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Market integration and TSO-DSO coordination for viable Market-based congestion management in power systems

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HIGHLIGHTS

- Market integration is one way of increasing system operators' access to flexibility
- TSO-DSO coordination helps mitigate the adverse impact of flexibility activation
- Intraday and balancing market bids could be used for congestion management
- Flexibility-related data can be gathered, stored, processed in a centralized system
- Access to Flexibility-related data can improve visibility and decision-making

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ABSTRACT

The article presents the findings on market-based congestion management (CM) in power systems. The main idea is to unlock flexibility from both small and large-scale resources by creating a platform so that flexibility can enter the markets through the platform and be used by system operators (DSOs and TSOs) for CM. The article recognizes two pressing issues in market-based CM: low liquidity and adverse impacts of flexibility activation. The article proposes leveraging market integration and TSO-DSO coordination to address the pressing problems and incorporate them into the platform. Bids from the intraday market at Nord Pool as well as the balancing market bids, were used for CM to show the possibility of addressing the low liquidity issue by receiving bids from well-established markets. In TSO-DSO coordination, an algorithm-agnostic process is proposed and implemented to involve SOs' network limitations before flexibility is traded to mitigate the adverse impacts of flexibility activation. As the market integration and TSO-DSO coordination functionalities rely on flexibility-related data that are often in huge quantities, a metadata register is also implemented to gather, process, and store data to be smoothly accessed by different stakeholders depending on their needs and access rights.

1. Introduction

In the European Union (EU), decarbonization, decentralization, and digitalization [1] are the frame of substantial transformations in different sectors, such as energy, particularly electricity. In the power system context, decarbonization is attributed to renewable electricity production using wind, solar, and biogas as the primary energy source, which naturally leads to decentralization because they are often smaller

Abbreviations: AC, Alternating current; API, Application programming interface; CM, Congestion management; DA, Day-ahead; DSO, Distribution system operator; ETPA, Energy trade platform Amsterdam; EU, European Union; FR, Flexibility register; FSP, Flexibility service provider; GCT, Gate closure time; HP, Heat pump; ID, Intra day; LFM, Local flexibility market; mFRR, Manual frequency restoration reserve; MOL, Merit order list; MO, Market operator; MV, Medium voltage; MVP, Minimum viable product; NVSF, Network voltage sensitivity factor; PLT, Power limit table; PTDF, Power transfer distribution factor; SO, System operator; TDCM, TSO-DSO coordination module; TSO, Transmission system operator; UI, User interface; UK, United Kingdom; R&D, Research and development; SFP, Single flexibility platform; KPI, Key performance index.

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than conventional power plants. Digitalization is also happening simultaneously, which can produce a massive amount of data and metadata, useful for forecasting and monitoring the power systems variables such as load and generation. With the changes necessary and mostly inevitably happening, the power system has to be able to operate under new requirements and circumstances. Today's power system, at least major parts of it, if not the whole, was designed and implemented decades ago under different assumptions, such as unidirectional power flow at the distribution level and centralized power production at the transmission level. Therefore, it is reasonable that the already built power system must be updated, reused, and, if necessary, reinforced to accommodate the transition toward sustainability so that minimum integration costs are imposed on network users through the network tariffs.

Wind and solar power generation are typical examples of decarbonization and decentralization causing challenges to system operators (SOs). Renewable power production is often intermittent compared to controllable power production of conventional power plants (e.g., coal, natural gas), leading to increased balancing needs [2]. As balancing power reserves are limited on the generation side, maintaining the delicate generation-demand equilibrium requires transmission system operators (TSOs) to seek additional flexibility from the consumption side. Meanwhile, decarbonization measures such as transport and heating electrification on the consumption side could already cause another problem known as congestion. The congestion can emerge as voltage violations or thermal overloading of the network components. Similar to balancing, flexibility from electricity production and consumption could give SOs operational freedom to mitigate congestion. The transition toward sustainability in the electricity sector, as recognized in EU legislation [3], requires SOs to utilize flexibility to reduce balancing and congestion management (CM) costs.

Utilizing flexibility in the power system might look simple in theory; however, it is a complex task. The complexity lies in the fact that several stakeholders with different roles [4] and responsibilities must find common ground so that flexibility from end customers' assets is presented in the flexibility market by a flexibility service provider (FSP) and is used efficiently at the buyers' end. The challenges can be classified into three dimensions: regulatory, economic, and technical [5]. Those aspects must work together, leading to a flourishing end-to-end process of flexibility utilization in power systems. While designing the process, satisfying all stakeholders' criteria in practice along the value chain is challenging. That is why negotiations and cooperation [6], [7] are essential to sometimes compromise so that all stakeholders' positions are considered. Coordination is necessary between stakeholders, such as TSOs and DSOs. Without TSO-DSO coordination, flexibility utilization can create problems for other stakeholders, negating flexibility's benefits. Several articles have been devoted to the TSO-DSO coordination topic, considering various aspects such as time horizon (e.g., short-term, long-term), vantage point (e.g., SOs, consumers, producers, FSPs), investment, and operation [6], [8–12].

TSO-DSO coordination in the short-term market-based CM context is a general term that embraces two interdependent parts. First, the article's focus, bid qualification, is necessary to avoid a situation when a bid activation causes another congestion problem. The second relates to the aspects that influence SOs' access to flexibility bids, such as market structure and SOs' roles and responsibilities. Various market structures could be used to define the rules of when and from which market SOs can procure flexibility. [6], [13] propose various market designs; among them, the distributed market model[1] in [6] is used because it can create a situation that thoroughly examines whether phase 1 works well. Nevertheless, the article's bid qualification process can potentially accommodate any market design selected in the second part of TSO-DSO coordination; therefore, this article complements the existing literature.

[14] propose that bid qualification is performed by flexibility resource's DSO before a bid is used for the TSO network. Although that could be one improvement compared to not having any bid qualification in place, it only considers one specific scenario among others. The proposed bid qualification within the TSO-DSO coordination of the article is algorithm agnostic, meaning that it can potentially accommodate any bid qualification algorithm (including one in [14]). Secondly, it allows a situation in which SOs' grid limitations are considered simultaneously in a centralized TSO-DSO coordination system. The latter makes it easier for SOs to utilize the proposed process and avoid a situation where each SO has its own bid qualification system in a decentralized manner. In addition, as decentralized coordination requires iteration between SOs, it seems that centralized coordination has an advantage in that respect.

In addition to coordination, low liquidity is a concern in market-based CM because the need for flexibility is often higher than the available flexibility, and this might be due to the unprecedented pace of commissioning renewable generation projects compared to hosting capacity enhancement projects such as network reinforcement. Much literature has focused on market integration in spot markets [15–19]; nevertheless, reserve, balancing, and LFM can also benefit from market integration [6], [13]. Unlike approaches taken in [6], [13], the market integration in the article does not add a new market for the CM use case; instead, the existing intraday and balancing markets, with minor adjustments, are proposed to be used for CM. The benefit is the avoidance of market fragmentation and the ease of market participation for FSPs.

As TSO-DSO coordination and market integration functionalities rely on flexibility-related data such as flexibility resources' location on the network, respective FSP, technology, and qualification certificates, data governance is crucial in enabling those functionalities. A metadata register is implemented to gather, process, and store flexibility-related data to be accessed by different stakeholders depending on their needs and access rights. From an information technology (IT) perspective, the proposed metadata register could be discussed in depth in the same fashion as in similar projects [20] nevertheless, to maintain the article focused, it is presented only from its functional perspective.

The article aims to publish a part of the progress made within the EU project INTERRFACE [21] by Nordic-Baltic demonstrators located in Finland, Estonia, and Latvia to address the low liquidity of markets for CM and avoid the adverse impact of flexibility activation through market integration and TSO-DSO coordination, which led to the development of an information technology (IT) platform. As the conceptual thinking and reasoning behind the designs of the platform are important for the replicability of the findings, discussions regarding the platform itself are not provided in the article as the platform is just one IT solution (possibly among others) for the existing power system problems. The main idea is to unlock flexibility (e.g., from small-scale resources) by creating a platform so that flexibility can enter the markets through it and seamlessly be used by SOs for CM. The concept aims to fulfill the EU's vision [3] to enable SOs to procure services (e.g., CM) from assets connected to the network, both at the transmission and the distribution level, in a coordinated way.

1.1. Scope and Hypothesis

The scope of the article is to present data exchange and relations between stakeholders within and outside the platform, as well as functionalities toward enhancing market integration and TSO-DSO coordination. The platform is one (among possible others) implementation of the designed functionalities, and therefore, the focus is not on how the platform is implemented from an IT perspective but rather on what the platform does, why, and how. The flexibility sellers provide flexibility from their physical assets (e.g., heat pumps (HPs)) to buyers that are only SOs. To keep the article focused, topics like regulations, end-user engagement, hardware requirements for flexibility extraction and

[1] Peers are the sole buyers (and providers) in the market, to solve local and/or central needs by DSOs and/or the TSO [6].

provision, settlement, and software implementation of the proposed solutions, although relevant, are outside the article's scope.

Table 1 provides information on the article's hypotheses, problem definitions, proposed solutions, and ways to realize them. The first hypothesis concerns the availability of flexibility for SOs' CM. Market integration is proposed as a solution to realize that. The article will present how bids from intraday and balancing markets can be used for SOs' CM. Once SOs have access to a larger pool of flexibility, the next issue is the usability of flexibility. Therefore, the second hypothesis concerns a situation when an SO's flexibility activation causes another congestion due to counter-activation.[2] Deployment of TSO-DSO coordination is proposed so that SOs' network limitations are considered before a bid is traded in the markets to minimize the probability of adverse impacts of flexibility activation. As a real-world solution, the designed TSO-DSO process must be defined to be simple, integrable to the platform, and algorithm agnostic (any bid qualification algorithm can be used).

1.2. Innovative contributions

The innovative contributions of the article are also around market integration, TSO-DSO coordination, and data governance. The article's findings take one step forward compared to current practices being used in Europe. The contributions are as follows:

The first contribution is that the article discovers the areas for improvement in flexibility utilization in power systems' CM. Finding the root cause of problems and understanding their associations are essential; otherwise, improving one area alone without considering the mutual impact on the whole system does not lead to a workable change in practice. Therefore, the article recognizes the two pressing issues[3] of low liquidity and adverse impacts of flexibility activation to be solved by market integration and TSO-DSO coordination, respectively, as provided in Table 1.

