Recommendations for a Consumer-Centric Products and Efficient Market Design

D3.3

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About OneNet

The project OneNet (One Network for Europe) will provide a seamless integration of all the actors in the electricity network across Europe to create the conditions for a synergistic operation that optimizes the overall energy system while creating an open and fair market structure.

OneNet is funded through the EU's eighth Framework Programme Horizon 2020, "TSO – DSO Consumer: Large-scale demonstrations of innovative grid services through demand response, storage and small-scale (RES) generation" and responds to the call "Building a low-carbon, climate resilient future (LC)".

As the electrical grid moves from being a fully centralized to a highly decentralized system, grid operators have to adapt to this changing environment and adjust their current business model to accommodate faster reactions and adaptive flexibility. This is an unprecedented challenge requiring an unprecedented solution. The project brings together a consortium of over 70 partners, including key IT players, leading research institutions and the two most relevant associations for grid operators.

The key elements of the project are:

1. Definition of a common market design for Europe: this means standardized products and key parameters for grid services which aim at the coordination of all actors, from grid operators to customers;
2. Definition of a Common IT Architecture and Common IT Interfaces: this means not trying to create a single IT platform for all the products but enabling an open architecture of interactions among several platforms so that anybody can join any market across Europe; and
3. Large-scale demonstrators to implement and showcase the scalable solutions developed throughout the project. These demonstrators are organized in four clusters coming to include countries in every region of Europe and testing innovative use cases never validated before.

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List of Abbreviations and Acronyms

Acronym	Meaning
aFRR	Automatic Frequency Response Reserve
BEUC	The European Consumer Organization (Bureau Européen des Unions de Consommateurs)
BR	Best Response
BRP	Balance Responsible Parties
BSP	Balance Service Provider
BTM	Behind the meter
CAISO	California Independent System Operator
CEP	Clean Energy Package
CCMD	Consumer-Centric Market Design
CM	Congestion Management
DA	Day-ahead
DER	Distributed Energy Resource
DN	Distribution Network
DR	Demand Response
DSF	Demand-Side Flexibility
DSO	Distribution System Operator
EBGL	Electricity Balancing Guideline
EC	European Commission
ENTSO-e	European Network of Transmission System Operators - electric
EU	European Commission
FAT	Full Activation Time
FGDR	Framework Guidelines for Demand Response
FSP	Flexibility Service Providers
FSR	Florence School of Regulation
GCT	Gate Closure Time
ICT	information and communication technology
IEM	Internal Energy Market
ID	Intraday
LG	Locational Granularity
MARI	Manually Activated Reserves Initiative
mFRR	Manual Frequency Response Reserve
MO	Market Operator
MTU	Market Time Unit
N/A	Not Applicable
NE	Nash Equilibrium

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NEMO	Nominated Electricity Market Operator
NRA	national regulatory authorities
PICASSO	Platform for the International Coordination of Automated Frequency Restoration
PTDF	power transfer distribution factors
RPG	Reserve Providing Group
RPU	Reserve Providing Unit
RSF	Residual Supply Function
SCADA	Supervisory Control and Data Acquisition
SME	Small and Medium-sized Enterprise
SO	System Operator
SP	Service Providers
SPU	System Protection Unit
TERRE	Trans-European Replacement Reserves Exchange
TMF	Theoretical Market Framework
ToE	Transfer of Energy
TSO	Transmission System Operator
UVAM	Mixed Virtually Aggregated Units (*Unità Virtuali Abilitate Miste)*
vRES	variable renewable energy sources
WP3	Work Package 3

Executive Summary

With the changing energy landscape at the generation, consumption, and storage levels, an increasing volume of flexibility potential is becoming available at different grid levels. Flexibility is the practice in which a user changes its consumption (grid withdrawals) or generation (grid injections) schedules as a service for the grid. This flexibility can then deliver services to system operators (SOs) at different levels of the grids (transmission or distribution), such as balancing services (in its varying types), congestion management, and voltage control, among others. This flexibility can, hence, stem from different grid levels, and can be offered to multiple SOs, where the SOs accessing the flexibility may or may not be operating the grid from which the flexibility is generated. For example, a flexibility asset (or aggregation thereof) at the distribution level can potentially offer flexibility to the distribution system operator (DSO) – e.g., for congestion management, or voltage control – as well as to the transmission system operator (TSO) – e.g., for balancing, or congestion management at the transmission level. This flexibility can be offered by flexibility service providers (FSPs) to the SOs through the means of market mechanisms, giving rise to flexibility markets. In this setting, coordination between SOs for flexibility provision is increasingly crucial for (i) maximizing the efficiency of the flexibility procurement process, where efficiency reflects the minimization of the flexibility procurement costs, by unlocking the value-stacking potential of flexibility (whereby, a flexibility offer can concurrently meet the needs of multiple SOs), (ii) enabling a transparent and consistent participation and valorization opportunities for the FSPs, and (iii) crucially, ensuring that the flexibility is delivered in a grid-safe manner for all the participating grids. Different coordination mechanisms can induce varying impacts on the efficiency of the procurement process, its adequacy for meeting the grid needs in a grid-safe manner, and its consumer-centricity.

This work explores and evaluates a number of TSO-DSO coordinated flexibility market models enabling the coordinated procurement of flexibility among the SOs. The analyzed TSO-DSO coordinated market models range from disjoint market schemes, in which each SO independently procures flexibility solely from resources connected to its own grid, to common flexibility markets in which multiple SOs jointly procure flexibility, in a co-optimized way, from a common pool of flexibility bids to meet their flexibility needs while abiding by their respective grids' operational constraints. Within this spectrum of possibilities, sequential market schemes are also explored and analyzed. Namely, multilevel and fragmented market schemes are considered, which are sequential market models that are composed of a local distribution-level market layer followed by a centralized transmission-level market layer, to sequentially meet the needs of the DSOs and TSOs. While multilevel markets allow for distribution-level FSPs' flexibility offers to be directly accessible to transmission-level markets – while giving priority access to DSOs to their local flexibility – fragmented markets prohibit it, and only enable the indirect access by TSOs to distributed flexibility through cumulative changes to the flow at the transmission-distribution interconnections. The evaluation of these schemes in the presented analysis considers several key factors such as (i) the economic efficiency of the TSO-DSO coordinated flexibility markets, and their key drivers

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and impacting factors, (ii) the consumer-centricity of the designs, (iii) the level of entry barriers they can exhibit for different types of FSPs, (iv) the ability of the proposed schemes to maximize value-stacking potential of flexibility, (v) the ability to efficiently resolve the system needs and the grid operational risks they can introduce, (vi) the level of opportunity they present for strategic behavior and gaming, and their sensitivity to such bidding mechanisms, and (vii) regulatory frameworks impacting different steps within their processes.

Towards these goals, different TSO-DSO coordination schemes are first introduced conceptually as well as developed mathematically, in the form of several optimization market clearing formulations, which are then implemented in code to develop a simulation environment. This simulation environment allows the simulation of different market clearing instances, following the corresponding TSO-DSO coordinated market designs, which in turn, enables their quantitative comparison. This process has allowed the identification of various key factors that can directly impact that efficiency and the quantification of their associated effects.

Indeed, the simulation results initially show that the joint procurement of flexibility in a common market results in a maximum theoretical efficiency due to the maximization of the value stacking potential of flexibility and the co-optimization of the procurement process, thus jointly and optimally meeting the needs of all SOs while collectively abiding by their grid constraints. However, this theoretical bound can be impacted by different practical implications affecting the potential efficiency of the common market. Indeed, the analysis has further shown that several identified key factors can directly impact the efficiency of the different TSO-DSO coordinated market models leading to their convergence or divergence. These factors include the i) interface flow pricing (which is an instrument for pricing the indirect, cumulative exchange of flexibility between systems), (ii) the FSPs' potentially varying sequential bidding processes, (iii) the entry barriers that different TSO-DSO coordinated market schemes can exhibit due to product attribute requirements and lacking consumer-centric mechanisms, (iv) varying flexibility bid formats, and (v) the FSPs' strategic bidding and gaming opportunities. In this regard, interface flow pricing has been shown to be a key impact factor especially in sequential market models (i.e., multilevel and fragmented markets). Improper pricing can lead to an acute loss of efficiency of those sequential market models due to excessive purchasing of downward flexibility in their local layers, whereas optimal interface flow pricing schemes can lead the sequential market's efficiency to match that of the common market. These results corroborate observations in previous large-scale European projects, namely, the H2020 CoordiNet project. The FSPs' sequential bidding process is also shown to have a direct impact on the efficiency of the multilevel market (in which differing bidding behaviors for distribution-level FSPs can take place in the sequential market layers), especially when FSPs have incentives to offer their flexibility at different prices in the different subsequent markets, wither due to perceived differing levels of competitions or participation costs in the different layers. In addition, the analysis captures the impact that entry barriers can have on the efficiency of each market scheme. In this regard, creating local market layers, such as in the multilevel market, can serve to reduce entry requirements of small-scale flexibility resources, enabling their increased participation, which may otherwise have not been possible in centralized and common markets. This increased participation, on the one

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hand, improves the efficiency of the multilevel market, as compared to the common market, but on the other hand, can lead to a loss of efficiency due to the fragmentation of the procurement process by the SOs over the different market layers, which reduces the potential of flexibility value stacking (a feature that is maximized under the common market). This tradeoff is shown to manifest at different levels in different TSO-DSO coordinated market models with direct impact on their efficiency. This market fragmentation is also shown to play a negative role when considering bid formats that impose minimum clearing requirements on their quantities (known as partially divisible bids), and when considering the possible strategic bidding behavior by the flexibility providers.

The efficiency improvement introduced by sequential market layers is primarily driven by their potential for improving consumer-centricity and decreasing entry barriers. These aspects have been considered and analyzed in preparation for the efficiency analysis.

Focusing on consumer centricity, the analysis first defines what consumer-centricity can entail, by relying on EU legislation and policy documents as well as different stakeholder perspectives, as a common definition of the term “consumer-centricity” is not commonly available. Then, these consumer-centricity principles are applied in the general context of existing and emerging electricity markets, in particular focusing on TSO-DSO coordinated flexibility markets. The analysis shows that, naturally, market schemes that do not allow participation of distribution-level flexibility (as, e.g., disjoint transmission-level markets and fragmented markets) would exhibit a low level of consumer-centricity, especially when considering small-scale consumers. Moreover, even when allowing this flexibility participation, the levels of consumer-centricity can still differ between schemes, depending on the existence of entry barriers, permitted aggregation, and the extent up to which consumers are enabled to valorize their flexibility, among others. The analysis showcases that meeting the different elements of consumer-centricity can be hindered by technical challenges stemming from the individual consumer’s flexible assets as well as from the requirements of the service to be delivered to the grid. This can pose, at instances, reliability concerns, as the requirements for the traded flexibility products are ideally designed to ensure the proper delivery of crucial services for the grid. In this respect, aggregation techniques can serve to alleviate some of those challenges, thereby improving the consumer-centricity of the flexibility procurement process while ensuring the reliable procurement of grid services.

Focusing on entry barriers, the work identifies and analyzes the entry barriers that different FSP types may experience in varying TSO-DSO coordinated market models. The work first proceeds by identifying the set of barriers, which can arise due to the different service requirements captured by the corresponding flexibility products’ attributes. These barriers generally apply to all TSO-DSO coordination schemes, but can potentially be exhibited at different levels of severity in different schemes. In this respect, the work projects those possible barriers on the TSO-DSO coordination schemes to determine whether a TSO-DSO coordinated market scheme can serve to attenuate or, in contrast, exacerbate the occurrence and possible impacts of such entry barriers.

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The main results showcase a main feature that the creation of a local market layer can serve to decrease entry barriers, as the design of such local market layers can take into consideration the local requirements of the grid as well as the constraints of local flexibility providers. However, as shown in the efficiency analysis, the overall impact of the creation of subsequent market layers on the market efficiency is case-dependent due to the tradeoff between the increasing efficiency due to the potential wider FSP participation driven by decreased entry barriers and the decreasing efficiency due to fragmentation of the procurement process.

Advancing the analysis on TSO-DSO coordinated market models and their efficiencies, the analysis also takes a key focus on the linking between flexibility markets through the forwarding of flexibility bids. This mechanism is defined in this work to capture a process through which flexibility bids in one market (which have been unused in that market) for a specific service can be forwarded to another subsequent market for potentially delivering other services, as, e.g., in multilevel markets but while having the subsequent market layers running independently without the need for exchange of network information (which gives rise to a special form of multilevel markets). The goal of these mechanisms is to enable an increase in the value stacking potential of flexibility, especially in settings in which the markets are not otherwise connected through their market clearing processes. For example, in a setting in which a local/regional congestion management market is set up, followed by a balancing market (e.g., for manual frequency restoration reserves (mFRR) through the Manually Activated Reserves Initiative (MARI)), unused flexibility in the congestion management markets can then be forwarded to the balancing market. The work identifies the mechanisms and processing steps needed for achieving such market linking through bid forwarding, including the requirements for compatibility of the products (and their attributes) traded in the two markets, the compatibility of the bid formats in the two markets, as well as, rather crucially, ensuring that the bids forwarded, when cleared in the subsequent market, would not cause network violations in their respective grids. These aspects are analyzed while also considering a regulatory perspective, identifying the existing and envisioned regulatory frameworks, which can enable or hinder the implementation of such bid forwarding mechanisms. Namely, the analysis highlights the possible requirement for updating the roles of the different actors involved – such as system operators and market operators – to be able to handle the bid forwarding needs and processes. In addition, market participation rules are also shown to play a key role in enabling bid forwarding when considering multiple subsequent markets. For example, differing prequalification rules and capacity reservation requirements can hinder the possibility of bid forwarding. Nonetheless, such requirements are typically needed to ensure the secure operation of the grid and the reliable procurement of services. As such, these elements must be concurrently examined when defining the possibilities for bid forwarding, as well as its feasibility, given the markets in place and the services considered.

