaded	95.52
42	2012-01-02	18:00:00	Not overloaded	95.11
43	2012-01-02	19:00:00	99.93	Not overloaded
44	2012-01-02	20:00:00	95.59	Not overloaded
65	2012-01-03	17:00:00	102.70	Not overloaded
66	2012-01-03	18:00:00	104.12	Not overloaded
67	2012-01-03	19:00:00	100.02	98.81
68	2012-01-03	20:00:00	101.44	99.98
91	2012-01-04	19:00:00	104.22	Not overloaded
92	2012-01-04	20:00:00	99.56	Not overloaded
102	2012-01-05	06:00:00	95.43	95.75
112	2012-01-05	16:00:00	95.08	95.41
113	2012-01-05	17:00:00	96.23	96.56

114	2012-01-05	18:00:00	95.08	95.40
115	2012-01-05	19:00:00	98.85	99.18
137	2012-01-06	17:00:00	100.34	Not overloaded
138	2012-01-06	18:00:00	96.50	95.74
139	2012-01-06	19:00:00	100.61	Not overloaded

The supply and demand curves, and the cleared quantities for a few of the hours are presented in Figure 3-15.

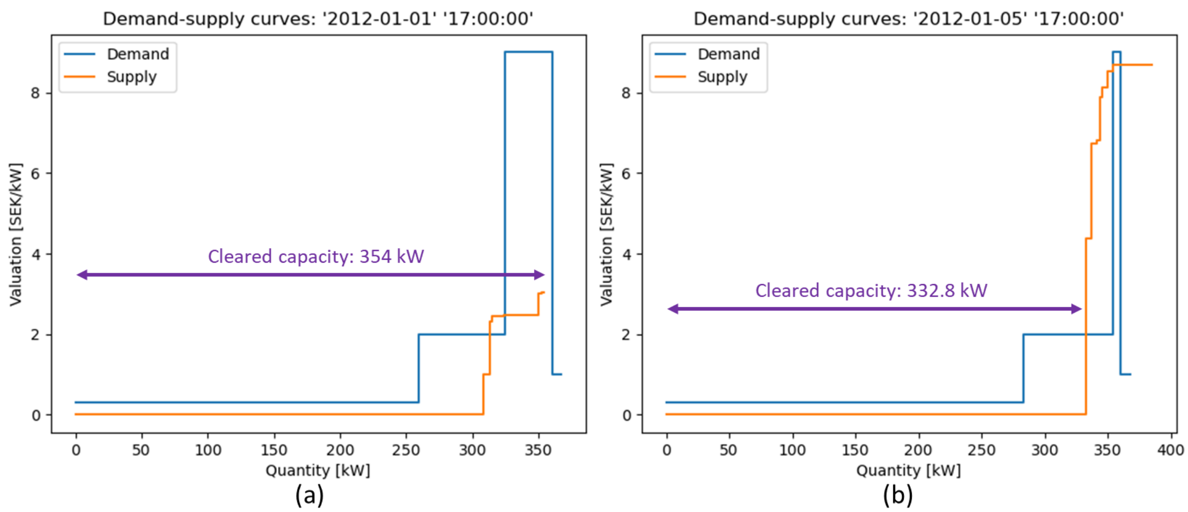

Figure 3-15 Two hours as examples for the supply-demand curves and the cleared capacities- "probability-based" demand curve market clearing

The loading of the transformer before and after are presented in both Figure 3-16 and Table 3-8. It can be seen that the loading has been reduced in 72% of the congestion occasions.

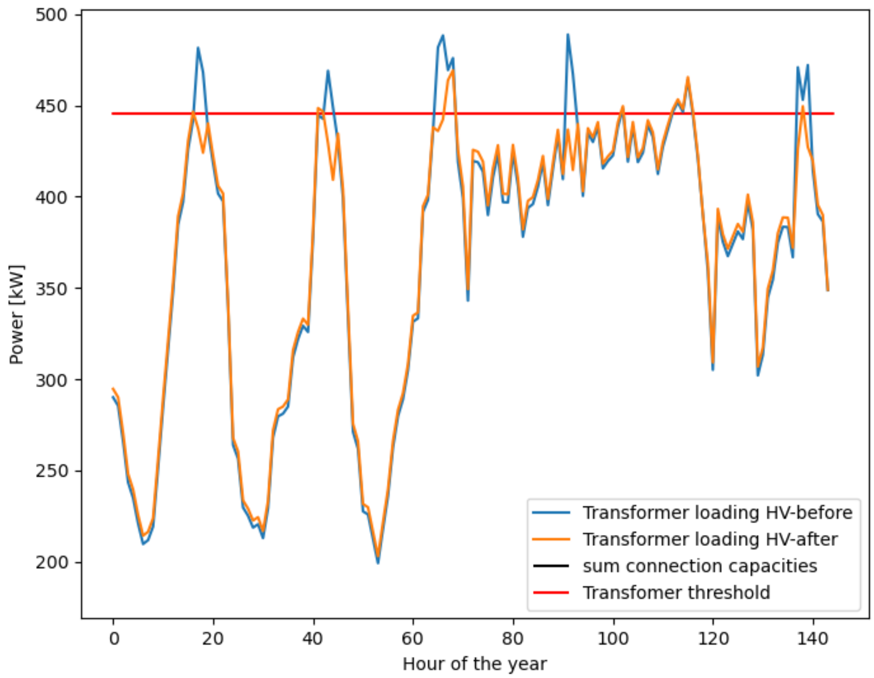

Figure 3-16 Transformer loading at R0 before and after market activation- "probability-based" demand curve market clearing

The VCG and Shapley payments for the 1st and 5th of January are presented in Table 3-9.

Table 3-9 Shapley and VCG payments for the "probability-based" demand curve clearing

	Shapley value	Shapley Cost/utility	Shapley payment	VCG payment
Date: 2012-01-01				
DSO	170.0	-834.9	-664.8	-215.4
FSP 1 (R16)	29.6	0.0	29.6	165.1
FSP 2 (R17)	42.9	0.0	42.9	237.0
FSP 3 (R18)	77.1	32.6	109.8	434.2
FSP 4 (R1)	130.6	0.0	130.6	540.6
FSP 5 (R11)	89.3	182.8	272.1	635.3
FSP 6 (R15)	79.9	0.0	79.9	412.7
Sum (budget balance)			**0.0**	**2209.5**
Date: 2012-01-05				
DSO	338.0	-916.3	-578.3	0.0
FSP 1 (R16)	22.0	0.0	22.0	77.6
FSP 2 (R17)	33.1	0.0	33.1	117.5
FSP 3 (R18)	86.7	0.0	86.7	330.3
FSP 4 (R1)	243.4	0.0	243.4	727.1
FSP 5 (R11)	92.6	0.0	92.6	352.5
FSP 6 (R15)	100.5	0.0	100.5	383.6

Sum (budget balance)	**0.0**	**1988.7**

The excess parameter of the Shapley payments has been less or equal to zero for all the days and thus the game has been stable with Shapley values in this case.

3.4.6 Discussion

In this section, the results and our observations are discussed, including analysis on the common design challenges and desirable market properties, the advantages and disadvantages of the capacity-limit products, the possible abnormal shape of the demand for such products, and the advantages and disadvantages related to the payment allocation mechanisms.

The results after the market clearing show that congestion events can be reduced through procuring capacity-limit cap products. However, the number of occasions and the level of reduction depends on the available flexibility in the area, the cost of providing flexibility, and the value of the flexibility for the DSO. Therefore, the bidding strategies, the cost of providing flexibility, and the value it can provide to the system operators need to be further investigated to better evaluate the effectiveness of such market-based solutions.

Moreover, it has been observed that procuring capacity-limit products can lead to rebound effects and cause congestions in other hours. This highlights the importance of the DSOs bidding strategy, by for example procuring flexibility for a broader time period including the hours that rebound effects can be expected before and after the congestion event, or exploring possible solutions to avoiding rebound effects within the market design.

Common design challenges, desirable market properties, and our proposed market design

In the proposed LFM, the mechanism is a monopsony i.e., there is only one buyer which can cause market power practices by this participant. However, as the DSOs are already highly regulated actors, there might be a possibility to prevent them from practicing market power by keeping their profit regulated or introducing further regulations.

To increase the transparency of the market and due to security concerns, grid-constraints are excluded from the clearing algorithm. This is because the grid topology and the related data is often considered as confidential information. In case of sharing such information there are security risks for resiliency of the grid, and in case of not sharing such information with the end-users, the market clearing algorithm would not be transparent to the FSPs. At the moment, the grid-constraints are to be managed internally in the bidding strategy of the DSO by selecting the appropriate location and quantity for the request.

As mentioned before, one of the potential challenges in local markets is the low level of market liquidity. A low liquid market is prone to untruthful bidding, market power practices, and low efficiency due to lack of competition. By utilising game theory payment allocation methods, we have tried to address this challenge through guaranteeing incentive compatibility in the market.

The long-term reservation market is introduced to address different concerns such as reliability and decision making, incentivising investments in smartness of the end-users, and facilitating market access criterion for the end-users/aggregators. Long-term reservation markets can benefit both buyers and the sellers of the service in their decision making long-ahead of the delivery time. Moreover, these reservation payments can compensate, at least partially, the investment costs of the end-users and aggregators on smart DERs.

The short-term activation market and the continuous adjustment market are introduced with different purposes. The short-term activation market is open for entry of the new FSPs to increase the competitiveness in the market, reducing the probability of the DSO being restrained to the reserved capacities. Furthermore, due to low aggregation levels at the local levels, forecasts' accuracy is lower. Therefore, a continuous adjustment market is introduced to provide the opportunity of adjustments and reduce the risk for participation.

Another desirable property is the cost recovery of the agents. In the introduced payment allocation mechanisms, the cost of an FSP is part of the payment calculation and therefore the cost of these agents are compensated to incentivise their participation.

The introduced capacity-limit based product is addressing the common challenge with defining the baseline. Moreover, it does not require extra measurements to be in place and thus reduce the implementation cost of this solution. However, such products have their own downsides which are discussed further in the next section.

Advantages and disadvantages of the capacity-limit product, and the abnormal shape of the "probability-based" demand curve

The proposed capacity-limit products can contribute to solving the common challenges related to defining the baseline and extra measurements. This is because these products are defined according to static and transparent parameters, such as the connection capacity or the fuse levels. Moreover, the only measurement required for validating the delivery of the service is the value from the smart meters at the point of common coupling. As a result, challenges regarding the accuracy of forecasting the baselines, the consensus between different market actors on the baseline, and extra requirements for measurements at each flexible asset can be avoided.

On the other hand, there are a few downsides with capacity-limit products. For example, the shape presented for the "probability-based" demand curve is not similar to the conventional demand curves in economic theory, although, such unusual shapes are mentioned as abnormal demand curves across economic literature (e.g., Giffen goods). The capacity-limit products can lead to a more sophisticated market clearing as presented in the "probability-based" demand curve clearing which can lead to challenges in recruiting market participants.

Such an abnormal demand curve can lead to multiple cross points of the supply and demand curve. Therefore, the interpretation of the crossing point of the demand and supply curves as the uniform clearing price would not be applicable anymore. Moreover, due to having integer variables in the optimization problem, obtaining the dual variable from the balance equation would be challenging. However, as the VCG and Shapley payments are calculated according to the contributions to the social welfare, multiple cross point would not impact calculating the payments by these methods. For example, it can be seen in Figure 3-15 that in subfigure (a), the algorithm clears a quantity larger than the first cross point since it sees a total higher social welfare. This is not the case, on the other hand, for the subfigure (b) in which the algorithm do not see a potential higher social welfare and clears the quantity corresponding to the first crossing point.

When procuring capacity-limit products, the cleared quantity can be less than the quantity that would actually impact the behaviour of the end-users, such as Figure 3-15(b). A question that can be asked here is that why the DSO should pay anything for purchasing low quantities of a capacity-limit product. It can be argued that such a payment can be seen as buying back the sold connection-capacity especially with "probability-based" demand curve market clearing, where the DSOs can bid low valuations for the first part of the demand curve and thus it would not impose high costs to the DSOs. Moreover, the congestion forecasts are not accurate in real cases and purchasing such levels of capacity-limit would still ensure the DSOs that the loading would not go over the purchased limitation.

Advantages and disadvantages of payment allocation mechanism

The VCG and Shapley payments guarantee incentive compatibility property of a market, which is one of the common challenges in low liquid markets such as local markets. However, these two more advanced payment mechanisms have some drawbacks as well.

For example, VCG payment, although incentive compatible and simple, is not budget balanced for the market operator. This issue has been mentioned in "The Lovely but Lonely Vickrey Auction" [54] and other sources. A way to address this issue is proposed in [43]. To achieve the budget balance, they propose to have a "uni-sided VCG" which means the DSO's payment is not calculated by VCG and instead the DSO shall pay the sum of VCG-calculated payments for the FSPs. This can lead to losing the incentive compatibility on the DSOs side. However, they argue that the DSOs are strictly regulated monopolies and therefore they can be forced to bid truthfully by regulations.

One of the drawbacks with the Shapley value is its computational burden. For Shapley payments, the value of the game needs to be calculated for all the subsets of the grand coalition. The number of subsets is $2^{|\mathcal{N}|}$ which can become computationally interactable as the number of market participants ($|\mathcal{N}|$) increases. However, this might not be a challenge due to several reasons. One is the number of participants in a local market is likely to be limited due to geographical limitations. Two, the end-users are not likely willing or capable of participating directly in the market and thus their participation would probably be aggregated under the umbrella of an aggregator. Third, the payment calculations can be carried out after the delivery and thus not limited by very short time-constraints. Based on these reasons, we believe that Shapley payments can potentially be a suitable alternative for payment allocations in local markets.

3.5 Conclusion and suggestions for future work

In this chapter, different market designs were proposed for local energy and flexibility markets. The products, market horizons, clearing mechanisms, and payment allocation methods were presented and discussed. An illustrative case study was carried out for local flexibility markets to demonstrate the functionality of the market design.

The authors see the below topics as potential future work to explore alternatives for improving the proposed market designs:

- Inclusion of forecasts and forecast errors to test the adjustment market
- Exploring further the DSO's cost and revenues within the context of local markets to improve its bidding strategy

- Exploring further the advantages and disadvantages and necessity of including the grid-constraints in the market clearing algorithm
- Inclusion of other flexibility resources such as HPs, thermal energy storage, micro-CHPs, ventilation systems
- Exploring hybrid solutions: volt-var control in combination with LFM for active power to address potential voltage band violations issues
- Exploring simultaneous market clearing mechanisms for trading both active and reactive power flexibility to utilise all the available potentials in solving local grid challenges
- Demonstrating the proposed market solutions in the demonstration phase of the project. The peer-to-pool markets will be demonstrated in work package 6. The test-system will be adapted to the demo site's system and the test cases are according to Deliverable 6.1.
- Exploring the baseline-based product with a linkage between LEM and LFM to find out the effectiveness of using schedules from LEM as the baseline for LFM products

4 Peer to peer technologies

4.1 Introduction

Conventional energy markets or centralized energy supply involves electricity generation in large-scale at centralized facilities such as fossil fuel power plants and nuclear power plants. These generation facilities are located far away from the consumers and the energy is transmitted via high voltage transmission lines managed by complex systems and intermediaries. This type of generation results in air, water and land pollution. With these problems in mind and the falling cost of renewables and improved electricity storage systems people are opting for clean energy. Decentralized or local power supply involves electricity generation in house or near a place where it will be used, from solar, wind and geothermal. They are generally managed locally by prosumers who produce electricity for their own consumption, selling excess to the grid. The large-scale systems are very small in number so an authority can easily manage these systems without security risks. The prosumers are large in number, therefore a digital platform to facilitate secure buying, selling, billing and auditing is necessary. A peer-to-peer energy trading business model powered by blockchain helps in facilitating distributed energy systems.

Traditional markets, whether financial or electricity markets, are based on a trading pool mechanism, which means “A pool in which the stock is manipulated by purchases and sales in the open market. For example, pool operators affect a stock's price and volume by making purchases in the open market, thereby attracting the interest of other investors “ [60].The energy market differs from other markets in that each of the participants has a direct impact on the flexibility and management capabilities of the energy system. This should be a major incentive for each participant to reduce the negative impact of the sudden exit of a large number of consumers from the electricity grid. There are various opportunities for participation in the energy market direct method, indirect method and feed-in-tariff, which have their advantages, but also their limitations, which can cause prosumer to leave the market [61]. At the same time Peer-to-peer uses transparent clearing mechanisms that give equal rights to all users, the ability to negotiate between each user and ensure the security of personal data, while also affecting the complexity and efficiency of the market [62].

