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Review

Distribution-Level Flexibility Markets—A Review of Trends, Research Projects, Key Stakeholders and Open Questions

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Abstract: In modern power systems high penetration of renewable energy sources and decentralized paradigm are regarded as the path toward more sustainable electricity landscape. This includes distributed energy resources whose intermittency and uncertainty may cause issues to the system operators. Distribution system operators have an obligation to ensure secure and stable system operation. Hence, they seek the most efficient methods to deal with these challenges. Flexibility procurement is considered as one of the prerequisites for painless and successful integration of renewable sources. Furthermore, distribution-level flexibility markets are modeled and tested to trade flexibility locally, solve congestion issues and defer grid expansion. This paper surveys the ongoing research in the field of flexibility markets, its design, open questions and most promising research projects. The key stakeholders are identified, overview of the current trends in the power system and research initiatives are presented, accompanied with the dilemmas being discussed in the power systems community.

Keywords: flexibility markets; aggregator; distribution system operator; congestion; network; demand response

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1. Introduction and Motivation

1.1. Evolution of the Power Systems

Power systems around the globe have been evolving since the first power systems started operation. Nowadays, electrical energy takes an important share in the total energy consumed. For instance, in the USA, around 40% of the total energy consumed is used to make electricity [1]. Furthermore, the way the electricity is produced is also changing. From large, centralized, fossil-fuel based power plants [2] towards the accelerated renewable energy sources (RES) and the distributed paradigm. The conventional (old) model consists of generating the electricity from centralized power plants, then transforming the generated alternate-current (AC) to higher voltage and delivering it to the distribution grid using transmission lines. The traditional distribution network setup is characterized by the unidirectional power flow. While, on the other hand, ongoing processes result in bidirectional power flows [3]. It is the combination of the decentralized energy generation and smart distribution grids that is considered as a key to the European Union's (EU) efforts for accomplishing higher energy efficiency [4]. Under the term distributed energy resources (DERs) we presume electricity-producing resources or controllable loads that are connected to a local distribution system or connected to a host facility within the local distribution system [5]. Among others, these include photovoltaics (PVs), wind energy power plants, but also energy storage and electric vehicles [2].

1.2. Why Is Flexibility Needed?

Taking into consideration the past, the present and the future trends that characterize power systems, one can easily conclude that the path toward the modern structure of power system that fits the needs of the 21st century is paved with many challenges. High penetration of intermittent energy sources introduces additional uncertainty on top of the uncertainty on the demand side [6], hence the need for a service to increase the resilience of the system has also emerged. The general definition of flexibility is pretty clear: The ability of a power system to reliably and cost effectively manage the variability and uncertainty of demand and supply across all relevant timescales, from ensuring instantaneous stability of the power system to supporting long-term security of supply [7]. Flexibility is the solution to deal with load changes, weather forecasts errors, generation and/or transmission line outages [8]. One type of problems that the high RES penetration rates without secured flexibility may cause are high curtailment rates such as those reported in the German region Schleswig-Holstein [9], which has high penetration of wind energy and curtailed energy in 2015 of 2934 GWh, which resulted in costs of about 295 million € [10]. When considering the entire country, about 4.7 TWh of potential distributed generation was curtailed [11]. Furthermore, it is important to note that the power system flexibility may not always be so easy to achieve, as several reasons affect on it, some of them are [12]:

- Intermittent sources penetration,
- Variable fuel prices,
- Environmental concerns,
- Orientation towards new technologies and approaches.

Meaning that in addition to the increased flexibility provision requirements caused by the high RES penetration and bi-directional power flows, some conventional flexibility providers (i.e., fossil-fuel based power plants) due to their environmental impact and economical viability reasons are being decommissioned. Resulting with a possible paradox that nowadays we are witnessing both increased need for the flexibility, and decommissioning of some old flexibility providers. Consequently new approaches are being considered and developed. Furthermore, different flexibility providing units have different characteristics; from ramp rates to peak powers. In a system paradigm where changes may be rapid, it is also important to achieve such flexibility provision mix to accommodate very complex system requirements. Having in mind above mentioned problems that may cause the problems both in the economic and the technical sense, local electricity markets (LEM) are regarded as a potential solution, but their shortcomings such as vulnerability to exercising market power due to small liquidity should be taken into account also [13].

1.3. Paper Contribution and Structure

The aim of this review paper is to present the most salient features of the ongoing trends in the power market structure, with an emphasis on the distribution-level flexibility. The review includes analysis of the existing market structure so the reader may better understand changes needed to accommodate future flexibility markets. Furthermore, the term and different shapes of flexibility services are presented, the most promising projects and platforms are listed, key stakeholders explained and open questions identified. After the introductory part, the following Section 2 provides a status report on the current trends in the EU. Section 3 shortly presents the existing market structure, while Section 4 explains the most important flexibility mechanisms and characteristics. Section 5 introduces the most important characteristics concerning the distribution level markets, including market designs, clearing approaches and trading services. Next, Section 6 describes TSO-DSO coordination and possible solutions for coexistence of the wholesale and local markets. Section 7 presents the most promising research initiatives and developed platforms, followed by Section 8, which introduces two already widely used conventions. Section 9 explains the most important stakeholders and the role of the flexibility market operator (FMO), while Section 10 concludes the paper.

2. Status in the European Union

Currently, the EU may be regarded as a leader in the race for sustainability. To justify that role and progress toward a sustainable power supply, numerous public initiatives and regulatory measures have been undertaken. One of them is the commitment to cut greenhouse gas emission by at least 40% until 2030 [14]. Moreover, by the same year the expected share of RES should be at least 50% in the entire energy mix [14]. EU regulatory measures are being shaped in such ways that the resources connected to the distribution grid (DERs) are enabled to participate in the markets [15]. Consequently, the task of defining new roles and coordination models between system operators has been placed before the academia and other dedicated task forces [16]. The regulations suggest that the Transmission System Operator's (TSO) responsibility are balancing services, while the distribution system operator (DSO) does not deal with those, but the provision of the balancing services by distribution-level resources is to be agreed between the respective DSO and TSO [17].

Concerning the activities at the distribution level, EU bodies have identified that local-level activities may boost the penetration of RES and secure reliable and safe supply of energy under high share of intermittent and decentralized energy resources. In that manner, Local Energy Community (LEC) has been included in the proposal for the Directive on common rules for the internal market in electricity [18] which follows the EU goals on liberalizing and interconnecting the internal electricity market [19]. Although LECs are described as citizen-led noncommercial cooperatives that mainly produce (renewable) energy for self-consumption [20], they are considered to be under some sort of local flexibility market (LFM) whose task is to manage demand response sources in a market-based manner [18]. With a note that small-scale prosumers should be able to interact with each other and trade flexibility as commodity to adjust their needs in near real-time and avoid penalty costs due to uncertainty and variability of the DERs under their control [21]. The DSO's role is therefore emphasized [22] as the entity that operates exactly the grid where most of the DERs are connected [23].

3. Overview of the Existing Markets

3.1. General Characteristics

Should we observe the existing markets in chronological order, then the markets with the most distant delivery time are forward markets that are based on the long-term contracts [24]. They are mostly used both for buyers and sellers to hedge the risk by contracting price and quantities for delivery in some future point in time [25]. Closer to the delivery time is first the day-ahead market, then the intraday and the balancing market.

Besides chronological order, important fact is the area that respective markets covers and if the trading is conducted on a basis of a copper-plate network representation (no network constraints considered) [26] or with network constraints (nodal approach). In the former, the location of the user is irrelevant, only their bids and offers are considered and any possible congestion is resolved by the TSO with unit re-dispatch, while the latter takes into consideration network constraints. Traditionally, only the transmission system was considered in so-called network-aware models, while the distribution level was considered as a node.