In terms of the underlying grid-safety conditions for bid forwarding, the work also explores and compares three different approaches for grid-impact aware bid forwarding, to manage the risk that the forwarding of bids can pose to the local grids, inspired by propositions initially conceptualized in previous European projects, including the H2020 CoordiNet project, the H2020 Interrface project, and the H2020 SmartNet project. The introduced methods in this work build upon these previous concepts and further develop them, through the proposition of three different methods, namely: (i) a first method consisting of a 3-layer market method, in which a third market layer is set up for enabling corrections after bid forwarding, hence resolving possible network constraint violations that might have been caused by the clearing of forwarded bids using an added third flexibility procurement market layer (ii) a second method in which a dynamic bid prequalification mechanism prior to bid forwarding is implemented, as well as (iii) a third method consisting of a bid aggregation method taking into account the local grids' limitations in the form of residual supply functions, which are then forwarded instead of the individual bids. The adequacy of these mechanisms is quantitatively analyzed, based on developed models and a simulation environment, where the quantitative analyses focuses on their achieved efficiencies, level of guarantee of grid safety, and computational complexity. The analysis also considers a regulatory perspective, investigating the level of harmony of these methods with existing and envisioned European regulations. The analysis showcases that the bid aggregation method can theoretically lead to a maximized efficiency and improved grid safety, especially when the aggregation mechanism and the prices of aggregated flexibility, captured in the residual supply function, are well-designed (which can pose technical challenges). However, its computational burden is higher than the presented alternatives, which can hinder its practical implementation. In addition, as this method requires aggregation of bids, it poses regulatory challenges stemming from the requirements on the entity that would take up this role, and hence can face regulatory obstacles. The 3-layer market method is shown to provide a simple alternative in terms of computational complexity, and it provides coherence with existing regulations as it does not require interference with the market process or updating of roles, but rather relies on an addition of a market layer akin to a market-based redispatch mechanism. The efficiency and grid-safety of this process depend on the liquidity of flexibility available from the distribution layers, where low level of liquidity can jeopardize the possibility and efficiency of performing a redispatch step. The dynamic bid prequalification method is also shown to be of low computational complexity while fairly meeting the current regulatory requirements, under the condition of enabling SOs (DSOs or TSOs operating the grid from which the forwarded flexibility originates) to dynamically prequalify and filter out grid-unsafe bids prior to their forwarding. Its grid safety and efficiency is dependent on the nature of the grids involved (i.e., radial vs. meshed), the relative prices of the offered upward and downward flexibility, as well as the sophistication of the bid filtering process, which should ideally filter out only grid-unsafe bids (or unsafe portions thereof), which can be a complex task. Indeed, as this process is ex-ante, it raises a tradeoff between grid-safety and optimality when designing the bid filtering step. Overall, even when considering these identified challenges, bid forwarding is shown to contribute to an increase in efficiency, if implemented adequately, as compared to disjoint or fragmented market settings that limit the use of flexibility to meeting the grid needs of the grid from which it originates.

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In this respect, through the introduced concepts, models, and mechanisms and the associated quantitative and qualitative analyses, this work provides key insights on the design of efficient and coordinated markets for the procurement of flexibility in Europe, contributing to the overarching goals of the OneNet project.

1 Introduction

1.1 Task 3.3: Motivation, Objectives, and Methodology

This document reports on the work conducted within Task 3.3 (T3.3) of the OneNet project. The general focus of the work is on the design of efficient, integrated, and scalable markets for the procurement of system services by the distribution system operators (DSOs) and transmission system operators (TSOs) in seamless coordination between the different actors involved. Within this scope, we focus, in particular on the development of TSO-DSO coordinated flexibility market schemes and models that enable a market-based procurement of flexibility from different voltage levels to meet the varying services needs of different system operators (SOs) in a coordinated and efficient manner. The developpe mechanisms aim to achieve a market-based procurement of flexibility that enable:

i. An economically efficient, seamless, and practical TSO-DSO coordination mechanisms and schemes for procurement of flexibility, minimizing the incurred system costs for all the SOs involved;
ii. A grid-impact aware procurement of flexibility, which not only ensures that the flexibility purchased meets the system needs, but that it also abides by the grid operational requirements and constraints of all the grids involved;
iii. A consumer-centric design, enhancing the participation potential of different types of consumers in flexibility markets;
iv. Maximizing the value-stacking potential of flexibility, through which a flexibility offered by a provider can be used to simultaneously, or subsequently, meet the needs of multiple SOs; hence, maximizing the value brought to flexibility providers and minimizing the incurred system costs.

The design of efficient TSO-DSO coordinated flexibility markets is a key objective of this work. Efficiency, in this sense, refers to the economic efficiency of the procurement or purchasing of flexibility by different SOs to meet their services (e.g., balancing, congestion management, voltage control, etc.) needs. Efficiency, hence, captures the costs of the coordinated purchasing of such flexibility, where the more efficient the TSO-DSO coordinated flexibility market is, the lower the costs of meeting the needs of the different SOs. We thus aim at identifying and addressing TSO-DSO flexibility markets' efficiency drivers and distortions, aiming at analyzing the impact several factors can have on the efficiency of TSO-DSO coordinated flexibility markets and the identification of remedial measures and alternative design options, allowing us to generate insights on the most adequate TSO-DSO flexibility market schemes for implementation.

Indeed, several dimensions can have a direct impact on the efficiency of the TSO-DSO coordinated flexibility procurement process. One main element is the TSO-DSO coordination scheme [1], [2], which reflects the way in

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which TSOs and DSOs coordinate the procurement of flexibility capturing several dimensions such as (among others):

- The system(s) in which the flexibility need is located (e.g., at TSO-level, at DSO-level, or in several SOs) with implications on which SOs would be the primary buyers of flexibility;
- The systems or grid levels from which flexibility is offered through market participation;
- The number of markets or market layers in place in which the SOs can separately, jointly, or sequentially procure flexibility;
- Access-level of different SOs to flexibility outside their grids/operational areas;
- The way in which flexibility service providers (FSPs) can participate and offer their flexibility in those markets;
- The way power exchange between SOs – capturing the use of cross-grid flexibility – is priced (to which we refer as the *interface flow pricing*);
- The access and sharing of network information between SOs or with neutral market platforms.

The design of the TSO-DSO coordination scheme to be implemented, by coordinating the access of different SOs to flexibility and (co-)optimizing the market clearing process generating the optimal sets of flexibility offers to purchase from FSPs to resolve the needs of the SOs at minimum cost, has a direct impact on the resulting efficiency of the procurement process. In addition, within those schemes, another key element affecting market efficiency or introducing distortions are the product specifications and requirements (commonly referred to as the product attributes [3]), specifying the technical needs required by a flexibility resource to participate and deliver its flexibility as part of such TSO-DSO coordination schemes.

Such market designs and product requirements have a (positive or negative) direct impact on the efficiency of the flexibility market – that goes beyond the mere impact of the market clearing formulation (i.e., how the TSO-DSO coordinated procurement of flexibility is (co-)optimized) – through several additional factors, such as (among others):

- The levels of entry barriers introduced;
- The consumer-centricity of the design;
- The ability to achieve value stacking potential of flexibility;
- Introducing or removing grid operational risks;
- Opening space for strategic behavior and gaming.

As such, this work analyzes the adequacy of different TSO-DSO coordinated market designs along those key dimensions. To achieve this objective, a detailed methodology was developed based on quantitative and simulation-based analyses, coupled with qualitative mechanisms and conceptual definitions, in addition to stakeholder consultation sessions. Through this methodology, we provide a structural comparison between different TSO-DSO coordinated markets design options. The implemented methodology follows multiple steps, as highlighted in Figure 1-1.

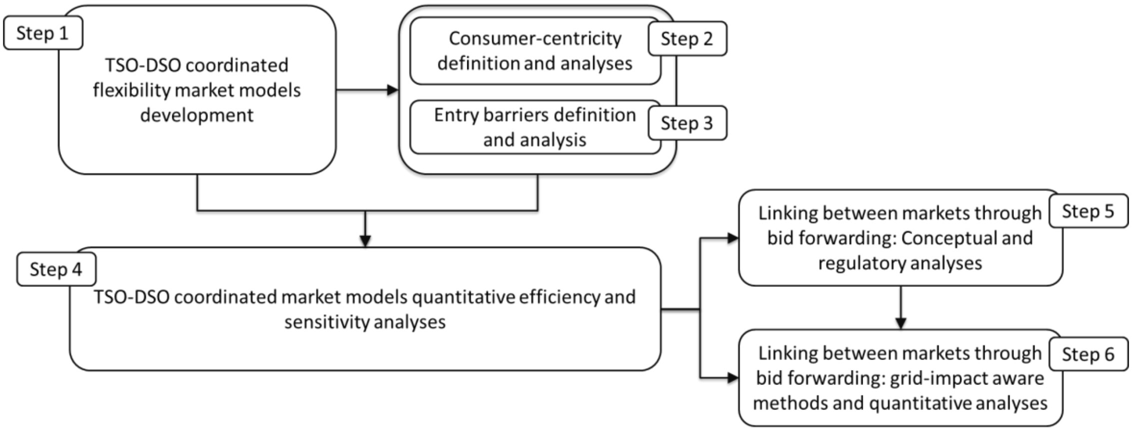

Figure 1-1 Methodology and Different Steps (Subtasks)

Step 1 (TSO-DSO coordination schemes and market models development): We first start by presenting a set of key TSO-DSO coordination schemes and resulting TSO-DSO coordinated flexibility market models, relying on previous developments within [1]. The definitions are introduced conceptually, and developed mathematically, also using initial mathematical developments reported in [1], resulting in several optimization formulations which are then implemented in code forming, thus, a simulation environment capable of running market clearing instances of the different TSO-DSO coordinated market designs and analyzing/comparing their outcomes. These developed TSO-DSO coordinated schemes form the basis for the rest of the analysis in the document.

Step 2 (consumer-centricity definition and analyses): We then focus on analyzing those TSO-DSO coordination schemes from a consumer-centricity perspective. In that respect, we first aim to define what a “consumer” is and then what consumer-centricity can entail, by relying on EU legislation and policy documents as well as different stakeholder perspectives, especially focusing on their possibly differing definition of consumer-centricity. The reason that this step was performed is that common and generally approved definitions do not seem to be always available. We then focus on what consumer-centricity can entail in the context of existing and emerging types of electricity markets, with a particular focus on TSO-DSO coordinated flexibility markets.

Step 3 (Entry barriers definition and analyses): We then analyze the entry barriers (for different types of FSPs) that each TSO-DSO coordination scheme can experience. We first identify the set of barriers that can arise due to the different product requirements (i.e., attributes) and project the barriers on the TSO-DSO coordination schemes, supported by stakeholder consultations, with the goal of identifying whether a coordination scheme can attenuate or exacerbate the occurrence and impacts of such entry barriers.

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Step 4 (TSO-DSO coordinated market models quantitative efficiency and sensitivity analyses): Step 4 constitutes the core of the efficiency analysis of the different TSO-DSO coordinated market models. After developing Steps 1-3, we quantitatively analyze, based on the simulation environment, the efficiency of each TSO-DSO coordinated flexibility model and the key factors that can drive or affect this efficiency. In this respect we investigate the efficiency of the different TSO-DSO coordinated market models' and their sensitivity to different factors, by focusing on the impact of: (i) the structure of the procurement mechanism (captured, technically, by the underlying optimization formulation of the market clearing problem) of each TSO-DSO coordinated flexibility market model on its resulting efficiency (ii) interface flow pricing (i.e., a measure of the pricing of the exchange of flexibility between systems), (iii) FSPs' sequential bidding processes, (iv) entry barriers (also resulting from non-consumer-centric mechanisms), (v) different bid formats, and (vi) FSPs' strategic bidding and gaming opportunities.

Step 5 (Linking between markets through bid-forwarding – conceptual and regulatory analyses): After the conducted efficiency and sensitivity analyses in Step 4, we focus our attention on analyzing sequential market settings. Sequential flexibility markets describe a setting in which different markets are set up for different services (e.g., a regional congestion management market followed by a country-level or European level balancing market such as the Manually Activated Reserves Initiative (MARI)). In such mechanisms, to reinforce the value stacking potential of the offered flexibility, these markets can be linked through bid forwarding, a process in which bids that were submitted to the first market when unused can be forwarded to the next market, hence, maximizing their potential use and benefiting both the FSP and the grid. In Step 5, we focus on providing a conceptual definition of this bid forwarding as a linking instrument between markets and define the requirements needed for its implementation, including any bid processing steps required to enable and organize the forwarding of bids, taking into account compatibility requirements of the sequential markets in place.

Step 6 (Linking between markets through bid forwarding - grid-impact aware methods and quantitative analyses): The sequential market aspects analyzed in Step 5 are taken further in Step 6. Indeed, when allowing flexibility to be forwarded from one market to the other (i.e., from Market 1 to Market 2), one must not only make sure that the forwarded bids abide by the format and product requirements of Market 2 (which is an aspect analyzed in Step 5), but one must also make sure that when the forwarded bids are purchased and activated in Market 2, those bids would abide by the grid constraints of the grids from which the flexibility is generated. This is especially important in the case where Market 2 does not explicitly constraint its market clearing based on the constraints of those grids. For example, in the case in which Market 1 is a regional congestion management market, and Market 2 is a European-level balancing market (following, e.g., MARI), as the MARI market clearing mechanism would not take into account intra-grid constraints of the grids participating in Market 1, the bid forwarding mechanisms has to make sure that only grid-safe bids can be forwarded. In this respect, we develop three different methods, namely, (i) a three-layer market scheme, adding a third market layer to correct grid issues that might arise based on the clearing of Market 2 (hence, further extending the

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concept of multilevel markets analyzed in this document), (ii) bid-prequalification, in which the bids are checked and prequalified against the grids of the local SOs (e.g., the SOs participating in Market 1), where only prequalified bids can then be forwarded, and (iii) a bid aggregation method (based on the concept of residual supply functions), offering aggregated bids to Market 2 (instead of individual bids) which abide by the constraints of the local grids. We then extend the models developed in Step 1 and analyzed in Step 4 to investigate those three options. In this respect, we develop the mathematical models needed, and translate them as well into code to generate a simulation software capable of comparing their efficiency and performance. In this respect, we compare the different proposed options in terms of (i) their economic efficiency (i.e., the costs for meeting the different systems' flexibility needs), (ii) the level up to which each mechanism can guarantee grid safety and the factors that play a key role in that respect, (iii) computational efficiency of each approach, and (iv) their overall practicality. In addition to the quantitative analysis, the analysis of the three methods is also considered from a regulatory perspective, taking into account their level of harmony with current European regulations as different methods entail different levels of interference in the market processes and adjustments to the role of different actors (especially to that of SOs).

Each of those steps constituted a subtask in the analysis and required its own methodology. The details of the methodologies employed are included in the respective chapters reporting the analysis within each step. The mapping between the steps and the chapters of this report is presented in Section 1.3.

The work in this task, following the different subtasks/steps, has also included interactions with other tasks and work packages. The key interactions are highlighted in Figure 1-2.