4.1.1 Definition for peer to peer

In Collins English Dictionary[5] the definition for peer to peer is explained as "A relationship between two computers on the same network such that they are able to share information without a third computer having to act as a server." A peer to peer in fact is a network that allows participants to share the resources they have. In this way, participants reduce their investment costs while increasing the energy transferred, reducing peak loads and contributing to an increase in the share of decentralized energy sources and energy storage systems.

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[5] *Collins English Dictionary – Complete and Unabridged, 12th Edition 2014*. S.v. "peer-to-peer." Retrieved July 28 2021 from https://www.thefreedictionary.com/peer-to-peer

In the context adopted by us, the peer-to-peer flexibility trading platform will allow energy market participants to take an active position by participating in local energy and service markets. The active participation of the participants connected in the energy system will allow to optimize the costs, to provide flexibility of the electricity transmission network and to provide financial income for both the consumers and the electricity distribution network operator.

The blockchain generates decentralized storage of encrypted data and allows transactions between two parties (peer to peer), without using a central structure for information processing. The process allows high results at lower costs, increased security, speed, authenticity and flexibility. Blockchain is characterized by improved interaction between the individual participants related to the traceability and irreversibility of the agreed terms. The five-step process of blockchain is given in Figure 4-1. This provision is the perfect and proactive basis for the expansion of the smart grid and thus for the interaction of the various players in the organisationally and spatially decentralised electricity market.

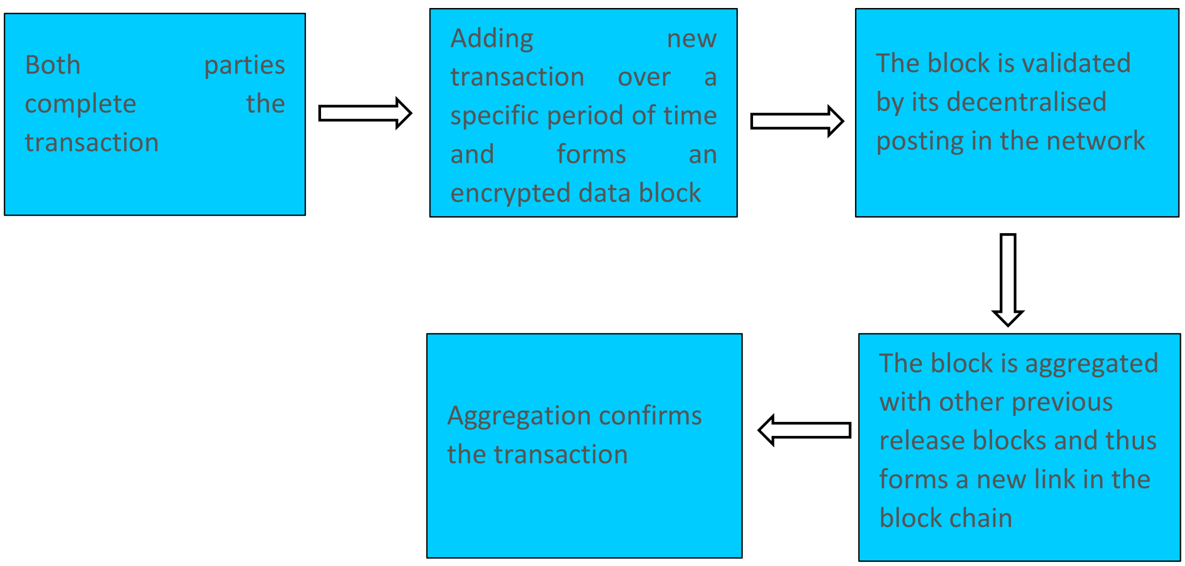


Figure 4-1: The process of blockchain between two parties

4.1.2 Peer to peer technology and blockchain benefit and challenges

The increase of the added value for the electricity distribution network can be realized through new business models, which will ensure the entry of new technologies for production and transmission and storage of electricity with transparent and competitive offers on the market, through financial incentives for all market participants, which contribute to increasing the flexibility of the energy system.

In order to easily make this transition to improving the flexibility of the electricity system and under fully transparent conditions, it is necessary for all participants to have real-time information on both consumption and production, as well as on the available storage options for electricity.

Despite the many advantages of peer to peer and blockchain, such as transparency and security, there are a number of challenges Table 4-1. With the widespread penetration of peer to peer networks, both technically related to the upgrade of the electricity distribution network and legal related to the circulation of personal data, at the same time a number of economic difficulties exists, such as different geographical features in the distribution of consumers and producers of electrical energy. Not insignificant is the energy used to encrypt and transfer data between individual participants in the peer to peer network coupled with blockchain technology. According to Digiconomist's Bitcoin Energy Consumption Index (BECI), each individual bitcoin transaction consumes up to 275 kWh of electricity [63]. The same amount of energy should be expected when using this type of technology in decentralized electrical networks.

4-1: Use cases of blockchain in the energy sector

Consumer Expectations and Uses	Issues to be addressed
• Consuming green energy; • Understanding and paying the right price; • Consuming and selling self-generated energy; • Buying electricity on the move.	• Traceability and Transparency; • Smart contract.
Usefulness of Blockchain technology	**Usefulness of Blockchain technology**
• Traces the complete history of all transactions in chronological order; • Each user can become a node of the blockchain network; • Offer the consumer the certainty of consuming energy produced by renewable energies.	• Automatically executing conditions of sale, transfer or purchase of electricity; • Conditions defined in advance and recorded in the blockchain; • The smart contract ensuring the transfer of an asset when the contractual conditions are met.

4.1.3 Digitalized network operation

European Union defines digitalization as “The process of implementing and operating a set of assets through the monitoring, transfer and analysis of data generated by one of the actors in the energy system” The digitalisation of the energy sector makes it possible to make the connection between the individual actors in the energy system, such as markets and services that would not otherwise be possible [64]. Digitization on electrical distribution will improve operations and increase flexibility throughout the energy value chain, from generation to customer relationship management [65]. The International Energy Agency's analysis shows that in the 1970s, electricity distribution companies were the first to use digital technologies to optimize the operation of electrical networks, and that today almost all electronic devices are connected to communication networks to provide many additional ancillary services through various applications. These include personal healthcare, smart grids, surveillance, home automation and smart transport [66].

The operation of the distribution network is related to the management of many and complex processes (Figure 4-2). It is necessary to upgrade the existing infrastructure and all participants connected to the energy system to become part of the new digitalization to ensure a reliable transition to digital management of electricity distribution networks. There is already experience in the management of digital distribution network management systems, both in a number of demonstration projects and in a number of electricity transmission networks around the world. Of course, this digitalization and the new business models must also be seen as a new consumer of electricity, which is comparable to the electricity consumption of a Western European country.

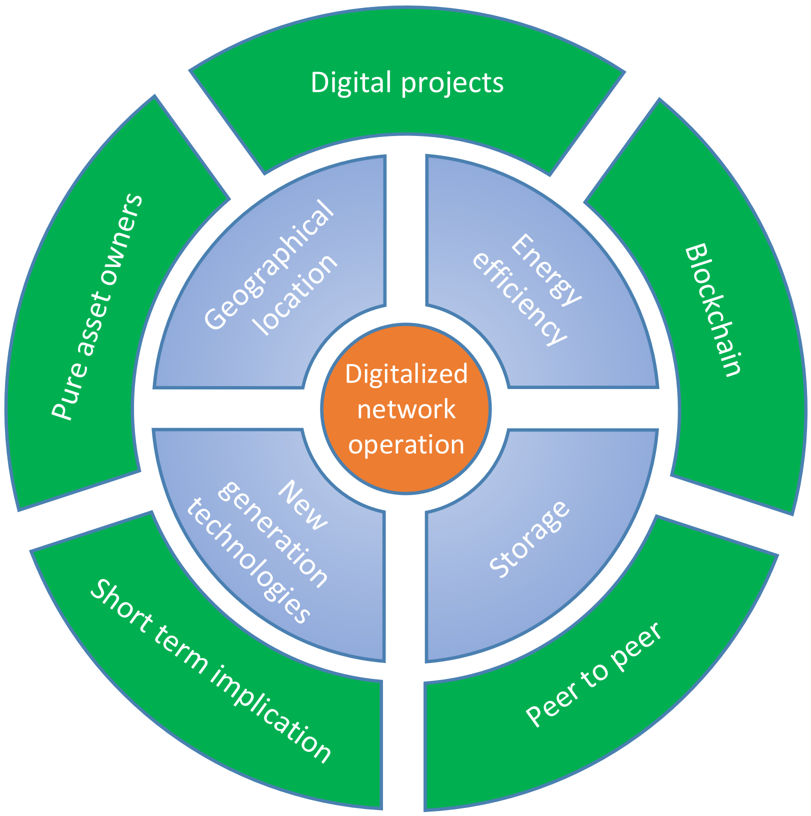


Figure 4-2: Structure of Digital network operation

4.1.4 Studies of similar blockchain initiatives

There are different examples of project related to the possibilities that blockchain can provide in energy sector. Some of more contributing ones are summarized in Table 4-2 according to The European association of cities in energy transition [67].

Although there are various studies, there is still a lack of a comprehensive overview of blockchain-based energy trading schemes, as well as a clear classification according to the challenges facing the electricity system. The presented blockchain-based energy scheme and applications have their advantages, but still do not ensure full equality of the various actors and do not take into account many important factors important for balancing the electricity system, such as the geographical location of both consumers and electricity producers.

Table 4-2: Examples of blockchain in the energy sector

Blockchain projects	Based on and aim	Induced innovation
Solution Sunchain *"closed" blockchain with a limited number of actors*	Solar electricity in social housing and housing estates; Solar electricity on nearby separate buildings; Solar electricity for recharging electric vehicles (roaming). The production of the solar installations and the electricity consumptions of the participants to be encrypted, signed, and recorded in a blockchain.	Certified transactions; Traceability of the solar kWh and the possibility to invoice the housing for its real share; Automatic transfer to network manager software; Cost accounting – dashboard; Facilitate the integration of solar energy in the municipal heritage with various uses
DAISEE *semi-public company the municipality (60%); the municipal electricity board (20%) and a collective of citizens (20%).*	Connection and facilitate the crossroads between actors of the territory; to be a producer of knowledge and know-how to snowball elsewhere, in other territories; first and foremost to empower people to make. The aim is to accompany a territory in its quest for energy autonomy by using blockchain technology	Hardware; Software (Ethereum and other technologies allowing a distributed, secure, transparent system); Network infrastructure and governance
I-NUK *Start up*	The emissions of its users; works with small solar energy producers (including local authorities) in France and internationally (installations between 200-300 KWh) to help them better monetize their produced energy. The aim is to reform the carbon credit system, by creating a blockchain application to allow each individual to easily offset their daily carbon emissions, and to reinvest these offsets in the construction of new solar power plants.	By relying on the Ethereum blockchain and its smart contracts, make the certification process transparent, efficient, secure and automated. A permanent audit and publicly verifies that the certification process applied is correct. Includes the energy consumption induced by the use of Ethereum in the carbon offset, thus ensuring the carbon neutrality of its approach. The model allows small solar energy producers to make better use of the energy they produce and thus promote the development of clean and local energy.
KLENERGY TECH *Start up*	Pylon Network proposes to use Blockchain technology to facilitate the knowledge of flows for energy vendors. The product is aimed at renewable energy cooperatives. The renewable energy community can play on demand and optimize flows in real time	Transparency of flows; Reliability and security; Accessible to all; Low-energy server running on surplus renewable energy.

Tal.Markt *municipal energy supplier for the city of Wuppertal*	Creates a local and regional market for renewable energy produced in Wuppertal. The aim is to connect local renewable energy producers with citizens, especially the 5000 wind turbines that will no longer be supported by subsidies after 2020	Flexible and transparent, and allows citizens to follow in real time the volume of renewable energy produced and to know which local supplier it comes from. The guarantee of origin of the renewable energy is ensured by the infallibility of the blockchain; Obtain a new form of income, but also to support local producers who will no longer be able to count on the support of the German Renewable Energy Act (Erneuerbare Energien Gesetz) after 2020; If there is a lack of renewable energy (e.g. because there is little wind or no sun), the WSW ensures security of supply; Allows investors to form a large enough group of citizens to encourage the construction of new wind turbines or solar plants, outside of the support of the Erneuerbare Energien Gesetz.
Gruenstromjeton *Public company*	Regionally produced renewable electricity and wants to target families in particular; The aim is to offer its clients a new service to encourage them to use more renewable energy.	Citizens are encouraged to consume more renewable energy in their energy mix and thus not only promote the development of renewables in the territory, but also benefit from it themselves; The SEV takes advantage of the block chain to reduce transaction costs (smart contracts) and the costs of billing processes, among other things; Since the architecture of the blockchain is Open Source, the SEV does not have to pay any license fees.
Power-ID *University project*	The aim of the project is to create a small local energy market between 20 producers/consumers and 20 consumers using the block chain. This decentralised network relies on solar energy and storage (batteries) and aims to cover at least half of Walenstadt's energy needs. The aim of linking local players is to reduce the costs of the system for everyone and	Peer-to-peer exchange in a small decentralized network, which keeps the creation of value (energy produced and consumed) on the territory; The development of network costs is transparent thanks to the blockchain; The ESCO is involved in the project, but does not assume its traditional role as an intermediary, thus leaving room for

	to encourage the production and consumption of local renewable energy.	the emancipation of producers/consumers and consumers participating in the network; Instead of paying a premium on locally produced energy, this pilot project aims to reduce the cost of local energy to enhance its value and increase its attractiveness to citizens; Finally, in this pilot project the cost of the network is determined bottom-up, instead of being imposed top-down by the large network operators.
NRGoin *University project*	The idea behind NRGCoin is to respond to the inadequate (not flexible enough) subsidy of renewable energy and to encourage citizens to consume local renewable energy by paying them with the NRGcoin cryptomoney	By using the Ethereum blockchain, NRGcoin benefits from the advantages of this blockchain (disintermediation, transparency, decentralisation, reliability and indelibility). In addition, NRGcoin wants to add value to the renewable energy installations of these producers/consumers, ensure a local market management that does not impact the capacity of the network and make the consumption of locally produced renewable energy cheaper.
Brooklyn microgrid *Private company*	Solar panels installed on the roofs of five residential buildings produce electricity, the surplus of which is sold to neighbours. These buildings are connected to a conventional grid whose transactions are managed and stored via a block chain. One of the objectives of the project is to create a local renewable energy community. 130 new households have expressed an interest in joining such a network.	Peer to peer; Smart contracts and payments technology through a virtual currency (Ether); A "community and shared energy market", with surplus electricity being exchanged between neighbours through secure transactions.
SolarCoin *International company*	Any owner of a photovoltaic installation can participate in the grid. promote renewable energy by allowing all solar energy producers to obtain a remuneration depending on the amount of energy produced. Solar energy producers can claim 1 SolarCoin for every 1 MWh produced and fed into the grid.	Low energy consumption; Reduces the amortisation period of the solar system; An evolution desired by the initiators: The recognition of this currency by the local authorities

4.2 Market Design for peer-to-peer Trading

4.2.1 Business use cases for the market design

One of main outcomes of this chapter is to prepare necessary market design elements to be implemented in the demonstration of WP7, which we will demonstrate DSO-consumer flexibility market platform for local grid imbalance, congestion and voltage management.

In general, the peer-to-peer flexibility trading platform enables end users/grid users to become active and participate in local energy and service markets, and creates a revenue stream by offering local flexibility to the DSO and optimizes costs for DSOs and Prosumers.

One of business use cases, which will be considered in WP7 for the peer-to-peer trading platform, is long-term congestion management and operational congestion management are. The table below summarises a short description of

Table 4-3 Summary of Business Use Cases

#	Service	Business Case of the Service
1	Flexibility services for long-term congestion management allowing more renewable connection without further DSO network investments	• The envisaged service may serve several purposes (a) network reinforcement deferrals, (b) congestion management in transmission and distribution network, (c) voltage control (d) network support during construction and planned maintenance (e) obtaining transparency in the activation of DERs. By temporarily relieving constraints on a piece of hardware, or even postponing or avoiding reinforcement there is strong value in long—term planning. • For example, load related reinforcement schemes could use flexibility to defer a planned network upgrade into the future. The benefit is the net present value of deferred capital expenditure. In parts of the network that are planned for reinforcement or maintenance, flexibility could be used to increase the security of the network before completion. The benefit is the reduced impact of a low probability outage event. By enabling customers to reconnect faster after an outage or reducing outages due to work on the grid or incidents there is strong value
2	Flexibility services for operational congestion management reducing the impact of outage events or forecast deviations	

		for operation management i.e. reduced cost of unserved energy.