The second contribution is the improvement of market integration to address the low liquidity of flexibility markets without adding a new market for CM. In collaboration with Nord Pool (i.e., the leading electricity market in Europe), bids from the intraday market as well as the balancing market, were used for CM. The demonstrations showed the possibility of using existing markets for new use cases like CM.

The third contribution is proposing a simple and algorithm-agnostic process for bid qualification within TSO-DSO coordination so that SOs' network limits are considered effectively in market activities. Its simplicity facilitates its implementation for DSOs, and its agnostic feature allows the proposed coordination process to accommodate different bid qualification algorithms suitable to the needs and computational capability of DSOs.

As realizing the proposed solutions in Table 1 in the real world requires data from different stakeholders, the fourth contribution is to improve governance of flexibility-related data by proposing and implementing a metadata register. The digital data of all involved stakeholders, from end customers to flexibility service providers, flexibility markets, and SOs are gathered, processed, and stored securely and smoothly. It must be emphasized that in increasingly decentralized power systems, a massive amount of data has to be handled, which makes data governance highly important; otherwise, market integration and TSO-DSO coordination functionalities could be disrupted. The flexibility-related data is proposed to be gathered in a centralized system to be accessed by different stakeholders depending on their needs and access rights to enhance data visibility.

All the improvements have been achieved thanks to partners with diverse expertise within the project [22] and tight collaboration with experienced piloting partners (e.g., Nord Pool [23]) in the area to ensure the viability of the proposed solutions. Finally, simplicity has been central to all the designs, making the proposed solutions easier to understand and implement and paving the way for upscaling and commercialization. Following that, the approach was not to provide a unique solution for one region or country in Europe but to clarify the problematic areas, propose realistic solutions, and discuss the reason behind them so that the solutions can be improved, customized, and built upon.

Table 1
Article's research questions.

Number	Hypothesis	Problem definition	Proposed solution	How?
1	More flexibility is needed for market-based CM in power systems.	How to enhance SOs' access to flexibility?	Improve market integration.	Allow bids from balancing and intra-day markets to be used for CM.
2	Flexibility activation can cause adverse impacts. Flexibility activation can remove congestion and create one at another location where counter-activation occurs.	How to avoid adverse impacts of flexibility activation?	Leverage TSO-DSO coordination.	Propose a simple TSO-DSO coordination process, integrable into the platform and algorithm agnostic.

2. Relevant research and developments

To understand where the R&D related to flexibility markets stand and highlight the values made in the article's work, two pioneering commercial flexibility markets, including Piclo Flex [24] in the UK and NODES [25] operating in Norway, Germany, and the UK, will be scrutinized. In addition, since the article's proposed platform is not a marketplace but a coordinating platform, GOPACS [26] in the Netherlands, as a CM platform, is also investigated.

2.1. PicloFlex

Piclo Flex is a flexibility market designed to provide services to DSOs [24]. The market enables FSPs to capture new revenue opportunities on the one hand and DSOs to procure local flexibility at scale to solve network congestion on the other hand. Among the market's features, it has a well-designed user interface (UI) that allows users to search through the map and find out where their needs (e.g., DSOs) and interests (e.g., FSPs) can be fulfilled. These features enhance the market's transparency and visibility. Piclo Flex has developed three qualification stages: asset, company, and competition. Once an FSP passes three qualification steps for its flexibility assets, it is ready to compete in the market. The qualification process in Piclo Flex, in general, is similar to what is implemented in the proposed platform of the article; however, as the TSO does not participate in the market, it seems that TSO's network limits are not taken into account in calculations. In addition, DSOs cannot be assured that their network limits are considered on other market platforms (e.g., balancing). Perhaps Piclo Flex as a marketplace does not find itself responsible for shielding the DSOs from ongoing trading activities on other markets; regardless, uncertainty from adverse impacts caused by actions in parallel markets can reduce the DSOs'

[2] Counter-activation is required when flexibility is activated that is in the opposite direction of the original flexibility in order to maintain the system balance.

[3] The issues were identified collectively by project partners in the first year of the project as a result of using surveys, discussions, and workshops.

willingness to participate in PicloFlex. This is one of the reasons that the proposed platform has the functionality to check each flexibility bid against network capacities, ensuring that flexibility trades from various marketplaces do not violate any network limitations. Secondly, the relevant network operator is aware of ongoing flexibility tenders. As a result, the proposed platform of the article could complement a marketplace like PicloFlex to involve TSOs in network capacity calculations and to avoid congestion for SOs when flexibility is traded outside PicloFlex.

2.2. NODES

The marketplace NODES was established in early 2018 as a joint venture between the Norwegian utility Agder Energi and the European power exchange Nord Pool. Both DSOs and TSOs can use the NODES market. NorFlex is a pilot project where NODES operates a flexibility market in the DSO Agder Energi Nett and Glitre Energi Nett grids in southern Norway [27]. The project aims to demonstrate how the DSO can use flexibility to increase the efficiency of network operations and network connection capacity and postpone network investments [27]. As integration into other markets could boost liquidity, in NorFlex, integration to the manual frequency restoration reserve (mFRR) market has taken place. Any available flexibility not utilized by the DSO two hours before the operating hour is automatically bundled and aggregated up to the mFRR as a separate bid to be used for either CM or balancing by the TSO [27]. Due to the importance of market integration, as also acknowledged by NorFlex, in the article's proposed platform, special attention and effort were paid to the market integration aspect, demonstrating the integration of not only balancing but also intraday bids into the platform for CM. The benefit that the platform could bring to marketplaces like NODES is that the market integration efforts can be shifted to the platform, and therefore, marketplaces with a limited modification on the flexibility products and UIs could realize market integration more readily.

In NorFlex, meter data is reported to AssetHub. AssetHub is a platform developed by the DSO. Within the project, it is believed that this is not a scalable solution, considering that there are hundreds of DSOs in Europe [28]. Developing a custom solution for each market would limit the expansion of FSPs and impair the use of those assets [28]. From a data management perspective, in line with what was found in NorFlex, data management was considered while designing the platform. The idea is that a module in the platform is designed to integrate the data related to flexibility from different data sources. In fact, it functions as a metadata registry and facilitates linking flexibility-related data together from various sources that otherwise would cause data to be siloed. One benefit is that each stakeholder would not need a separate data hub for storing and managing the data; instead, all flexibility-related data are stored on a common platform, paving the way for the solution's scalability.

2.3. GOPACS

GOPACS is a coordination platform used by DSOs and TSOs that procures flexibility from the intraday market (the energy trading platform Amsterdam (ETPA)) for CM [26]. The main idea is that SOs coordinate with each other to predict congestion in their networks and buy flexibility to solve it without causing more congestion. GOPACS assures that the market-based CM of an SO will not harm another SO, for example, when counter-activation occurs to offset the imbalance. Nevertheless, GOPACS does not protect SOs from market activities not initiated from CM use case (i.e., the buyer is not an SO) that might cause a problem for an involved SO. On the other hand, although not demonstrated in the article, the proposed platform can potentially address that issue if the flexibility bids are exchanged through the platform.

2.4. Improvements

PicloFlex, NODES, and GOPACS were investigated and presented as notable examples of recent developments in the CM area in Europe to set the ground for highlighting the value achieved within the proposed platform of the article. The improvements will be around three key aspects: coordination, market integration, and data governance.

2.4.1. TSO-DSO coordination

Coordination, in general, is a broad topic that embraces different aspects such as time horizon (e.g., short-term, long-term), vantage point (SOs, consumers, producers, FSPs), and an operational or investment viewpoint [8]. The coordination in the article considers short-term and operational TSO-DSO coordination for CM and balancing.

In literature, much debate over TSO-DSO coordination toward cost minimization of network operation and, eventually, welfare maximization has occurred [9]–[12]. The short-term and operational coordination from close to real-time (e.g., a day ahead (DA)) to real-time has to first deal with not violating the network limits, and after that, the network's operational state can be optimized, for example, to reduce network losses. The article did not use optimization approaches to minimize the SOs' costs. The first reason is that SOs' cost minimization is an internal problem and should not be included in a platform meant to be used by several stakeholders of different types. Secondly, SOs might not be willing to share their cost functions with the platform. Due to these reasons, the coordination in the article only tends to obey the network limits and create a merit order list (MOL) based on the price of flexibility without deploying an optimization. Then, the respective SO can optimize its decision-making internally to select the most cost-efficient combination of bids.

From the TSO-DSO coordination perspective, congestion can be categorized into two groups. We shall call the first "non-market-induced congestion," which results from the power systems' natural dynamics, which are often predictable. The congestion may stem from daily/seasonal load and production variations, scheduled maintenance, load and generation growth, network topology changes, and non-predictable network issues. SOs, using their network tools and weather forecasts, can largely predict non-market-induced congestions and coordinate, for example, using an approach like GOPACS to find and buy flexibility. The second type shall be called "market-induced congestion," which can occur on a network due to trades in flexibility markets. For example, an FSP sells a flexibility service from a flexibility asset connected to a DSO's system to a TSO's balancing market; however, that might cause congestion for the DSO. Since market activities create this type of problem and cannot be predicted by SOs alone, a proper mechanism has to be in place to avoid such incidents. In the proposed platform, however, not only can non-market-induced congestion be relieved, but market-induced congestion can also be avoided. In other words, by introducing required application programming interfaces (APIs) to connect the platform to various markets like local flexibility market (LFM), ID market, or balancing market, coordination can prevent a trade if it causes congestion for an SO. As the need for small-scale flexibility connected to low voltage networks is rising, so is the number of flexibility markets, especially regional ones (e.g., LFM); thus, this feature is substantial for SOs, especially DSOs, because it protects them from market activities. This feature is missing from GOPACS, while the proposed coordination process has the potential to address that, and therefore, it is more inclusive than in GOPACS. It must be mentioned that asking permission from the proposed platform to trade a bid might not be favorable nor necessary to some marketplaces; nevertheless, the importance here is the possibility of leveraging that feature when deemed necessary.