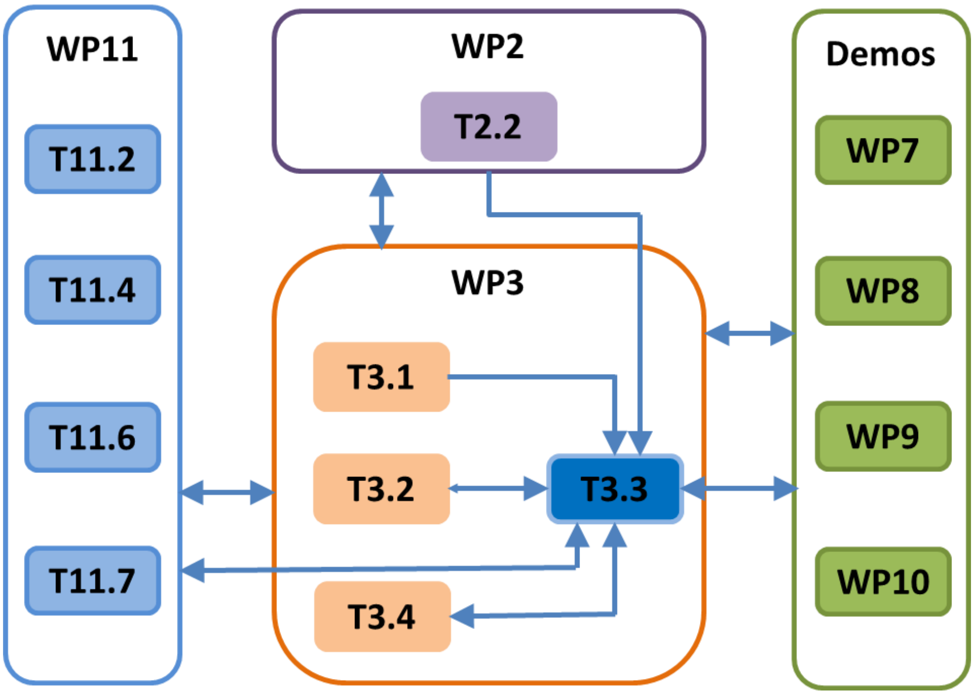

Figure 1-2 Interaction of T3.3 with Other WPs and Tasks within OneNet

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1.2 Objectives of the Work Reported in this Deliverable

The overarching goal of this work is to identify the efficiency drivers, barriers, and distortions of different TSO-DSO coordinated flexibility market schemes, and compare their adequacy focusing on different factors such as:

1) Their economic efficiency (capturing the ability to meet the flexibility needs of the SOs at the minimum cost) and the key factors that can affect this efficiency (i.e., identifying efficiency drives, challenges, and the sensitivity of the efficiency of the different TSO-DSO coordinated market models on these key factors);
2) Their level of meeting consumer-centricity goals;
3) Their effects on attenuating or exacerbating entry barriers for different types of flexibility providers;
4) Their ability to maximize the value-stacking potential of flexibility;
5) Their ability to safeguard the grid, thereby enabling the provision of flexibility from different voltage levels to meet the needs of different SOs while ensuring that not only the original services' needs are met, but that also the purchasing and activation of this flexibility would not cause network issues and constraint violations in other parts of the grids involved.
6) The possibility of gaming and strategic behavior that each scheme can make possible.
7) The regulatory mechanisms that can impact different key steps in the coordinated markets process.

Achieving this overarching goal requires the exploration of several key research questions, which constitute different sub-objectives of the current work:

1. How can different TSO-DSO coordinated flexibility markets be organized and formulated?
2. How can consumer-centricity be defined in the context of TSO-DSO coordinated flexibility markets?
3. How can TSO-DSO coordinated flexibility markets be impacted by (or even introduce or attenuate) entry barriers for different types of flexibility providers?
4. How do the different TSO-DSO coordination schemes compare in terms of efficiency, and what are the key drivers and factors impacting this efficiency? In particular, through quantitative analyses and numerical simulations, what is the sensitivity of different TSO-DSO coordinated flexibility market schemes to the following factors?
    a. The interface flow pricing options (exploring several pricing mechanisms);
    b. The FSPs' sequential bidding processes in sequential flexibility markets;
    c. Different entry barriers by considering, e.g., barriers driven by minimum quantity requirements;
    d. Different bid formats;
    e. FSPs' strategic bidding and gaming opportunities.

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5. What are the means for interconnecting between separate flexibility markets (for different services) allowing the forwarding of unused flexibility bids from one market layer to a subsequent one to maximize the value of the offered flexibility?
    a. What are the mechanisms that should be implemented to enable such bid forwarding?
    b. What are the regulatory aspects affecting the possibility of bid forwarding?
    c. What risks are posed to the grid from which flexibility originates when flexibility bids are forwarded?
    d. What techniques can be developed and implemented to ensure the grid-safe forwarding of flexibility, focusing on (i) the implementation of market mechanisms for the correction of any grid issues that arise, (ii) dynamic bid prequalification mechanisms that enable the forwarding of only bids that are deemed grid-safe, and (iii) bid aggregation mechanisms allowing the creation of aggregated functions from individual bids (known as residual functions) that can be offered from one system to the next in a grid-safe manner.
    e. How do these three approaches compare (quantitatively) in terms of economic efficiency, grid-safety, computational complexity, and practicality in terms of coherence with existing and envisioned regulations?

1.3 Outline of the Deliverable

The different steps of the analysis are mapped to the different chapters of the document, which is structured as follows:

1. Chapter 2 presents the different TSO-DSO coordinated flexibility market models, covering Step 1 of the methodology in Figure 1-1.
2. Chapter 3 presents the analysis of consumer-centricity, covering Step 2 of the methodology in Figure 1-1.
3. Chapter 4 presents the analysis of entry barriers, covering Step 3 of the methodology in Figure 1-1.
4. Chapter 5 presents the quantitative efficiency analysis and simulation results, analyzing and comparing the efficiencies of the different TSO-DSO coordinated flexibility markets and their sensitivity to the different identified key factors. This chapter covers Step 4 of the methodology in Figure 1-1.
5. Chapter 6 presents the conceptual analysis on linking markets through bid forwarding, covering Step 5 of the methodology in Figure 1-1.
6. Chapter 7 presents the quantitative and regulatory analysis of the different methods for a grid-impact aware linking between markets through bid forwarding, covering Step 6 of the methodology in Figure 1-1.
7. Chapter 8 concludes the document, highlighting the key insights derived from the performed analyses.

1.4 How to Read this Document

The document is written with a high level of self-sufficiency in terms of contents. Hence, the concepts used are typically also first introduced in the document so it can be read independently to a large extent. However, for management of the length of the report, some background information can be at instances provided in a summarized or abstracted way, while the complete information can be found in the respectively references works. The work benefits from different developments within the OneNet project (as highlighted in Figure 1-2) and builds further upon different initial developments in previous European projects (such as H2020 CoordiNet, H2020 Interrface, and H2020 Smartnet) as well as in the scientific literature. In this context, references are included in the form of citations to other deliverables (e.g., the OneNet deliverables of the tasks captured in Figure 1-2) as well as to previous works in European projects and the scientific literature along with their documentation when adequate. For further information on such previous works, the reader is encouraged to explore the references cited in each chapter, whose information is provided in the bibliography of this document.

Chapter 2 , Chapter 5, and Chapter 7, respectively introduce the different TSO-DSO coordinated models and perform detailed analytical and quantitative analyses (as initially indicated in Section 1.1 and Section 1.3). These analyses required the developed of different mathematical models. The mathematical details are not included in the chapters but are rather available in a set of papers published based on this work [4], [5], [6]. As such, in each chapter, we refer to those papers for readers interested in the mathematical details, as well as relevant papers in the literature that provide the relevant mathematical descriptions.

In general, the document provides a holistic analysis of TSO-DSO coordinated flexibility markets along different directions, in such a way that one step of the methodology can feed into the other. Nonetheless, for ease of presentation, the different chapters are written in a way to be as self-sufficient as possible. However, they will, when needed, refer to different other chapters in the deliverable in which the relevant information needed or part of the analysis can be found. To provide an easy to follow mapping, the following guide can help the reader navigate through the document in case interested in only a subset of the questions:

- For interest in the conceptual definition of TSO-DSO coordinated market models, the reader is referred to Chapter 2. The core quantitative analyses of the efficiency of these TSO-DSO coordinated models is provided in Chapter 5.
- For the sole interest in consumer-centricity and its implications to TSO-DSO coordinated flexibility markets, the reader is referred to Chapter 3, which uses inputs on the definition of the market schemes from Chapter 2.
- For the sole interest in entry barriers and their applications to TSO-DSO coordinated flexibility markets, the reader is referred to Chapter 4, which also relies on inputs from Chapter 2 for the definitions of the different TSO-DSO coordinated market schemes.

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- For the sole interest in the conceptual and regulatory characterization and analysis of linking between markets through bid forwarding, the reader is referred to Chapter 6.
- For a detailed proposition of different grid-impact aware methods enabling grid forwarding, the reader is referred to Chapter 7 (with initial background from Chapter 2), which includes a quantitative, simulation-based analysis and comparison of these different methods.
- Chapter 2, Chapter 5, and Chapter 7 present the core of the quantitative analyses in this document, while Chapter 2, Chapter 3, Chapter 4, Chapter 6 have introduced a conceptual and qualitative analyses of the different addressed questions.

2 TSO-DSO Coordinated Flexibility Market Models

2.1 Introduction to TSO-DSO Coordinated Flexibility Markets and Models

Flexibility is increasingly available from resources connected at different voltage levels of the grid. This flexibility, in its turn, can be used to deliver grid services to different system operators at different grid levels (i.e., transmission or distribution levels). For example, a flexibility asset or a collection of aggregated assets from a user (producer, consumer, or prosumer) or aggregated users connected at the distribution level can offer flexibility to the DSO (e.g., for congestion management at the distribution level), as well as to the TSO (e.g., for balancing or congestion management at the transmission level). This flexibility can be offered by FSPs to the SOs through the means of flexibility markets.

TSO-DSO coordinated flexibility markets enable coordinated procurement mechanisms between all SOs interested in purchasing flexibility originating from different grid levels and impacting different grids' operations. Coordination between system operators for flexibility provision/purchasing is crucial for (1) maximizing the efficiency of the flexibility procurement process/flexibility market, (2) enabling a consistent and transparent valorization by the FSPs of their flexibility potential, and (3) ensuring that the flexibility is delivered in a grid-safe manner for all participating grids[1]. These aspects can be further elaborated as follows:

1. Maximizing the value-stacking potential of flexibility: As a certain flexibility activated by a flexibility asset can concurrently deliver services to different SOs, the coordination between the different operators in the procurement of flexibility enables the SOs to coordinate the purchasing in such a way to maximize the value extracted from the delivered flexibility and, hence, reduce the volume of flexibility required and the resulting costs. This, in turn, yields a reduction in the costs to the consumers reflected on their electricity bills.
2. Returning consistent and transparent valorization opportunities to FSPs/consumers: through TSO-DSO coordination for the need of flexibility, FSPs can have a coordinated access to the different possible uses of their flexibility enabling the valorization of their flexibility potential. This coordination can provide clear and consistent remuneration mechanisms and transparency in the market mechanisms, which encourages participation of FSPs/consumers and, hence, improves market liquidity. Such coordination can also avoid sending opposing signals to an FSP in terms of flexibility needs that can exist in different markets.

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[1] Here, coordination is taken in the sense of coordinating the procurement/purchasing of flexibility. Other forms of coordination can clearly exist to coordinate along other dimensions, such as metering needs, communication needs, prequalification processes, verification and settlement processes, reliability and adequacy calculations, etc. However, in this part, we solely focus on the coordination aspect that directly impacts the way in which the markets are cleared (i.e., the market clearing formulations/models).

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3. Grid-impact aware procurement of flexibility: As flexibility procured by one SO can be provided from a grid inside or outside its direct operational area, any purchasing of flexibility by one or multiple SOs would have to take into account the network limitations not only of their own grids but also the network limitations of the grids from which the flexibility is being offered. For example, a TSO purchasing flexibility from a resource connected to the distribution grid for balancing services would lead to a deviation in the operational state of the distribution grid when this flexibility is activated. The purchasing of such flexibility would, hence, have to take into account this effect on the distribution grid and ensure that the purchasing of flexibility is constrained in such a way to optimize the purchasing of flexibility while respecting the distribution network constraints. Hence, the coordination between TSOs and DSOs ensure not only that the flexibility purchased can solve the initial grid needs in place, but that purchasing would also not cause additional issues in any of the grids involved.

These flexibility markets receive inputs submitted by the FSPs and the SOs, aiming at choosing the optimal sets of bids to clear (from the set of bids submitted by the SO) to meet the flexibility needs of the grid (captured through the inputs submitted by the SOs). In this respect, the FSPs submit flexibility bids, i.e., upward flexibility (entailing an increase in generation/injection or decrease in consumption/offtake) or downward flexibility (entailing an increase in consumption/offtake or a decrease in generation/injection) and the bids' technical requirements/clearing constraints[2]. The inputs from the SOs specify their flexibility needs and network limitations. The flexibility needs and grid limitations would require providing a certain form of representation of the grid (which can be as simplified or detailed as needed for the particular setting in which the market is set up). The flexibility needs can be provided through a network representation (e.g., using base power flows, base injection/offtakes at the different nodes, coupled with a form of power flow modelling) or through explicit stated quantities of flexibility volumes (upward or downward) to be purchased from different grid locations and limitations thereon to ensure grid safety. The flexibility market, then, receives these inputs and clears the market to maximize the flexibility procurement efficiency (minimizing total flexibility procurement cost), while meeting the (coordinated) needs of the SOs, the bids' technical requirements, the grids' operational limits, and abiding by the structure of the TSO-DSO coordination mechanism in place. An optimization-based market clearing mechanism can then be developed to meet these concurrent and coordinated flexibility needs when clearing the market [7].

The flexibility market clearing returns the sets of bids purchased (and the portion at which each is cleared) and a set of other possible outputs including: the market prices (depending on the pricing scheme, i.e., pay-as-

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[2] The bid technical requirements differ depending on the types of bids submitted. For example, for a simple price-quantity pair bid (i.e., a bid composed of an offered quantity that can be cleared at any proportion along with a price specifying the unit price) the maximum quantity offered would constitute the main bid technical requirements, in addition to the bid requirements that can be specified by the market design itself (such as, e.g., granularity of bid quantities cleared). On the other hand, more complex bid forms can include logical clearing constraints (linking them, e.g., to the clearing state of other bids submitted by the same FSP) as well as intertemporal constraints, i.e., linking between the clearing levels of bids submitted by the FSP through different time periods, or market time units (MTUs).

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bid vs. pay-as-cleared), total flexibility purchasing costs, FSP remuneration levels, and the updated state of the grid after flexibility activation. This process is showcased in Figure 2-1. An example of the implementation of such an optimization-based market clearing module in the Northern demonstrator of OneNet is explained in [7]. Chapter 4 in [7] explains the functionality and input/output specifications of a developed optimization-based market clearing module, with a number of implemented power transfer distribution factors (PTDF)-based use cases using different levels of granularity in the network models (the data for the use cases is also included in Appendix F-L of D7.4 [7]).