The business use case for long-term congestion is then converted to a process of high-level necessary steps (Figure 4-3), which are crucial for designing of market setting and trading platform.

- Step 1: Product and grid prequalification. This is necessary to allow flexibility sources to be connected to the grid and guarantee certain level of system security.
- Step 2: DSO defines congestion areas and publishes auction phase on the trading platform. This is necessary to broadcast their needs to wide service providers. This will improve the transparency of information sharing, and allow service providers to have sufficient time to react to the DSO’s request. This will increase the market liquidity at the end.
- Step 3: Flexibility resource submits the offer
- Step 4: Matching offers with requests. This will be done manually or automatically with supported by a matching algorithm
- Step 5: Activation. The trading is happened long time in advance but the activation of flexibility is happened closed to real time. Depending on system condition of the network, DSO will activate needed assets
- Step 6: Flexibility delivery validation. This is necessary to double check if the committed assets deliver what were promised.
- Step 7: Settlement. Money transaction will occur as long as the validation is checked.

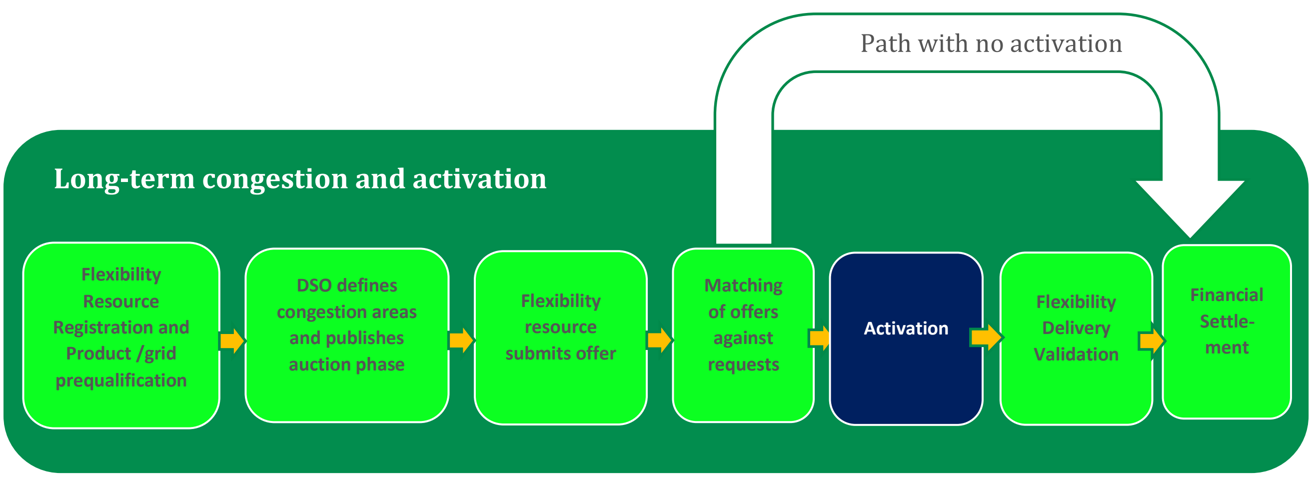


Figure 4-3 Process diagram summary for business use cases

The timeframe of a long-term congestion management is several months or years ahead before the planned delivery. We understand that reserving flexibility months or years ahead might hinder the FSP to participate in short-term markets. However, we overcome this drawback via activation process where FSP gets remunerated for responding to activation signal close to real-time. In addition, FSPs are motivated to participate continuously in the short-term markets by aggregating resources or when the volume is big enough to get better impact on price. Therefore, we select this option of long-term congestion management to allow many small FSPs to enter the market as they only need to participate several times in a year.

Here, the DSO reserves flexibility months ahead but does not necessarily activate it, since the requirement may vary with various circumstance of load, generation etc. over a period of time. DSO would only pay a reservation fee to flexibility assets. During the service period, after analysing the distribution grid, if the DSO perceives congestion in the coming days or during the day, the DSO may issue activation instruction specifying the reserved flexibility asset to dispatch flexibility. Here, the DSO will pay reservation as well as activation fees. We call this activation of flexibility asset from the reserved list of assets as operational congestion management. The DSO may also decide to procure flexibility from other markets e.g., through short-term buying, if the need remains unfulfilled.

4.2.2 Architectural System Requirements

In Figure 4-4, we depict the high-level system architecture for the proposed flexibility market platform. The architecture comprises the following essential modules: Flexibility offer field, which resides at the prosumer level and connected to the devices using the IoT platform. This module is responsible for collecting flexibility from various sources, including distributed energy resources (DER) and other tools such as EVs. This module is connected to the Flexibility aggregation or Broker module via consumer applications such as web API or mobile API. The Flexibility Broker module essentially aggregates the flexibilities generated at the Flexibility offer field and performs various optimisation operations. This module is also connected to the smart meters and the cloud gateways for transmitting information gathered from the third module to the prosumer level. Finally, we have a market module, which is at the DSO level. Here we have the Flexibility Market Platform that will receive aggregated flexibility from the Flexibility Broker and schedules the flexibility as per the pricing signals and overall renewable generations.

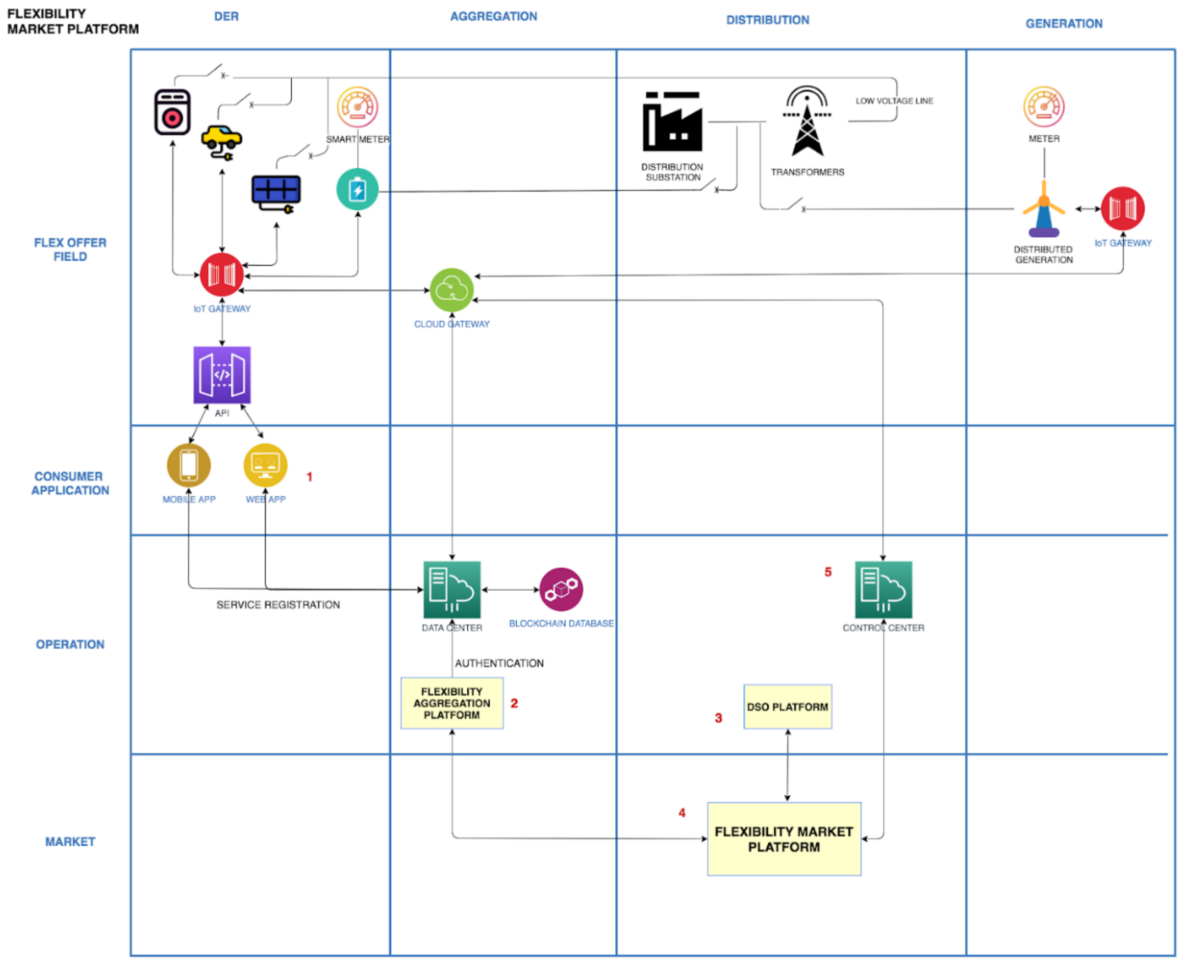


Figure 4-4 Flexibility Market Platform

The proposed system is designed to have a bottom-up three-layered architecture, as depicted in Figure 4-5. The bottom layer component, known as the 'Flexibility Collector,' resides at the whole system's consumption layer. This layer is responsible for connecting the household or commercial flexibilities to the IoT platform. The individual flexibility sources are then communicated to the middle layer, known as 'Flexibility Broker,' which is primarily responsible for three tasks: i) collect all the individual flexibility sources and aggregate them, ii) bid the aggregated flexibility in the flexibility market iii) obtain the bidding signals from the market and pass them on to the flexibility collector. Finally, the top layer, the 'Flexibility Market' layer, employs the energy trading platform to match the available flexibility with the flexibility demands. Here, we plan to create a blockchain-based flexibility platform where individual DSOs can offer or request flexibility. With blockchain, the whole process of flexibility trading, billing, and communicating it with the prosumers and the DSOs become seamless and transparent.

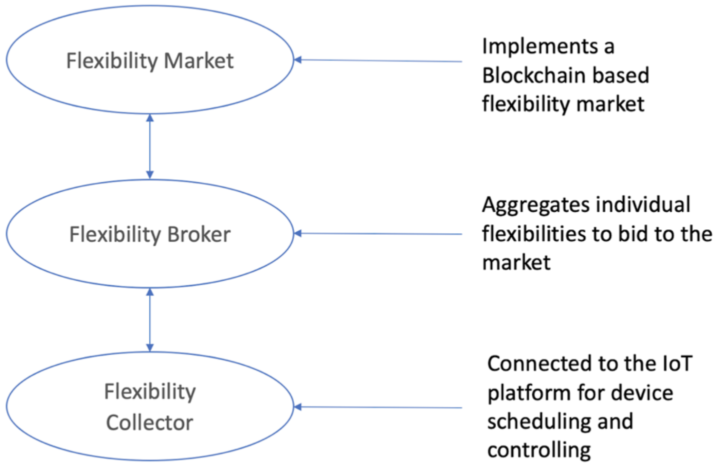


Figure 4-5 Architecture Diagram of Flexibility Layers

4.2.3 EFLEX Blockchain-based trading process flow

The scenario in Figure 4-6 explains the information flow, energy flow and token flow for Blockchain-based trading in greater detail:

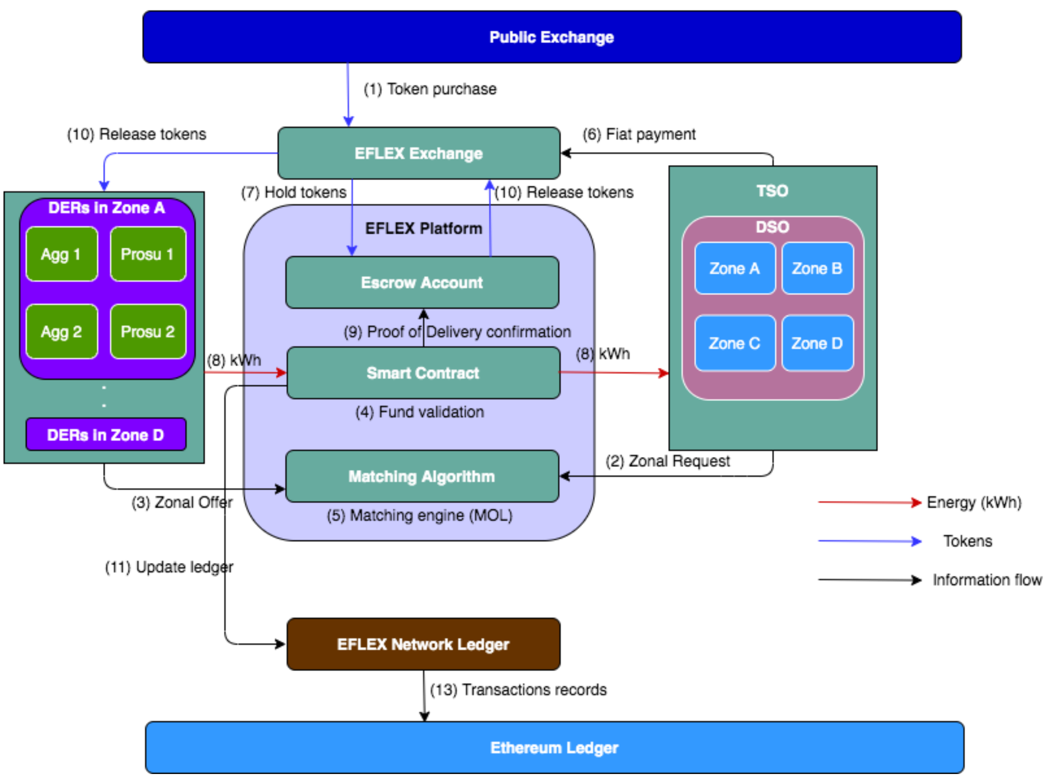


Figure 4-6 Blockchain-based trading process flow

1. EFLEX purchases tokens from a public token exchange
2. DSO has a kWh energy requirement (up-regulation) in zone A and places a “zonal request” to the EFLEX for a kWh at a price (request publication in zone/substation area)

3. Prosumers 1 and 2 have a kWh energy surplus (up-regulating offer) in zone A. Aggregators 1 and 2 in zone A can decrease consumption (also up-regulating offer). They all place "zonal offers" to the EFLEX to sell respective kWh at a price
4. On receiving a request, EFLEX validates that DSO has the funds, either via prepaid fiat in the DSO's wallet, or via a billing relationship, to pay for and fulfil the request for kWh.
5. On a successful match of requests against offers in zone A, the order is sent to the trading algorithm (matching engine)
6. DSO sends the agreed amount in fiat (EUR) to EFLEX, and EFLEX provides tokens to enable the transaction.
7. DSO's tokens are held in escrow until exchange of energy has been verified (verification of smart meter readings and trading related data)
8. Corresponding up-regulation kWh is provided by matched aggregators and prosumers to the DSO.
9. When this exchange is confirmed by EFLEX (through "Proof of Delivery"), the smart contract executes the transaction.
10. Tokens are released from the escrow and the ledger is updated.
11. The corresponding amounts of fiat (EUR) are sent to EFLEX to cover operating costs. Operating fees cover any server, processing, and Ethereum blockchain costs associated with the transaction.
12. On a daily basis, the ledger publishes a digest of all transactions to the private Ethereum ledger (enabling sound coordination and effective signalling with TSO and other stakeholders)

4.2.4 The Data input template

To support trading process, we will need data layers for DER assets (generation, electrical load, storage and EV charging stations) as well as distribution network maps from DSO partners. Table 4-4 is the sample data layer template to capture information about electrical loads. Detailed requirements will be defined in WP7.