When trading electricity, there is also a distinction whether the trades are conducted bilaterally or using organized commodity-exchange institutions. Conducting the business using the former option assumes a direct contact between the interested parties without any intermediator. All details (price, quantity, terms of delivery, etc.) are agreed directly between the buyer and the seller [27]. Statistics suggest that almost 85% of all electricity exchange in Europe is traded bilaterally, especially the long-term contracts for which this is the usual way of conducting trades [28]. On the other hand, organized exchanges trade commodities with well defined rules and a third party acts as a middleman between the buyers and the sellers who have no direct contact between each other. This is how the day-ahead and the intraday markets are commonly organized.

The price itself in different markets may be formed using two main mechanisms: (i) pay-as-bid and (ii) pay-as-cleared. In the first approach, the sellers get the price that they want if their bid is accepted, i.e., the buyer agrees with the offered price and quantity [29], while the second approach matches the demand and the supply and all market participants pay/receive the same price if their offers are accepted. The price equals the most expensive bid that is accepted, i.e., the marginal price of the most expensive generating unit that operates at least some amount of time in the observed time frame. The day-ahead energy market is a typical example of the pay-as-cleared mechanism. Moreover, reserve and ancillary markets are also more prone to the pay-as-cleared approach, but Italy serves as an example of the pay-as-bid approach for procuring the system reserves [30]. It is important to add that when considering system constraints (e.g., congestion) the pricing can also be nodal or zonal. If congestion than do occur the market may be split into multiple zones with appropriate prices according to the activated constraints.

3.2. Example: Denmark

The market setup in Denmark is used to briefly introduce how different markets actually operate. The setup is similar with other EU countries, but each of them may have its own peculiarities. Those differences are dependent on many factors; from the country's level of development, composition of the energy mix to the memberships in different alliances (e.g., EU) and connection capacities with neighboring countries.

Nord Pool [31] runs a power market for several countries in Europe, including Denmark. It offers the energy day-ahead and the intraday trading. Day-ahead energy market in Denmark is known under the term Elspot [32]. The players are able to trade power contracts for the next day physical delivery with the trading horizon from 12 to 36 h ahead. At 12:00 CET each day the trading closes, and the price is determined by creating demand and supply curves–pay-as-cleared mechanism. Currently, there is a restriction that the published prices must be between −500 €/MWh and 3000 €/MWh. When occurred in the grid, congestion causes price difference between different zones. Intraday energy market in Denmark is known under the term Elbas [33], the power trading continuously flows until one hour before the actual delivery moment. It is settled using the pay-as-bid method.

Denmark has also the balancing markets, also sometimes referred as real-time market. They are used as the last instance to balance the production and the consumption before the physical delivery point. The balancing market itself is divided into two subcategories, namely: (i) regulating and (ii) balancing power market. In the first, the respective TSO (Energinet [34]) buys/sells the needed regulating power (up/down). The stakeholders may offer both the reserved capacity and the energy, or only energy. The latter is used to settle all imbalances occurred in the observed time period. The system is modeled in such fashion so the commercial stakeholder cannot profit from accidentally favorable imbalances (e.g., system needs up regulation, while a commercial stakeholder has taken from the grid less energy than planned).

In addition to the above mentioned markets, the Danish power system structure also incorporates ancillary services: primary reserve (FCR), secondary reserve (aFRR) and tertiary reserve (mFRR). The first is an automatic regulation whose task is to stabilize the frequency following a disturbance. The first half of the activated reserve must be supplied within 15 s, while the rest under 30 s, and it must be able to maintain the regulation for at least fifteen minutes. The supplied energy is settled as ordinary imbalances. The second one is used to restore the system frequency back to 50 Hz. It follows after the FCR so it must be fully in service fifteen minutes after the accepted activation signal at latest. The availability payment is settled using the pay-as-bid mechanism, while provided energy is paid considering the direction (upward and downward regulation) and the spot price. mFRR is used not only to support and replace FCR, but also to ensure balance when disturbances affect production facilities and interconnections. The response time is the same as for FCR. Reservation is conducted via once a day held auctions for each hour of the upcoming day (pay-as-clear mechanism), while the activation is settled following the balancing market rules.

After this introduction to the Danish power market structure, it is important once again to mention that Denmark has been chosen as an example that resembles other EU power markets, but each country's power market structure may differ. Some market mechanism may be altered or even missing due to a number of reasons.

4. Flexibility in General

Two methods are common for providing flexibility in conventional power systems: (i) generation planning and (ii) reserves that are also used to secure system stability in the case of sudden generation outages or transmission line failures [6]. More generally speaking, the flexibility needs may be categorized in four types [35]:

1. Power flexibility,
2. Energy flexibility,
3. Transfer capacity flexibility,
4. Voltage flexibility.

The first one concerns stabilizing and maintaining the frequency stability–in modern era often jeopardized by intermittent energy resources. The second one is to ensure the equilibrium between the energy supply and demand over a longer period of time. The third one is important to avoid possible congestion. Finally, the fourth one is used to maintain bus voltage values within the required limits which are endangered by bi-directional power flows and intermittency.

The three main characteristics that give full information about flexibility provision possibilities are [36,37]:

- The energy capacity [MWh] that can be provided continuously,
- The maximum (and minimum) power output [MW],
- The ramp rate [MW/min] to indicate how fast an unit may change its power output.

In modern power systems the flexibility on the demand side may be provided using energy storage, demand side management (DSM) [38], demand response (DR) as an instance of the DSM that is based on rescheduling the end-user's operation [39] and responsive distributed generation [6]. Considering the flexibility on the supply side, different generation units have different characteristics and, consequently, slower or faster response rate (power ramp) to the load changes [40,41]. Hence, some are more adequate than others to adjust rapidly upon unexpected occurrences. So over the course of years, methods have been developed to take advantage of technology complementarity and its by-products (e.g., heat and electricity in combined heat and power (CHP) plants). In that manner, the USA have in previous years relaxed the problem of their nuclear power plants which must work in a stable manner by installing the pumped hydro-power plants to provide flexibility to the system. When nuclear power plants produce more than the demand, surplus energy is stored in the accumulation lakes, while in the opposite case accumulation lakes are used to produce electricity [42]. Another good example is co-generation—CHPs which are currently producing around 11% of electricity and 15% of heat in Europe [43]. Moreover, combined cycle gas turbines (CCGT) [44], power to gas (P2G) equipment [45], heat pumps [46] and heating, ventilation and air-condition systems (HVACs) [47] are all good examples of increasing energy efficiency and flexibility by combining different energy elements. As the third possibility of creating stable and secure power system under the high RES penetration is the connecting different regions and market coupling. Here the main problem may present bottlenecks—insufficient transfer capacity on some inter-regional lines [48,49].

In the conditions of high penetration of the RES, activation of prosumers and, in general, higher activities on the distribution level grid, Clean Energy Package for all Europeans [50] clearly emphasizes that the DSOs need to procure the required resources from DERs, DR, energy storage systems and similar sources when they, trough a market-based process, offer cheaper services that investing in the network reinforcement and expansion [51].

Flexibility provision from the resources at the distribution level may be used for multiple purposes:

- Congestion management,
- System balancing,
- Portfolio balancing (by balance responsible parties (BRPs)).