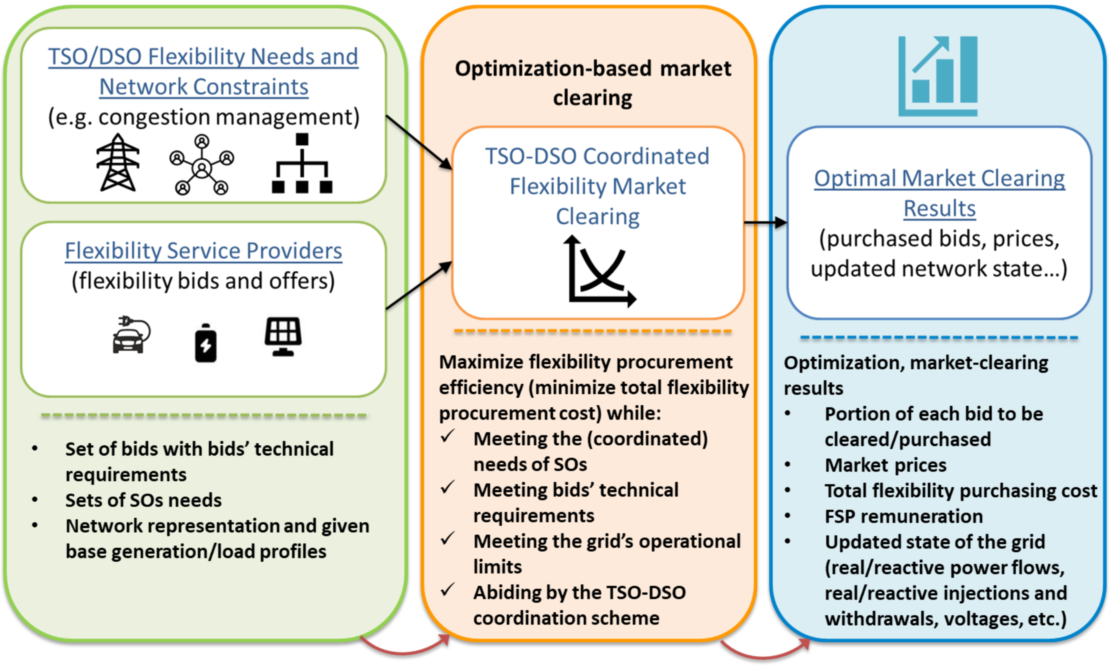

Figure 2-1 - TSO-DSO Coordinated Flexibility Market

The market clearing step, would then take into account the TSO-DSO coordination scheme in place. This scheme organizes the way flexibility is procured among the different SOs, with options ranging from totally disjoint markets to common (jointly co-optimized) markets as well as sequential market schemes. In what follows, we introduce four fundamental TSO-DSO coordinated market models, originated from the CoordiNet project [1], capturing these different options. These coordinated market models are referred to regularly in the different parts of the analysis reported in this document.

The initial concept of these TSO-DSO coordination schemes have been proposed in [8] and further elaborated in [1] as part of the H2020 CoordiNet project. The initial differentiation between coordination schemes, was performed along the dimensions of: 1) the system in which the flexibility need is located, 2) the primary buyer of the flexibility, 3) the number of markets (i.e., market layers) set up to purchase flexibility, and 4) the level of access by the TSO to flexibility bids submitted from the distribution systems. This classification resulted in the

TSO-DSO coordination schemes presented in Figure 2-2. These original TSO-DSO coordination schemes were then further analyzed and elaborated conceptually and mathematically in [1], [2], and [9].

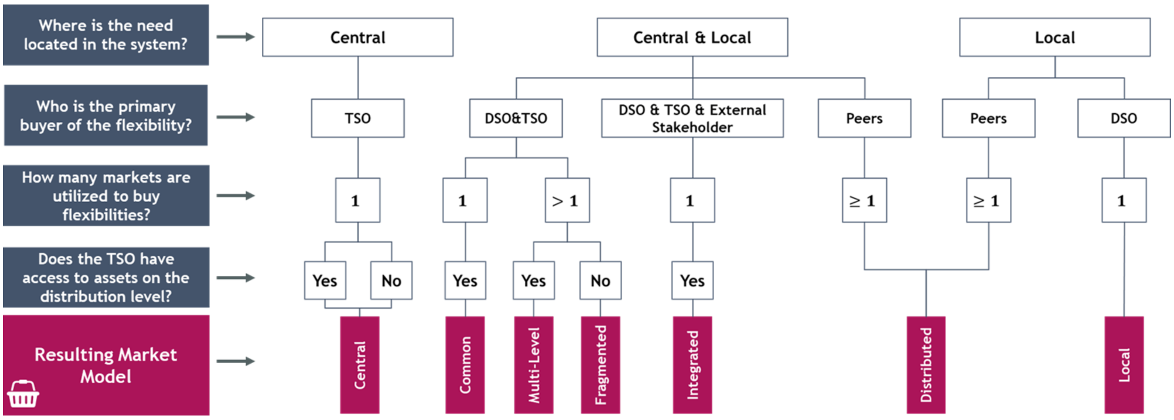

Figure 2-2 Different TSO-DSO Coordination Schemes and Flexibility Market Models. Retrieved from the CoordiNet Project D6.2 [1, p. 46].

We next present five fundamental TSO-DSO coordination schemes (namely, central markets, local markets, common markets, multilevel markets, and fragmented markets), that are of most relevance to the work in this document. The presentation in this chapter of the different TSO-DSO coordinated market models builds upon the original introduction of those schemes in [1] and their conceptualization in [8].

2.2 Disjoint Distribution- and Transmission-level Market Models

The most basic form of flexibility markets are disjoint transmission and distribution level markets. In such settings, a market is set up at a level of a system operator (i.e., TSO or DSO), through which a TSO or DSO can purchase flexibility only from resources connected to its own grid, following the flexibility market set-up described in Section 2.1. In other words, each disjoint market clearing aims at purchasing available flexibility from the grid of the SO for which the market is set up to resolve the grid needs at the minimum possible cost. This process does not entail the use of flexibility by an SO from a grid outside its area of control, and hence, requires the market to only consider the grid constraints of the SO for which the market is set up. Hence, this captures a set of flexibility markets running independently and virtually in isolation (i.e., without much impacts imposed on each other). As such, a disjoint DSO-level market, in which a DSO purchases flexibility from resources connected only locally to its own grid is a form of local markets (as described in [1]). Similarly, a transmission-level market in which the TSO purchases flexibility from resources connected only of its transmission grid is a form of a central market (as also described in [1])[3] without the participation of distribution-level resources.

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[3] This is one form of central markets, while other types can allow the participation of distribution level resources in the procurement of TSO-level services. The different variations to that scheme were introduced in [1].

Now, we discuss a general representation of such disjoint market models as optimization problems, which provide an abstraction of the underlying mathematical models to capture the main features of each market model. The full mathematical formulation of distribution and transmission level market models can be found in [10, 4, 2, 9]. Figure 2-3 and Figure 2-4, respectively, represent a disjoint transmission and disjoint distribution-level market models. The representations are given in the form of an optimization problem to be solved by the market operator to clear the market. In these representations, lower-case symbols are used to indicate distribution-level quantities while upper-case symbols are used for transmission system quantities. In this regard, $\Delta\boldsymbol{p}/\Delta\boldsymbol{P}$ and $\Delta\boldsymbol{d}/\Delta\boldsymbol{D}$ are abstractions of the vectors of upward and downward flexibility offered from each system by the different FSPs, and $c(\Delta\boldsymbol{p},\Delta\boldsymbol{d})/C(\Delta\boldsymbol{P},\Delta\boldsymbol{D})$ are cost functions reflecting the cost of purchasing a certain set/vector of upward and downward flexibility. The presented formulations in Figure 2-3 and Figure 2-4 are general representations in which (1) and (6) capture the objectives of decreasing the total flexibility procurement cost of the DSO and the TSO level markets, respectively; (2) and (6) capture power flow calculations returning, e.g., the real/reactive power flows in the system, voltage levels (magnitudes and angles), etc., resulting from the base injection and loads at the nodes (captured through vectors $\boldsymbol{p}^o/\boldsymbol{P}^o$ and $\boldsymbol{d}^o/\boldsymbol{D}^o$), the deviations caused by the purchased upward and downward flexibility $(\Delta\boldsymbol{p},\Delta\boldsymbol{d})/(\Delta\boldsymbol{P},\Delta\boldsymbol{D})$**,** the interface power flow levels with other systems captured through $T^P/\boldsymbol{T^P}$**,** and the different network parameters (such as the network topology, line resistances and reactance) abstracted using the vector $\boldsymbol{u}/\boldsymbol{U}$; (3) and (8) are constraints on the purchased flexibility to abide by the operational limitations of the grid (the functions $\boldsymbol{g}/\boldsymbol{G}$ are abstract representations of limits on the line – real and/or reactive – power flows, voltage magnitude limits, etc.); (4) and (9) are the limits on the amount of flexibility that can be purchased from each bid, imposed by the bids' submitted maximum quantity (i.e., technical requirements of simple price-quantity pair bids); while (5) and (10) capture that the interface flow between the DSO and TSO is kept at a constant (i.e., no flexibility is accessed from other grids, and each market has to be solved without causing deviations to its original imbalance state), where, here we consider the transmission network to be connected to a set N of distribution networks each indexed using the index i, for which (10) holds for each i.

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Disjoint Distribution-Level Market

$$\min_{\Delta p,\Delta d} c(\boldsymbol{\Delta p},\boldsymbol{\Delta d}) \tag{1}$$

s.t

$$\boldsymbol{f}(\boldsymbol{\Delta p},\boldsymbol{\Delta d},\boldsymbol{p^o},\boldsymbol{d^o},T^P,\boldsymbol{u}) = \boldsymbol{0} \tag{2}$$

$$\boldsymbol{g}(\boldsymbol{\Delta p},\boldsymbol{\Delta d},\boldsymbol{p^o},\boldsymbol{d^o},T^P,\boldsymbol{u}) \leq \boldsymbol{0} \tag{3}$$

$$\boldsymbol{0} \leq \boldsymbol{\Delta p},\boldsymbol{\Delta d} \leq \boldsymbol{\Delta p^{max}},\boldsymbol{\Delta d^{max}} \tag{4}$$

$$T^P = constant \tag{5}$$

Figure 2-3 Disjoint Distribution-Level Flexibility Market Model (Disjoint Distribution Market / Local Market)

Disjoint Transmission-Level Market

$$\min_{\Delta P,\Delta D} C(\boldsymbol{\Delta P},\boldsymbol{\Delta D}) \tag{6}$$

s.t

$$\boldsymbol{F}(\boldsymbol{\Delta P},\boldsymbol{\Delta D},\boldsymbol{P^o},\boldsymbol{D^o},\boldsymbol{T^P},\boldsymbol{U}) = \boldsymbol{0} \tag{7}$$

$$\boldsymbol{G}\left(\boldsymbol{\Delta P},\boldsymbol{\Delta D},\boldsymbol{P^o},\boldsymbol{D^o},\boldsymbol{T^P},\boldsymbol{U}\right) \leq \boldsymbol{0} \tag{8}$$

$$\boldsymbol{0} \leq \boldsymbol{\Delta P},\boldsymbol{\Delta D} \leq \boldsymbol{\Delta P^{max}},\boldsymbol{\Delta D^{max}} \tag{9}$$

$$T_i^P = constant\ \forall i \in \mathrm{N} \tag{10}$$

Figure 2-4 Disjoint Transmission-Level Flexibility Market Model (Disjoint Transmission Market / Central Market with No TSO Access to Distribution Flexibility)

As can be seen from Figure 2-3 and Figure 2-4, each market clearing problem only depends on local decision variables and there are no coupling between the markets (i.e., flexibility procured from an SO’s own system and constraints on the SO’s own grid, with the interface flow kept at a constant). As such, disjoint markets can run in parallel and with a large degree of independence.

2.3 Common Market Model

In contrast to disjoint markets, the common market is a setting in which one market is set up in which all system operators flexibility needs are jointly procured, in a co-optimized way, from flexibility available from all participating grids, while abiding by the network limitations of all the grids involved. Hence, the common market is a setting of full cooperation between SOs [9], in which all available flexibility resources are pooled together, and the choice is jointly made (by, e.g., the market operator) over which bids to clear and to what proportion, to jointly meet the needs of all SOs and, hence, maximize the value stacking potential of flexibility. This move

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from isolated disjoint markets to a common joint market is showcased in Figure 2-5, depicting one common market containing one TSO and N DSOs.

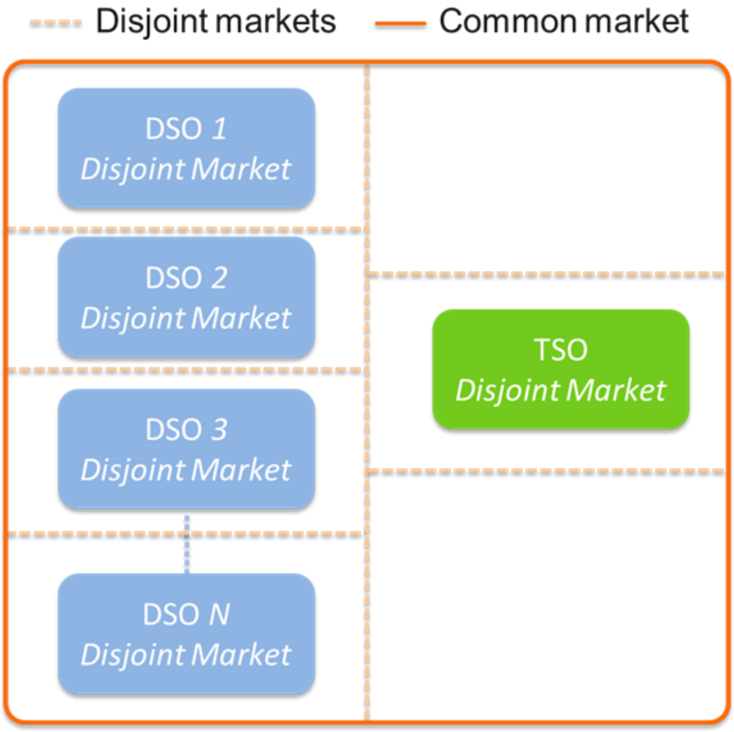

Figure 2-5 From Disjoint to Common (Joint) TSO-DSO Coordinated Flexibility Markets

A general representation of the common market model (including one TSO and a set N of N DSOs, where each DSO is indexed by index $i \in \mathrm{N}$), in the form of an optimization problem is provided in Figure 2-6, where the notations used are similar to the one in Figure 2-3 and Figure 2-4. The full mathematical representation of a common market can be found in [4, 2, 9, 5]. As shown in (11) in Figure 2-6, the common market aims at minimizing the joint costs of producing flexibility (from resources connected to the transmission and distribution levels), while meeting the grid constraints of the transmission and all distribution systems concurrently – as captured by the set of constraints in (12) and (13) respectively – hence, resolving the flexibility needs of each system while also not leading to additional network violations in the process. As can be seen in (15), in the common market, the interface power flows are no longer held at a constant but rather can deviate within specified limits (which can be based on physical substation limitations or financial agreements on interface power limits [11]) and this deviation is based on the amount of flexibility purchased and the initial base injection and load profiles as shown in (14).