Table 4-4 General information of electrical load

<table>
<tr><th colspan="2">General information about Electrical Load</th><th>Input value</th></tr>
<tr><td colspan="2">Name of the Property</td><td></td></tr>
<tr><td colspan="2">Type of Property
(Office, Industrial, Commercial Warehouse Unit, Domestic Dwellings, Others)</td><td></td></tr>
<tr><td rowspan="4">Location of the Property (geographical connection to electricity network)</td><td>Address (Street Name, Building Number)</td><td></td></tr>
<tr><td>Postal Code</td><td></td></tr>
<tr><td>City</td><td></td></tr>
<tr><td>State</td><td></td></tr>
<tr><td colspan="2">Coordinates (Latitude, Longitude)</td><td></td></tr>
<tr><td colspan="2">Public Information (background about property)</td><td></td></tr>
<tr><td colspan="2">Status (connected, under construction, removed from use, disconnected)</td><td></td></tr>
<tr><td colspan="2">Target date for provision of connection</td><td></td></tr>
<tr><td colspan="2">Service Operator</td><td></td></tr>
<tr><td colspan="2">Further Information about the Property (link or attachment)</td><td></td></tr>
</table>

4.2.5 Access right

Each business entity within the private/consortium blockchain network will have membership services and credentials that define what transactional data within the distributed ledger that they can view/edit, and which distributed ledger technology processes they are able to execute. For example:

- The Regulator may require full access to view all transaction records in the distributed ledger to ensure regulatory compliance.
- Administrators have full access to view all peer-to-peer energy trade transaction records in the distributed ledger to ensure effective operation of the peer-to-peer market.
- DSO entities may only require access to transactional records associated with aggregate energy supply and demand in the pool. These transaction records could be held in the distributed ledger, or in a separate distributed ledger that would store the transaction records associated with peer-to-peer energy trades.
- Retailers may only require access to transaction records in the distributed ledger associated with their customers.
  Prosumers and Consumers will not require direct participation in the blockchain business network but should gain access to the peer-to-peer Energy Trading Platform via their Retailer's on-line channel(s) or website.

4.2.6 Settlement processes

Propose settlement processes between actors and between actors and DSOs.

- Receive granular meter data from DSO for specific metering points
- Request meter data from a datahub
- Request financial settlement for a given market trading session
- Calculate energy settlement
- Provide trade reimbursement value

Settlement:

Since blockchain systems ensures pre-trade transparency between the involving parties' transaction and settlement happens instantly eliminating the need for centralized clearance. Business processes no longer need to synchronize directly with each other, but rather via an adapter that maps process states and data onto the Blockchain as a transport container. Here, the objective is to test state-of-the-art digital technologies, such as Blockchain based smart contracts for peer-to-peer energy transactions that promote local markets and smart asset management. Smart contracts' automated execution aims to reduce transaction costs and ensure higher contractual security, as subsequent actions that deviate from what was agreed upon are rendered impossible or highly complicated. The financial settlement of flexibility reservation and activation will be carried out through the market platform based on predefined contract and agreed to prices.

When the DSO initially procures a flexibility offer the amount (tokens) will not be sent directly to the asset owner. Instead, we implemented a mechanism where the tokens will be stored in the smart contract mapped to the address of the corresponding prosumer, following the concept of escrow. The delivery data/consumption data is fetched from IoT enabled smart meter, verified using a baseline methodology (we are working on the baseline methodology). Currently, the entire token amount is transferred after verification to the prosumer.

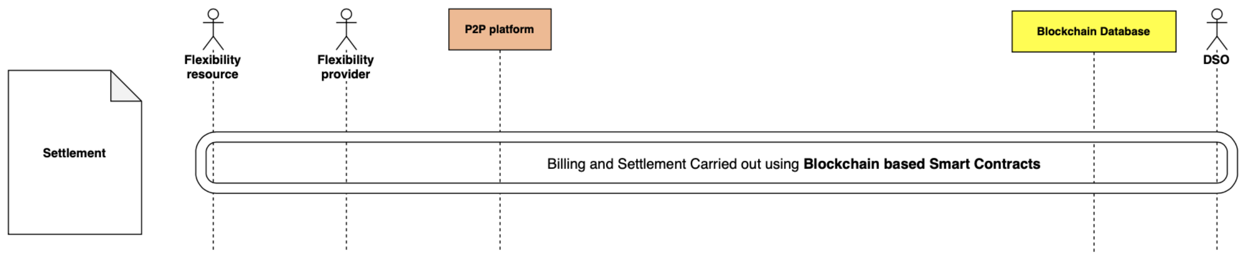


Figure 4-7 Data exchanging among parties during the settlement process

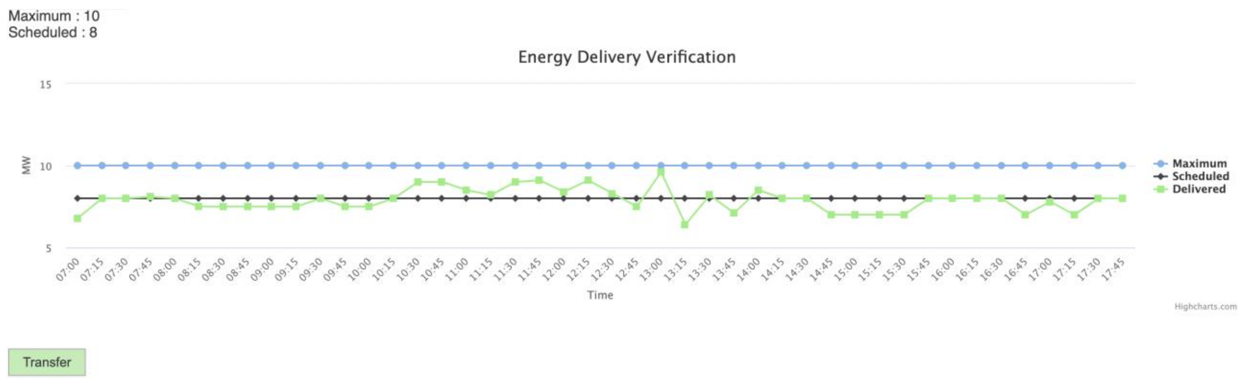


Figure 4-8 Visualising data of flexibility delivery of asset, supporting settlement process

4.2.7 Main functions of peer-to-peer Blockchain Platform

The trading platform will not only support the trading activities to happen smoothly, but also provides great trading experiences for users.

The key functionalities performed in the peer-to-peer Blockchain platform are the following:

- Flexibility asset onboarding on Blockchain
- Visibility of flexibility assets and needs
- Listing assets, requests and offers
- Validation of delivery using smart contracts
- Settlement using Blockchain-based smart contracts

Onboarding

The users of the platform install Metamask wallet extension to their browser (Chrome or Firefox) This step enables simple and smart token-based micropayments thereby reducing the intrinsic market entry barriers for distributed generators and other flexibility assets (electrical loads, storage, EVs) and increasing overall market efficiency.

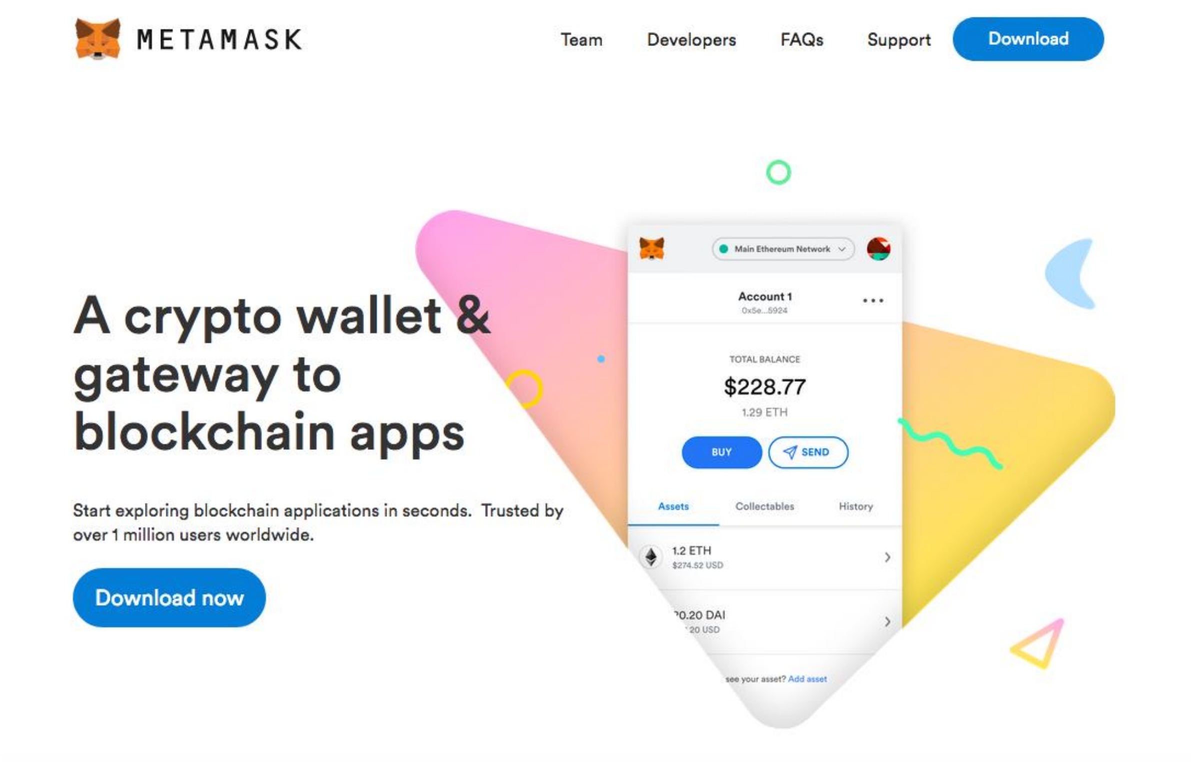


Figure 4-9 Metamask configuration to start using blockchain

Once wallet extension is added users can register themselves on EFLEX marketplace and configure their needs and submit request / offers. The platform will open the dashboard based on the user's role. The prosumers will be allowed to add, view and edit assets and offers whereas the DSO is restricted to only add, view and edit requests.

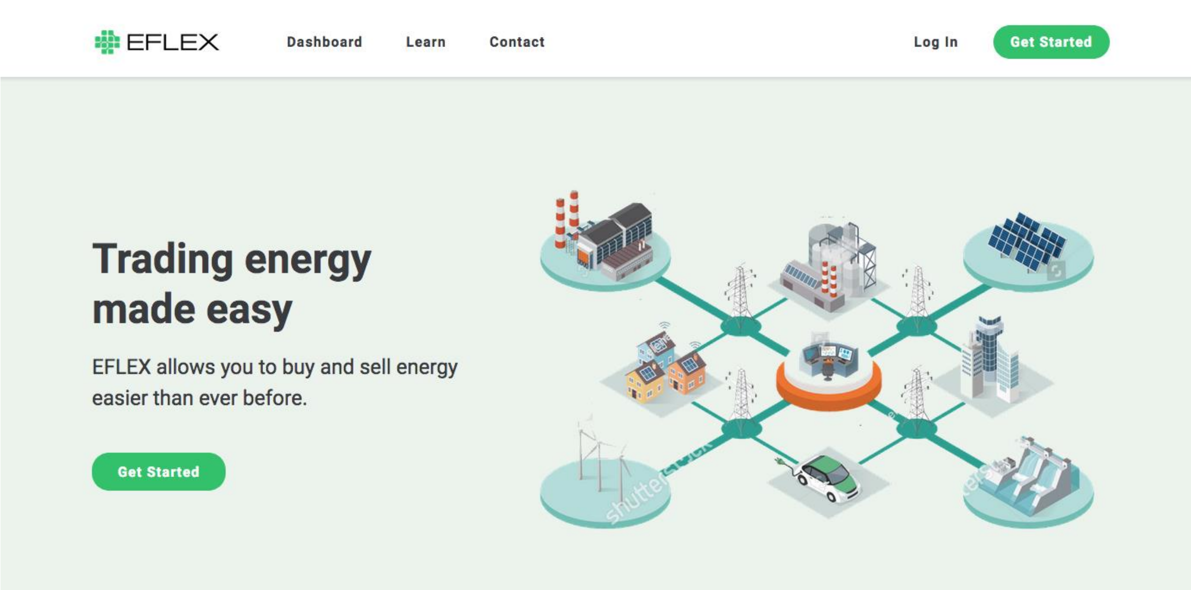


Figure 4-10 Dashboard

Visibility

Once registration is complete, we make it possible for asset owners and DSOs to visualize the evolution of congestion five years ahead.

Below is an example of opening of “on-demand” locational order books on the market using flexibility. Here DSO or any buyer can filter flexibility assets based on search criteria and preferred options. Followed by this, DSO or buyer can place a request on the marketplace. At the same time, flexibility asset owner can visualize on marketplace whether a DSO or a buyer has placed an offer requesting flexibility for current or future period.

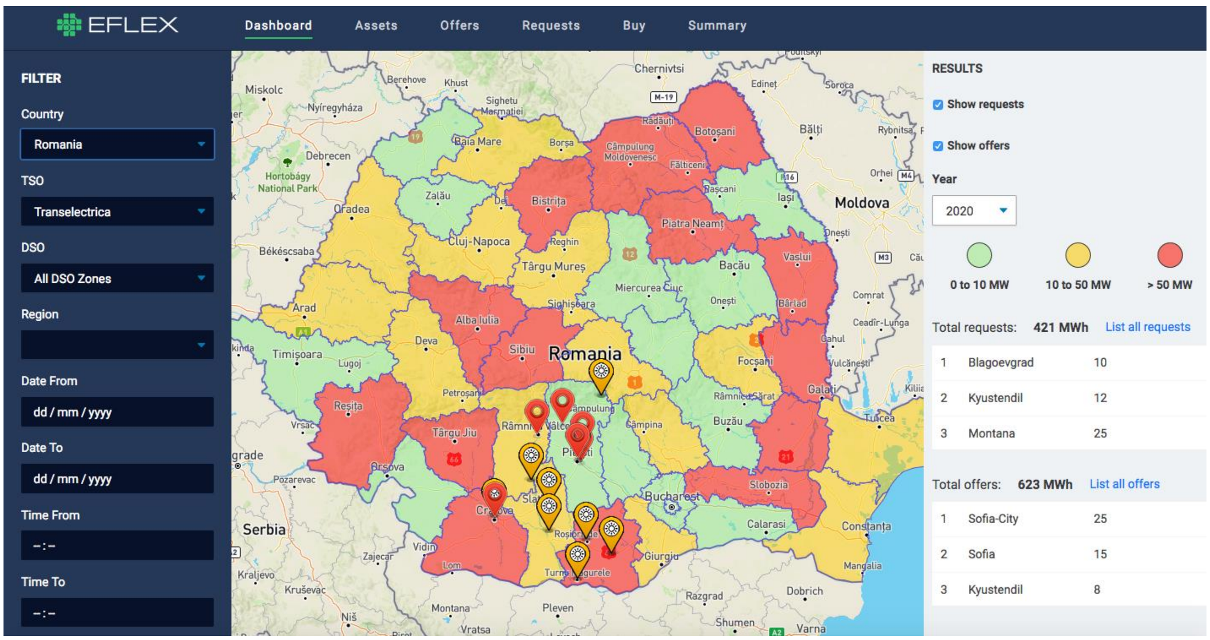
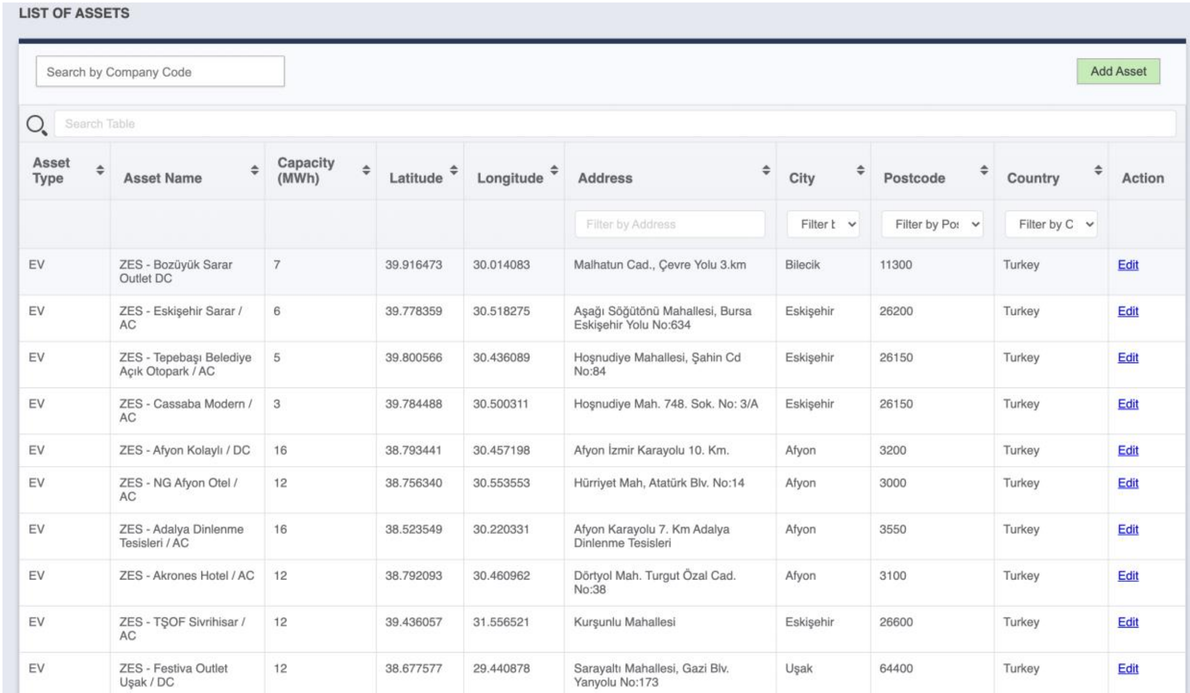


Figure 4-11 Visibility on congestion, offers, requests

Listing Assets, Offers and Requests

The users can fill in the form and add assets to the platform. Currently, all the assets are considered qualified. We are working on a mechanism to qualify assets. The figure below shows a list of assets in the platform. Likewise, the offers and requests can be submitted.