Furthermore, concentrating only on demand flexibility, academia states its numerous benefits [52]; from grid expansion deferral, reduced network losses, peak shaving (reduced generation capacity) to better control of voltage and frequency deviations and, consequently, shorter duration and less outages [53]

Long-term flexibility procurement may be beneficial in terms of the grid expansion deferral, as this is the investment whose effect is based on a longer period of time [54]. So, if the flexibility procurement date and interval is suitable for comparison with the effects of the network expansion, the DSO will have the opportunity to calculate and forecast possible grid constraints and have a clear view of alternatives. In that way, the DSO would have the possibility to opt for more sound option.

Although it might seem pretty simple and obvious, it is not out of place to explain why does exactly flexibility enable faster and higher penetration of RES. Higher rates of flexibility presumably reduce the curtailment of RES and associated negative market prices. In such environment curtailment of RES is down to almost a negligible percentage and market prices are (if not stable, at least) always positive. This creates solid grounds for a viable business plan, favorable cost-benefit analysis (CBA), meaning that both the investors (entities that invest money) and the creditors (entities that lend money) are more willing to participate in such projects due to lower level of risks in the following aspects:

- Market prices (for how much the generated energy will be sold),
- Revenue stream (if there is little curtailment, it can be considered stable) [55].

5. Distribution Level-Markets

Section 3 explained the existing power market structure. Conventional transmission-level wholesale market structure was appropriate for the traditional power systems where electricity generation was centralized. The generated energy was transferred from large generating units using transmission system to different distribution zones where end-consumers were located. Moreover, in the conventional setup the respective DSOs had the task of passively operating, maintaining, reinforcing and expanding the distribution network to meet the demand requirements and ensure safe and reliable power supply [56]. However, nowadays the paradigm has changed and distribution networks face challenges due to increased share of: intermittent decentralized (small-scale) energy resources and energy storage systems.

Such decentralized paradigm causes many technical challenges: bi-directional power flows, congestion and voltage limit violations [57]. Furthermore, although DERs may potentially trade their services, due to their small capacities, the decentralized paradigm requires a new market structure to accommodate services that small decentralized distribution-level units (both RES and energy storage systems) may provide.

5.1. Architectures

Although there are already several pilot projects and operational local markets (see Section 7), it is fair to say that they are still under the research and development phase. As such, various architectures are under consideration, and it is still unclear what is the optimal solution. Moreover, it would be perhaps better to say that different market models fit different purposes and one should not exclude the other counting on their specific characteristics. Perhaps the most general question is who are the main and required market players. In the most abstract sense, this can be tackled in the following ways [58]:

1. Peer-to-peer (P2P) trading,
2. Trading through a mediator,
3. Combination of the two previous cases.

In the first case, only buyer and seller entities are necessary, as they conduct trades directly, without thee need for a third party [13,59–62]. In the second case, besides the seller and the buyer, a third party is also present. It is an intermediary between two parties willing to conduct a trade. Nowadays, most of the proposed models include some sort of third party whose role is assigned to various stakeholders (DSO, aggregator, independent market operator, . . .) [18,63–68]. The third case simply combines the first two options. After defining the roles in an abstract manner (more detailed explanation in Section 9), according to Jin et al. [69], distribution-level flexibility markets may be divided into four main groups. Namely: (i) centralized optimization models, (ii) auction-theory based models, (iii) simulation models and (iv) game-theory based models.

5.1.1. Centralized Optimization Models

In centralized optimization models the focus lies on one participant. The model consists of an objective function accompanied by technical and economical constraints. Two main types of objective function are: (i) social welfare maximization and (ii) operational cost minimization. The term "social welfare maximization" comes from the economy and is calculated as the summation of the utility of all buyers minus the cost of all sellers (revenue minus cost), while non-profit market operator's welfare should be zero [58]. On the other hand, the operational cost minimization objective seeks to minimize all the costs (e.g., DSO's). Depending on the case, the objective function may put focus on different stakeholders (DSO, aggregator, . . .).

5.1.2. Auction-Theory Based Models

As opposed to the centralized optimization model approach, in models based on the auction theory, the focus is on finding the market clearing price in accordance to the stakeholders' bidding strategies (both sellers and buyers). The mediator in the process, the auctioneer, collects the bids and determines the clearing price. In the pay-as-cleared system, the nominated buyers pay the same price, while the nominated sellers all receive the same fee. Nominated are those sellers whose offered price is lower or equal to the cleared price, while nominated buyers are those whose offered price is higher or equal to the cleared price. In the pay-as-bid system, the nominated sellers receive the fee they asked for. When speaking about auction-theory based models, it is also important to distinguish single- and double-side models. In the former, there are either several buyers and one seller (forward auction), or several sellers and one buyer (reverse auction). The latter model includes multiple sellers and buyers. The double-sided auction is the most general type, thus most appropriate in vast number of occasions. Should only one DSO procure flexibility services from various aggregators, then the reverse auction would be suitable.

5.1.3. Simulation Models

Multi-agent based simulation models [70] are constructed so an agent simulates the behaviour of the participant it represents. Hence, it is a good method for situations with multiple participants, as it captures the dynamics of the electricity market and can be applied to huge systems [58,71,72].

5.1.4. Game-Theory Based Models

According to the Stanford Encyclopedia of Philosophy [73], game theory is the study of the ways in which interacting choices of economic agents produce outcomes with respect to the preferences (or utilities) of those agents, where the outcomes in question might have been intended by none of the agents. Thus, the models based on game theory focus on competition of all market participants who are rationally trying to maximize their profits. There are two major groups of algorithms: the cooperative game, which models a competition between stakeholders who present cooperative behaviour, and non-cooperative game, where stakeholders plan their strategies individually.

Cooperative Game Theory

The cooperative game theory focuses on rational cooperative players with cooperative behaviour [69]. The method is applicable in situations where information sharing among participants is possible, allowed and desirable. In the case of flexibility markets, normally the DSO is not willing (or even allowed) to share network information to other participants. Considering the possible applications in modern power systems, Reference [74] presents a survey on cooperative game theory expansion planning strategies, while Kristiansen et al. [75] analyse the benefits of alternative flexibility providers, such as fast-ramping gas turbines, hydro power plants and demand-side management using the cooperative game theory.

Non-Cooperative Game Theory

Non-cooperative game theory describes a competition among participants who have partially or entirely conflicting interests [69]. The non-cooperative game theory is better suited for situations where participants may acquire only partial information, as it expects from players to decide their strategies without any information exchange with other participants. Non-cooperative game theory is widely spread in the energy trading literature, even for distribution-level markets. In that manner, Reference [76] considers electricity market structure with high DERs penetration and proposes a general framework for implementing a retail energy market. As an instance of the non-cooperative game, the Stackelberg model is a leader-follower model where the leader takes the action first and then the follower acts sequentially. The premise is that the leader decides on its actions by knowing the expected reaction from the follower. Haghifam et al. [77] proposed a novel framework for participants in the local markets using the Stackelberg approach to deal with the inherent conflict between the existing players' interests. Furthermore, Bruninx et al. [78] captured the aggregator-consumer interaction using Stackelberg and Nash Bargaining Game. The authors argue that demand response provider-aggregator cooperation may yield significant monetary benefits.

5.1.5. What Design to Choose?

Each of the described architectures has its own pros and cons. Also, different situations require different architectures. When only one participant is in the focus of interest, than the best solution is an centralized optimization model. This simplifies the model, but neglects certain aspects, such as utility goals of the non observed participant When considering a vast amount of players, centralized models have scalability issues. Moreover, all the other listed models provide somewhat more accurate description of the participants' behaviour, but causing higher computational burden. It is interesting to mention that centralized optimization models may be used to focus on behaviour of one agent in multi-agent models [69]. The drawback of the auction-theory based models is the fact that excessive competition may lead to unwanted auction price spikes, while the biggest perk is the ability to quickly reach equilibrium between the supply and demand curve with low computation effort. The main characteristic of the agent-based modeling is that it is a simulation, so it tries to replicate possible human behaviour and present it using mathematical models. When using game-theory models, one should have in mind that they assume rationality for all players, which is often not the case in real-life situations.