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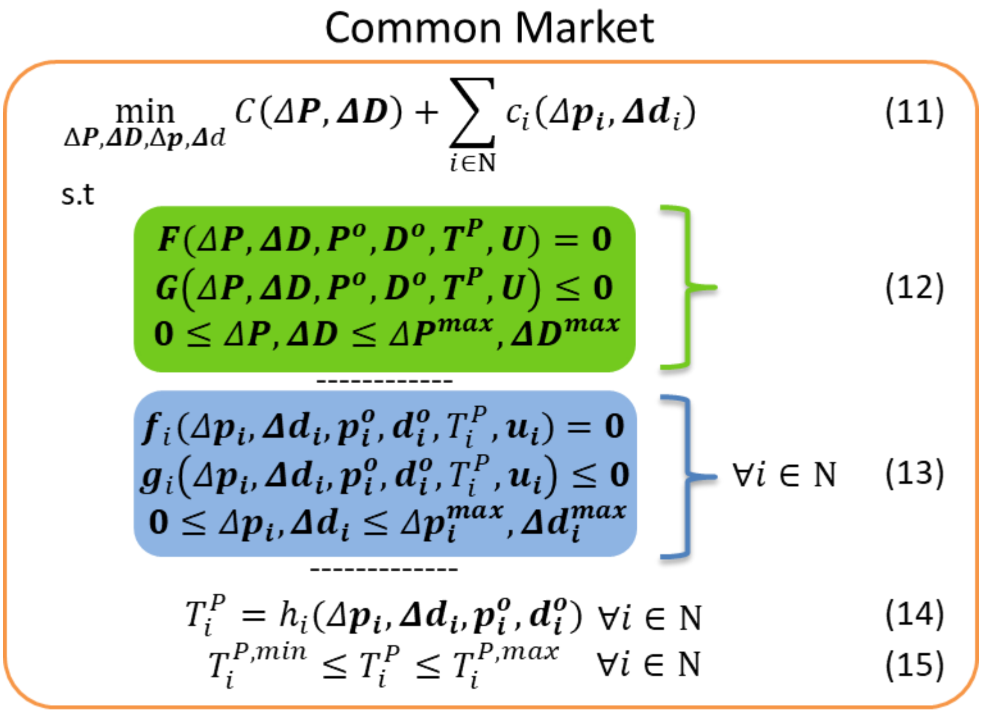

Common Market

$$\min_{\Delta\boldsymbol{P},\Delta\boldsymbol{D},\Delta\boldsymbol{p},\Delta d} C(\Delta\boldsymbol{P},\Delta\boldsymbol{D}) + \sum_{i\in \mathrm{N}} c_i(\Delta\boldsymbol{p}_i,\Delta\boldsymbol{d}_i) \quad (11)$$

s.t

$$\left.\begin{array}{l} \boldsymbol{F}(\Delta\boldsymbol{P},\Delta\boldsymbol{D},\boldsymbol{P}^o,\boldsymbol{D}^o,\boldsymbol{T}^P,\boldsymbol{U}) = \boldsymbol{0} \\ \boldsymbol{G}\big(\Delta\boldsymbol{P},\Delta\boldsymbol{D},\boldsymbol{P}^o,\boldsymbol{D}^o,\boldsymbol{T}^P,\boldsymbol{U}\big) \leq \boldsymbol{0} \\ \boldsymbol{0} \leq \Delta\boldsymbol{P},\Delta\boldsymbol{D} \leq \Delta\boldsymbol{P}^{max},\Delta\boldsymbol{D}^{max} \end{array}\right\} \quad (12)$$

$$\left.\begin{array}{l} \boldsymbol{f}_i(\Delta\boldsymbol{p}_i,\Delta\boldsymbol{d}_i,\boldsymbol{p}_i^o,\boldsymbol{d}_i^o,T_i^P,\boldsymbol{u}_i) = \boldsymbol{0} \\ \boldsymbol{g}_i\big(\Delta\boldsymbol{p}_i,\Delta\boldsymbol{d}_i,\boldsymbol{p}_i^o,\boldsymbol{d}_i^o,T_i^P,\boldsymbol{u}_i\big) \leq \boldsymbol{0} \\ \boldsymbol{0} \leq \Delta\boldsymbol{p}_i,\Delta\boldsymbol{d}_i \leq \Delta\boldsymbol{p}_i^{max},\Delta\boldsymbol{d}_i^{max} \end{array}\right\} \forall i \in \mathrm{N} \quad (13)$$

$$T_i^P = h_i(\Delta\boldsymbol{p}_i,\Delta\boldsymbol{d}_i,\boldsymbol{p}_i^o,\boldsymbol{d}_i^o) \ \forall i \in \mathrm{N} \quad (14)$$

$$T_i^{P,min} \leq T_i^P \leq T_i^{P,max} \quad \forall i \in \mathrm{N} \quad (15)$$

Figure 2-6 Common Flexibility Market Model (Common Market)

As shown in Figure 2-6, as the common market procured flexibility in a co-optimized manner, requiring the inclusion of constraints of all the network involved, this requires exchange of network information with the market operator or an entity responsible for the coordination between TSOs and DSOs such as the Transmission-Distribution Coordination Platform introduced in D7.4 of OneNet [7].

From this comment market, another form of central markets can be derived considering only the TSO as the purchasing party. This version of the central market was also introduced in [1] and is different than the one introduced in Figure 2-4, in that it allows the TSO to have access to flexibility bids submitted by the FSP connected to the distribution system. The formulation of such a central market would coincide with that of the common market but while only considering that the cost of purchased flexibility is borne by the TSO, as the DSO in this case, is not purchasing flexibility but only lists the constraints to be respected when distributed flexibility is used.

2.4 Multilevel Market Model

The multilevel market is as sequential market composed of two layers or market stages. Layer 1 is a DSO-oriented layer. In Layer 1, each DSO procures flexibility from FSPs operating flexibility resources available in the DSO's own grid, while abiding by the operational constraints of its own grid. Layer 2, on the other hand, is a

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transmission system layer, in which the TSO procures flexibility to meet its own grid needs, from flexibility resources available from its own grid, as well as from bids (or portions of bids) that are unused by the DSO in Layer 1 and that are forwarded to Layer 2 from Layer 1. Hence, in this scheme, the TSO does have access to distribution-level flexibility. However, the DSO is provided with a priority access to this flexibility to meet its own grid needs, while the remaining unused portions can then be forwarded to the subsequent TSO-level market.

A general representation of the multilevel market model considering one TSO and *N* DSOs in the form of an optimization model is presented in Figure 2-7, in which the notations follow the same notations as in the previous models presented in Figure 2-6 for the common market and Figure 2-3 and Figure 2-4 for the disjoint market. The full mathematical representation of a multilevel market can be found in [2, 4, 5]. As can be seen in Figure 2-7, in Layer 1, each DSO minimized its total procurement cost (as captured in (16)) for meeting its own flexibility needs while abiding by its own network constraints (as captured in (17)-(18)) and the submitted bids' requirements (as captured in (19)). However, differently from the disjoint distribution level market in Figure 2-3, the DSO can modify the interface flow, hence, the DSO can change its original imbalance position (as captured in (20) and (21)). The change in imbalance position would be corrected if needed in Layer 2, unless it is netted out due to other changes in the different systems. Layer 1 would then forward the unused portions of bids to Layer 2, along with the updated base generation and load profiles (i.e., the original base generation and load profiles $\boldsymbol{p}_i^o/\boldsymbol{d}_i^o$ are updated by the level of flexibility purchased in Layer 1), which are captured by $\boldsymbol{p}_i^{o^*}$and $\boldsymbol{d}_i^{o^*}$ in Figure 2-7. Layer 2 would then minimize the total costs of procuring flexibility form resources connected to the transmission and distribution systems (as captured in (22)), for meeting the flexibility needs of the TSO, while abiding by the grid constraints of the transmission system (as captured in the set of constraints in (23)) and distribution systems (as captured by the set of constraints in (24)). The interface flow can also be modified, as the TSO can procure flexibility from the distribution systems, as captured in (25) and (26). We note here that, as shown in (24), the bid limits are modified to subtract the portions that were cleared in Layer 1 (denoted by the starred quantities $\Delta\boldsymbol{p}_i^*$ and $\Delta\boldsymbol{d}_i^*$) and the power flow calculation and constraints take into account the updated base generation and load profiled resulting from Layer 1, namely, $\boldsymbol{p}_i^{o^*}$and $\boldsymbol{d}_i^{o^*}$.

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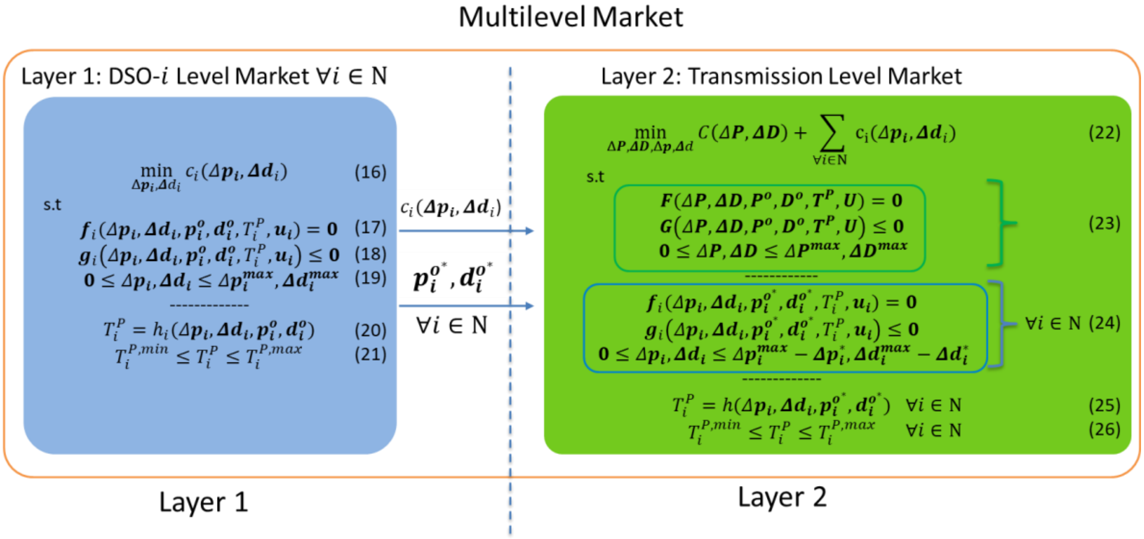

Figure 2-7 Multilevel Flexibility Market Model (Multilevel Market)

The multilevel market includes two types of sharing of flexibility, direct and indirect sharing, which are defined next (and had originally been introduced in [1]).

- Direct sharing of flexibility: the mechanism in which an SO can purchase flexibility bids from resources connected to grids outside its own grid. For example, in Layer 2 of the multilevel market, the TSO can purchase flexibility bids originating from resources connected to the distribution systems. Hence, in this respect, there is a direct sharing of flexibility from the distribution systems with the transmission system.
- Indirect sharing of flexibility: the mechanism in which, while purchasing flexibility from its own grid, an SO creates system needs that are rectified in a subsequent market using flexibility available in that market. For example, in Layer 1 of the multilevel market, the DSO does not access bids from resources connected at the transmission level. Hence, there's no direct sharing of flexibility from the TSOs to the DSOs. However, in the process of Layer 1, the DSO, while procuring flexibility, can change its imbalance position (i.e., the interface power exchange with the TSO), hence creating imbalances to the TSO[4], which are then rectified in Layer 2 using flexibility available in Layer 2 from

---

[4] In practice, as the imbalance is caused in the area of the TSO, the TSO would be responsible for balancing its grid through the different national, regional, or European platforms such as the Manually Activated Reserves Initiative (MARI) for mFRR, the Platform for the International Coordination of Automated Frequency Restoration (PICASSO) for automatic frequency restoration reserves (aFRR), or the Trans-European Replacement Reserves Exchange (TERRE) for replacement reserves (RR), depending on the time-scale of the running markets and caused imbalances. However, this imbalance can directly impact the balancing positions of balance responsible parties, in whose perimeters the units providing flexibility are located. Hence, even though the TSO would be responsible of balancing its grid, the financial responsibility for the caused imbalances can be borne by different parties depending on the adjustment and rectification processes in place (typically referred to as the Transfer of Energy (ToE) mechanisms). The most common implementations of ToE apply a perimeter adjustment to the BRP so that the BRP does not bare financial responsibility of the caused imbalances. In this case, other entities, such as, e.g., the BRP of the FSP providing flexibility can bare that responsibility. Different other alternatives also exist and are in discussion or implementation in different member states .

the transmission and distribution layers. Hence, Layer 1 showcases an indirect sharing of flexibility between the TSO and DSO.

This direct and indirect sharing of flexibility that take place in the multilevel market are also highlighted in Figure 2-8.

The presented version of the multilevel market implies a direct forwarding of unused bids from Layer 1 to Layer 2. Hence, in this setting, the FSP would not have the chance to make modifications to its bid before it being forwarded. Other variations to the multilevel market can rather consider that the FSP can make modification to its bid between the two market layers. In this respect, two variations can take place: (1) in the first variation, the FSP can observe the results of Layer 1 before making modifications to its bid to be sent to Layer 2 (this is a form of sequential bidding); (2) in the second variation, the FSP cannot see the results of Layer 1, which is equivalent to a parallel form of bidding in which the FSP has to decide before participating in the market the portion of its bids that would need to be sent to layer 1 and that which would be sent to Layer 2. These variations have been introduced in [1] and are analyzed in the efficiency analysis presented in Section 5.2.3.