LIST OF ASSETS

Search by Company Code | Add Asset

Search Table

Asset Type	Asset Name	Capacity (MWh)	Latitude	Longitude	Address	City	Postcode	Country	Action
					Filter by Address	Filter b	Filter by Pos	Filter by C	
EV	ZES - Bozüyük Sarar Outlet DC	7	39.916473	30.014083	Malhatun Cad., Çevre Yolu 3.km	Bilecik	11300	Turkey	Edit
EV	ZES - Eskişehir Sarar / AC	6	39.778359	30.518275	Aşağı Söğütönü Mahallesi, Bursa Eskişehir Yolu No:634	Eskişehir	26200	Turkey	Edit
EV	ZES - Tepebaşı Belediye Açık Otopark / AC	5	39.800566	30.436089	Hoşnudiye Mahallesi, Şahin Cd No:84	Eskişehir	26150	Turkey	Edit
EV	ZES - Cassaba Modern / AC	3	39.784488	30.500311	Hoşnudiye Mah. 748. Sok. No: 3/A	Eskişehir	26150	Turkey	Edit
EV	ZES - Afyon Kolaylı / DC	16	38.793441	30.457198	Afyon İzmir Karayolu 10. Km.	Afyon	3200	Turkey	Edit
EV	ZES - NG Afyon Otel / AC	12	38.756340	30.553553	Hürriyet Mah, Atatürk Blv. No:14	Afyon	3000	Turkey	Edit
EV	ZES - Adalya Dinlenme Tesisleri / AC	16	38.523549	30.220331	Afyon Karayolu 7. Km Adalya Dinlenme Tesisleri	Afyon	3550	Turkey	Edit
EV	ZES - Akrones Hotel / AC	12	38.792093	30.460962	Dörtyol Mah. Turgut Özal Cad. No:38	Afyon	3100	Turkey	Edit
EV	ZES - TŞOF Sivrihisar / AC	12	39.436057	31.556521	Kurşunlu Mahallesi	Eskişehir	26600	Turkey	Edit
EV	ZES - Festiva Outlet Uşak / DC	12	38.677577	29.440878	Sarayaltı Mahallesi, Gazi Blv. Yanyolu No:173	Uşak	64400	Turkey	Edit

Figure 4-12 List of all assets

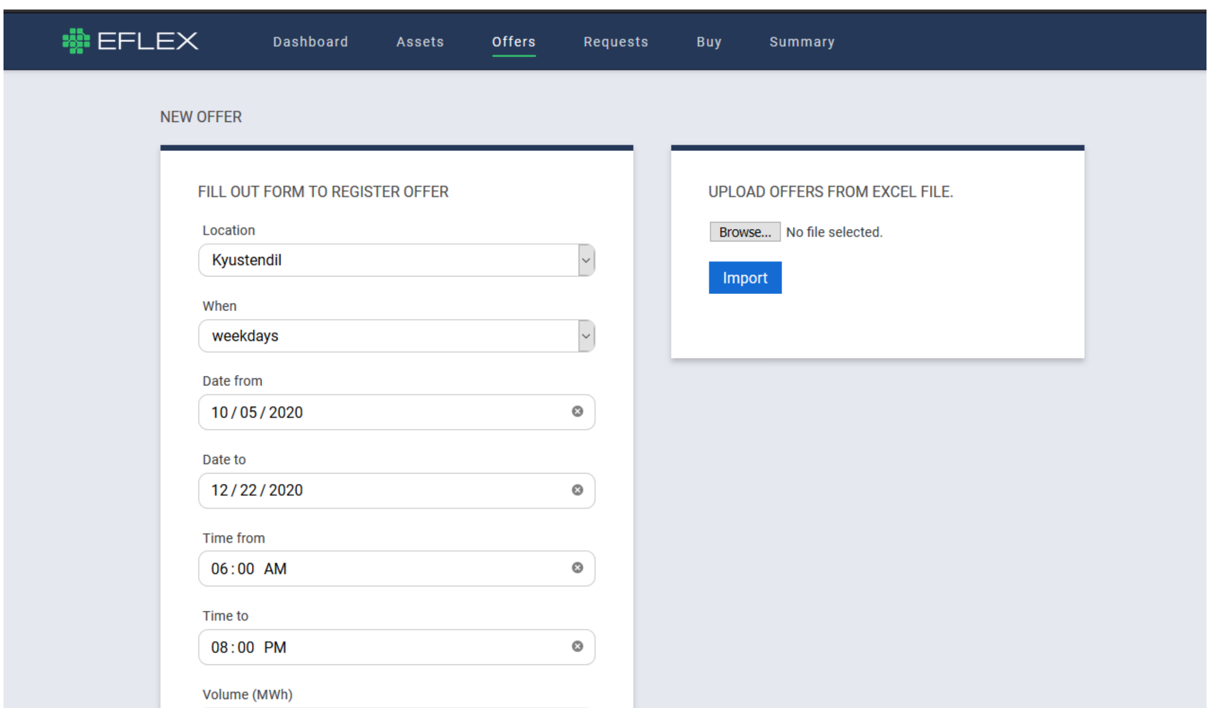


Figure 4-13 Add offer page

Trading

Currently DSOs can select or filter available offers on the market and proceed to manually purchase these offers. Matching algorithms will be integrated in the later phase. Below is an example of how we use Blockchain-based wallets to facilitate micro-payments between buyers and sellers.

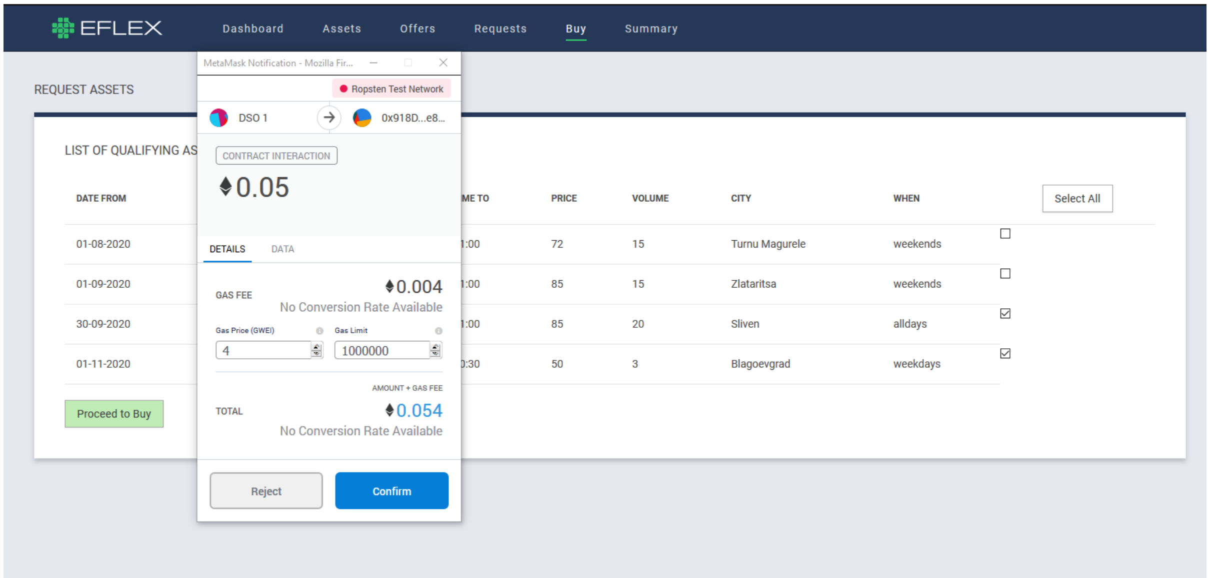


Figure 4-14 Blockchain based wallet to facilitate payments between buyers and sellers

After transaction is successful, the DSO wallet balance will be debited, and corresponding asset owners wallet balance will be credited.

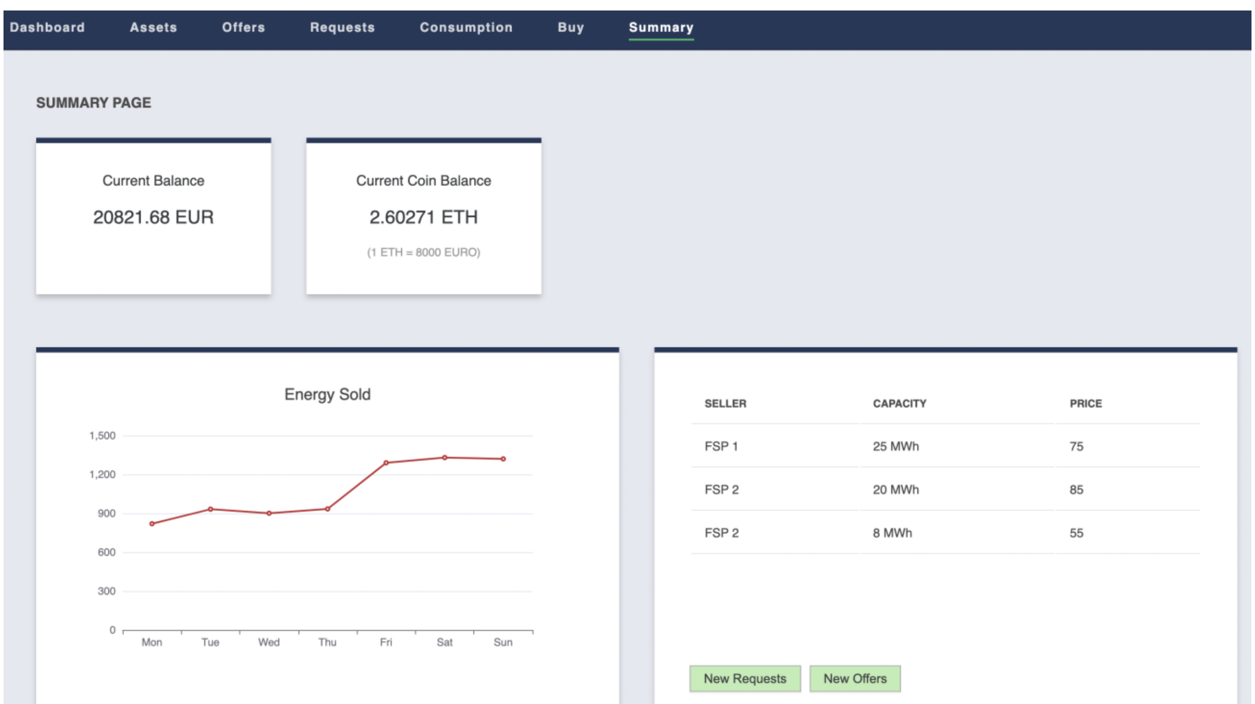


Figure 4-15 Overview of transactions, balance

4.3 Conclusion

A peer-to-peer architecture for electricity markets is an option when millions of flexibility assets are at the DSO network. Thanks to applicable concept from Blockchain for the peer-to-peer flexibility market, we have overviewed existing initiatives in the chapter, identified their innovative aspects and considered in the context for FlexiGrid project.

One of main outcomes of this chapter is to prepare necessary market design elements to be implemented in the demonstration of WP7, which we will demonstrate DSO-consumer flexibility market platform for local grid imbalance, congestion and voltage management. We highlight business use case, requirements of system architect, activation and process of trading flow, access right, data input, etc. These are important aspects to be considered for development of the trading platform. We have presented a real-time peer-to-peer energy trading system where the users can buy and sell electricity in a secure and profitable manner.

At the end, the trading platform will not only support the trading activities to happen smoothly, but also provides great trading experiences for users. Main functions of peer-to-peer Blockchain Platform is initially designed and further implemented in WP4 and WP7.

5 Self-adaptive market structure

5.1 Introduction

The previous chapters presented standalone markets for specific trading environments, such as peer-to-peer and peer-to-pool. The design illustration in the previous chapters explains the internal processes in each market model, without interaction with other markets, external signals, or factors that affect the process flow. This assumption is reasonable for a preliminary design. Intuitively, with two market designs in hand, it becomes necessary to coordinate the operations of the two markets (as well as any other market processes), such that these processes do not conflict with each other, but actually, interact in order to compliment and back-up each other.

The goal of this chapter is designing a self-regulating and adaptive market. The adaptive market design builds up on the separate market designs, to learn from the work already completed. The design scope is to combine the existing market designs to run within a larger framework. The adaptive market design identifies the controllable parameters of the individual markets in order to adjust these markets. The adaptive market design also comprises mechanisms which fall outside the Peer-to-peer and Peer-to-pool markets.

The existence of random variables and uncertain conditions in any system model complicates controlling and optimising it. It is possible to design a static control mechanism of such a system. Such static design must be robust, such that the mechanism is stable and demonstrates adequate performance under all different plausible scenarios of uncertainty. Such robust mechanisms are relatively easy to design, however, this comes at the cost of optimality and performance. Alternatively, a complex, dynamic and adaptive mechanism can observe the uncertain conditions, and adjust itself accordingly to maintain optimal performance. Such mechanisms are usually more complex to design and are prone to instability. However, they provide better performance.

With the rise of the RES penetration in the power grid, the average μ net load (i.e. P_{demand} - P_{RES}) is smaller, however, the net load's standard deviation σ and volatility are much higher. In addition, the ongoing electrification of the transportation sector will introduce additional uncertainty in the power system. Therefore, a holistic and adaptive mechanism is required to observe and control the whole system's performance from different perspectives.

Objectives & purpose:
The objectives of this chapter are:

1. Expand the market horizons plan proposed in chapter 3, such that the market process accommodates and orchestrates the peer-to-peer market, and also unilateral actions by DSO.
2. Design a holistic work frame which adapts to market dynamics, such as:
   A. Atomic (non-granular) Energy deals in the peer-to-peer market which cannot offer CL flexibility like BRPs.
   B. The individual role of each user on network challenges (i.e., sensitivity)
   C. bilateral energy contracts announced at different points in time, disturbing market plans.

3. Design a holistic work frame which tackles the following challenges:
   A. The impact-based demand curve with ascending order, in chapter 3
   B. Insufficient quantity of flexibility despite all efforts and market negotiations
   C. Economic withholding (market abuse by price manipulation)
4. Design a market work frame which achieves desirable objectives of mechanism design:
   A. Immune to market manipulation (Truthfulness): The renumeration scheme for the flexibility service cannot be manipulated by the service provider. The incentives and rewards paid for the service should reflect the real value of the service to the system.
   B. Efficiency: maximize social welfare.
   C. Budget balance: The auctioneer or market operator does not lose any money; and preferably, does not make any money either (strong budget balance).

In addition to the characteristics mentioned in chapter 2, the following characteristics are desirable in system design [15]:

D. Transparency and simplicity: The legal proceedings and the operation procedures are clear for all potential FSP, including small end-users.
E. Inclusive: The flexibility service program should be accessible to potential FSPs of all sizes and sectors. That is, there are no barriers against entry, such as minimum size.
F. Freedom-of-choice (compatibility with continuous control [15]): DERs are not forced to participate in the current market. Furthermore, the DERs are not exclusive to the local market, albeit, have full liberty to participate in any other market to sell any product they have. In summary, the DSO cannot monopolize these DERs services, or take them for granted without an existing contract.