2.4.2. Market integration

Market integration is an essential aspect of the electricity markets since it could bring affordable energy prices, secure energy supply security, and allow for the integration and development of DERs cost-effectively [29]. The benefits of market integration are also recognized in literature from different parts of the world [15], [16], [18], [19]. The market integration is not restricted to spot markets; reserve, balancing, and LFM can also benefit from that [6], [13].

In this article, the market integration is seen from one use case: CM. The idea is that exchanging bids from intraday (ID) and balancing markets should be possible through the platform to realize CM. For example, an ID market bid containing the assets' locational information is proposed to be used by SOs for CM. Flexibility markets like NODES and coordination platform GOPACS have already moved toward increasing their liquidity using the market integration concept. For example, NODES intends to exchange bids to ongoing (e.g., mFRR) and likely emerging markets. GOPACS procures CM bids from the ETPA. Although they are moving in the right direction, they will require much work regarding agreements between the markets, product harmonization, and designing and implementing the data exchange while considering data security and privacy. In the proposed platform, the integration burden from the marketplaces that tend to exchange bids was reduced using a predetermined, validated, and coordinated process. The aim was to facilitate market integration, such as ID, and balancing markets for the CM use case. In addition, the platform operates as a middleware between FSPs, SOs, and marketplaces, simplifying the integration to multiple and evolving markets from an information exchange viewpoint.

2.4.3. Data governance

Data governance is another essential aspect of the flexibility markets. The platform's main advantage concerning data gathering and storage is that valuable data of flexibility assets, their location on the network, respective FSP, technology, and qualification certificates can exist in the platform, enabling different stakeholders to take advantage of the data pool when necessary. There are, of course, certain rules and restrictions on data access to meet data privacy and data sharing regulations. This feature can replace the approach of flexibility markets like PicloFlex, where all flexibility assets data in PicloFlex are organized and used only toward PicloFlex functionalities, not beyond that. The proposed platform's approach prevents double effort in collecting and managing flexibility assets' data.

3. The proposed platform's architecture

The platform acts as a common architecture that will accommodate the connection of multiple actors such as MOs, SOs, FSPs, and settlement responsible parties, enabling data and information exchange among them. The platform's conceptual and logical architecture design allows the facilitation of interactions among SOs as well as cross-border (i.e., between countries) trading. Four main functional modules lie in the architecture, as shown in Fig. 1, following a modular approach to integrating complementary services and functionalities within the platform's architecture. The four modules include the flexibility register (FR), TSO-DSO coordination module (TDCM), single interface to markets, and settlement unit. It is important to stress that these modules can be independently running but can also be complemented with additional services according to the requirements of each application. The platform follows a modular design in the sense that demo-specific modules/services can be interconnected with the main function modules. The core functionalities of the platform are presented in the following sections.

3.1. Flexibility register (FR)

The flexibility register (FR) is a metadata register that collects the flexibility resources' data, grants the flexibility resources access to specific market products according to the qualification results, and gives flexibility buyers visibility to available data. Processes performed within this module include resource registration and grouping, product definition, product and grid qualifications, and user management. The data that the FSP registers to the FR are resource locations, technology, capacity, and responsible FSPs. The resource then must undergo product and grid qualification processes. Product qualification is about checking whether the unit can (technically) deliver the product it wants to sell or deliver [30]. Grid qualification is about whether the unit(s) connected to the network can realize the product delivery, considering the unit's technical characteristics and the network's capabilities [30]. If the resource passes the qualification tests, the FSP, according to its bidding strategy, may group individual flexibility resources and make a larger

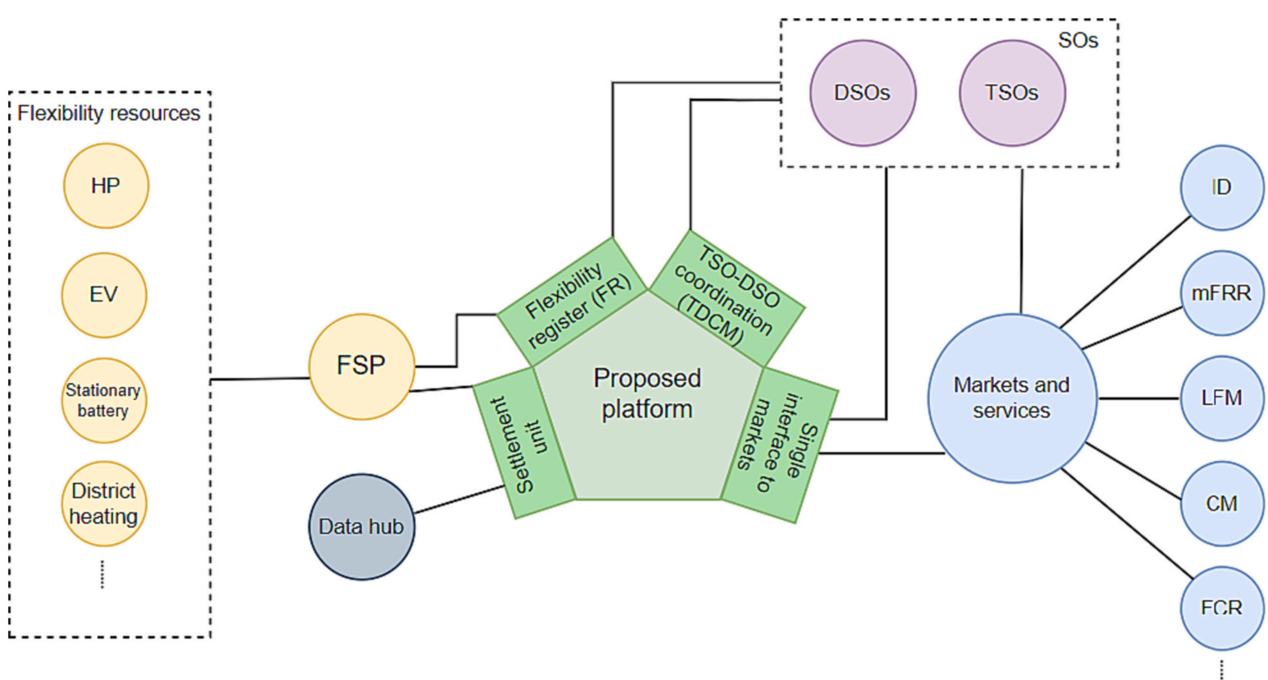

Fig. 1. The platform's architecture in relation to the markets, FSPs, and SOs

pool of flexibility. MO must fill in the product definition in the FR, the attributes that mainly reflect the need of a flexibility buyer, for example, minimum bid size, duration, and technology. The platform's users, such as FSPs, MOs, and SOs, each have different access rights in the FR module. FR is a module in the platform that realizes most of the data governance functionalities, and therefore, it can be seen as an enabler of market integration and TSO-DSO coordination functionalities.

3.2. TSO-DSO coordination module (TDCM)

Product, grid, and bid qualifications must be completed before a trade is finalized in a market. The TDCM handles the bid and grid qualification processes. Before a bid is traded on a market platform, bid qualification is performed to ensure that any SOs' network limits are not violated when the bid is activated. The main difference between bid and grid qualification is that bid qualification occurs every time a bid is submitted to a market considering the latest changes in the system (e.g., network's topology), whereas grid qualification happens a few times a year, which roughly examines a resource and its impact on the network. The TDCM enables bid qualification before a bid is traded to avoid bid activation that might cause a problem for an involved SO.

3.3. Single interface to markets

The single interface to markets module enables a uniform information exchange interface for markets communicating with the platform. In fact, the single interface to markets is essentially a backend component that acts as the gateway to connect various marketplaces with the platform to enhance market integration (e.g., exchange of bids between markets).

3.4. Settlement

Finally, the settlement unit identifies whether the traded flexibility was delivered as promised and communicates these results with the relevant market platforms, and stores them in the data hub. It performs the energy settlement of all trades by comparing the metered values with the baseline or schedule. FSPs upload documents related to metered or sub-meter readings along with activated volumes for all the metering points affiliated with the particular resource object for all metering points.

4. Developments in the TSO-DSO coordination module (TDCM)

The TSO-DSO coordination functionalities are performed in the TDCM. In the current implementation, there are two ways that SOs can exchange data with TDCM according to the level of simplicity and accuracy they desire. According to the left side of Fig. 2, SO1 can send data including the network voltage sensitivity factor (NVSF) matrix [31–33], power transfer distribution factor (PTDF) matrix [34], network topology and constraints, and state forecast to enable TDCM to calculate how much upregulation and downregulation capacity in kW exist at each node without violating any network limits (i.e., voltages, currents). NVSF is a matrix containing the sensitivities of node voltages to the changes in power injections at nodes. Likewise, PTDF contains the sensitivities of branch power flows to the changes in power injections at nodes. In fact, NVSFs and PTDFs are used to avoid voltage violations and thermal overloading, respectively. As shown on the right side of the figure, SO2 must send only two files, including the power limit table (PLT) and network topology, to TDCM. Initially, support for the simpler PLT-based coordination was developed as a minimum viable product (MVP). The TDCM can utilize either PLT or sensitivity matrices to avoid congestion, and both methods are presented in this article to show that the TDCM is algorithm-agnostic.

4.1. Grid qualification

In the platform, a two-stage coordination process protects SOs from flexibility activations that would cause congestion on the network. The first stage, grid qualification, compares the combined flexibility potential against the networks' available free capacity. In grid qualification, for example, seasonal worst-case scenarios provide information for SOs and FSPs. The SOs are adviced on locations that may experience market-induced congestions, and FSPs are informed which of their flexibility resources may later be subjected to activation restrictions. The analysis is still very rough at this stage because the final combination of active resources is still unknown, and the network state cannot be predicted accurately. The second stage is bid qualification, presented in the following section.

4.2. Bid qualification

The more accurate bid qualification stage happens closer to real-time (e.g., day-ahead) when the FSPs have placed their flexibility bids, and better forecasts for consumption, generation, and grid configuration (i.e., switching state) are available. The combined effect of flexibility bids is analyzed separately for up and downregulation. If congestions are forecasted, bids are disqualified one by one, starting from the most expensive ones, until the congestions are avoided. Bids that could, if activated, cause congestion for involved SOs are removed from the MOL shown to the SOs. Therefore, SOs can procure through the platform flexibility bids to alleviate non-market-induced congestion without worrying about the adverse consequences of their trade for themselves or other SOs.