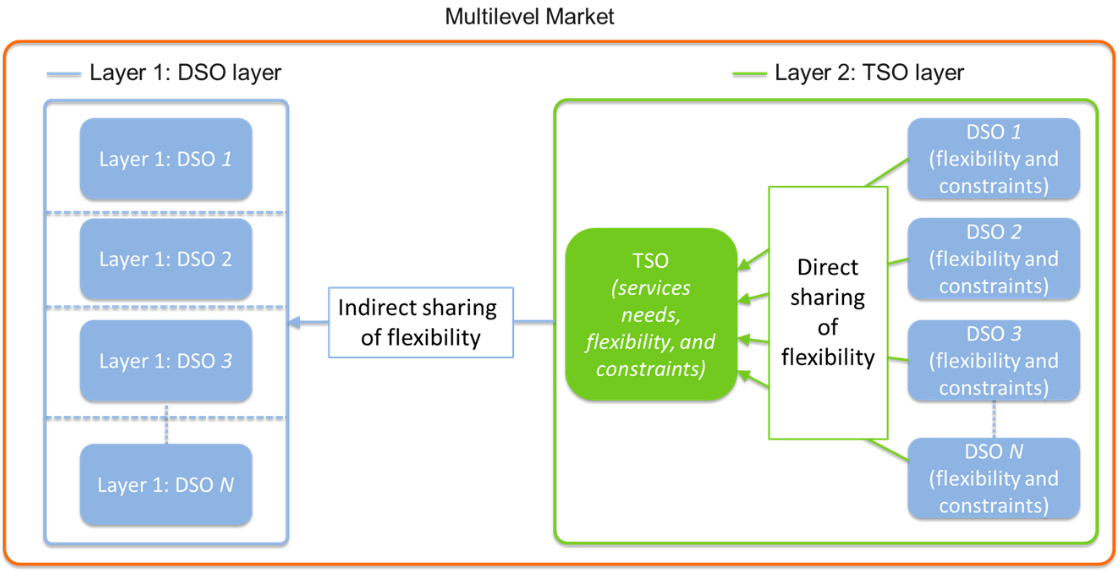

Figure 2-8 Direct and Indirect Sharing of Flexibility in Multilevel Flexibility Markets

Another key variation of the multilevel market is one in which Layer 2 does not include distribution system constraints in its market clearing. This captures a central market setting in Layer 2 (coupled with a local market in Layer 1), in which the DSO is unable to share its network information externally. Hence, Layer 2 can use flexibility bids submitted by FSPs connected at the distribution systems (i.e., direct access of distribution-level flexibility by the TSO). However, as no distribution network constraints can be added in the market clearing of Layer 2, this market clearing can lead to network constraint violations within the distribution systems. These types of violations have been showcased and analyzed in [1]. Chapter 7 presents and addresses different methodologies for the safe forwarding of bids from Layer 1 to Layer 2, reducing the risk of Layer 2 for causing any distribution-system constraint violation when clearing distribution-system flexibility even when distribution system constraints are not explicitly added in the market clearing formulation of Layer 2.

2.5 Fragmented Market Model

Similarly to the multilevel market, the fragmented market is a sequential two-layer market. Layer 1 is similar to Layer 1 of the multilevel market. In this respect, Layer 1 of the fragmented market is a collection of DSO-level markets, in which each DSO procures flexibility from resources connected to its own grid to meet its own grid needs, while abiding by its own grid constraints. In the process, each DSO can change its imbalance position and hence have indirect access to flexibility from the TSO. However, Layer 2 of the fragmented market is different than that of the multilevel market in the sense that, in Layer 2 of the fragmented market, the TSO does not have access to flexibility resources connected to the distribution systems.

A general representation of the multilevel market model considering one TSO and *N* DSOs in the form of an optimization model is presented in Figure 2-9. The notation in Figure 2-9 follows the same notation as in the previous models presented in Figure 2-7 for the multilevel market, Figure 2-6 for the common market and, Figure 2-3 and Figure 2-4 for the disjoint markets. The full mathematical representation of the fragmented market can be found in [2, 5]. As can be seen from Figure 2-9, Layer 1 is the same as that of Layer 1 of the multilevel market in Figure 2-7. However, Layer 2 aims at minimizing the costs of procuring flexibility (as captured in (33)) for meeting the transmission system needs, while abiding only by the constraints of the transmission system (as captured in the set of constraints in (34)). As no flexibility is used from the distribution systems, there is no need to add a network representation and constraints for the distribution systems in Layer 2. Compared to Layer 2 of the multilevel market, no network constraints nor bids from the distribution system appear in Layer 2 of the fragmented market. In addition, the interface flow is kept at a constant, resulting from the interface flow achieved at the end of Layer 1 (as captured in (35) and (36)). The only inputs forwarded from Layer 1 to Layer 2 are the updated base injection and load profiles resulting from Layer 1, captured by $\boldsymbol{p}_i^{o^*}$ and $\boldsymbol{d}_i^{o^*}$. As such, in the fragmented market, the DSO would not need to share network information outside their own market layer.

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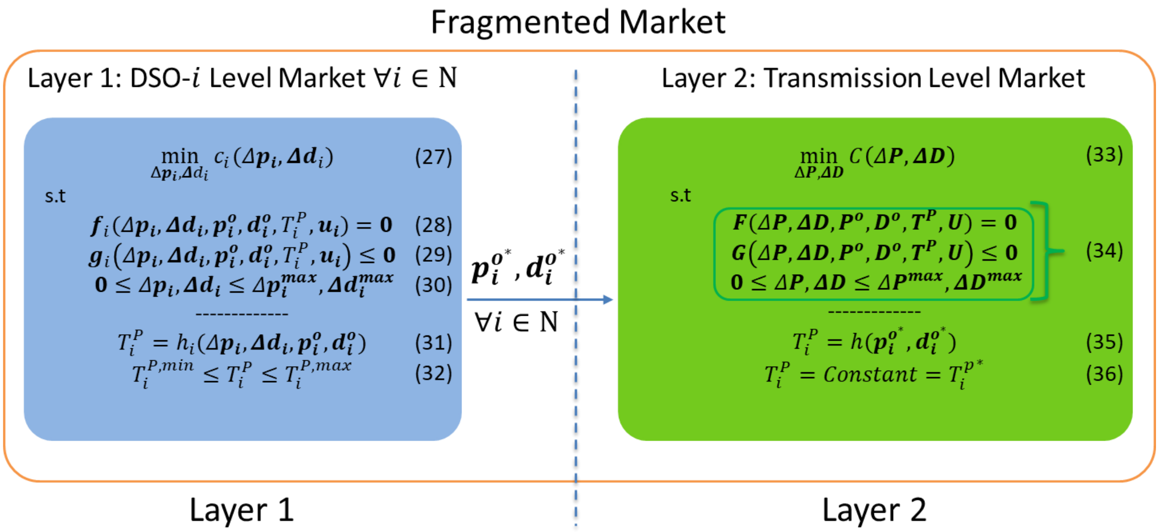

Figure 2-9 Fragmented Flexibility Market Model (Fragmented Market)

As captured in the description of the fragmented market, the DSO does have indirect access to flexibility from the TSO, as Layer 1 can cause changes to the imbalance position of the DSOs which is then rectified in Layer 2 (or in European balancing platforms) unless the imbalance changes is netted out by other imbalance modifications in the systems. However, no SO has access to direct flexibility (i.e., flexibility bids) from other systems. These features of direct and indirect access to flexibility in the fragmented market model are showcased in Figure 2-10.

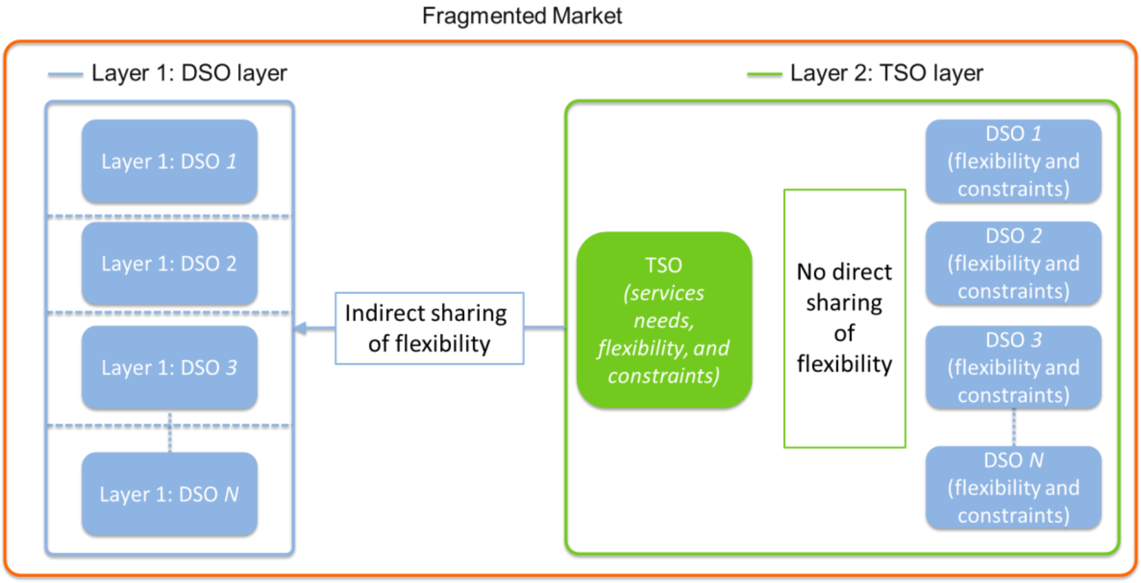

Figure 2-10 Indirect (Only) Sharing of Flexibility in Fragmented Flexibility Markets

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2.6 Comparison and Evaluation

A summary of the different features of the presented TSO-DSO coordinated markets is provided in Table 2-1. A number of variations to these coordination schemes can also be derived, some of which were introduced in [1], and illustrated in Figure 2-2. Note that, in Figure 2-2, we can also see the suitability of these coordinated schemes under different scenarios.

In general, the comparison among these schemes can take into account several factors, which we consider in the analysis within this document: 1) economic efficiency of the procurement process under each market model (Chapter 5 and Chapter 7), 2) the consumer-centricity level of flexibility markets and implications on each scheme (Chapter 3), 3) barriers to entry that each scheme can exhibit while analyzing different product attributes and requirements (Chapter 4), 4) synergy with current and envisioned future regulations, especially when applied to the set-up of sequential markets (Chapter 6 and Chapter 7), 5) grid safety of the different market mechanisms, especially in the context of sequential markets Chapter 7, and 6) computational complexity aspects (Chapter 7). In addition, aspects such as 1) network information sharing requirements among system operators and its feasibility, 2) information and communication technology (ICT) requirements, 3) associated costs of setting up the different market platforms, among others, play a key role in the practical implementation possibility of the solutions and their replicability and scalability potentials. These aspects have been investigated for example in the CoordiNet project in [1, 12, 13, 14].

Table 2-1 TSO-DSO Coordinate Flexibility Market Models - Features Summary

Market			**Flexibility & Network Information Sharing**		
Model	**Clearing**	**Stages**	**TSO resource**	**DSO resource**	**Network information**
Disjoint transmission-level	Independent	N/A	No		
Disjoint distribution-level					
Common	Joint	1	Complete sharing		Yes
Fragmented	Sequential	2	Indirect	No	No
Multilevel				Direct (with priority access to DSO)	Yes (in Layer 2)

3 Consumer-centricity in the Context of Electricity Markets

Consumer-centricity is a relatively new term in the European electricity sector. On the policy level, it emerged in the context of the Energy Union Package of 2015 [15] and manifested in the successive lead-up to the Clean Energy Package of 2019 [16]. However, a clear definition appears to be missing despite the frequent use of the term in policy [15], [17], legislative [18] and regulatory files [19], [20], stakeholder reports [21], [22], [23], as well as the academic literature, e.g., [24], [25], [26].

This chapter explores the concept of consumer-centricity in the context of existing and new types of electricity markets. These new types of markets have been given different names over the past years, such as “flexibility markets”, “local markets”, or “TSO-DSO markets.” We understand that these can have (slightly) different meanings, which is why, in this chapter, we consistently use the term that is used by the respective reference we quote. When focusing on TSO-DSO coordinated flexibility markets, we follow the description provided in Chapter 2. The chapter puts a focus on the “consumer” on the one hand, and market arrangements and regulation on the other hand. This chapter has two primary goals. First, we aim to carve out a broad definition of the concept of consumer-centricity by looking at where and how the concept has been used so far in electricity markets. Second, we apply such a definition to the specific case of products that satisfy system needs and to TSO-DSO coordination schemes, in order to gain insights on how a higher level of consumer centricity might be pursued. However, in this chapter, we do not pretend to provide any specific policy recommendation, as this would require a more extensive investigation of the advantages and disadvantages of introducing more consumer-centric products and TSO-DSO coordination schemes. Indeed, recommendation on the application of consumer-centricity aspects would require a complete analysis of their impact on potential consumer participation, on the one hand, and their possible effects on the reliable operation of the grid (i.e., through the reliable procurement of system services) on the other hand. This is not within the scope of the current chapter. Nonetheless, any such analyses of the effects of inclusion of consumer-centric designs and measures require, at first, defining what consumer-centricity is and what it could entail. This latter aspect, is the goal of this chapter.

Consistently, the analysis revolves around three questions. First, *how can consumer-centricity be formally defined?* Second, *what makes a product definition consumer-centric?* And third, *what makes a TSO-DSO coordinated flexibility market consumer-centric*?

This chapter is split into four sections. Section 3.1 discusses different definitions of the term “consumer” that are utilized in European legislation and policy documents on electricity markets. Section 3.2 provides an overview of the different perspectives on “consumer-centricity” in electricity markets that were identified in legislation and policy documents, regulatory documents, academic contributions, and stakeholder reports. Section 3.3 introduces novel definitions of consumer-centricity, consumer-centric products, and consumer-

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centric TSO-DSO coordinated flexibility markets. Section 3.4 enlarges the focus on TSO-DSO coordinated flexibility markets and qualitatively applies the proposed definitions to discuss the implications of different regulatory choices on the level of consumer-centricity of such markets. Section 3.5 concludes the chapter.

3.1 Definition of Consumer in European Legislation and Policy Documents

An explicit definition of the term “consumer” does not seem to exist in the European legislation on electricity markets. Nonetheless, the term “consumer” appears in European legislation and official policy documents on electricity markets. It is often synonymously used with “customer” and can be understood to include different types of consumers or even different groups of consumers. For example, according to recital 1 of Directive 2009/72/EC, consumers can be understood to be “citizens or businesses”, while according to the European Commission (EC) communication on the New Deal for Consumers, consumers can be understood to be “households, businesses, and industry” [17].

The various directives on the internal market for electricity that followed one another from the first EU Energy Package in 1996 to the Clean Energy Package (CEP) in 2019, make use of the term “customer” and provide a series of the definitions of the different types of “customers” which have largely remained the same. However, subsequent legislative packages have introduced new customer types. The total list of definitions of different customer types throughout the four packages is included in Table 3-1. It is composed of “customer”, “wholesale customer”, “final customer”, “household customer”, “non-household customer”, “eligible customer” and “active customer.” The CEP introduced two new types of “consumer”, namely “renewables self-consumer” and “jointly acting renewables self-consumers”, in addition to new collective schemes through which active consumers can engage, namely “citizen energy communities” and “renewable energy communities.”