5.2. Market-Clearing Models

The previous section shortly described the most important distribution-level designs, but without an explicit mention how such models clear the market. This section provides a glimpse into the market-clearing models with a note that the market architecture and the clearing models are strongly connected. Thus, when opting for a market-clearing model, the model architecture is practically given and vice-versa. According to [69], market clearing methods may be divided as depicted in Figure 1.

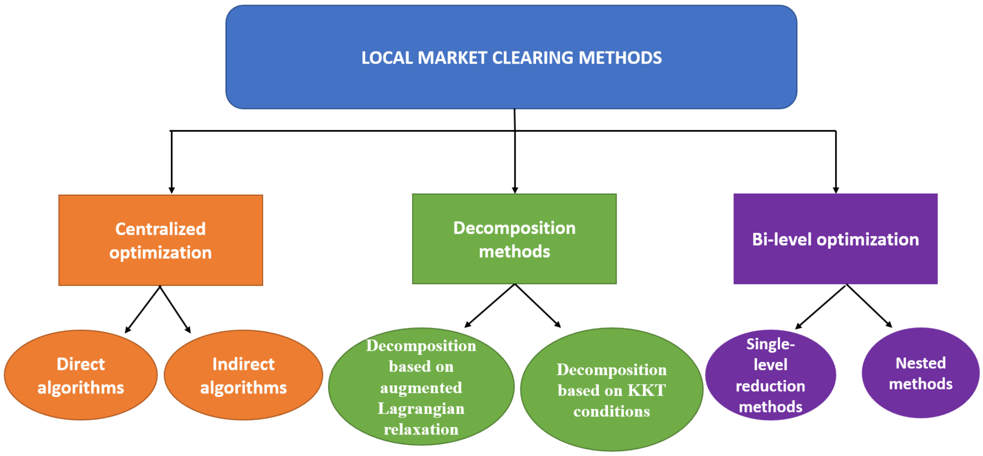

Figure 1. Local markets clearing methods.

5.2.1. Centralized Optimization

As the name suggest, centralized optimization is the clearing method for the centralized optimization models. It consist of an objective function (to be minimized or maximized) and a set of constraints. Depending on the constraints, the problem may be linear, non-linear, mixed integer (non)linear, quadratic, ... Direct and indirect algorithms may be used to solve such problems. Direct algorithms can be directly solved using existing commercial solvers, such as GUROBI [79], CPLEX [80], IPOPT [81] and others, while indirect algorithms need to be converted to a format suitable for the existing solvers. For instance, when network constraints are included in the model, AC OPF introduces a non-convexity that needs to be relaxed to obtain a convex optimization problem. Generally, direct algorithms clear linear convex centralized optimization problems and problems that are converted to that format. On the other hand, the indirect approach is usually used when network constraints are taken into account, and this should be the case in the local energy markets so congestion and voltage problems are considered.

5.2.2. Decomposition Methods

We already mentioned that problems with a large number of participants may cause scalability issues when using centralized optimization methods. Hence, a logical way to deal with huge models that cause high computational burden is to divide them into smaller sub-problems. Exactly this is the *modus operandi* of the decomposition methods. Solving sub-problems individually lowers the computational burden, as it decentralizes the efforts to each respective sub-problem. Reference [69] names two groups of decomposition methods. The first one relies on the augmented Lagrangian relaxation, while the second one is based on Karush-Kuhn-Tucker (KKT) conditions. Although the augmented Lagrangian relaxation does not have scalability issues regardless on the number of constraints, the problem occurs when a problem is non-convex and has a dual gap. To overcome this problem, a relaxation technique is used—an augmented penalty function. Reference [69] explains four main decomposition methods based on the augmented Lagrangian relaxation. Namely, alternating direction method of multipliers (ADMM), analytical target cascading (ATC), proximal message passing (PMP) and auxiliary problem principle (APP). KKT-based decomposition primarily uses optimality condition decomposition, where first-order KKT optimality conditions are decomposed and solved by sub-problems [69].

5.2.3. Bi-Level Optimization

Stackelberg model was already mentioned as a possible architecture for distribution-level energy markets. There is a clear hierarchical structure consisting of a leader (or multiple leaders) and a follower (or multiple followers). Exactly this type of problems is solved using bi-level optimization. Bi-level problem is an optimization problem constrained by another optimization problem (in addition to the conventional constraints) [82]. Bi-level problems are solved either using single-level reduction techniques (using only KKT conditions or using KKT conditions and duality theory) or nested methods [69]. When both the upper- and the lower-level problems are linear, KKT conditions are enough to reduce the problem into a single-level equivalent and solve it using available commercial solvers. Bi-level problems where the upper-level is non-linear cannot be solved using only KKT conditions, but with help of the dual theory the upper level may be linearized and then solved. The nested methods are used for bi-level problems where the lower-level problem is non-linear. In the nested method, an appropriate optimization algorithm deals with each of the levels depending on the mathematical properties [69]. Although this provides a possibility to solve even the most complex problems (upper- and lower-level problems ARE non-linear), it comes AT a price of high mathematical burden.

5.3. Trading Services

The proposed distribution-level markets are a tool intended to help DSOs and enable integration of high amount of DERs into the power system. However, the question is what exactly a DSO needs. An article written by Silva et al. [83] listed and explained in detail the DSO local system needs. In this section we list those services and describe them briefly. For a thorough survey, an interested reader is invited to read [83]. The most common problems (especially under a high DERs share) include voltage limit violations and congestion problems. However, there are other problems the DSOs may face. The following list brings the most widespread ones according to the [83] and research conducted by EUniversal project [84]:

- Congestion management,
- Voltage control,
- Support for network planning,
- Phase balancing,
- Support for extreme events,
- Support for planned/unplanned operations.

Congestion management is a common problem at the distribution level which can be dealt with by flexibility procurement. Depending on the time horizon the congestion is dealt with, problem may be solved in the long-term, the short term (day-ahead, intra-day, month-ahead), or during operation (real-time). Voltage control is of high importance because over- or undervoltages and other voltage extreme situations may cause damage to the loads. Under high DERs penetration, increase in voltage regulation and balancing capabilities is currently considered as a viable solution. More specifically, remote DER control could be very helpful, and this could also be achieved using market-based mechanisms. Phase balancing, needed mostly due to uneven connection of single-phase loads, could be solved either indirectly when dealing with voltage limit violations or directly by reconfiguring the low-voltage networks or controlling the single-phase DERs. In case of network planning, flexibility services may help defer the grid expansion needs and lower the capital expenditure. Flexibility services may help in reducing energy demand shedding both for the planned and the unplanned operations. When network reconfiguration and flexibility services are not an option, alternatives are islanding, black-start, emergency load control and mobile generation capacity. Similar solutions are also valid during extreme events [85].

5.4. Alternatives to the Distribution-Level Markets

Distribution-level markets are generally poised as a solution for possible problems generated by DERs at the distribution level. Although this literature survey focuses on distribution-level markets, it is useful to briefly mention and describe alternatives of solving problems generated by DERs at the distribution level. Jin et al. [69] divided congestion management and voltage control methods into two groups. The first one considers market-based methods and consists of:

- Local flexibility markets,
- Local energy markets,
- Price-based control,
- Transactive energy.