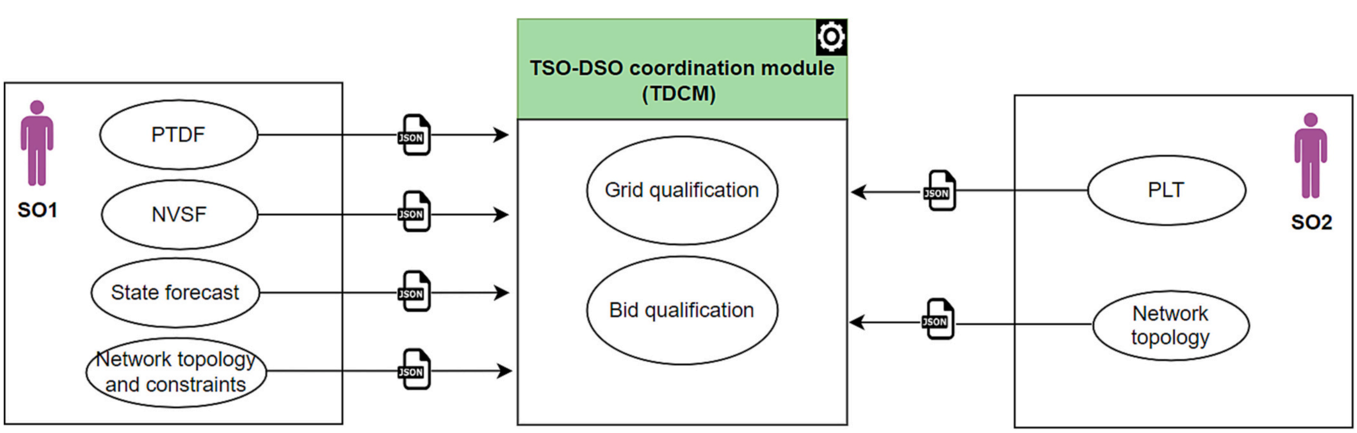

Fig. 2. TSO-DSO coordination module (TDCM) and its inputs

4.3. Power limit table (PLT)

The PLT-based grid qualification has been designed to be a low-threshold MVP solution. This method offers a simple, easy-to-understand way to communicate the capacity of the most crucial network bottlenecks to the TDCM. The power limit table tells how much free capacity there is on selected key network components. The critical network components can be, for example, primary transformers, medium voltage (MV) feeders (power limiting factor: feeder protection relay over current setting), distribution transformers, and low voltage fuses. The idea is to select network components where power flow-based bottlenecks are most likely to appear. The power limit tables, calculated by SOs, tell how much upward or downward flexibility can be activated below each component without causing overloading.

Fig. 3. shows an example of a distribution network with power and current limits on different network components. In addition to these limits, the network load must be known before the values in the power limit table can be calculated. For example, the free capacity of a transformer is determined by its nominal capacity and loading without flexibility activation. Table 2 shows examples of power limits, loadings, and capacities available for flexibility. Only the data in the last two columns is sent to the TDCM. The maximum upregulation and maximum downregulation values are calculated separately based on minimum and maximum loadings without flexibility activations, and it is assumed that flexibility affects only active power because active power-only markets have been considered in the article. This leads to the following equations:

$$P_{max,\text{upregulation}} = max\left(0 - \left(\pm\sqrt{S_{lim}^2 - Q_{min,load}^2} - P_{min,load}\right)\right) \quad (1)$$

$$P_{max,\text{downregulation}} = max\left(\pm\sqrt{S_{lim}^2 - Q_{max,load}^2} - P_{max,load}\right) \quad (2)$$

where S_{lim} is the component's bi-directional power flow limit,

Q_{min} and Q_{max} are reactive loads during minimum and maximum loading situations,

P_{min} and P_{max} are active loads during minimum and maximum loading situations,

and production is handled as a negative load.

For grid qualification, seasonal or yearly maximum and minimum loads can be used to calculate the maximum amounts of upregulation and downregulation. The grid qualification is indicative in nature, and the final qualification of flexibility happens during the bid qualification. For bid qualification, temporally more precise power limit tables can be used. Power limits can be defined, for example, with hourly intervals. If hourly loading information necessary for calculating hourly power limits is not available, the power limit tables used in grid qualification can also be used for bid qualification. However, it should be noted that this approach allows less flexibility to be activated since all hours are treated the same as the worst-case hour.

PLT and simplified network topology can be sent to TDCM's qualification service. The simplified topology contains information on how metering points are connected to selected upper-level components. Topology can contain the following network levels: metering point, low voltage feeder fuse, distribution transformer, MV feeder, primary transformer, and TSO-DSO connection point.

4.4. PTDF and NVSF matrix calculations

The principles of sensitivity matrix calculation have been described in numerous literary sources [34–36]. Generally, the PTDF matrix can be calculated using the incremental method [36] or averaging susceptance matrices [36].

This article applies the susceptance-based method to calculate PTDF using AC power flow because it can handle both DSO and TSO networks [37], and NVSF, which is needed for voltage violation assessment, is easily calculated as a by-product of this process. To calculate the PTDF, a base case situation is defined first as the maximum loading situation the network can handle without exceeding line current or node voltage limits. All the forecasted network loads are increased incrementally until any further increase would cause the first congestion, and that is our base load situation. The reason for taking this approach is to ensure that the inevitable linearization errors are, more often than not, in the safe direction for the SO.

Newton-Raphson-based load flow is run for the base case, and the Jacobian matrix J and node admittance matrix Y are extracted from this calculation. Eq. (3) is then used to calculate how individual active power changes (ΔP) affect node voltage angles ($\Delta\delta$) and magnitudes ($\Delta|V|$) as follows:

$$\begin{bmatrix}\Delta\delta \\ \Delta|V|\end{bmatrix} = [j]^{-1}\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} \quad (3)$$

where ΔP is $(N-1)\times(N-1)$ diagonal matrix (in this case, populated with 1 kW values),

ΔQ is $(N-1)\times(N-1)$ zero matrix,

N is the number of nodes.

The final node voltage sensitivities are calculated from per unit valued $\Delta|V|$, considering the direction of power change, different voltage levels, and scaling. The NVSFs are given in kilovolts per added megawatt (load), meaning that the sensitivity factors for a radial network will be negative.

$$NVSF_{kV,MW} = \begin{bmatrix}0 & 0 \\ 0 & 0 - \Delta|V|{*}1000{*}V_n\end{bmatrix} \quad (4)$$

Where V_n is a $(N-1)\times(N-1)$ matrix of node nominal voltages in kilovolts, excluding node 1.

These angle and magnitude changes, and node voltages from the base case, are then used to calculate the newly changed node voltages. Once the new node voltages are known, basic power flow equations can calculate the new line currents and power flows. In this case, we can use the already calculated admittance matrix (Y):

$$I_{new,sr} = Y_{sr}\times\left(V_{new,r} - V_{new,s}\right) \quad (5)$$

$$S_{new,sr} = V_{new,s}\times I^*_{new,sr} \quad (6)$$

$$P_{new,sr} = real\left(S_{new,sr}\right) \quad (7)$$

where $I_{new,sr}$ is the new current flow between sending node s and receiving node r,

$V_{new,r}$ is the new voltage in node r,

$S_{new,sr}$ is the new apparent power flow between nodes s and r,

and $P_{new,sr}$ is the new active power flow between nodes s and r.

Once the new power flows are known, they can be compared to the base power flows, and the elements of the PTDF can be calculated as follows:

$$PTDF_{i,j} = \frac{P_{new,ij} - P_{base,i}}{\Delta P_j} \quad (8)$$

where $P_{new,ij}$ is the new active power flow on line i when power injection on bus j changes,

$P_{base,i}$ is the base active power flow on line i,

and ΔP_j is the active power change on bus j.

Since the effects of active power changes are calculated individually, the calculation can end up having two levels of loops. With vectorization and matrix operations, the loops can be eliminated. This way, the AC-PTDF calculation is several times faster than the incremental method calculation. If the network contains several voltage levels, the diagonal element sizes of ΔP can be varied so that larger values are used in stiffer parts of the network.