5.2 Self-adaptive local flexibility and energy market framework

5.2.1 System State, Condition and Performance Indicators

A fundamental part of an adaptive control system is the observation of the exogenous random variables and continuous evaluation of the system conditions. The system condition should be evaluated using measurable quantities. In this work, the system condition is evaluated from three perspectives:

- Physical: This concerns the physical state of the grid and its technical components. To evaluate this side of the system, several system parameters and states can be monitored. Examples of such parameters are:
  - Voltage deviation index
  - Loading level of all transformers
  - Peak to average load ratio
  - Any planned maintenance events
  - How frequent the transformers’ tap-changers were operated
  - Percentage of transmission losses within the grid
  - Load shedding: Expected energy not served in the system
  - The state of charge of all energy storage devices in the grid

- Economic: This concerns the state of the market in terms of market power, abuse and stability. To evaluate this state, market parameters and phenomena can be monitored. Examples of such indicators are:
    - Is all flexibility coming from the same provider?
    - What is the market share of each flexibility provider?
    - Seller satisfaction index [68]
    - Buyer satisfaction index [68]
    - Market tendency index

- Time state: How close the system is to the delivery time, and within the remaining window of time until delivery, how fast can the potential flexibility sources be contracted and how fast can they deliver contracted flexibility.

5.2.2 Inventory of Control Actions and Measures

Another fundamental aspect of any control system is identifying the available control actions, control or decision variables which are adjusted with the goal of correcting the system's conditions. For example, in an airplane system, the control variables are the engine thrust and the angle of wing flaps.

The illustration of the two market models (peer-to-peer and peer-to-pool) in the previous chapters highlights the following control actions which the overall system operator can adjust:

Control Variables in the peer-to-peer Market:

- Suspend certain energy trades
- Recommend trades to open offers and bids, with incentives
- Set the grid tariff.
- Apply a dynamic grid tariff.
- Auction the right of use of the grid to Peer-to-peer deals

Control Variables in the peer-to-pool Market:

- Break down wide market to local feeder market
- Carry out sealed-bid auctions
- Repeat auctions, with price caps on bids-to-sell, and price floors on offers-to-buy.

5.3 Market clearing mechanisms

Auctions have been in use since ancient times to allocate goods among competing buyers. Since then, the concept of markets has developed beyond a gathering place, to online platforms and automated bidding. Furthermore, auctions are not limited to a single item, rather, an auction may involve the sale of several items of the same type of good, such as event tickets, company stocks, and limited-edition cars. At the same time, not only tangible products are sold in today's auctions, but resources such as electromagnetic frequency bandwidth, and semi-infinite resources such as music downloads, internet hosting services and broadcasting rights for sports events. In order to maximise the social welfare in these auctions, the field of game theory has witnessed the development of numerous types of auctions for specific purposes and circumstances.

The goal of auction design is to achieve certain desirable properties. Intuitively, a good auction design maximises the seller's profit. In the case of buyers competing to obtain an item from a single seller (i.e., government selling licenses to release CO_2 emissions), the auction design should maximise the welfare or the benefit to society, also known as social welfare. In a broader context, auction design aims to maximise social welfare, whether the auction involves competing buyers, competing sellers, or competitors on both sides (i.e. sellers and buyers). An auction mechanism which maximises social welfare is also known as *efficient*.

Another highly desirable property in an auction mechanism is *truthfulness*. In a truthful auction, bidders are better off if they tell the truth, and disclose their true valuation of item, and item preferences, instead of gaming. In a truthful auction, a bidder who does not provide their true valuation is likely to achieve less profit. Truthfulness is also known as *incentive compatibility*, and it is always achievable in the design of any auction [69]. On the other hand, *efficiency* might be difficult to obtain in some auctions.

5.4 Adaptive Market Scheme

After a brief introduction on auction clearing mechanisms, and cost allocation techniques, this section explains how these mechanisms and techniques are employed in the proposed adaptive market. This section also explains how to coordinate the peer-to-peer and peer-to-pool markets. In peer-to-peer market, agents hold mutual agreements for energy transfer. The current practice is that the partners of the deal inform the DSO about their energy transfer and pay the fixed grid tariff. The operation premise here is that the right to use the grid is a guaranteed entitlement, and the DSO cannot interfere with this deal. The definition of an energy deal can be extended beyond the peer-to-peer frame to also include all kinds of energy exchange agreements in the Peer-to-pool market or in any work frame.

With the rising number of RES units installed at the distribution level, and the gradual decrease of the feed-in tariff, bilateral agreements will grow in number. More technologically-savvy and energy-aware end-users will enrol in the peer-to-peer market. This market will observe an increase in the number of micro-prosumers making micro-transactions, with some of these agreements being made at the last minute. Local trades may only stress short segments of a feeder. However, inter-zonal energy exchange travels a longer distance through equipment with limited capacity. The energy transmitted across the grid may consist of a swarm of micro-transactions, however, the net size of this energy transfer is significant. Sooner or later, the market or system operator must suspend the guaranteed right of use of the grid and throttle such transactions.

5.4.1 Overall Process Flow

The overall flow of the adaptive market is illustrated in Figure 5-1. The peer-to-peer and peer-to-pool markets operate independently and communicate their deals to the independent system operator. Deals are appended to the energy ledger. At each hour, the system state and health are evaluated. The different performance indicators of the system determine which state the system falls into: Secure (Green), Caution (Orange), Critical (Red). Based on each state of the system, the response strategy is determined. The strategies materialise into actions in each one of the market components: peer-to-peer, peer-to-pool and unilateral actions available to the DSO. This state of the system, the corresponding strategies and actions are illustrated in the decision-making matrix in Table 5-1.

A system in green state does not require any urgent intervention. The system operator may opt for making fine improvements to the system, if affordable. Examples are harnessing cheap and available flexibility in order to reduce transmission losses. Power system operation is characterized by a high reliability standard. The system operator announces a caution (yellow) state while the system is still stable and secure, but the spare and safety margins of equipment capacity have fallen below a safety margin. These thresholds may be a function of the remaining time till gate-closure or delivery time, and statistical analysis of historical data. In the caution (yellow) state, the system operators start preparing to take actions and studying alternative action plans. The system operator refrains from taking major actions, and waits for possible updates that may resolve the situation naturally, without intervention such that costs of incentives are avoided. The operator may initiate the process of rematching certain deals where the rematching does not incur any incentive payment.

Refraining from taking actions should not, however, tolerate severe violations of equipment limits and grid standards. The system enters the critical stage before the system's safety margins are fully exhausted. The system's critical state is also determined by the remaining time till gate-closure. In the critical (red) state, the operator must have already determined the least-cost combination of actions, and the system operator proceeds to implementation.

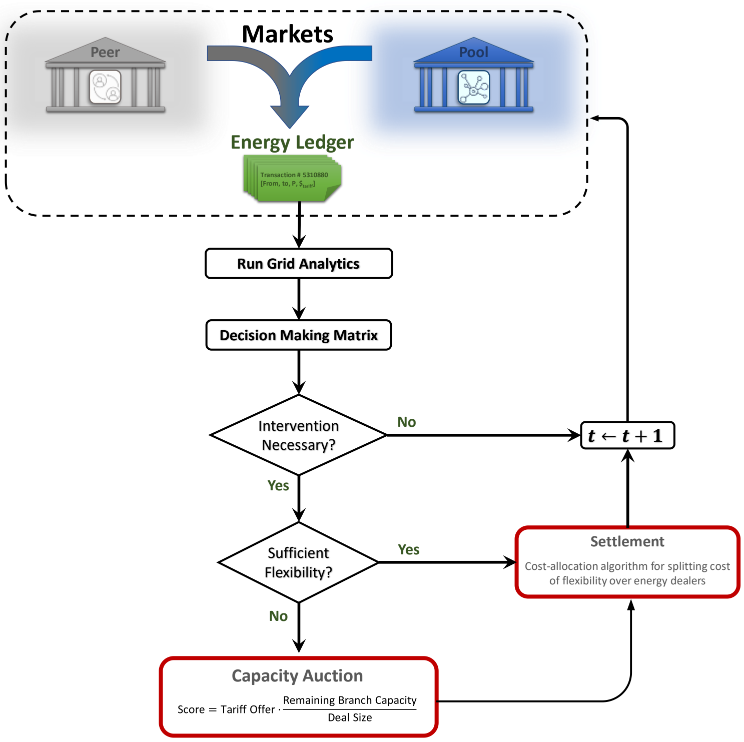
If the system enters the critical (red) state and sufficient flexibility is acquired successfully, the system can be deemed secure (green) or cautious (yellow), and operator intervention is not necessary on the following interval $t + 1$. For example, if an auction for flexibility is held and the competition for grid capacity is settled, there should not be another flexibility auction for the same target interval.

Table 5-1 Decision Making Matrix

	Before GC: Strategy & Approach	After GC: Actions & Procedures		
		peer-to-peer Market	peer-to-pool Market	Unilateral / Technical
Secure	Business as usual Take minimal actions to minimise losses Observe & report	Approve all deals Charge the standard fixed tariff for all	Run dummy auctions at random times, without committing to buy	Approve maintenance plans Redact system information at random times
Caution		**Determine Least Cost Combination**		

	Attempt to find solutions, ideally, without suspending any deals Seek solutions to prepare to intervene. Wait for future deals that may solve the problem and save on incentive payments	Highlight healing deals in the energy ledger Search the open platform for healing deals Rematch existing deals	Hold closed-bid auctions without making commitment. Repeat auction. Set price-caps on bids-to-sell, and price-floors on offers-to-buy	Analyse consequences of overloading the system, or violating voltage limits (i.e. long term cost) Redact system information

Critical	Implement least cost combination of actions using an optimization model	**Implement Least Cost Combination**		
		Match vacant healing offers with a partner.	Buy flexibility from Peer-to-pool market	Violate grid limits temporarily



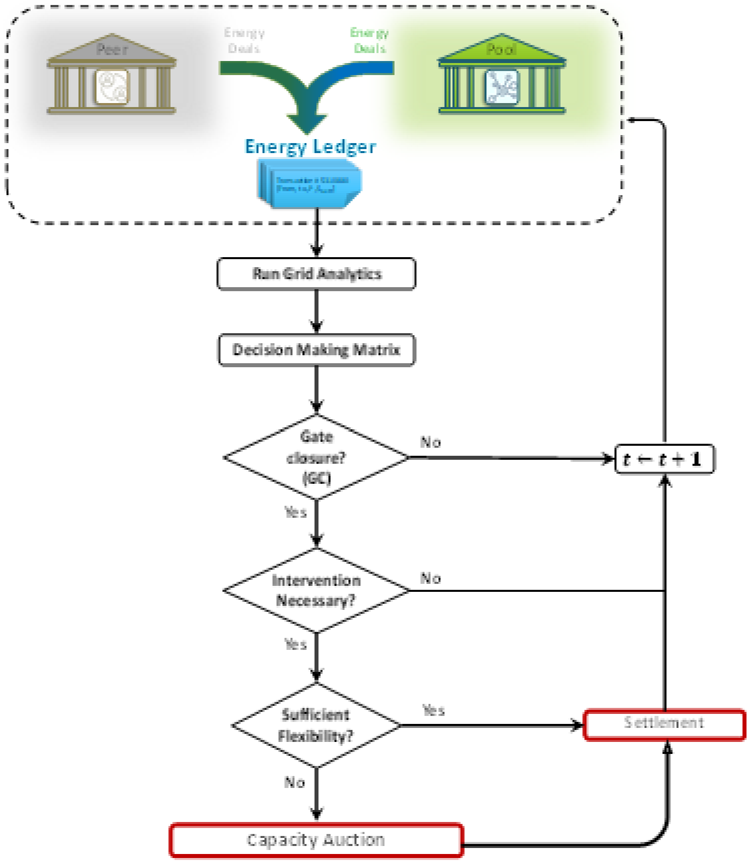


Figure 5-1 Overall Market Process

Rematching Deals:

Before the system enters the critical (red) state, the market operator may take initiative and take minimal actions. For example, the operator may catalyse new deals which would relieve the contingency, or rematch an existing deal such that this relieves the contingency.

Consider the scenario of an energy trade ushered in the peer-to-peer market. Agent 1 is a prosumer, who is selling energy to Agent 2, who is a consumer. Agent 2 lies on a branch suffering from an overload and an undervoltage. This pair (agents 1 and 2) are nominated for a rematch. The system operator approaches agents 1 and 2 with an offer:

- The partners agree to break their deal. Agent 1 (residing outside the troubled zone) accepts a rematch with a third partner: Agent 3 in a non-congested zone.
- The partners reject the rematch and decide to take their chances in the auction.

Agent 1 does not benefit from the rematching process. Naturally, Agent 1 will always opt for proceeding to the auction. A tie-breaking rule must be agreed upon beforehand, during negotiations in the market. For example:

- The agent in the troubled zone (Agent 2) has no choice. Agent 1 decides whether to accept the rematch and annul the existing deal, or proceed to the auction. This is problematic as agent 1 may develop bad reputation in the peer-to-peer market over time.

- During the negotiation stage (early in the peer-to-peer market), either agent pays a premium to the other agent, in order to retain the right to make decisions on rematch offers.
- The partner paying the bigger part of the bid price (if they were to proceed to the auction) retains the right to make a decision on rematching offers.

Designing a tie-breaking mechanism is out of the scope of this report.

A proposed rematch must provide the rematched partner (i.e. agent 1) with an alternative opportunity which is at least as good as the trade being annulled. If a rematch opportunity has less merit than the original deal, the partners have to weigh the risk of proceeding to the auction against the reduced profit from the rematch offer. Hence, paying incentives is vital for the success of a rematching mechanism. On the other hand, a primary challenge in designing an incentive program is discouraging gaming behaviour. Users in any zone may submit dummy deals to create a fake congestion, and wait for rematching offers and incentive payments.

Even if incentives are not paid directly to the rematched partner, but as a form of tariff subsidy or to reduce the price spread between a buyer and a seller, agents may still benefit from such incentives to increase their profits. Therefore, rematched partners who benefit from the incentive mechanism must be audited closely, and the incentive mechanism must be inspected and updated thoroughly.

5.4.2 Grid Tariffs and Grid Capacity as a Scarce Resource

The primary principle of the proposed design is that all energy deals (from peer-to-peer or peer-to-pool) held in the grid must seek approval from the designated authority, such as the DSO or a third-party independent market operator. The two sides of a bilateral contract are required to inform the DSO of their deal before delivery time. The information dossier must include the location of the energy injection and consumption (from, to), the amount of energy, and naturally, the time of delivery.

When energy is traded across the distribution grid in present-day market models, the two sides of a deal pay a static grid tariff to the DSO. This tariff is designed to cover the investment and maintenance costs of the grid, and the DSO operations cost. When the system is running securely below its capacity, applying a static tariff is reasonable. This is represented by the green demand curve in Figure 5-2.

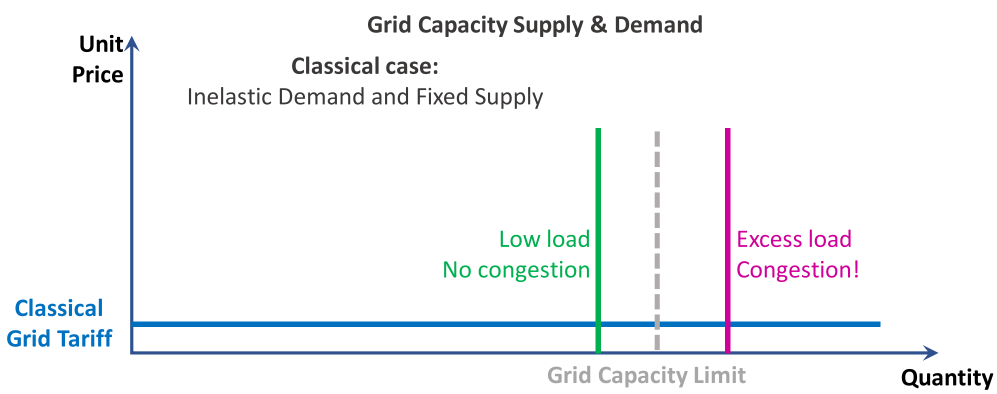
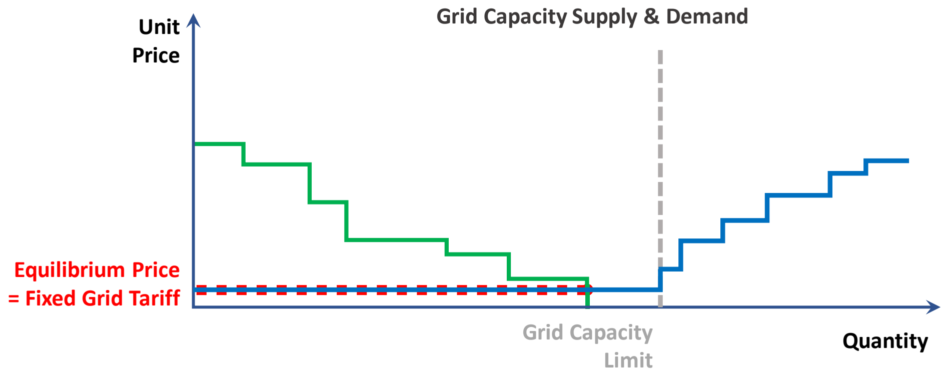


Figure 5-2 Supply and Demand Plot for Grid Capacity

We argue that the laws of supply and demand should be enforced in cases of limited resources and supply. That is, the grid tariff should be determined by the supply-demand equilibrium ideally. Theoretically, the DSO can set the grid tariff ahead of time, based on historical data and forecasts of the size of energy transferred across the grid. Adjusting the grid tariff dynamically to influence and filter out energy deals may not be effective without human intervention. With every tariff update, the partners of an energy deal would be required to discuss and respond to the tariff. It is even more inhibitive to update the tariff continuously based on the latest information updates about the grid state.