The second group considers control-based methods and consists of: (i) virtual power plants and (ii) active network management.

Both local flexibility markets and local energy markets are the core topic of this article, so they won't be further explained in this section. Their alternatives start with price-based control. It heavily relies on the accuracy of forecasts, as the DSO publishes the congestion price somewhat prior to the some event in future when potential congestion may occur. According to the price signal, flexible demands adjust their consumption curve if possible. Next, transactive energy is *a set of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter* [86]. Reference [87] proposed a framework based on network-constrained transactive energy to coordinate flexibility at the distribution level and enable the aggregators' participation in the balancing market avoiding congestion and voltage level violations in the distribution network. Using the transactive energy approach TSO-DSO coordination has been accomplished while preserving users' privacy. Similarly, Reference [88] also used the transactive energy approach, but with the emphasis on EV aggregators. Authors praise this decentralized approach for improved users' privacy and light computational burden.

When it comes to the control-based methods, Refenence [69] described DERs aggregated in a virtual power plant as method to achieve system visibility, controllability and impact like a conventional generator. While active network management is a DSO's tool to solve congestion and voltage limit violation problems by controlling the DERs, flexible demands and grid equipment in a centralized way.

When comparing these methods with the distribution-level markets, it is important to note that distribution-level markets offer an opportunity for all included parties to benefit from participating. On the other hand, the control-based methods are developed in such manner to directly benefit the DSO, while other participants are obliged to follow the signals (be they control or price signals). Meaning that in terms of the general social welfare, distribution level markets are indeed necessary to successfully accommodate high share of RES and provide possibilities for everyone to benefit from the need newly caused need for the flexibility.

6. Wholesale Meets Local Markets and TSO Faces DSO

In the conventional (old) power systems, the structure was centralized. TSO had the dominant role and energy trade was conducted under its supervision in wholesale markets. High penetration of DERs (that are predominantly connected to the distribution grid) causes disruption of the established paradigm. Not only that generation doesn't come anymore from the centralized generating units, but RES bring higher dose of uncertainty, and consequently bigger need for flexibility services. Hence, both TSO and DSO face a lot of pressure, with emphasis on dealing with uncertainty, bi-directional power flows, voltage limit problems and congestion at the distribution level. In the past, DSO was a passive entity which had the task of securing safe and reliable power supply, and that was mostly achieved with network expansion investments using fit-and-forget approach [89,90]. That included planning grid expansion according to the worst-case-scenario, no matter how unlikely is to happen, and economical viability of such investment. Other methods such as flexibility procurement or active network control were not used because they were either forbidden for DSOs, or the respective DSOs did not have financial incentive to do it.

DSOs are slowly evolving to more active players, engaging in control of DERs to solve problems on the distribution level. The problem arises as DSO interferes with TSO's tasks, but on a lower level. So, without proper coordination mechanism, fixing a problem on the distribution level may cause additional headaches on a transmission level and vice-versa. The EU has put emphasis on active role of DSO and distribution grid and efficient DSO-TSO coordination to successfully accommodate high penetration of RES and EU climate goals [16]. Although they are intended for ancillary services, according to the EU directive [16] they also include congestion management. So in addition to the grounds for efficient flexibility markets, such coordination mechanisms provide also alternative approaches to solve possible problems generated by high share of DERs.

All of the observed TSO-DSO coordination mechanisms share similar prequalification, activation and settlement of flexibility resources, but from the first mechanisms towards the last (in the enumerated list attached below in the text), it is noticeable the evolution of the DSO role as it becomes more and more active participant. By the term prequalification, we understand the process of checking the potential impact of some flexibility service that TSO procured would have on distribution grid. Should the impact be negative, the DSO would send appropriate signal to the respective TSO to alter its plans. Such methods offer solution of the problems caused by DERs even without the distribution level flexibility market. In that manner Moon et al. [91] used prequalification process to accommodate high DERs penetration for the case where DSO cannot directly dispatch the resources. The similar idea had the authors in [92], where DSO checks the feasibility of the bids in the day-ahead energy and reserve markets using AC OPF. To distinguish aggregator and DSO problems, decomposition technique divided original problem to separate sub-problems.

The TSO-DSO coordination mechanisms for procuring ancillary service in Europe can be divided into five different types [93]:

1. Centralized ancillary services market model,
2. Local ancillary services market model,
3. Shared balancing responsibility model,
4. Common TSO-DSO ancillary services market model,
5. Integrated flexibility market model.

6.1. Centralized Ancillary Services Market Model

In this model TSO has the active role, while the DSO is entirely passive. Flexible resources connected both to the transmission and distribution grid are only to be activated by the TSO which isn't obliged to consider distribution grid constraints. The TSO is in the same time system and market operator, and no local markets are intended for this model. DSOs are not allowed to solve its problems using DERs in near or real-time. Eventually prequalification may be used to ensure compliance with distribution grid constraints. Comparing current market setup with the centralized ancillary service market model, it is easy to conclude that they are very similar so one of the perks of this model is the ease of implementation. Furthermore, centralized market removes any concern about possible low liquidity, while its main disadvantage is the fact that system operator cannot use DERs to solve the problems on the distribution grid. TSO-DSO communication is leaning towards none, the exception are distribution level network constraints if the respective TSO considers them

6.2. Local Ancillary Services Market Model

This model shifts some jurisdiction towards the distribution level. Opposed to the centralized market approach, here are existent local markets also. They are operated by DSOs, while TSOs still operate central market. The DSO (which considers its constraints) has the priority to use the DERs connected to the distribution level for the local congestion management and voltage control, therefore local market (with DSO as only buyer) is cleared before the market operated by the TSO. The remainder of the services offered in the local market is then offered in the central market. Here, the DSO-TSO coordination is necessary to avoid the flexibility services procurement in the opposite directions. Furthermore, opposed to the centralized ancillary service market approach where is no fear of low liquidity, vast number of local markets may cause liquidity problems. Although in theory this can help create tailor-made flexibility services for each local district, it also causes aggregation problems when offering the remainder of flexibility services in the TSO operated market. Furthermore, it raises the danger of RES curtailment or load shedding if DSO needs and flexibility offers in some district aren't harmonised.

6.3. Shared Balancing Responsibility Model

This model is at first similar to the previous one. Two markets are present. TSO operates the central market, while DSO operates the local market. The big distinction from the previous model is the fact that the TSO may procure flexibility only from the central market, while the DSO procures the needed flexibility from the local market and both markets are cleared simultaneously. Now DSO is not only market operator, but is also takes a share of responsibility for the distribution grid balancing (in addition to the congestion management). Prerequisite for such model is TSO-DSO communication to agree on predefined schedules which eliminate the possibility for TSO and DSO to operate the system independently. To define the schedule, two methods are used:

- nominations of balance responsible parties taking the energy-only market as a base,
- nominations of balance responsible parties and historical forecasts at each TSO-DSO interconnection point.

The first method requires only one schedule for entire area operated by the local DSO, but it is not able to account for real-time or near-to-real-time constraints at TSO-DSO connection points. The second method brings somewhat bigger burden for calculation and TSO-DSO communication, but it determines a schedule for each TSO-DSO connection point considering network constraints. This model may also encounter liquidity problems and higher price for ancillary services and higher operational costs for DSOs (but lower for TSOs) as the local markets are separated from the central market and operated by local DSOs. The biggest threat is the total system instability if the DSO is not able to realize balancing responsibilities for the respective area.