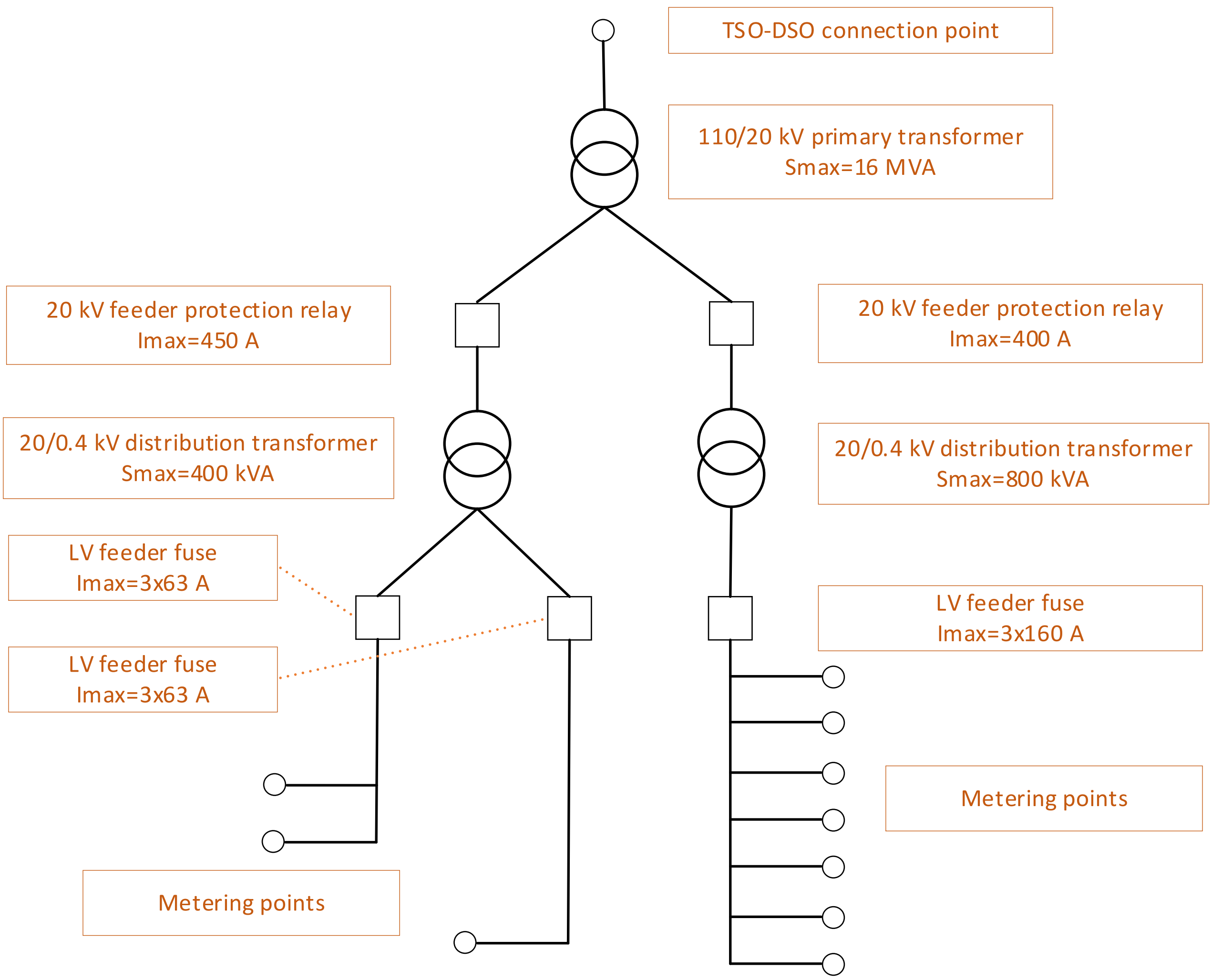

Fig. 3. Example network with power flow limiting components.

Table 2
Example of power limits, loads, and free capacity calculation results.

Component	Power flow limit kVA	Maximum load		Minimum load		Free capacity available for flexibility ($cos\varphi$=1)	
		kW	kVAr	kW	kVAr	Max. upregulation (kW)	Min. downregulation (kW)
Primary transformer	16,000	14,500	3200	3700	680	19,686	1177
MV feeder (I_{max}=400 A)	13,856	4260	830	1200	260	15,054	9571
Secondary transformer	400	235	40	78	19	477.5	163
LV fuse (3*63 A)	43.6	31	6	−20	−3	23.5	12.2

4.5. Bid qualification using the PTDF and NVSF matrixes

Once the PTDFs have been calculated, the SOs interact with the TDCM by sending network topologies, PTDF and NVSF matrices, network topology constraints, and network state forecast in JSON[4] format, as shown in Fig. 2. This can be done automatically through API endpoints.

In the coordination module, the order is such that DSO bid qualification precedes TSO bid qualification, and power flow qualification precedes node voltage qualification. In the present implementation, there is no feedback loop from voltage qualification back to power qualification, although this could have some marginal benefits. Both power flow and node voltage qualification were further divided into two phases, where down and upregulation bids were checked separately. A worst-case situation was assumed, where bids are activated only in one direction.

4.5.1. Downregulation, upregulation

In the power flow qualification's downregulation phase, we go through the following steps, as also visualized in Fig. 4:

1. Calculate the total amount of downregulation that the bids can supply to each node.
2. Calculate for all (m) conducting equipment how power flows change if all downregulation bids are activated.

The new active power flow for conducting equipment *i*, is calculated using the state forecast, PTDF matrix, and node-specific downregulation capacities determined in step 1.

[4] JavaScript Object Notation

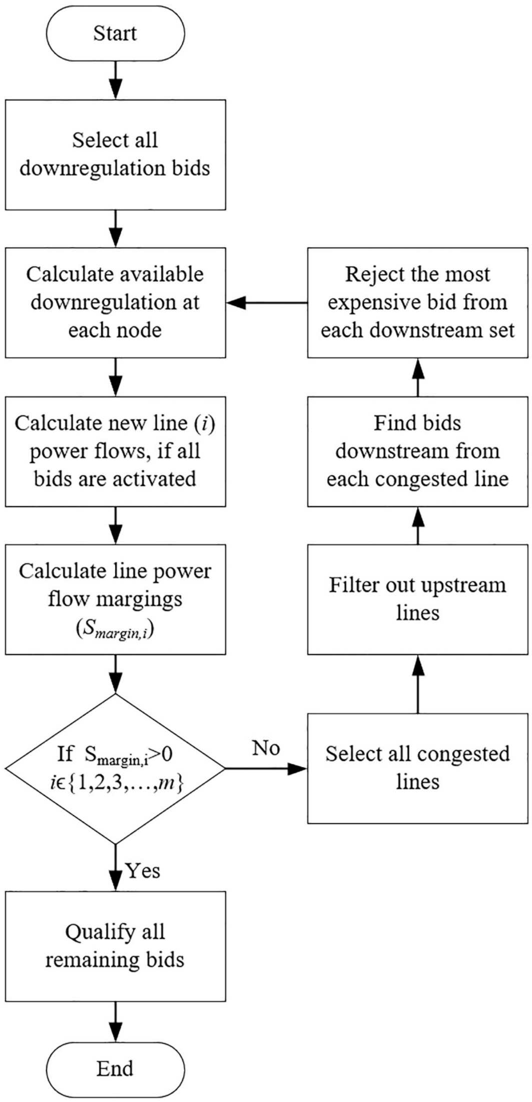

Fig. 4. Flow chart for power flow qualification (downregulation).

$$P_{new,i} = P_{forecast,i} + \sum_{j=1}^{N}\left(PTDF_{i,j}*P_{down,j}\right) \tag{9}$$

Where $P_{new,i}$ is the new active power flow on conducting equipment i, $P_{forecast,i}$ is the forecast for active power flow on conducting equipment i, N is the number of nodes, $PTDF_{i,j}$ is the sensitivity of power flow on conducting equipment i to power injection on node j, $P_{down,j}$ is the total amount of downregulation at node j. The reactive power flows are assumed unchanged, and after the new active power flows have been calculated, new apparent power flows are calculated as follows:

$$S_{new,i} = \sqrt{P^2_{new,i} + Q^2_{forecast,i}} \tag{10}$$

3. Compare the new apparent power flow to the maximum apparent power flow and calculate the power flow margin.

$$S_{margin,i} = S_{max,i} - S_{new,i} \tag{11}$$

4. If power flow margins in all nodes are positive, the downregulation can never cause congestion, and all downregulation bids can be qualified (given a green traffic light [13]). If any negative power flow margins exist, continue to step 5.
5. The congestion-causing bids are filtered out one by one starting from the most expensive bids. The sub-steps for this are:

   i) Select all congested conducting equipment.
   ii) Filter out conducting equipment that supplies other congested conducting equipment.
   iii) Loop through all remaining conducting equipment and do the following:

a) Find nodes below selected conducting equipment.
b) Find bids associated with nodes found in step 5-iii-a.
c) Reject the most expensive bid from the bid group found in step 5-iii-b.
d) Recalculate the active power flow for the selected conducting equipment.

$$P_{new,i} = P_{old,i} - PTDF_{i,j}*P_{rejected\_bid,i} \tag{12}$$

e) Recalculate the new apparent power flow with (10).
f) Recalculate the apparent power flow margin with (11).
g) If the power flow margin is still negative, return to sub-step iii-c.

6. If any negative power flow margins are still left, return to step 2 in the main algorithm, else end bid power flow qualification.

When considering power flow limits in a radial network, bid rejections in the congested area can be done purely based on price because the difference in bid impacts on the network in different locations are marginal (as long as they are within the same congestion area). However, in meshed networks, the selection of bids is not that simple, and further development of bid selection methods is needed.

The upregulation phase for resource power flow qualification is very similar; the main difference is the direction of the active power flow change.

4.5.2. Bid qualifications using NVSF

Analogously to steps 1–4 in section 4.5.1, the NVSF matrices can be used to determine the effect of the flexibility bids on node voltages and to identify which nodes are congested in case all the bids are activated. In step 5, where congestion-causing bids are rejected one by one, bid rejections are done firstly based on their network effect and secondly based on their price. We start by selecting the most congested node, find the bid node with the highest voltage sensitivity in relation to this node, and if this bid node has more than one bid, then sort the bids in this node from the most expensive to the cheapest. The most expensive bid is removed from the MOL, the effect of removal is checked, and if congestion is still possible, the next bid is removed. This is repeated until the node voltage limits are no longer violated. In the case of node voltage-based congestions, it is essential to consider to what degree each bid affects the congestion. Rejecting bids merely based on price could lead to situations where bids that have little or no effect on the congestion are rejected. The simplified bid evaluation method presented above is by no means optimal. Therefore, improvement is needed, and future research could develop a bid rejection metric that considers both the bid price and the impact on congestion.

5. CM use-case and demonstrations

Two demonstrations are performed to deploy and evaluate the proposed platform from different perspectives under different conditions and requirements. Both demonstrations are for the CM use cases and are presented as shown in Table 3.

The resource pool used in the demonstrations utilizes six residential HPs with nominal capacities between 23 and 65 kW, as provided in Table 4. In addition, an aggregated 550 kW from several HPs from a large leisure center was used. The flexibility resources are real and

Table 3
Use case and demonstrations.

Use case	Demonstrations
CM	Integration of bids from the balancing market for CM Integration of bids from the intraday market for CM

Table 4
Flexibility resources.

Technology	Nominal capacity (kW)	Building type	Floor area (m2)
HP	23	Residential	1730
HP	27	Residential	1868
HP	16	Residential	1172
HP	25	Residential	1264
HP	25	Residential	1614
HP	65	Residential	2861
HP	550	Leisure center	47,000

located in different areas in Finland controlled by real FSPs. The scenarios in this chapter mainly aim to indicate the possibility of using balancing and intraday market bids for CM. In addition, modules, including FR, TDCM, settlement, and single interface to markets, are tested in those scenarios to assure their viability and determine possible improvement needs.