Table 3-1 - Definitions of Different Types of Consumers in EU Legislative Files

Consumer type	Definition	Legal reference
Customer	*wholesale and final customers of electricity*	Directive 96/92/EC, Art. 2(7) Directive 2003/54/EC, Art. 2(7) Directive 2009/72/EC, Art. 2(7) Directive (EU)2019/944, Art. 2(1)
Wholesale customer	*any natural or legal persons who purchase electricity for the purpose of resale inside or outside the system where they are established*	Directive 96/92/EC, Art. 2(8) Directive 2003/54/EC, Art. 2(8) Directive 2009/72/EC, Art. 2(8) Directive (EU)2019/944, Art. 2(2)
Final customer	*customers purchasing electricity for their own use*	Directive 96/92/EC, Art. 2(9) Directive 2003/54/EC, Art. 2(9) Directive 2009/72/EC Art. 2(9) Directive (EU)2019/944, Art. 2(3)
Household customer	*customers purchasing electricity for their own household consumption, excluding commercial or professional activities*	Directive 2003/54/EC, Art. 2(10) Directive 2009/72/EC, Art. 2(10) Directive (EU)2019/944, Art. 2(4)

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Non-household customer	*any natural or legal persons purchasing electricity which is not for their own household use and shall include producers and wholesale customers*	Directive 2003/54/EC, Art. 2(11) Directive 2009/72/EC, Art. 2(11) Directive (EU)2019/944, Art. 2(5)
Eligible customer	*customers who are free to purchase electricity from the supplier of their choice*	Directive 2003/54/EC, Art. 2(12) Directive 2009/72/EC, Art. 2(12)
Active customer	*a final customer, or a group of jointly acting final customers, who consumes or stores electricity generated within its premises located within confined boundaries or, where permitted by a Member State, within other premises, or who sells self-generated electricity or participates in flexibility or energy efficiency schemes, provided that those activities do not constitute its primary commercial or professional activity*	Directive (EU) 2019/944, Art. 2(8)
Renewables self-consumer	*final customer operating within its premises located within confined boundaries or, where permitted by a Member State, within other premises, who generates renewable electricity for its own consumption, and who may store or sell self-generated renewable electricity, provided that, for a non-household renewables self-consumer, those activities do not constitute its primary commercial or professional activity*	Directive (EU) 2018/2001, Art. 2(14)
Jointly acting self-consumer	*group of at least two jointly acting renewables self-consumers in accordance with point (14) who are located in the same building or multi-apartment block*	Directive (EU) 2018/2001, Art. 2(15)

As will also be detailed in Section 3.2, there have been multiple steps in the evolution of the notion and role of consumers throughout the EU energy packages: from a passive consumer to an informed (or "eligible") consumer to an active consumer. This final notion reflects the emergence of consumers who are also producers of electricity, the so-called "prosumers", and consumers who are able to store electricity as well, the so-called "prosumager".

Note that within the OneNet project, some research on the term "consumer" was also conducted in the context of WP4 [27]. Overall, it was found that the terminology to refer to consumers differs among EU acts, research projects, and other initiatives depending on their specific perspectives, but that a harmonization of the term going forward could be beneficial.

3.2 Different Perspectives on Consumer-centricity

As with the term "consumer", a legal definition of the term "consumer-centricity" does not seem to be presently available. To carve out a broad definition of the concept of consumer-centricity in electricity markets, this section explores relevant legislative, policy and regulatory files, academic literature, and stakeholder reports.

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3.2.1 Consumer-centricity in Policy and Legislation

3.2.1.1 Consumer, Information, Protection, Choice and Empowerment (First, Second and Third Energy Package)

The first, second, and third EU energy packages made significant contributions to the creation of the Internal Energy Market (IEM) [28]. They aimed to enable effective consumer choice and boost competition through the availability of transparent, comparable, and reliable information on prices, costs, energy consumption, fuel mix, and environmental impact of electricity suppliers; and to enable/incentivize energy savings through sufficiently frequent feedback to consumers about their energy consumption and the cost thereof. Electricity Directive 2003/54/EC of the second energy package was the first to set out a catalogue of measures for consumer protection. To guarantee consumer choice, all consumers were given the right to freely choose their energy supplier as of 1 July 2007. Directive 2009/72/EC of the third energy package introduced a set of consumer rights that aimed to improve the position of consumers in energy markets through their empowerment. Relevant provisions to boost consumer empowerment were related to electricity supply, such as switching and contract termination fees, billing of actual electricity consumption, the right to receive information on energy consumption, and quickly and cheaply resolve disputes.

The third package aimed at fostering smart-meter roll-out and the active participation of consumers in the electricity markets. However, the [29] reports that the package did not achieve the complete removal of barriers for the participation of the residential and commercial sector in balancing and flexibility services, including demand response (DR). In particular, the package did not achieve the removal of the primary market barriers for independent demand response service-providers and the creation of a level playing field for them [29].[5] The reason was the heterogeneous way in which demand response had developed across Member States as a result of the high degree of freedom allowed in the European legal framework. Relevant barriers included the lacking definition of roles and responsibilities for aggregators, discriminatory treatment of independent DR service providers by suppliers, significant compensation payments from aggregators to balance responsible parties (BRPs) and/or suppliers, and discriminatory timing, rules, and technical requirements at national balancing, wholesale and capacity markets [29]. This report states that such different treatment of demand response, related service providers and products in electricity markets risked undermining the large-scale deployment of demand response that was needed for the functioning of the internal energy market going forward.

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[5] Note that also the Energy Efficiency Directive 2012/27/EU included provisions on demand response aimed at incentivizing flexibility and participation of consumers in the market.

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With the adoption of the 2020 targets in 2009,[6] it became clear that the EU's energy system was already undergoing a profound change. The goal of decarbonizing the energy system became more prevalent, which created new opportunities and challenges for market participants. Technological progress was allowing for new forms of consumer participation and cross-border cooperation. The European Commission noted, however, that the "*existing market framework was designed in an era in which large-scale, centralised power stations, primarily fired by fossil fuels, supplied passive customers at any time with as much electricity as they wanted in a geographically limited area – typically a Member State. This framework is not fit for taking up large amounts of variable, often decentralised electricity generation nor for actively involving more consumers in electricity markets*" [30]. As such, there was a need to adapt the EU's electricity market rules to a new market reality.

3.2.1.2 Citizen-centric Energy Union (Energy Union Package), Consumer-centric Energy System (European Commission Communication on the New Deal) and Consumer-centric Electricity Markets (Clean Energy Package)

In late 2014, the European Commission announced a reform and transformation of Europe's energy policy in line with the endorsement of the 2030 Climate and Energy Framework expressed by the European Council in October that same year. The way forward was laid out in the Energy Union Package [15], which first introduced a citizen-centered vision of the European energy sector, envisioned as follows: "*our vision is of an Energy Union with citizens at its core, where citizens take ownership of the energy transition, benefit from new technologies to reduce their bills, participate actively in the market, and where vulnerable consumers are protected*." The growth of variable renewables made energy efficiency and active participation of consumers through demand response, self-consumption, or storage ever more important. The EC thus proposed a new deal for consumers, which would aim at – as stated in the text – "*putting consumers at the centre of a thriving and functioning energy system*" [17].

The Clean Energy Package later tabled this new deal for consumers with a view to creating what is defined as "*competitive, consumer-centred, flexible, and non-discriminatory electricity markets*" in Directive (EU) 2019/944 (Art. 3). Next to reiterating the consumer rights introduced in previous energy packages, the CEP aimed to boost consumer empowerment by providing consumers with the right to participate in all electricity markets. On the one hand, this right covers existing markets, including new ways to participate such as through energy communities or aggregators. On the other hand, this right can be understood to cover also new types of markets, such as (local) flexibility markets or peer-to-peer trading schemes for renewable energy.

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[6] See the website of the European Commission for more information on the 20-20-20 targets, available at < https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2020-climate-energy-package_en>.

The objective of the EC behind the legislative proposals included in the CEP was that the participation of consumers in all electricity markets would unlock vast system resources that could help reducing system costs [30]. Consumer participation in electricity markets was expected to further increase the flexibility of the electricity system and the volume of resources available that can deliver services to TSOs and DSOs, and thus leading to a more efficient operation of the entire system. The expansion of distributed generation and storage associated with a stronger participation of consumers in energy markets was also expected to strengthen security of supply, contribute to the balancing of energy grids at the local level, and help to achieve the renewable and overall decarbonization targets. By increasing their active involvement, the EC believed consumers could benefit through augmented competition and innovation at retail level, which would in turn result in more choice and lower energy bills.

3.2.2 Regulatory Perspective on Consumer-Centricity

Consumers are at the center of focus of national regulatory authorities (NRAs) in Europe. First, it is normally acknowledged that consumers need to be aware of the key features of the market, empowered and enabled to engage in market activities [31]. However, as stated by CEER in [32], it should be the consumer's choice whether or not to take an active role in the market. Consumers' basic rights should be protected also in case they decide to participate in new ways, e.g., as part of an energy community offering flexibility or consumption management [33]. An important aspect highlighted by CEER is also that energy supply must be ensured for all energy users and that vulnerable consumers are provided with extra protection, where needed. All this enhances consumer trust in the market and its actors.

Second, it is essential that market arrangements and regulations provide all customers with the ability to engage in the market and benefit from it [32]. Regarding flexibility provision to the market, this would ensure a level playing field for all types of resources and allow the flexibility needs of the system to be met at the lowest cost. In its strategy for 2022-2025, [19] puts forward what is referred to as a "consumer centric smart regulatory model", which aims at placing the consumer as a central component of all regulatory activities. It incorporates the concept of dynamic regulation, which acknowledges that regulation must be stable, but not static, and that the way NRAs regulate the energy sector needs to evolve so as to ensure that consumers are protected and empowered also in the new market reality [34].[7] The report [19] identifies the following elements of a consumer-centric design:

- Ensuring that the energy sector delivers affordability, simplicity, protection, inclusiveness, reliability, and empowerment for all consumers.[8]

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[7] [34] states that the main areas, in which dynamic regulation tools have so far been implemented, are tariff structure, price or revenue controls, and smart metering.

[8] Affordability, simplicity, protection, inclusiveness, reliability and empowerment are the so-called six LET'S ASPIRE principles .

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- Consumer rights and protection for all consumer groups, in particular the vulnerable and disadvantaged ones. Trustworthy and clear information allows all consumers to make informed choices, and tools are available to provide advice and support to consumers to understand their energy use.
- Energy efficiency incentives support an efficient use of energy by all consumers.
- Acknowledging that different consumer groups have different needs and priorities, and varying levels of engagement with the market.
- Ensuring that consumer groups affected by energy poverty and vulnerability are not left behind.
- Establishing rules for protecting consumer data and for data management. For example, consumer-centricity in terms of consent management systems for data access means that those management systems are reliable by design, yet simple to understand and user-friendly. A consumer-centric model also means that access to data is carried out in the customer's best interest, and that energy regulators collaborate with regulators from other sectors to ensure adequate levels of data protection and privacy [20].[9]

3.2.3 Academic Views on Consumer-centricity

The use of the expression consumer-centricity in the academic literature on electricity markets is relatively recent. The contributions that refer to it often relate it to the spreading of distributed energy resources (DERs) and variable renewable energy sources (vRES), which is adding stochasticity in the system with associated risks in terms of mismatches between energy production and consumption, and calls for a more flexible energy demand, able to follow supply rather than solely supply following demand [25]. In light of this, reshaping consumers' demand can contribute to ensuring the balance of the system. However, in order to foster consumers' willingness to participate in the provision of flexibility, system operators and market players should understand their preferences and expectations, also taking into account psychological and behavioral aspects [24]. A consumer-centric approach can then counteract the current lack of engagement by energy customers and encourage optimal participation in the market [35], [36], [37].

Although the issues behind consumer-centricity in electricity are not new per se, there is apparently no clear definition of consumer-centric markets. A review of the academic literature shows that the term "consumer-centric markets" typically appears in relation to "peer-to-peer" (P2P) or "local" markets [26]. These expressions refer to a series of new types of trading arrangements, whose deployment is so far mostly limited to pilot projects, in which any small and non-professional consumer can trade with its peers [38]. In fact, different energy prices can coexist in a P2P market, as each price refers to an individual transaction and reflects the preferences

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[9] In the context of data access, [20] suggests that there are four different types of consumer groups that require different regulatory responses: unengaged, informed, passively engaged, and actively engaged. These categories seem to be applicable beyond this specific context and are in line with the evolution of the notion of consumer described in Section 3.2.1.

of the involved peers [39]. In this perspective, a consumer-centric market can be seen as a market in which consumers are not simply price-takers; on the contrary, they are able to obtain an energy price that reflects their own preferences, for instance, in terms of service quality, reliability, and origin of the energy consumed [40], [41] [41]. The countless consumer preferences can be reflected in different economic solutions with the retailer or other actors (e.g., the flexibility service operator or the system operator) [26]. Among others, participation in flexibility mechanisms can be interpreted as one of the alternatives offered to consumers to economically value a specific preference [42]. In this way, consumers are no longer exposed to a price that is imposed by the market and essentially reflects the production costs of a commodity. Instead, consumers will disclose the value they associate with the consumption of a kWh, to which specific additional attributes can be associated [43].

However, a review of the existing literature suggests that, beyond the basic characteristics just mentioned, there is no unified view on the structure of future consumer-centric markets. In fact, several forms of self-organized prosumers might emerge, such as the “federated power plant” proposed by [44]. Some authors argue that in a consumer-centric market, consumers do not necessarily have to manage their own energy trades, but they can be supported by a third party that does not own any physical assets (e.g., a generator or load) [45]. In this regard, set-and-forget programs can be designed to minimize the impact on consumers’ daily life [25]. Beyond the traditional energy suppliers, a third party can offer consumers a set of different types of services according to their specific preferences and needs, such as a minimum level of battery charge after one night or a minimum amount of kilometers that a car can travel regardless of when it is plugged in [46].

Lastly, it is important to note that the development of a consumer-centric paradigm is not necessarily a means for system support. Some consumers may, indeed, decide to become prosumers with the intention to depend on the public network as little as possible or not at all; therefore, they may no longer contribute to network cost sharing and system support [47], [48].

As mentioned above, in order to understand what drives consumers’ choices, more attention should be paid to the behavioral dimension of their decision-making processes [37]. Indeed, a number of works in the literature, such as [37] and [36], have explored the decision-making processes of prosumers in terms of how uncertainty is weighted – with implications to risk averseness vs. risk seeking behaviors – and how outcomes can be subjectively valued with the goal of incorporating them in the design of electricity markets that are cognizant of the preferences and decision-making processes of prosumers. For example, the works in [49], [50], [51], [52] have focused on the design and reactions to price signals (e.g., as part of a tariff structure) taking into account prosumers’ differing operational reactions, while the works in [53], [54] have focused on investment and efficiency gap analyses, respectively, under possible behavioral biases.

Given these differing aspects, regulators, policy maker and market players should be able to distinguish among techno-economic and behavioral barriers that hinder the realization of well-functioning consumer-centric markets [55].[10]

3.2.4 Stakeholders’ Views on Consumer-centricity

Some associations of energy stakeholders have publicly expressed their perspective on consumer-centricity. Some individual actors, such as the Belgian electricity TSO, Elia, have done the same, providing their own view on the general scope, definitions and elements constituting consumer-centricity in electricity.