6.4. Common TSO-DSO Ancillary Services Market Model

There is only one ancillary services market jointly operated by the TSO and DSO. Neither of system operators have the priority as the system equilibrium is the ultimate goal of the model and the flexibility is therefore provided to the entity which needs it more. The model may be realized in two ways; (i) one central market operated by TSO and DSO and (ii) multiple local markets. The firs solution decreases market operating costs for TSO and DSO, using the DERs to operate the system in the most efficient manner including the distribution grid constraints in the market clearing, but as transmission and distribution network constraints are observed simultaneously–for big systems the optimization problem may present big mathematical burden. While the other option brings higher operational costs and possible liquidity problems. But, as firstly only local grid constraints are considered and then shared with TSO and integrated into second optimization including TSO constraints, it relaxes the mathematical burden of big systems. Some suggest that an independent market operator is necessary for both solutions to ensure neutrality.

6.5. Integrated Flexibility Market

In this model, alongside system operators (TSO and DSO), deregulated participants may also procure flexibility. They are allowed both to sell and buy ancillary services. In this market setup, independent market operator is necessary prerequisite to ensure neutrality and equal playground for all market participants, and market clearing process should take into account distribution level constraints. Such market setup ensures high market liquidity and lower prices as all of the services are located in one common market, but this could influence trading volumes in the day-ahead and intraday energy markets. Furthermore, acquired flexibility may be resold (if not necessary for the entity that procured it), and the financial burden of running the market shouldn't stress anybody as it may be share among high number of participants. Perhaps the biggest downside of this model is the possibility that TSO may acquire ancillary services to maintain stability of the system outside of the market if deregulated players cause that with their market actions. Some scenarios even include that the competition may lead to activating services in opposite direction at the distribution and transmission level, resulting with high costs for the end-users. But on the other hand, price may be good measure how badly TSO needs such services, and with proper safety mechanisms such fatal scenarios may be avoided.

6.6. Alternative Grouping of TSO-DSO Coordination Mechanisms

When observing the five TSO-DSO cordiantion mechanisms for procuring ancillary services, the roles of TSO and DSO may be divided in three big groups. Namely, (i) TSO managed model, (ii) TSO-DSO hybrid managed model, and (iii) DSO managed model. Exactly this grouping introduces [90]. The first model is the most similar to the current situation and it may be considered as a step towards the successful integration of high share of DERs. Although it may consider distribution level constraints, its biggest drawback is the scalability. While in the other two models, the DSO is given a more active role. In the hybrid model the DSO validates the bids, while in the DSO managed model both validation and dispatch are under DSO's jurisdiction. As this is somewhat generalization of the five methods explained above, other details won't be listed, but they are explained in [90].

7. Research Initiatives and Platforms

Local flexibility markets and flexibility in general are not so far from the infancy stage in the real-life. On the other hand, both academia and R&D oriented departments in the commercial sector are extremely active in exploring various flexibility provision and high RES penetration models. There has been a significant number of research initiatives over the past years. Many projects have already proposed various views on how the distribution level markets should be organized, how to secure optimal provision of flexibility and analysis of how would enhancements of the existing power market structure benefit all interested stakeholders, from the profit-oriented ones to the people in general considering environmental protection. Consequently, many projects deal with the high RES penetration, TSO-DSO coordination, distribution level flexibility trading and similar topics. Moreover, there are already many platforms which may still be under development, in beta phase or even fully functional and used in some areas for flexibility procurement and trading. Two following subsections will provide a short overview of the most advanced and promising projects and platforms with small note that EU as the leader in the research towards sustainable power system is sponsor of the most below listed projects and platforms with its HORIZON 2020 program [94].

7.1. Projects

SmartNet (H2020, finished in 2019) [95] considered the TSO-DSO coordination under different scenarios including the development of the LFMs, among which two types are considered:

- local ancillary services real-time market,
- TSO-DSO ancillary services market model.

They conclude that low liquidity would inevitably cause exercising the local market power in addition to higher ICT costs, so the local flexibility should be "reasonably" large, and small DSOs should pool-up and create a common congestion management market [18].

EMPOWER (H2020, finished in 2018) [96]—investigated the development of local electricity retail markets to encourage citizens, future prosumers, to produce and consume energy in a more energy efficient manner. They concluded the project with proposals with three basic types of market platforms for local electricity trading, local flexibility trading and other services.

INVADE (H2020, finished in 2020) [97]—although not directly dealing with LFM design, their findings are of great importance as they were considering new business models and way of doing day-to-day business in power sector to support the distribution grid and electricity market while coping with grid limitations, uncertainty and variability with high penetration of renewable energy, electric vehicles and an increased number of diverse smart grid actors.

FLEXGRID (H2020, ongoing) [98,99]—development of a holistic smart grid architecture based on the inclusion of distribution level markets to accommodate high RES penetration. In the project emphasis is given on the integration of the future distribution level markets with the existing market structure. In that manner, article [100] observes integration of two types of the distribution level markets. One type is cleared before the day-ahead energy market, while the other is cleared after. The goal is to develop functioning trading platform for flexibility providers and entities (DSO) that need to procure the flexibility services.

INTERFLEX (H2020, finished in 2019) [101]—they developed local market mechanism with main goals of dealing with congestion management and grid reinforcement deferral in addition to the development of DERs and preparing the electric system for new uses, including e-mobility. The DSO was the single buyer on those local markets. It included various energy carriers (electricity, gas, heat) and multi-service and islanding options, in addition to the demand response schemes.

The REnnovates project focused on residential households and price incentives to provide congestion flexibility services. The construction company (BAM) equipped each of these homes with an insulating shell, consisting of secondary facades and an extra roof layer with solar panels. The goal was to examine the extent to which older rented houses can be converted in a cost-efficient manner, in such a way that they meet today's efficiency and comfort standards. Available results suggest that the total energy consumption of the homes in the Rennovates project will decrease by more than 60% [102].

iPOWER (over in 2016) [66] proposed a number of potential distribution grid flexibility services, as a result FLECH have been developed and demonstrated, for formalized and transparent interaction between suppliers and consumers of flexibility. FLECH [103] is a flexibility clearing platform relying on the customer-aggregator-DSO setup. As the main drawback, neglecting the TSO may be mentioned.

Coordinet (H2020, ongoing) [104] emphasizes the TSO-DSO coordination and their usage of the same pool of resources. It thoroughly analyzed different TSO-DSO coordination mechanisms and constructed seven different models to analyze over the course of the project. The models include various scenarios (e.g., in some solutions TSO doesn't have access to DERs, in some has, . . .) and they have encompassed all of the general TSO-DSO models. Research results should provide valuable insight about each of the observed models.

INTERRFACE (H2020, ongoing) [105] focuses on the DSO-TSO coordination and interaction with customers for a smooth and reliable flexibility procurement through an Interoperable pan-European Grid Services Architecture (IEGSA) that is to be designed and developed as a part of the project. It focuses on joint TSO-DSO market model. AS the project is still ongoing, until now extensive survey on TSO-DSO coordination schemes has been conducted and based on that market designs were developed which will act as the blueprint for the implementation of different markets in the demonstration projects.

InteGrid (H2020, finished in 2020) [106] proposed solutions for DSOs how to operate grid in order to enable high penetration of DERs and to motivate all stakeholders to actively participate in (local) energy market. With the emphasis on informing passive consumers how can they become prosumers and how can they benefit from that change.

EU-SysFlex (H2020, ongoing) [107] proposes solutions to challenges concerning integrating large-scale renewable energy and provide assistance to power system operators across the Europe. Until now they have put great emphasis on current status pf RES integration in Europe, analyzing existing market models, regulatory framework and simulations how would high(er) RES share affect respective markets.