For demonstration purposes, the resources were connected to a modifiable fictional distribution network model that allowed us to run simulations on different scenarios where flexibility procurement might be beneficial for DSO or where the DSO's network congestion prevents resource or bid qualification. As Fig. 5 shows, the demonstration network contains three different voltage levels. The residential resources are connected to the low-voltage network, and the leisure center is connected to the medium-voltage network, as it is in real life. An Octave model of the network was used when running the scenario simulations, and a network model in the form of topology, PTDF, and NVSF matrices, power flow, and node voltage forecasts, and a PLT was sent to the proposed platform.

5.1. Integration of balancing market bids (mFRR) to the platform for CM

The demonstration was conducted in Finland, based on connecting the proposed platform with the Finnish balance management system (BMS) operated by Finnish TSO Fingrid. The demo includes using locational information on the mFRR market to provide bids not only for balancing use but also for CM. These bids were available in the platform for TSO and DSOs. A set of practical scenarios, three of which are provided in Table 5, have been designed, which, on the one hand, reflect different real-world flexibility needs of the SOs and, on the other hand, test various aspects of the platform functionalities. The three end-to-end test scenarios containing real flexibility bid activations are as follows:

The trading process flow starts with FSP placing a bid on the mFRR market hosted by Fingrid's BMS, as shown in Fig. 6. The BMS, in turn, sends the bid through the single interface to markets to the TDCM after the gate closure time (GCT) of the hour in question. If the bid is

Table 5
Scenarios.

Scenario	Story	Usecase
1	TSO procures and activates flexibility to maintain operational security during a planned maintenance of a network's component.	CM
2	Planned maintenance is causing a short-term (less than 1 h) need to use a backup connection, which is congested. DSO procures upregulation (load reduction) from the flexibility market to solve the congestion.	CM
3	Excessive solar generation is forecasted to cause distribution transformer overloading. DSO procures downregulation (load increase) from the flexibility market to clip the peak caused by solar generation.	CM

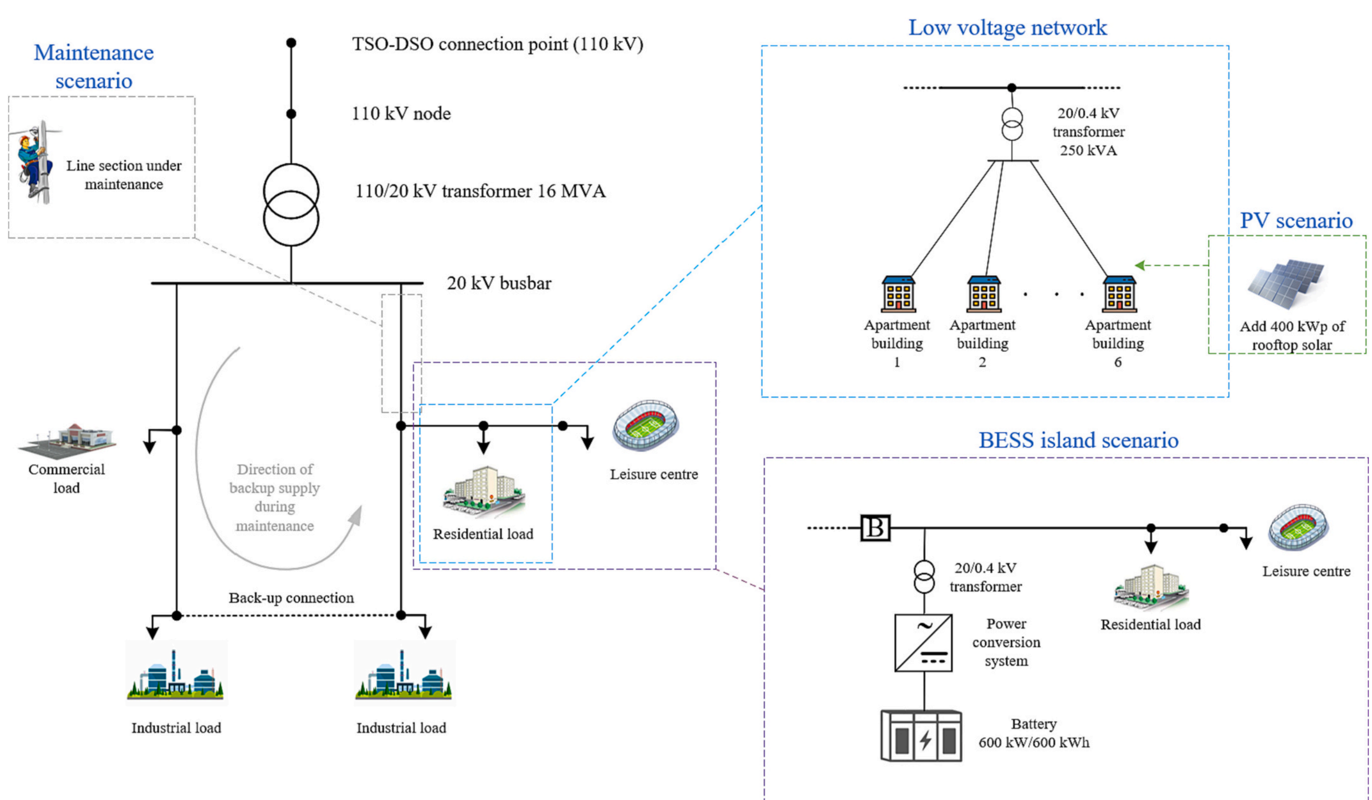

Fig. 5. Distribution network used in the demonstrations

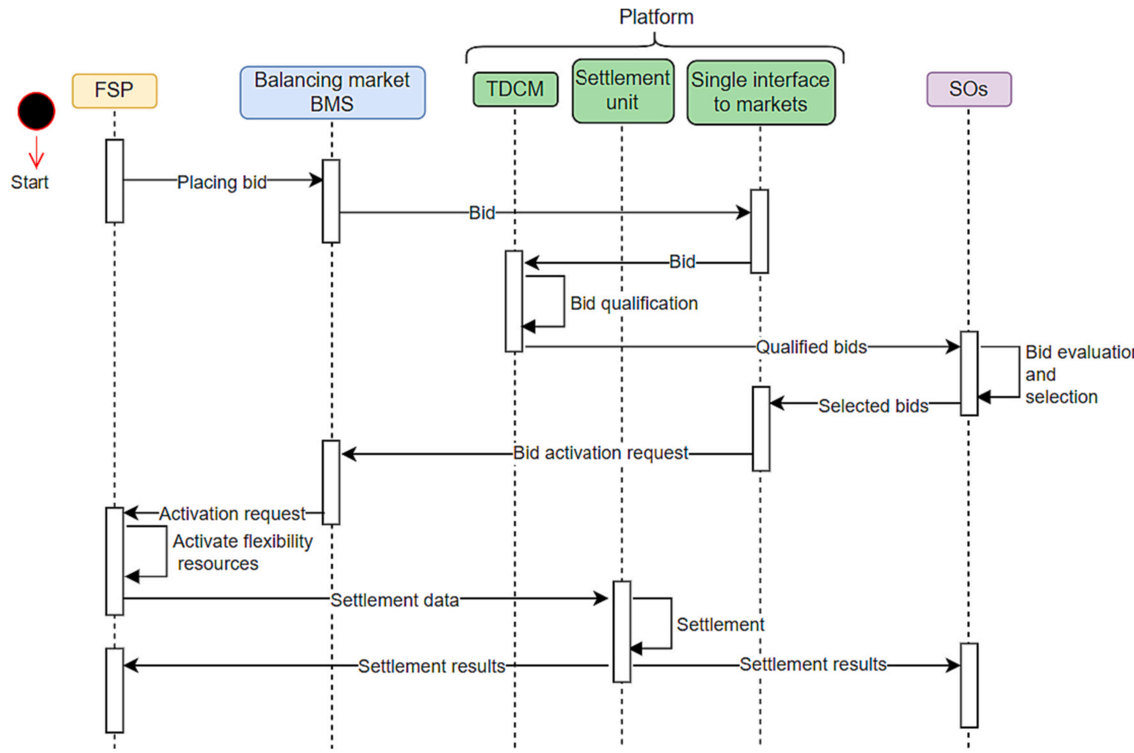

Fig. 6. UML (Unified modeling language) sequence diagram of mFRR integration into the platform for CM

successfully qualified in TDCM against the network model and its capacities (i.e., bid qualification), then it appears on the MOL 40 min before the hour's start. If the bid does not qualify due to insufficient network capacity, it never appears on the MOL list and thus is unavailable for purchase. While the bid is on the MOL list, it could be purchased by any SOs. As a default, the activation time is for the whole delivery hour, and the quantity is the available maximum for the node in question, but the purchasing SO can set them as follows:

- Activation time: 1–60 min within the delivery hour in 1-min resolution.
- Activation volume: Between zero and available maximum (partial activation or split bids depending on the flexibility product definition).

Once a bid is purchased, the platform sends it to the BMS system. Next, the BMS system forms the related bid activation request and sends it to the FSP. The FSP, in turn, activates the resources according to a schedule set in the activation request. To run the final step, settlement, the platform needs input data from the FSP covering activated volumes and measurement values for each metering point in one-minute resolution for the period covering both the activation period and the hour before. Settlement is to be run by the platform once a day every morning for all activations that have taken place the day before, giving enough time for the FSP to collect all measurements and validate the input data for settlement. Settlement results are available on the platform's UI and through the API request.

5.2. Integration of intraday market bids to the platform for CM

The demo integrated Nord Pool's ID marketplace into the platform for CM. The demo was carried out in tight cooperation with Nord Pool as an external partner. This setup enables SOs to purchase flexibility for CM directly using the platform and for FSPs to place bids directly to the Intraday market. The main idea of ID market integration to the platform for CM is to increase SOs' access to flexibility as the ID market is well-established and highly liquid. The sequence diagram of the process is similar to what was presented for mFRR integration for CM, shown in Fig. 6, with the difference that the ID market system replaces the MO's BMS in the diagram.