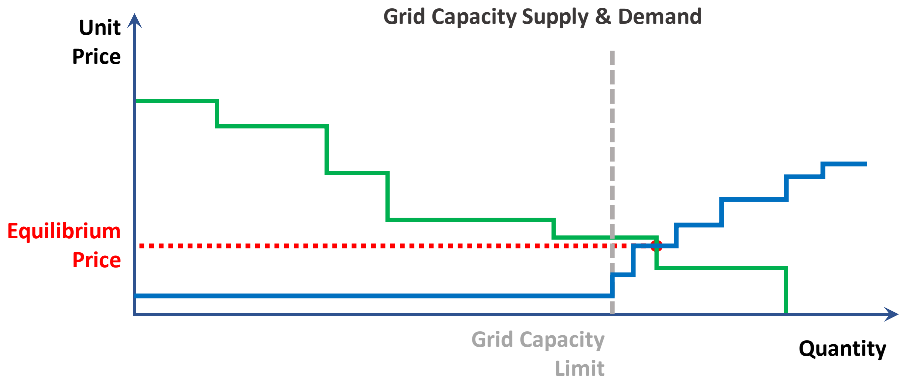
Perceiving the problem from another point of view simplifies the solution. In case of a scarcity event (i.e., congestion), the partners of each energy deal should compete to buy a part of the grid capacity, in order to earn the approval of their deal. Hence, the partners in an energy deal bid against other energy deals in an auction for grid-capacity. It is very important to understand that the bid price for grid capacity is completely different from the energy price within the deal[6]. Therefore, at the time the energy deal is communicated to the DSO seeking approval, the deal dossier should quote the tariff bid, along with the information about the location and size of energy transfer.

This offer represents the bid-price of the dealers, to be used only in the case of a scarcity event. In fact, the base tariff would be the price of equilibrium when the system is not congested. This is depicted in Figure 5-3a. Flexibility service providers (FSP) compete to provide flexibility at competitive prices. Their flexibility represents a virtual increase to the grid's transfer capacity, and hence, the flexibility quantity appears in the blue supply curve. In a scarcity event, the grid's transfer capacity is auctioned among the owners of the energy deals. The merit-order principle is applied, where the bids are sorted based on their unit price. The bids with the highest buying price are the most favourable, and appear first. Putting all bids in order constructs the demand curve. The equilibrium price can be deemed as the price of flexibility.



A. No Congestion. Grid Capacity Price Is The Standard Tariff.

[6] The energy price in the deal is the price which the two partners have negotiated and the monetary value which the partners have exchanged. This piece of information plays no role in evaluating the deal from the system operator's perspective.



B. Congestion Occurs. Congestion Is Solved By Acquiring Flexibility

Figure 5-3 Supply and Demand Curve for Grid Capacity in Proposed Scheme

Even in the case of a scarcity event (i.e. congestion), the actual (installed) grid capacity accommodates the majority of energy deals. Hence in the case of a scarcity event, it is reasonable to assume that the amount of acquired flexibility is small (i.e. 10%-20% above grid capacity at most). Without market abuse by FSPs, the equilibrium price of flexibility should naturally occur slightly above the standard grid tariff. This price is paid only by the users in a troubled zone, whose usage (i.e. consumption or injection of energy) makes part of the scarcity event. This is illustrated by Figure 5-3b. The long term-consequences of this operation paradigm are discussed in a later part of this chapter.

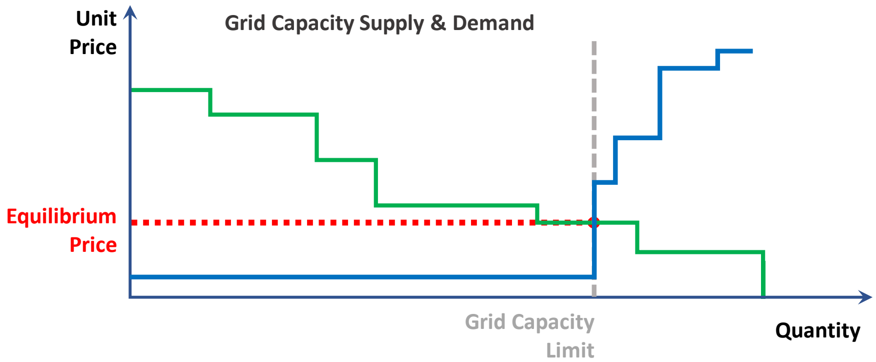


Figure 5-4. Supply and Demand of Flexibility with Flexibility Price Spikes or Flexibility Providers' Abuse

Stakeholders of the auction:

Ideally, the concept of supply and demand should be implemented indefinitely to all market participants. However, abrupt changes to the market disturb the business models of corporations. Eventually, price spikes propagate to end-users, instilling wide disapproval of new policies. We propose that only private energy traders in the peer-to-peer or peer-to-pool markets should compete to earn the right to use the grid (i.e. grid's transfer capacity). At the initial stage of implementation, BRPs and aggregators continue to announce their load forecasts and buy energy in the same manner.

Hypothetically speaking, if BRPs and aggregators were required to compete for the right to use the grid (i.e. the network's transfer capacity), along with small energy traders, the following challenges are expected:

- Balance responsible parties and aggregators cannot sell flexibility products, because their loads were not already approved. Therefore, they cannot promise reducing (or increasing) their loads to sell flexibility. Effectively, flexibility can only come from free agents, who are not preoccupied by any energy deals.
- BRPs and aggregators can only submit their load forecasts at the day-ahead milestone, and update their load forecasts at the hour-ahead milestone. Small energy traders can make deals much earlier.
- BRPs and aggregators cannot wait for the last hour or for the closing of the continuous adjustment market to receive final confirmation of their load demands. BRPs and aggregators would need to operate with large safety margins such that their loads are always cleared.
- The BRPs and aggregators manage much larger load and energy transfers than bilateral contracts. The BRPs and aggregators would possess large market power in the auction.

At the same time, if aggregators were given priority to use the grid, and had their load forecasts automatically approved for transfer, aggregators can intentionally give inaccurate load forecasts, in order to sell flexibility in the auction. In extreme cases, the aggregators can fake scarcity events to benefit from selling flexibility. In order to prevent this scenario, and reduce the aggregators' market power, the following steps can be taken:

- The network share reserved for the aggregators, based on the aggregators' load forecast, is granted on a "use them or lose them" basis. If an aggregator's final load estimate at gate closure time is below its earlier forecast, the aggregator loses the right to use the grid.
- The aggregator may face harsh penalties if its actual load deviates significantly from its forecast. This leads to another challenge, of setting the penalties, and determining the tolerance threshold for forecast inaccuracies.

Even with the two remedial actions above, an aggregator may analyse the market, estimate the elasticity of flexibility buyers to set a price that guarantees all its flexibility is sold. Furthermore, the aggregator can sell the flexibility in the continuous adjustment market. Further actions may help fight aggregators abuse of their guaranteed right-to-use the grid.

- Even after selling flexibility, aggregators still have to support the remaining of their actual load with energy. Instead of paying the fixed standard network tariff, the aggregators are charged a tariff proportional to the clearing price for flexibility. Therefore, aggregators are affected by the price outcome of their own selling bids. If FSPs are paid on a pay-as-bid basis, then aggregators selling flexibility do not make any revenues. Therefore, the FSPs are remunerated based on the highest flexibility bid.

5.4.3 Long-Term Consequences of Adaptive Market Scheme

Applying this scheme brings along the same benefits of a free market vs. a controlled market with government intervention and deficit. In the short-term, energy traders will seek deals in other zones, even if trading in these zones achieves smaller financial profit. The reduced profit balances with the cost of buying flexibility on the troubled zone, and a grid-wide equilibrium is achieved.

In the long-term, scarcity events happen less frequently in the concerned zone. Naturally, investments in infrastructure expansion can be deferred. In fact, less stress on grid components extends their lifetime. At the same time, the price profile of flexibility provides the DSO with an indicator of the need to upgrade grid components.

Moreover, flexibility providers in the concerned zone make relatively more profit. Consequently, aggregators who act as flexibility providers pursue potential small sources of flexibility with more attractive offers, as well.

Small prosumers and responsive demand units have two options to participate in the electricity market.

- Tech-savvy: Participate directly in the peer-to-peer market, negotiate deals and choose their bid price. This option brings along more profit, however, it incurs more risk and effort. That is, the prosumer must interact with the market, choose their bid price, and operate their generation resources according to a strict schedule.

- Risk-averse: Join an aggregator. Sell energy or flexibility at a pre-defined fixed rate and quantity upon request from the aggregator.

From an economical perspective, the availability of these two options reduces market power. Aggregators have less control over small prosumers. At the same time, an easy and risk-averse option is available to prosumers. From a technical perspective, a thriving peer-to-peer market improves the visibility of RES units to the system operators, which has been a primary challenge to TSOs.

5.5 Settlement

In case of a scarcity event and a flexibility auction, Figure 5-1 depicts a settlement stage where the cost for flexibility is split among flexibility buyers. If the set of buyers is treated as a coalition, myriad cost sharing algorithms exist for such a situation. The Shapley value algorithm is widely utilized for sharing costs within a coalition, and has been used in [71] to distribute the cost of flexibility among buyers who benefit from the same flexibility services. However, calculating the Shapley value requires evaluating all $n!$ permutations for a case with n agents (i.e., buyers). If a web-based platform is developed to submit and match energy deals for the peer-to-peer market, it is reasonable to expect there will be a large number of deals. Such deals involve trading small amounts of energy. Evaluating $n!$ scenarios becomes prohibitive, and the marginal contributions in each of these permutations will be very small.

Furthermore, we believe that it is worthwhile to encourage participants in the local distribution market to finalize their negotiations and inform the DSO as early as possible. For that reason, the order of deals joining the auction is meaningful. Evaluating $n!$ permutations destroys the sequence, and therefore, the Shapley value may not be the best approach for settling expenses in these flexibility auctions.

The DSO is not allowed to pursue making profits in the flexibility auction. Therefore, in the likely scenario that the total sum of buyer's bids exceeds the total sum of flexibility seller's payouts, then a surplus is obtained. In mathematical terms, this settlement scheme is not budget balanced. The following hypothetical scenarios explain further why collecting the full amount of bid price is problematic:

Carrying over budget surplus for future events complicates the settlement issue drastically, and the fairness of such an approach is highly disputable.

The scenarios explained above inspire that only the total sum of FSP pay-outs should be divided among buyers. Charging all flexibility buyers the same unit price for flexibility (i.e. uniform pricing) does not motivate truthfulness. Consider the case where the total cost of flexibility is divided equally among flexibility buyers (also known as the *Average cost rule* [72][72][72]):

$$\text{Payment}(i) = \text{Total Cost of Flexibility} \cdot \frac{\text{Quantity } (i)}{\sum_i \text{Quantity}(i)}$$

In such a case, the bid prices of flexibility buyers can only determine the winners in the auction. The uniform price is determined by the last winning bid (aka the marginal unit) and the asking price of the last winning FSP. The buyers of flexibility can bid high prices to guarantee winning, without worrying about paying their actual bid price. In fact, applying the VCG mechanism on an auction to sell a commodity dictates that all buyers pay the same price of the highest losing bid. To maintain budget balance, these bid prices are scaled down to sum up to the total pay-outs to the FSPs. The following rule can be applied:

$$\text{Payment}(i) = \text{Total Cost of Flexibility} \cdot \frac{\text{Price } (i)}{\sum_i \text{Price } (i)} \cdot \text{Quantity}(i)$$

More cost sharing rules are also available for this type of problem, such as the increasing serial rule. In this rule, buyers' are put in an increasing order of their demanded quantity:

$$q_1 \leq q_2 \leq q_3 \leq \cdots \leq q_n$$

then:

$$\text{Payment}(1) = \frac{\text{Cost of flexibility if total demand was } (n \times q_1)}{n}$$
$$\text{Payment}(2) = \text{Payment}(1) + \frac{1}{n-1}[\text{Cost if remaining demand was } (n-1) \cdot q_2\,]$$
$$\text{Payment}(3) = \text{Payment}(2) + \frac{1}{n-2}[\text{Cost if remaining demand was } (n-2) \cdot q_3\,]$$

and so on. The fundamental principle of this rule is that the agent with the lowest quantity is not responsible for the larger unit-cost of large quantities of more greedy agents. After removing this agent (i.e. lowest quantity), the agent with the second lowest quantity is not responsible for the larger unit-cost of the large quantities of the remaining agents, and so on.
It is guaranteed that the total payments will add up to the total cost of flexibility:

$$\sum_i \text{Payment}(i) = \text{Total cost of flexibility}$$

Since thermal losses in the power system are quadratically proportional to power consumption, this rule is a good candidate for our purpose.

When the cost function is concave and the unit-cost drops with larger quantities, a decreasing serial rule can be adopted, which adopts the opposite principle: the agent with the largest quantity (smallest unit cost) is not responsible for the larger unit-cost associated with smaller quantities from the other agents. However, this does not apply to the electric power system.

As mentioned earlier, we believe that it is worthwhile to encourage participants in the local distribution market to finalize their negotiations and inform the DSO, as early as possible. For that reason, instead of using the $\frac{\text{Price}}{\text{Quantity}}$ criterion, we modulate the *Energy* in the denominator by the *remaining capacity of the branch* at the time that this deal was communicated.

$$\widetilde{\text{Price}}(\text{i}) = \frac{\text{Price(i)}}{(\text{Remaining Branch Capacity})^{\alpha}}$$

This modulation gives an advantage for earlier bids, where arrival time is measured by the amount of remaining branch capacity rather than a time period (i.e. days). This modulation can be fine-tuned to balance between goals of the market operator, by giving the modulation factor (*Remaining Branch Capacity)* a smaller weight $0 \leq \alpha \leq 1$.

In the case of a scarcity event, the remaining branch capacity becomes negative. Therefore, it is reasonable to shift this value up by an offset (i.e. 20%) for all bids, or to normalize the set of all bids to be strictly positive.

When the grid is stressed, it must be kept in mind that energy deals which have a healing effect on the problem (i.e. power injected into the grid in a feeder suffering overload or undervoltage) should not be involved in the competition for grid capacity. The auction for grid capacity involves only these energy deals which are causing the problem. In case of a congestion (i.e. overload), relieving actions can only come from downstream of the congestion point. Therefore, the auction involves only these energy deals where the receiving partner (consumer) lies on the concerned feeder.