GOFLEX (H2020, finished in 2019) [108] focused on local distribution markets for distributed flexibility and automated dynamic pricing with the main goal of accelerating

RES penetration and flexibility services development. It demonstrated flexibility-trading solutions for cost effective use of demand response schemes in distribution grid, disregarding TSO.

DRES2Market (H2020, ongoing) [109]—the main goal of the project is to propose accurate and affordable approaches for effective integration of distributed generation based on variable renewable energy. As the project is in its early stage, first firm results are still awaited.

EUniversal (H2020, ongoing) [110]—aims to develop a universal approach on the use of flexibility by Distribution System Operators (DSO) and their interaction with the new flexibility markets, enabled through the development of the concept of the Universal Market Enabling Interface (UMEI). The prerequisite for UMEI development was to define the flexibility services considering the DSOs needs in different time frames, from real time operation to long-term planning. And those were already listed in this article in the section about trading services.

sthlmflex (Swedish project) [111]—in cooperation with NODES their goal is to test a regional flexibility market in the Stockholm area to bridge the capacity gap that can be experienced during winter months.

OneNet (H2020, ongoing) [112]—the goal is through a proposal of new markets, products and services to create conditions for fully exploiting DR, storage and DERs and to create fair, transparent and open conditions for the consumers.

7.2. Platforms

The following five platforms are all developed to make flexible resources at the distribution level possible to the Flexibility Service Providers (FSPs) [113]:

- Cornwall Local Energy Market [114]
  - Owned by centrica and it encompasses the TSO-DSO level
  - Pricing method: Pay-as-clear
- Enera [115]
  - Owned by TSO, DSOs and EPEX SPOT, and it encompasses the TSO-DSO level
  - Pricing method: Pay-as-bid
- GOPACS [116]
  - Owned by TSO and DSOs and it encompasses the TSO-DSO level
  - Pricing method: Pay-as-bid
- NODES [117]
  - Owned by power exchange (NordPool) and encompasses the TSO-DSO level
  - Pricing method: Pay-as-bid
- Piclo Flex [118]
  - Owned by Piclo and encompasses only the DSO level
  - Pricing method: Pay-as-bid

In addition to the above mentioned market platforms, here we list others that do not share exactly the same goals as the ones listed above:

- CoordiNet [104]
  - Owned by TSOs and DSOs and it encompasses the TSO-DSO level
  - Pricing method: Pay-as-bid and Pay-as-clear (depends from case to case)
- INTERRFACE [105]
  - The ownership is not yet decided, but the platform will encompass the TSO-DSO level
  - Pricing method: Pay-as-bid
- FLEXGRID ATP [98]

- No market stakeholder or grid owner can be a major owner of the FLEXGRID marketplace, ideally it would be fully independent. It is focused on the DSO, but interaction with the is taken into account
- Under development

- InteGrid [106]
  - Owned by TSOs and DSOs and encompasses the TSO-DSO level
  - Pricing method: Pay-as-bid
- EU-SysFlex [107]
  - Owned by TSOs and DSOs and it encompasses the TSO-DSO level
  - Pricing method: Pay-as-bid and Pay-as-clear
- GOFLEX [108]
  - Owned by smaller DSOs and local energy suppliers and encompasses the TSO-DSO level
  - Pricing method: no unambiguous answer
- DRES2Market [109]
  - The ownership is not yet decided, but it will encompass only the DSO level
- InterFlex [101]
  - Owned by DSOs and encompasses only the DSO level
- EUniversal [110]
- Flexible Power [119]
- sthlmflex [111]
- OneNet [112]

8. Conventions

The standards ensure that goods or services produced in a specific industry come with consistent quality and are equivalent to other comparable products or services in the same industry. Standardization also helps in ensuring the safety, interoperability, and compatibility of goods produced [120]. The most important thing about standardization is the fact that it lowers the costs, introduces uniqueness and therefore accelerates the adoption of services (or goods). Hence, for the distribution-level (local) markets, it is advantageous to standardize the framework and build models in the regulated manner. Research conducted in the field of distribution level flexibility has already produced some demos and results, but also by surveying the articles it is noticeable that few conventions stick out. This section brings short introduction to the two frameworks that are regarded as potentially useful guidelines when dealing with TSO-DSO coordination, LFMs and similar subjects.

The question which stakeholder should have priority, in what manner should LFM operate and what is it primary purpose under different circumstances is one of the hot topics in academia, and also an important dilemma to be agreed on before designing and developing markets for the 21st century. To regulate this important hierarchy of the stakeholders connected to the LFMs and their roles in different scenarios, one of the most commonly used system is so called Traffic Light Method (TLM) [121], shown on the Figure 2. The green state represents normal operating state in which the network doesn't face any threats in the imminent future and the LFM operates freely. The amber state indicates that the grid operators should actively engage with the LFM to prevent going to the red state. The red state denotes that the grid operator should take control of the LFM and it may override existing contracts if it finds such measures necessary [18].

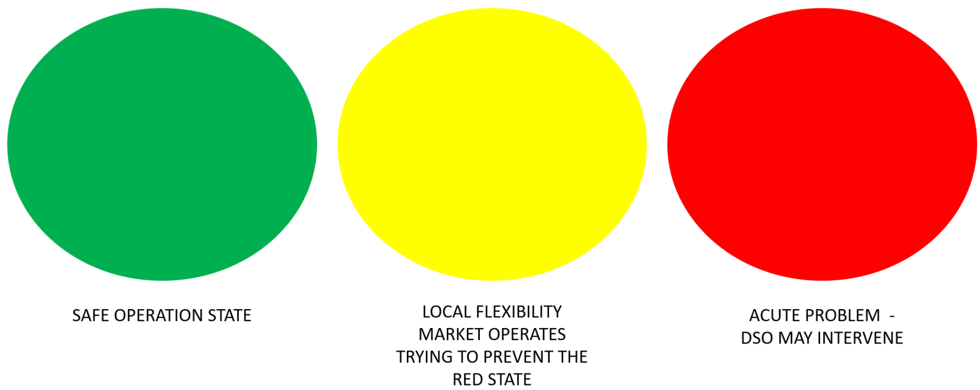

Figure 2. Traffic Light Method

Among the surveyed articles, Refs. [17,18,67,122,123] are good examples of mentioning and using the TLM concept.

One of the main challenges when designing LFMs and expanding the operations of the DSOs is how these changes will affect the respective TSO and how should they interact or should they even interact. Universal Smart Energy Framework (USEF) [124] is a framework for modeling and creating an integral market for energy flexibility trading [18]. It provides a set of specifications, designs and implementation guidelines that enable interested party to establish a fully functional smart energy system [125]. It is developed by an alliance of national and international companies and planned demonstration projects are to connect thousands of residential and small business users. Among surveyed papers, we single out the following works that relied on USEF: [18,68,126].

9. Stakeholders and Role of the FMO

In this section three most important stakeholders in the terms of LFMs are shortly explained, namely: (i) prosumer, (ii) aggregator and (iii) DSO. Furthermore, the role of the FMO is discussed.

9.1. Prosumers

Prosumers [127] are the one of the key factors in the novel distribution level flexibility markets. They are consumers that actively participate in the markets by not only consuming energy, but also producing it and/or providing up and down flexibility services when appropriate signals are received. They may posses renewable energy sources such as PV panels and wind turbines, energy storage systems and other controllable and uncontrollable units. They may act on their own and even engage in the P2P trading [60], but due to their usually small size (capacity and power) it is sound to cluster them and then offer the clustered flexibility. Aggregators (described in the next subsection) are then intermediary between the prosumers and flexibility procurers.