In this pilot, the fully functional integration was done using an API provided by the platform. In addition, Nord Pool developed its own information technology (IT) systems to enable integration into the platform. Also, as the flexibility assets' location is crucial in CM and TSO-DSO coordination, the ID market introduced an asset identification number (i.e., Asset ID) to tie the bids with the location of physical resources. Therefore, offering flexibility to the regional ID market only slightly differs from the regular intraday market. In fact, the only major difference is that a bid must include an Asset ID that refers to the resource group defined in the platform, and each individual resource in a resource group has location information in the form of the identified network connection point. The platform connects the bid connection point to the SOs' network topology to assess and present flexibility impact on the SOs. All intraday bids that include the Asset ID are automatically forwarded to the platform through the single interface to markets module using the API, and SOs can buy the flexibility directly from the platform. GCT in the platform is 40 min before the start of the delivery period, and after that, bids are no longer accepted.

After an SO purchases its desired bid and enters the preferred activation time and quantity in the platform, the bid activation request is sent to Nord Pool to verify if the bid is still available. At the same time, the bid is tentatively marked as traded (highlighted in green) so that no one else can purchase it anymore on the platform side. If the bid is still available in Nord Pool's intraday market and the activation request could be accepted, Nord Pool confirms the trade. If, on the contrary, the activation request cannot be accepted, Nord Pool rejects the trade. If rejected, the bid is removed from the MOL list in the platform. The settlement process is run daily for all new trades, and as an input, it needs, e.g., measurement data of resources that have been activated as a result of those trades. FSP can see the results and download needed reports straight from the platform.

6. Results

This chapter provides the results concerning market integration, TSO-DSO coordination, and solutions' impact on CM. The results include key performance indexes (KPIs) achieved at the end of the demonstrations.

6.1. Market integration

Table 6 indicates the impact of the single interface to markets module on integrating marketplaces into the platform. It has to be mentioned that, in fact, four marketplaces were integrated into the proposed platform; nevertheless, the results from only two of them were used in the article.

6.1.1. balancing market integration

Following the three scenarios presented in section 5.1, the FSP placed flexibility bids to the mFRR market, and SOs activated them through the platform's UI. The realized responses were analyzed, and real-life activations were combined with simulated bottleneck situations or other situations where flexibility activation might benefit the SOs.

The responses of individual flexibility resources varied; in some cases, the responses were excellent, as shown in Fig. 7, where 14.9 kW up-regulation occurred at 9 am, but sometimes the responses were less optimal. On an aggregated level, as in Fig. 8, this variation was smoothed, and the responses were clearly observable. However, there is some room for improvement. In both Fig. 7 and 8, the responses were delayed by a few minutes, and the FSP should address this in the future. It is also clearly visible FSP's preheating action before activation of up-regulation in Fig. 7. This is naturally a way to realize the requested up-regulation without compromising the heating requirements of the sites. However, suppose the SO's network is close to the maximum limit also before the activation. In that case, the bid qualification and the bidding data requirements should consider this phenomenon (and the potential rebound effect after the activation). Overall, the results proved the viability of using mFRR bids for CM, and the whole end-to-end process was successfully piloted. In addition, all platform modules were found to be practical and useful during the piloting, although some improvement needs were identified. A summary of the results per selected scenario is given in the following.

6.1.1.1. Scenario 1. TSO procured a maximum amount of upregulation for the whole hour to maintain operational security in the area during a planned outage. However, the amount of activated flexibility did not meet the TSO expectations. The settlement revealed that only 45% of the procured flexibility was delivered. This was a recurring issue at the beginning of the demonstration. It took several flexibility activations before the FSP learned to size the bids correctly. This experience highlighted the importance of testing and developing demand response models before entering the market.

6.1.1.2. Scenario 2. DSO procured upregulation (load reduction) for one hour from a resource located at the end of the feeder to solve a short-term voltage violation issue arising from the short-term use of a backup connection. Without flexibility, the voltage was forecasted to drop below the allowed minimum voltage at the MV level. The leisure center responded to the upregulation request by cutting consumption from 8 to 9 am by 180 kW compared to the forecasted consumption, as is shown in Fig. 9. This raised the MV network minimum voltage back to the acceptable range. The next hour, after flexibility activation, shows a 128-kW increase in consumption compared to the baseline,[5] which can be mainly influenced by the rebound effect of the HPs.

Although the voltage issue was solved in this individual case, further statistical analysis of the activation hour, considering the hourly load forecast variances on the test feeder, revealed that 225 kW of additional load reduction, evenly distributed along the feeder, would have been needed to achieve 95% confidence that the minimum voltage limit is not violated. The load rebound was not considered to cause congestion in this scenario because the network was assumed to return to a normal, non-congested switching state before activation ended. In other scenarios, where the network was operated close to the limit longer, the rebound did become an issue and highlighted the need for rebound management.

6.1.1.3. Scenario 3. In this simulated scenario, excessive solar generation was forecasted to cause distribution transformer overloading. DSO procured downregulation from the market, and FSP activated flexibility resources. Consumption in the congested area increased by 10 kW during the first activation hour and by 11 kW during the second activation hour. Congestion would have been avoided if PV production had not exceeded the forecasted production. About 75% of the procured flexibility was activated outside the congestion area, and the HP resources used in this demonstration could provide flexibility for only two consecutive hours. Typically, downregulation for at least four hours is needed in this kind of scenario. This scenario revealed the limitation of HPs in providing flexibility for longer hours because the comfort of the asset owner must be first satisfied, and flexibility is considered a by-product of HP.

6.1.2. Intraday market integration

Like the mFRR integration, bids from Nord Pool's ID market were integrated into the platform for CM in the demonstration. Nord Pool did two things to make that happen. It developed its own IT system to be integrated into the platform; in addition, the Asset ID attribute was added to the bids (as optional) so that FSPs aiming to access markets beyond ID could use that. The intraday pilot case proved that CM could be part of the international and liquid ID market with relatively small system-level exceptions and modifications. This allows SOs and FSPs to participate in the regional intraday-based flexibility market without major updates to systems or operative processes.

6.2. TSO-DSO coordination

Table 7 compares the calculated value of network capacity using PLT-based and sensitivity-based methods. As the flexibility markets depend on the network capacity available in the market, a higher available network capacity is always desired. The results show that the TSO-DSO coordination module works irrespective of the algorithm used, whether it is PLT or sensitivity-based. In addition, it indicates that the sensitivity-based method could lead to a higher network utilization degree compared to the PLT method. The importance here is that the platform could allow various algorithms to perform TSO-DSO coordination, and therefore, the platform does not mandate or favor one algorithm over another but facilitates using different ones depending on

Table 6
The impact of the single interface to markets module on market integration.

Functionality	KPI	Formula/ measurement	Achieved value	Objective
Single interface to markets	The impact of the single interface to market to linking different markets together	Number of MOs providing access to more than one product	2 (4 in total)	Show the functionality of the single interface to markets

[5] Baseline was calculated by averaging similar days from 30 previous days and applying temperature dependency correction. Several baseline methodologies are discussed in [38].

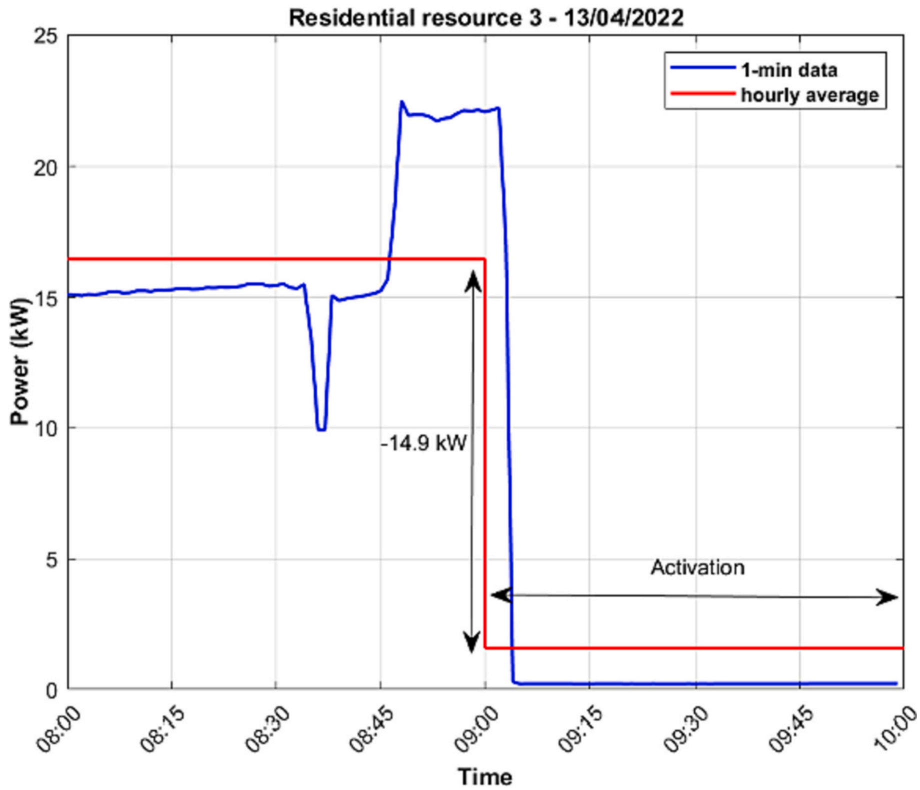

Fig. 7. Activation of an individual resource.