On the other hand, voltage deviation events are, however, more interdependent and affected by the whole grid. The healing / congesting effect of each deal should be involved in the deal's score. The marginal effect of power injection at a certain point on the voltage at a certain point can be obtained from the inverse of the system's Jacobian matrix. The fact that the system is radial and weakly connected renders calculating the inverse of this matrix less computationally expensive.

$$J = \begin{bmatrix} \frac{\partial P_1}{\partial |V_1|} & \cdots & \frac{\partial P_1}{\partial |V_n|} & \frac{\partial P_1}{\partial \theta_1} & \cdots & \frac{\partial P_1}{\partial \theta_n} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n}{\partial |V_1|} & \cdots & \frac{\partial P_n}{\partial |V_n|} & \frac{\partial P_n}{\partial \theta_1} & \cdots & \frac{\partial P_n}{\partial \theta_n} \\ \frac{\partial Q_1}{\partial |V_1|} & \cdots & \frac{\partial Q_1}{\partial |V_n|} & \frac{\partial Q_1}{\partial \theta_1} & \cdots & \frac{\partial Q_1}{\partial \theta_n} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n}{\partial |V_1|} & \cdots & \frac{\partial Q_n}{\partial |V_n|} & \frac{\partial Q_n}{\partial \theta_1} & \cdots & \frac{\partial Q_n}{\partial \theta_n} \end{bmatrix}, \quad J^{-1} = \begin{bmatrix} \frac{\partial |V_1|}{\partial P_1} & \cdots & \frac{\partial |V_1|}{\partial P_n} & \frac{\partial |V_1|}{\partial Q_1} & \cdots & \frac{\partial |V_1|}{\partial Q_n} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial |V_n|}{\partial P_1} & \cdots & \frac{\partial |V_n|}{\partial P_n} & \frac{\partial |V_n|}{\partial Q_1} & \cdots & \frac{\partial |V_n|}{\partial Q_n} \\ \frac{\partial \theta_1}{\partial P_1} & \cdots & \frac{\partial \theta_1}{\partial P_n} & \frac{\partial \theta_1}{\partial Q_1} & \cdots & \frac{\partial \theta_1}{\partial Q_n} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial \theta_n}{\partial P_1} & \cdots & \frac{\partial \theta_n}{\partial P_n} & \frac{\partial \theta_n}{\partial Q_1} & \cdots & \frac{\partial \theta_n}{\partial Q_n} \end{bmatrix}$$

It is important to note that $\frac{\partial V_i}{\partial P_j} \neq \left(\frac{\partial P_j}{\partial V_i}\right)^{-1}$ in general. The matrix inverse must be calculated to obtain the value of $\frac{\partial V_i}{\partial P_j}$. The value of $\frac{\partial V_i}{\partial P_j}$ incorporates the healing effect from reducing transmission losses as well. The effective score of the energy deals in this case is shown below, where V^* is the voltage on the stressed node. β is a weight factor which adjusts the effect of $\frac{\partial V_i}{\partial P_j}$ on the total score. $0 \leq \beta \leq 1$

$$\widetilde{\text{Price}} = \frac{\text{Price}}{(\text{Remaining Branch Capacity})^{\alpha}} \cdot \left(\frac{\partial V^*}{\partial [\text{Deal Size}]}\right)^{\beta}$$

$$\frac{\partial V^*}{\partial [\text{Deal Size}]} = \frac{\partial V^*}{\partial P} \cdot P_{\text{deal}} + \frac{\partial V^*}{\partial Q} \cdot Q_{\text{deal}}$$

A natural result of this modulation type is that energy trades which have a healing effect on the system, and also energy trades which have zero impact on the system, appear to have a zero or even a negative bid price. These deals should not enter the auction and should not be required to compete for grid capacity. Consequently, these deals should be approved automatically, and charged only the standard grid tariff. The relation between different types of deals and scarcity events is illustrated in Table 5-2.

Define the modulation factor as:

$$MF = \frac{\left(\frac{\partial V^*}{\partial [\text{Deal Size}]}\right)^{\beta}}{(\text{Remaining Branch Capacity})^{\alpha}}, \qquad \widetilde{\text{Price}}(i) = MF(i) \cdot P_i$$

This adjusted price gives advantage to deals whose impact on the voltage is mild. Deals with a strong impact on the voltage are more likely to lose the auction, which yields a bigger healing effect on the voltage.

It is essential that the final payment from each agent, using the modulated price $\widetilde{\text{Price}}$, does not exceed an agent's maximum bid Price. To ensure this, the following relation must hold true:

$$\frac{\text{Total Cost of Flexibility}}{\sum_i \widetilde{\text{Price}}(i)} \times MF(i) \leq 1$$

Table 5-2 Marginal Effect of Deals on System States

Exchange Type	Impact	Change Scenario[7]	System Impact: Numerically	System Impact: Overload/ Undervoltage	System Impact: Reverse flow/ Overvoltage
Import Energy (Load)	$\frac{\partial \lvert V \rvert}{\partial S} > 0$	Add load $\Delta S < 0$	$\Delta \lvert V \rvert < 0$	Worse	Healing
		Remove load $\Delta S > 0$	$\Delta \lvert V \rvert > 0$	Healing	Worse
	$\frac{\partial \lvert V \rvert}{\partial S} < 0$	Add load $\Delta S < 0$	$\Delta \lvert V \rvert > 0$	Healing	Worse
		Remove Load $\Delta S > 0$	$\Delta \lvert V \rvert < 0$	Worse	Healing
	$\frac{\partial \lvert V \rvert}{\partial S} = 0$	Any change	$\Delta \lvert V \rvert = 0$	Neutral	Neutral
Export Energy (Generation)	$\frac{\partial \lvert V \rvert}{\partial S} > 0$	Remove generation $\Delta S < 0$	$\Delta \lvert V \rvert < 0$	Worse	Healing
		Add generation $\Delta S > 0$	$\Delta \lvert V \rvert > 0$	Healing	Worse
	$\frac{\partial \lvert V \rvert}{\partial S} < 0$	Remove generation $\Delta S < 0$	$\Delta \lvert V \rvert > 0$	Healing	Worse
		Add generation $\Delta S > 0$	$\Delta \lvert V \rvert < 0$	Worse	Healing
	$\frac{\partial \lvert V \rvert}{\partial S} = 0$	Any change	$\Delta \lvert V \rvert = 0$	Neutral	Neutral

or simply:

$$MF(i) \leq \frac{\sum_j \widetilde{\text{Price}}(i)}{\text{Total Cost of Flexibility}}$$

It is important to note that $MF(i)$ itself appears inside $\sum_i \widetilde{\text{Price}}(i)$, and the relation needs further analysis. After some manipulation, the following relation can be established:

$$MF(i) \leq \frac{\sum_{j \neq i} \widetilde{\text{Price}}(j)}{\text{Total Cost of Flexibility} - \text{Price}(i)}$$

5.6 Methodology – Simulation based proof-of-concept

The previous subsection presented the theoretical foundations of the proposed adaptive market, illustrated the interactions between the system components, and explained the decision-making procedure. However, the design left the choice open for which specific algorithms to employ at each step.

[7] When modeling the power system mathematically, generation is modeled as positive power $S > 0$, and load is modeled as negative power $S < 0$. Therefore, more consumption (switching on more loads) appears as $\Delta S < 0$.

For example, determining the winners in auction might be straight forward, however, a pricing mechanism which promotes truthfulness and is widely accepted as fair is an intricate issue. It is common to apply different pricing rules in auctions to sell and auctions to buy. Even under the same category of auctions there are different algorithms to determine the quantities per bid, depending on whether a bid is divisible or not. Therefore, it is still necessary to test the theoretical design in a simulated environment first, and later, in an actual physical test bed. This subsection explains the first stage of testing the theoretical design, which is a simulated environment.

To test the market design, it is necessary to:

A. Identify essential and other desirable market properties: these properties were discussed in Chapter 2.
B. Identify quantitative measures of market performance in light of the desirable market properties.
C. Identify plausible scenarios which test the market's real stability and adaptability.

5.6.1 Market Performance Indices

The same indices used to determine the state of the system (secure/green, caution/yellow, critical/red).

For example:

- how much incentives are paid in rematching mechanisms
- Total payments made in flexibility auctions
- Total amount of flexibility bought in flexibility auctions
- Amount of energy-not-served from losing bids
- Amount of line losses
- Frequency of scarcity events and their geographic distribution

how much congestion relieved (achievement, efficacy of mitigative measures)

5.6.2 Plausible Market Scenarios

The following scenarios are proposed:

- Energy deals applying for approval at very late stage, taking benefit of better forecasts. Owners of these deals bid a high tariff and manage to get approval.
- Complex congestion scenarios:
    - A diverging branch suffers multiple congestions. For example, in Figure 2-1:
        - Opposite congestions: node 2 reports excess load, while node 26 reports excess generation, or vice versa.
        - Nested congestions: excess generation reported at both node 2 and node 26.
    - Congestion is caused by one particular load which violates grid requirements. For example, a load has a low power factor < 0.7
    - A certain energy deal relieves a congestion at one location and exacerbates another congestion in another location.
    - The grid capacity is exceeded by a small amount. Some buyers' bids are below the lowest flexibility seller's bid. However, collecting payments from all buyers would be sufficient to buy enough flexibility to clear the small congestion.
- Micro congestion: congestion on only a small section of a feeder, not affecting the transformer. In Figure 2-1, the flow between points 10 and 15 exceeds the cable's thermal capacity.

- Energy trades do not cause a congestion. Activating a certain flexibility deal for the TSO would cause congestion.
- Different control and interference levels of the DSO in the network:
    - DSO has full control over the market and the clearing process.
    - DSO participates as a market player, and the market is managed by an independent operator.
- TSO's participation level in the market
- Settlement and pricing for buyers and sellers of flexibility:
    - Average cost rule
    - Increasing serial rule
- Events timeline:
    - Gate-closure for each stage.

5.6.3 Test approach

Game theory models are used to simulate independent and rational market players (i.e., buyers and sellers). Each market player aims to maximise its own profits. Players may form coalitions and opt to cooperate if they seem to achieve higher profit in a coalition, compared to competing individually. Each player's model has a cost/benefit function with unique parameters, and the player interacts with the market based on the latest market information. Agents may develop experience through learning, and make different decisions based on historical and statistical data. An agent's model seeks to maximise its profits, or minimise its costs. The decision variables in this optimisation problem are the agent's price and quantity in different auctions or bilateral deals.

For every hypothetical scenario, the different algorithms are tested. To reduce the number of combinations, complex congestion scenarios can be combined in one simulation on different branches. The performance indicators are used to evaluate the performance of the market featuring a specific algorithm. It is likely that one algorithm cannot dominate all other algorithms in all aspects. This represents a classical pareto optimality situation. Instead of finding middle ground and making compromises on performance to choose one algorithm, the self-regulating market design has the flexibility and adaptivity to adjust its components. Algorithms which show dominant performance on several scenarios are identified. The subset of algorithms which spans all scenarios is defined. After that, the market operator is programmed to employ the most suitable algorithm for each scenario.

5.7 Conclusions

This chapter extends the design of Chapter 3. The system's state is evaluated continuously during operation, with respect to three dimensions: the grid's physical state, the market's economical state and the remaining time until delivery. For each dimension, measurable indices are evaluated, an overall state of the system is declared, and DSO's actions are determined, accordingly. The underlying concept of the design is to challenge the perception that using the grid is a guaranteed entitlement to all users. However, the right to use the grid is a scarce commodity which is sold to the highest group of buyers. In normal conditions (no overload), the available quantity of this commodity (network's capacity) is enough for all users. All users pay the standard grid-tariff. In case of a scarcity event (i.e. overload), FSPs represent sellers of virtual network capacity, and users compete to obtain the right to use the grid.

The processes and actions taken by the DSO in the proposed design do not necessarily replace the continuous adjustment market, but can aid it. When market operator's intervention is necessary, the gate-closure may be rescheduled earlier which impacts the continuous adjustment market. This is necessary to provide the DSO with time to take corrective actions. It is necessary to note that corrective actions taken by the DSO must come last, such that more recent trades do not disturb the security of the network, and negate the DSOs efforts. The actual characteristics of the proposed design are verified against desirable design objectives.

After illustrating the proposed market process and settlement mechanism, we revisit the design objectives, to highlight the compatibility of the design with the design objectives:

1. Immunity / truthfulness: we utilized an auction mechanism. The default setting of the design is that sellers are remunerated on a pay-as-bid basis. however, the option for uniform-pricing will also be considered during testing stage. Sequential clearing of the capacity auction was avoided, so as to eliminate the potential for gaming by agents cleared earlier. The cost-sharing algorithm also incorporates the concept of coalition stability and fairness.
2. Efficiency: the merit order (ascending supply curve, descending demand curve) and the settlement schemes comprise an auction scheme.
3. Transparency and Simplicity: Section 2.4 highlighted that prosumers and responsive consumers have two options to participate in the market: tech savvy and risk-averse. Furthermore, in a scarcity event, the DSO can offer a rematch to selected dealers, without obligation to accept. The verdict on the rematch is left for the dealers to make. When more flexibility is needed, the DSO utilizes the existing market platforms (peer-to-peer and peer-to-pool) as a trader, seeking deals that resolve network problems.
4. Budget balance: The settlement scheme in Section 5.5 highlights the obstacles against adopting the classical double-sided auction mechanisms. Furthermore, the total payments to the sellers are split among flexibility buyers using a budget balanced cost sharing algorithm.
5. Inclusive: This is dependent on the intrinsic design of the peer-to-peer and peer-to-pool platforms. Entities who are able to participate in any of the two platforms are automatically accessible in the design.
6. Freedom of choice: the characteristics of the design illustrated under point (3 Transparency and simplicity) also grant users the freedom of choice.

6 Conclusions and next steps

In this report, the focus has been on different market structures of peer-to-pool, peer-to-peer, and adaptive structures were explored for trading energy and flexibility locally. The market frameworks, product design, clearing algorithms, and payment allocation methods were proposed and discussed in detail. Moreover, the desirable market properties were explored from economic theory and stakeholders' perspectives. The roles and responsibilities of different market actors were discussed in each market mechanism. The value chain and the potential cost and revenue streams of the agents with a focus on the DSOs were analysed and presented as an initial step for future works in other work packages and subtasks of the project. An overview of the IoT platform and its functionalities were also provided highlighting the functionalities and the role of such platforms in the FlexiGrid solutions. Furthermore, different billing mechanism were explored and the pros and cons for each mechanism were discussed alongside the aspects to be considered in selecting an appropriate billing mechanism.

For a better alignment of the project partners and building a co-development atmosphere, different workshops has been organized on topics such as cost and revenue streams of the DSOs, local market design considerations and evaluation, and billing and payment alternatives. The conclusions from these workshops have been presented in the report.

There are pros and cons related to utilising different market structures. For example, in the peer-to-peer structure, there is no need for a centralized system to clear and manage the market and instead it is based on bilateral negotiations and blockchain contracts. However, the efficiency might be reduced as, in contradiction to peer-to-pool structures, there is not a centralized view on the social welfare maximization. Moreover, another concern regarding the peer-to-peer structures is the computational power required for blockchain technology and its potential environmental impacts. The adaptive structure tries to incorporate both of the structures according to the system's need, however, such structures can have high complexity that can cause challenges in the implementation phase. Therefore, it is important to take these pros and cons into consideration when deciding on which structure is more suitable for solving a specific problem.

In the peer-to-pool structure, market designs have been proposed for local trading of both energy and flexibility, however, the focus has been put on the flexibility market. The flexibility market design has been done considering the common design challenges in the local flexibility markets. Challenges with the baseline has been addressed by introducing a capacity-limit product. The reliability concerns have been tried to be addressed with long-term reservation markets beside a short-term activation and a continuous adjustment market close to the delivery time. The consequences of low market liquidity such as market power practices and untruthful bidding has been addressed by utilising payment allocation methods such as Shapley and VCG payments from game theory that are incentive compatible and reward truthful bidding.

A peer-to-peer electricity markets is an option when millions of flexibility assets are at the DSO network. Thanks to applicable concept from Blockchain for the peer-to-peer flexibility market, we have overviewed existing initiatives in Chapter 4, identified their innovative aspects and considered in the context for FlexiGrid project.

One of main outcomes of this chapter is to prepare necessary market design elements to be implemented in the demonstration of WP7, which we will demonstrate DSO-consumer flexibility market platform for local grid imbalance, congestion and voltage management. The trading platform will not only support the trading activities to happen smoothly, but also provides great trading experiences for users. We highlight business use case, requirements of system architect, activation and process of trading flow, access right, data input, etc. These are important aspects to be considered for development of the trading platform. We have presented a real-time peer-to-peer energy trading system where the users can buy and sell electricity in a secure and profitable manner.

Chapter 5 expands the action timeline proposed in chapter 3, such that the market process the peer-to-peer market, and also unilateral actions by DSO. The underlying concept of the design is to challenge the perception that using the grid is a guaranteed entitlement to all users. However, the right to use the grid is a scarce commodity which is sold to the highest group of buyers. In normal conditions (no overload), the available quantity of this commodity (transfer capacity of the distribution grid) is enough for all users. All users pay the standard grid-tariff. In case of a scarcity event (i.e. overload), FSPs represent sellers of virtual network capacity, and users compete to obtain the right to use the grid.

The design of market mechanisms is complex and requires multi-disciplinary assessments. Moreover, for a proof-of-concept demonstrations are required. In our future work the following items are going to be considered to have a more mature and practical design:

- Improvement of the market designs and bidding strategies based on the discussed pros and cons
- Exploring the pros and cons of including grid constraints in the market clearing and how it might impact alleviating distribution networks challenges
- Incorporating the market designs and the models into the IoT platform
- Demonstration of the solutions in the project demo sites. The market peer-to-pool and peer-to-peer markets are planned for demonstration in work packages 6, and 7 according to the test-cases provided in Deliverables 6.1 and 7.1.
- Inclusion of different flexibility sources available at each of the demo sites

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