9.2. Aggregator

The aggregators are an important entity to cluster small DERs and enable them to participate in markets. Aggregators may be defined as market intermediaries between flexibility providers (i.e., prosumers) and entities that want to procure flexibility services (e.g., DSO). One may distinguish industrial and residential aggregators. For instance, Energy Pool is a French aggregator whose beginnings date back to the 2008. year [128] and his clients are mostly large industries and heavy electricity consumers (e.g., data centers) spread all over the country. On the other hand, Voltalis is an aggregator focused on the residential customers who get a box installed in their home, named Bluepod, which reduces their electric heating device operation in short time intervals when Voltalis receives a signal from the TSO [129]. Besides those two, we mention also Flextricity (industrial aggregator) [130] and Delaware EV pilot [131]. Those aggregators and a project in the pilot phase (i.e., Direct Energy) are listed in the Table 1:

Table 1. Some of the existing aggregators.

Aggregator	Focus Group	Business Model	State
Energy Pool	Large industries and heavy electricity consumers	(1) DR flexibility–load reduction by making optimal decisions for each customer (2) Balancing markets, reserves, capacity and energy markets	France
Voltalis	Residential users	(1) Reductions in electric heating devices (2) Balancing markets and DR mechanism for TSO	Great Britain
Direct Energy	Pilot phase—users that used the same company as a retailer	Mainly users with water heaters and convector heaters Load-shedding programs	France
Flextricity	Large industrial and commercial customers	(1) Generation and load aggregation, (2) DR programs -triad management (3) Participating in the short-term operating reserve	United Kingdom
Delaware EV pilot	flexibility service providing Electric Vehicles (EVs)	(1) Vehicle to Grid (V2G) project (2) Frequency regulation	USA

In addition to the above mentioned and shortly described aggregators, as one of the most important entities in all proposed flexibility market designs, [113] mentions four other noteworthy aggregator platforms, namely: (i) TIKO [132], (ii) Equigy [133], (iii) Quartierstrom 1.0 [134] and Repsol Solmatch [135]. They are intended to cluster small flexible cluster, so that may participate on markets to offer their flexibility service. In addition to that, some of them promote P2P transactions ([134,135].

9.3. DSO

DSO's main task is to ensure secure operation of the distribution network and efficient service [136], such tasks have traditionally included planning, maintenance and management of the distribution level grid. They are also responsible for connection and disconnection of DERs and management of supply outages [10]. When planning future grid expansion to mitigate possible congestion, nowadays flexibility services are imposing as a very interesting alternative.

9.4. Local Flexibility Market Operator

The FMO is an entity that manages the operation of the most important aspects of the LFM, such as bidding, clearing and settlement of the market. When deciding who should run and own the flexibility platform the discussion in the academia becomes heated. Various articles discuss between DSO, aggregator or some independent 3rd party as a possible FMO. They all state pros and cons for their choice. One group of articles state that DSOs should run and own the market because for congestion management network-aware models are needed, both the TSO and DSO know the needs of the grid [25], and it would be breach of customer's privacy and possible security problem if some other entity would have access to it. Others argue that currently legal framework forbids the DSO to act as the market operator [63] and propose aggregator as the entity who should operate the market. Naturally, there are also counter arguments. Firstly, the respective aggregator should than be able to have (at least limited) access to network constraints, and as an interested party it could potentially be in a conflict of interest. Therefore, some researchers argue that the best option is to establish an independent entity [137]. The time and future discussion between academia, industry and regulatory bodies will show what direction shall be chosen as the most promising one. Table 2 depicts the choice for the FMO in various articles that deal with the distribution level flexibility. More than 50 % have opted for the third party solution, but DSO and aggregator flexibility market led solutions are also non negligible.

Table 2. The assigned Local FMO in various papers.

Paper	DSO	Aggregator	3rd Party
Olivella-Rosell et al. [18]		X	
Esmat et al. [126]	X		
Li et al. [122]	X		
Heinrich et al. [102]			X
Morstyn et al. [61]	X		
Ilieva et al. [62]		X	
Khajeh et al. [21]			X
Zhang et al. [103]			X
Torbaghan et al. [64]			X
Spiliotis et al. [13]		X	
Eid et al. [129]		X	
Ramos et al. [25]	X		X
Heussen et al. [67]			X
Kornrumpf et al. [123]			X
Köppl et al. [65]			X
Ross [52]	X		
Vallés et al. [54]	X		

10. Conclusions and Future Work

We live in the era of enormous shifts in the power system paradigm. People are becoming aware of the environmental changes, technology is moving forward and new ideas are coming to the light. In terms of the power market structure, the current trend is towards green decentralized energy resources, active participants–prosumers and sustainable use of energy. These changes the way how (and where) the electricity is generated, transferred and consumed and creates new challenges for ensuring secure and stable supply of energy. One term that is currently regarded as one of the most important factors for successful integration of high share of RES is flexibility. This review paper revises the conventional power system paradigm and explains the present and future trends. Furthermore, the flexibility in power system has been explained with an overview on different types of flexibility and involved stakeholders. The most important and promising projects and platforms are presented with a short overview of their characteristics. Finally, the dilemma who should be the market operator is discussed. Although both industry and academia are highly interested in this topic, a lot of questions still remains open. Firstly, there still isn't clear answer will the distribution-level markets increase the overall system cost. Current answer would be that all depends upon the chosen market model, TSO-DSO coordination mechanism and share of RES in the system. As this survey shows, some market models really do promise lower costs, but some impose even higher costs in some extreme cases. Hence, it is important to have cost in mind when opting for some of the possible distribution-level implementation strategies. Moreover, open debate is on the question do local markets bring more advantages than disadvantages. In the authors' opinion, that is correct. Despite the need for the shift in the power system market paradigm, possible additional costs and computational burden, the benefits such as stability and resilience of the power system under the condition of high RES share outweigh possible downsides. One should always have in mind that high RES penetration is an important prerequisite for the cleaner environment, a luxury which cannot easily be described with a monetary value. Currently there are already active few projects around the Europe that are trying to prove economical feasibility in the real-life situations, and it seems they are steering in the right direction. Nevertheless, literature provides great insight on current state in the power systems around the globe and problems that high RES penetration causes, especially when talking about DERs connected at the distribution level. Furthermore, various TSO-DSO coordination schemes and distribution level market models are presented with their main characteristics. What lacks is the pilot projects and research on applicability in different markets around Europe and the world generally. To conclude, the distribution-level flexibility market is a very appealing topic and it is almost certain to say that in the near future its most important market design features will be consolidated and flexibility markets will become an important part of every power market structure.

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Abbreviations

AC	Alternate-current
aFRR	automatic Frequency Restoration Reserve
BRP	Balance Responsible Party
CBA	Cost-Benefit Analysis
CCGT	Combined Cycle Gas Turbines
CHP	Combined Heat and Power
DER	Distributed Energy Resource
DSM	Demand Side Management
DSO	Distribution System Operator
EU	European Union
FCR	Frequency Containment Reserve
FMO	Flexibility Market Operator
HVAC	Heating, Ventilation, Air-Condition
KKT	Karush-Kuhn-Tucker
LFM	Local Flexibility Market
mFRR	manual Frequency Restoration Reserve
OPF	Optimal Power Flow
P2G	Power to Gas
P2P	Peer-to-Peer
PV	Photovoltaic
RES	Renewable Energy Source
TSO	Transmission System Operator
UMEI	Universal Market Enabling Interface

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