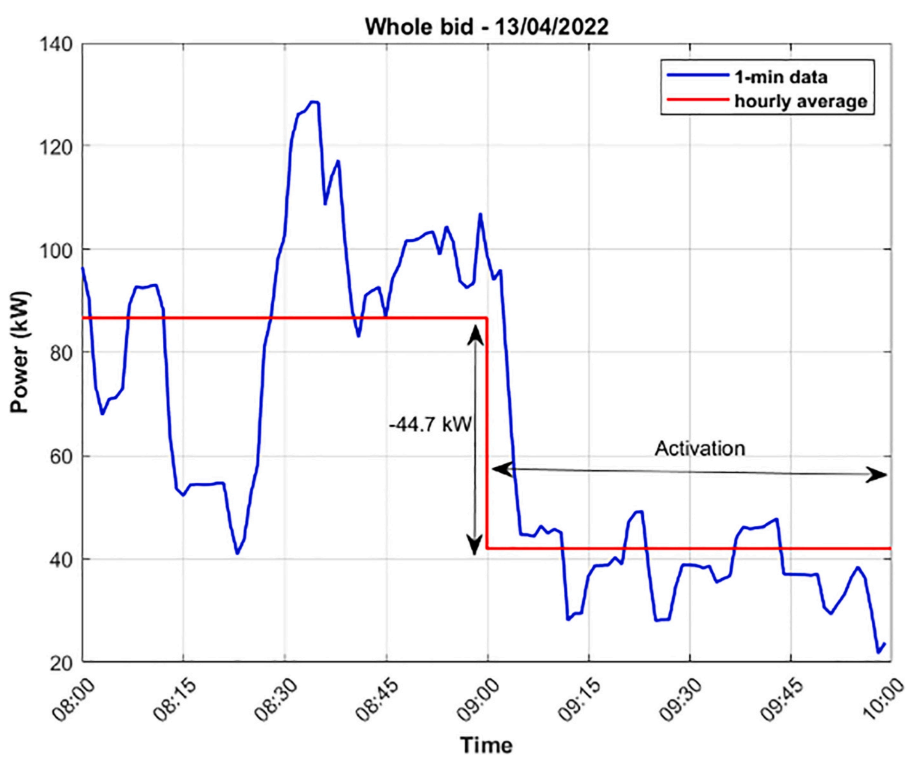

Fig. 8. Activation of aggregated flexibility resources.

the needs, available data, and computational capability of the users (e.g., DSOs).

6.3. *Congestion management*

Table 8 indicates that about a quarter of congestion cases were removed in two demonstrations using the proposed platform, while the

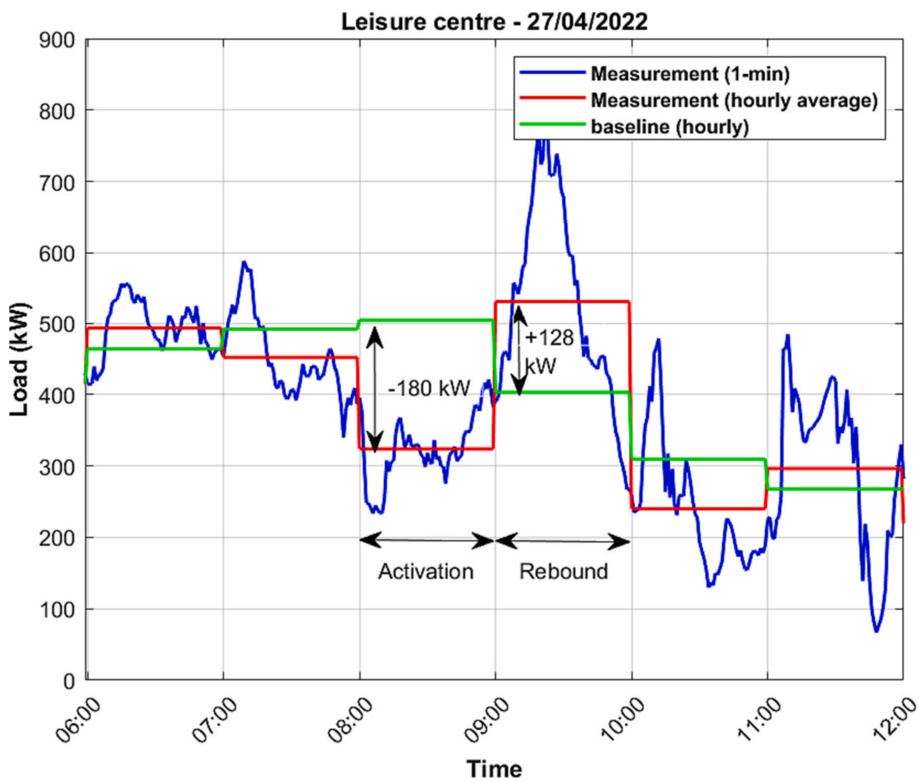

Fig. 9. Upregulation of the leisure center's flexible HP resources

Table 7
The comparison between PLT and PTDF.

Functionality	KPI	Formula/ measurement	Achieved value	Objective
Maximization of network utilization	Percentage of network capacity available for load and flexibility with PLT-based network qualification	Mean ((actual load + estimated free capacity) / (actual load + actual free capacity)) * 100%	61.8%	Show the network utilization degree achievable with the developed bid qualification method.
	Percentage of network capacity available for load and flexibility with PTDF-based network qualification[a]	Mean ((actual load + estimated free capacity) / (actual load + actual free capacity)) * 100%	89.8%	

[a] PTDF matrices-based network qualification for normal state and NVSF matrices-based for backup state

Table 8
CM effectiveness using the proposed platform.

Functionality	KPI	Formula/ measurement	Achieved value	Objective
CM	Effectiveness of using the platform for CM	Congestion cases fully solved / total congestion cases	¼ of congestion cases fully solved	Show the success rate of the market-based CM process using the platform

congestion intensity was reduced in some other congestion cases. Also, it shows that the market-based CM, even after leveraging market integration, might not be able to remove all the congestion cases, and therefore, expectations regarding the impact of using flexibility in real-world congestion cases have to be realistic.

6.4. Discussion

This section briefly discusses the challenges and needs for further platform improvement. Market integration can be challenging when it comes to convincing MOs to integrate the platform into their system. The MOs must see a concrete benefit for using it because some effort from their side (e.g., IT integration, modification in product attributes) is required to use the platform. In addition, as locational information is vital for CM, a market with bids without granular enough locational information (e.g., at least MV level) cannot use the platform, which might cause a barrier in market integration.

Although centralized TSO-DSO coordination based on sensitivity matrices and PLT was implemented, the other options, including centralized coordination based on power flow calculations and decentralized coordination, should be kept open as they have their benefits. Coordination based on a centralized power flow calculation would be the most accurate and expandable option, and decentralized based on communication and SOs internal calculations would be the best from SO's data security view.

One concern is that the proposed TSO-DSO coordination might qualify bids in an overly cautious manner and thus reduce the liquidity of a market that already suffers from low liquidity. At present, there are safety margins in three different levels, and their combined effect might further limit the number of qualified bids. Increasing the frequency at which the sensitivity matrices and load forecasts are updated would help to decrease the safety margins.

The demonstrations revealed development needs also outside of the platform. The FSPs should develop methods for forecasting the amount of flexibility their resources can supply at different times, and SOs should develop statistical network state forecasting tools that can consider the uncertainties in consumption, generation, and flexibility availability to manage the risks associated with both selling and buying of flexibility.

7. Conclusion

The article presented the approach taken and the results achieved in two demonstrations to overcome two challenges of enhancing flexibility availability for SOs' CM and its usability. As SOs' congestion problems are increasing and solving them through market mechanisms requires bids to have locational information, markets that offer CM services (e.g., LFM) often suffer from low liquidity. For that reason, the demonstration showed that, with limited integration efforts from MOs, it is possible to obtain liquidity from well-established markets, such as intraday and balancing, that are not initially designed for the CM use case. Another benefit of leveraging market integration to boost SO's access to flexibility is to prevent the introduction of new marketplaces for every new use case. Avoiding a myriad of markets is one important achievement of integrating existing marketplaces for a new use case like CM.

The second challenge is related to the absence of SOs' network limits (especially distribution networks) in market clearing processes. DSOs are often blind to stakeholders' market activities, and once a congestion problem occurs, they are responsible for resolving it. The demonstration's proposed solution was that SOs send their networks' sensitivity-based or PLT-based data to the coordination module in the proposed platform. Afterward, the TSO-DSO coordination module calculates free capacities on each network's nodes and checks each bid against the calculated capacities to ensure that the bid activation does not cause an adverse impact. The demonstration showed that the proposed coordination process, more importantly, works in real-world situations regardless of the algorithm (sensitivity-based or PLT), and it is possible not only to avoid congestion when an SO procures flexibility but also to protect SOs from the market activities of other stakeholders like FSPs as long as the bids go through the platform.

Some further findings were achieved while conducting the demonstrations that are worth mentioning here:

Enhancing the visibility of the flexibility-related data was one improvement in the article. Each stakeholder might have flexibility-related information that has value for another stakeholder; however, there is no systematic, automated, and reliable procedure and platform to share the data. The platform's metadata register (i.e., FR) shows that it can collect all the flexibility-related data, such as flexibility assets' location, technology, responsible FSPs, and qualification results. Different stakeholders can then use the collected data depending on their needs and access rights. The visibility of flexibility-related data that enhances the informed decision-making of stakeholders is improved thanks to the proposed metadata register.

Heat pump (HP) technology was used in the demonstrations as the flexibility resource, and therefore, two observations regarding that specific technology were achieved. Firstly, as HP's primary use case is for heating/cooling of indoor spaces, flexibility provision can be seen as a secondary use case. As a result, before flexibility activation, preheating was done by heat pumps in order not to compromise the indoor temperature due to flexibility activation. In addition, for the same reason, the rebound effect was visible in the consumption of the HP once the activation period ended. Due to the importance of indoor temperature, the duration of flexibility provision of HP technology is a few hours, perhaps one hour, which seems to be highly dependent on the outdoor temperature and insulation of the building. As a result, FSPs should have realistic expectations from the capability of HP technology in flexibility provision to avoid undelivered flexibility.

In the demonstrations, market integration enhanced flexibility availability for CM. The results show that only 25% of congestion cases were resolved using the proposed solution, knowing that the congestion removal might be higher if a mix of flexibility resource technologies had been used; nevertheless, expectations from market-based CM, in general, must be realistic. A high expectation from market-based CM could result in disappointment when applied in real-life, leading to mistrust among flexibility users (e.g., DSOs) toward the market-based solution.

CRediT authorship contribution statement

Mehdi Attar: Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Conceptualization. **Sami Repo:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis. **Antti Mutanen:** Writing – review & editing, Visualization, Software, Investigation, Formal analysis. **Jukka Rinta-Luoma:** Writing – review & editing, Software, Investigation. **Teemu Väre:** Writing – review & editing, Software, Investigation. **Kalle Kukk:** Writing – review & editing, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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