3.2.4.1 Consumer-centricity from the Perspective of Consumers’ Representatives (BEUC)

On the side of consumers, as stated by the Bureau Européen des Unions de Consommateurs (BEUC)[11] in [56], well-functioning (retail) markets need, in general, well-informed and sufficiently protected consumers to benefit from competition, be able to compare information on consumption and related costs, and be aware of their rights and means of (alternative) dispute resolution.

On the side of markets arrangements and regulation, the director of BEUC, Monique Goyens, stated in a presentation on how to make a consumer-centric market a reality for consumers that: “*Future markets will be decentralized [so there is a] need for a welcome culture for prosumers. Future markets will be flexible [so there is a] need for distributional analysis of demand-response impact [and] conditions for consumer engagement: simplicity, safety, rewards. Future markets will be complex [so there is a need to define] new potential, new roles, new responsibilities [and] to adapt regulatory frameworks to safeguard consumer rights*” [57].

According to [21], a consumer-centric market should be flexible and allow consumers to easily navigate, engage, and benefit from it. Importantly, consumers should always have the option to choose their level of engagement and, in case of usage of consumer’s flexibility, the resulting benefits of reduced grid costs should be passed on to them [58].

3.2.4.2 Consumer-centricity from the Perspective of Energy Communities (REScoop)

The report [59] by REScoop, the European association of renewable cooperatives,[12] considers – based on a study by [60]– that “*by 2050, almost half of all EU households could be involved in producing renewable energy, about 37% of which could come through involvement in an energy community; if demand response and energy storage are included, about 83% of households could become active*.” Accordingly, REScoop understands

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[10] For an extensive discussion of the economic, behavioral, legal and technical barriers to customer engagement in the markets for system services and the possible recommendations to address those barriers, see the deliverable D11.5 of the OneNet project [35].

[11] For more information about BEUC, see their website: https://www.beuc.eu/.

[12] For more information about REScoop, see their website: https://www.rescoop.eu/.

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consumer empowerment to go beyond consumer information and choice of supplier. It is about ensuring that consumers can become active, participate in the market as new actors either individually or collectively, and take ownership of the energy transition.

Cooperatives and energy communities provide the structures for such collective participation. At the same time, they are new market actors with specific characteristics whose integration into energy markets may not be compatible with traditional regulatory tools and practice and may, therefore, require market regulations to be adapted. In REScoop's view, electricity markets should be organized around the principle of allowing final customers and energy communities to participate across the electricity markets without seeing their rights restricted by market entry barriers and rules that do not correspond to their particularities as small and mostly non-commercial market participants [22].

3.2.4.3 Consumer-centricity from the Perspective of Businesses Engaged in Flexibility Provision (SmartEn)

In the literature review, a position by Smart Energy Europe (smartEn), formerly known as the Smart Energy Demand Coalition (SEDC),[13] specifically on "consumer-centricity" of electricity markets could not be found. However, SmartEn has published recommendations on an efficient European power market design [61] as well as regarding design principles for (local) markets for electricity system services [62] that are relevant in the context of consumer-centricity.

Generally speaking, SmartEn maintains that demand-side flexibility (DSF) should be given access to all markets (wholesale, balancing, system services, capacity). Indeed, according to SmartEn, markets should incentivize consumers that are willing and able to engage in DSF schemes, while ensuring that those who do not participate are not penalized. Also, DSOs should be encouraged to make use of DSF offered by market parties for system operation purposes. Customers should at least have the choice to be metered and settled at the same time resolution as the imbalance settlement period in national markets, whenever technically possible. They should not face any undue barriers if they choose to be exposed to time-of-use retail price contracts. Market prices should reflect the real value of electricity at any moment. Aggregation of resources should be allowed, to the extent considered efficient and secure, as well as measurable, and third-party aggregators, when technically feasible, should be able to access all markets without prior consent of the consumer's retailer. Gate-closure times should be closer to real time and there should be effective market monitoring in place.

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[13] SmartEn is the European business association integrating the consumer-driven solutions of the clean energy transition. Its members include several energy companies, innovative service providers, vendors and consultancies. For information about SmartEn, see their website at: https://smarten.eu/.

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According to [62], products should be designed to satisfy system needs, such as efficiency, rather than reflect the specific characteristics of the traditional suppliers of those products. The provision of products should be open to all possible solutions and based on the type of service delivered, rather than the type of technology providing the service. Product parameters could be diverse but should be compatible and streamlined across markets as much as possible, so as to facilitate interoperability, increase efficiency and ensure liquidity across markets.[14] Moreover, availability and energy products are required, both short and long-term, to provide investors with certainty and system operators with the possibility to avoid inefficient lock-in effects. Free bids should always be possible, as well as portfolio-based bidding. Products should be defined for the largest possible market area relevant to the provision of a specific service and imbalance prices should not be distorted by congestion management actions that lead to modifications of the merit order.

More specifically, as stated in [63], to enable residential consumers and small and medium-sized enterprises (SMEs) to actively choose to participate in DSF schemes, engagement options and services need to be designed in such a way that they deliver significant, predictable benefits without requiring too much change in consumers' lifestyle or affecting the level of comfort. The challenges in the residential and SMEs sector therefore lie in making this decentralized flexibility available and enabling the market to monetize it.

3.2.4.4 Additional Initiatives on Consumer-centric Market Designs

Next to umbrella organizations' perspectives on consumer-centricity, some individual actors (such as systems operators), have also developed their own concept of a "consumer-centric market designs". For example, the position of the Belgian electricity TSO, Elia, is referenced in Box 3-1.

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[14] As an example of compatibility and streamlining across markets, it is stated that product durations should be defined as multiples of the same denominator.

Box 3-1 Individual Stakeholder Views on Consumer-centric Market Design – The Case of the Belgian TSO Elia

The Belgian TSO Elia has published its vision of a "Consumer-Centric Market Design" (CCMD) that aims to make flexible and manageable electricity consumption the norm and address currently existing barriers to active participation of small flexibility assets in the electricity market [23]. The main objective is to open up the market and allow competition behind the meter (BTM) by making it easier for consumers to access services offered by third parties BTM (related to, e.g., electric vehicles, heat pumps, demand response, decentralized self-generation) without significant constraints such as heavy submetering requirements and obtaining consent from their main supplier.

Elia's proposal involves two main changes to the current market design. First, the development of a regulated exchange platform ("Exchange of Energy Blocks" hub), through which the decentralized exchange of energy would occur on a fifteen-minute basis between consumers and various suppliers and service providers. Second, the introduction of a robust price signal, which would reflect system conditions in real-time, and give consumers a default reference for consumption optimization, decentralized trading, or for estimating the value of services offered by third parties. These changes would affect the roles and responsibilities of several actors and would require adjustments to certain market rules (e.g., balancing obligation). Importantly, no consumer will be forced to engage in the hub, and consumers will keep the option to source their needs through a traditional contract signed with their supplier.

3.2.5 Summary of the Different Perspectives on Consumer Centricity

Throughout the EU energy packages, an evolution of the notion and role of consumers is visible. First, a passive type of consumer was envisaged, who is merely supplied at any time with as much electricity as needed. Later came the informed type of consumer (also "eligible customer" as described in Section 3.1) who can choose between different electricity suppliers.[15] Today we see the emergence of active consumers who can participate in the energy transition and engage in energy markets both individually and collectively. All levels of consumer engagement exist in today's electricity markets and, hence, adequate market arrangements and regulations need to be in place to accommodate consumers characterized by different levels of engagement. This is the case for both existing and new types of electricity markets including for system services. A summary of the different perspectives on consumer-centricity is provided in Table 3-2.

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[15] Note that from today's point of view, a consumer who switches supplier is understood to be an "active" consumer albeit at a "lower" level of activity. "Active" today is understood to take many forms, from consumers filing a complaint to consumers switching their suppliers, to consumers becoming prosumers and generating, selling and/or storing their own electricity. At the time of the second energy package when consumer choice was introduced, however, the concept of an "active" consumer did not yet exist.

Table 3-2 - Summary of the Different Perspectives of Consumer-centricity

Perspective	Main elements	Main references
Policy and legislation: Second and Third Energy Package	Consumer information, protection, choice, rights and empowerment. *Also*: 2020 targets, decarbonization… need for market rules to adapt to a new market reality.	Electricity Directive 2003/54/EC, Directive 2009/72/EC, EC Impact Assessment CEP (2016)
Policy and legislation: Energy Union and CEP	"Energy Union with citizens at its core", "consumers at the centre of the energy system", "competitive, consumer-centred, flexible, and non-discriminatory electricity markets". *Also*: consumer empowerment & right to participate in all electricity markets.	Energy Union Package, New Deal Communication, Clean Energy Package
Regulation	Consumer awareness and ability to engage. Consumer choice (whether to engage or not). Protection of consumer (basic) rights. *Also*: CEER's "consumer-centric smart regulatory model".	Various CEER documents
Academia	Need of a more flexible energy demand to deal with an increasingly variable energy generation. Emergence of new trading arrangements, such as P2P electricity trading and local energy markets, enabling the pricing of specific attributes of energy. Need to understand consumer preferences and expectations to engage them effectively. *Also*: no clear and well-defined consensus definition.	Various articles in *Energy Policy*, *Utilities Policy*, *IEEE Power and Energy Magazine*, and book chapters
Stakeholders: consumer organizations	"Welcome culture for prosumers": • simplicity, safety, rewards; • define new potentials, roles and responsibilities; • safeguard consumer rights. Flexible market that allows consumers to easily navigate, engage and benefit from it, and choose their level of engagement.	BEUC documents
Stakeholders: energy community representatives	Consumer empowerment beyond information and choice of supplier. A consumer must be able to become active and participate individually or collectively (through energy communities).	REScoop documents
Stakeholders: business representatives	Engagement options need to be designed so that they deliver significant and predictable benefits without requiring too much change in consumer's lifestyle/comfort.	SmartEn documents

3.3 A Definition of Consumer Centricity in Electricity Markets

As illustrated in Section 3.2, European policy makers, regulators, and stakeholders are increasingly referring to "putting the consumer at the center of the power system", and increasingly repeat the need to develop

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"consumer-centric markets" for electricity. However, the definition of this terminology is somewhat unclear in the current context, along with what those objectives would entail in terms of electricity market designs. Indeed, a clear definition of consumer-centricity, upon which there is general agreement, is still lacking or is in the making at best. The aim of this section is to introduce a definition of consumer-centricity in electricity markets that removes the ambiguities that often follow the use of this term, and that can be used to assess whether the products and the coordination mechanisms introduced in Chapter 2 are more or less consumer centric.

In the following, we first aim to answer the question of how consumer centricity can be formally defined. We then focus on what makes a product consumer centric in the electricity sector. Finally, we discuss what makes a TSO-DSO coordinated flexibility market consumer centric.

3.3.1 How can Consumer Centricity be Formally Defined?

The analysis of the various perspectives on consumer centricity conducted in Section 3.2 allows us to state that consumer centricity is, in general, an emerging concept that refers to the practice or ability of putting the consumer at the center of all the decisions made by a firm, a regulatory authority, or a policymaker. Consumer centricity means taking the point of view of the consumer, and not solely that of the producer, the regulator or the whole system, when developing a product, designing a market mechanism, or elaborating a public policy. This entails, among others, (i) starting from the identification of the value that the consumer can receive by consuming the good or the service under consideration, (ii) the way the consumer would experience his/her participation in the market, and (iii) capturing the fact that consumers are not all the same and may have different preferences and needs, and, as a result, may not attribute the same value to a certain good or service with specific characteristics. Ultimately, consumer centricity entails giving the consumer the concrete possibility to choose *what* to consume rather than just *how much*.

Under this definition, it is clear that consumer centricity was not a feature of traditional electricity systems. Consumers used to receive a standard service, normally under regulated conditions. Given the impracticality, most of the time, of any alternative to the centralized supply of electricity via the public grid, consumers could only choose when and how much to consume. The liberalization of the sector in several countries in recent decades has changed the situation, but only to a certain extent [64]. Where retail competition has been introduced, consumers can switch supplier (see Section 3.2), but usually still have a limited possibility to express their preferences. Consumers have then limited impact on the characteristics of the product they consume or the way they interact with the rest of the system, as those elements are specified by a precise set of rules or legacy solutions.

However, in recent years the development of new technologies for the generation, consumption and storage of electricity, the emergence of new digital solutions that enable a more granular and effective management of energy systems, the electrification of final uses, and the increasing consumer awareness of energy and climate issues have radically changed the landscape and are strengthening the case for the adoption of a more consumer-centric approach within the electricity sector.

3.3.2 What Makes a Product Definition Consumer-centric?

Based on the definition of consumer centricity proposed in Section 3.3.1, it can be argued that, generally speaking, i.e., looking beyond the boundaries of the electricity sector, a consumer-centric product is a product that enables a consumer to effectively express her/his preferences and needs. It is a product whose attributes the consumer is able to understand and select if consistent with the value she/he attaches to them. Therefore, a consumer-centric product is a product that can be accessed by the consumer, i.e., the consumer has access to the market where that product is traded, and is a product that can be customized, at least to some extent, to reflect the specific preferences and needs of the consumer. In turn, this requires that the attributes of the product must be distinguishable – i.e., the consumer can detect if they are present or not – and that it is possible to price them separately, i.e., the consumer can be charged differently depending on the presence of the various attributes and the values they assume. A consumer-centric product is also a product that the consumer can procure from different providers if she/he prefers. In other words, the consumer, when procuring the product, is not locked-in by a certain supplier and the identity of the producer is one of the attributes that the consumer can value and select. Finally, a product defined in a consumer-centric way is not dependent on specific technological choices (technological neutrality) or tradable only in volumes that are out of the reach of consumers. On the contrary, its provision is compatible with different hardware and software solutions that can be adopted by consumers, and the smallest tradable amounts are of the same order of magnitude of typical final consumption. Of course, the consumer centricity of a product definition is not a binary characteristic, but rather a matter of degrees: certain products can be defined in a way that is barely consumer-centric, while others can be specified in a much more consumer-centric way.

From these considerations, it is clear that electricity is a product that has traditionally not been defined in a consumer-centric manner. This can be hardly a surprise, given the highly stringent requirements needed to ensure the continuous and secure functioning of electricity system, the limits of the technology available until the relatively recent digitalization waves – e.g., the difficulty to meter consumption on short time intervals and communicate the data at low cost –, and the relatively stable and undifferentiated patterns of demand by many consumers. As a result of that, for decades the attributes of electricity supply were defined by incumbent producers or by regulators, considering first of all system requirements and the benefits deriving from the standardization of many parameters. Reliability standards used to be (almost) the same for all the consumers, irrespective of their individual willingness to pay for a superior service.[16] In that context, consumers did not have a direct say on the generation mix and could procure the electricity from only one supplier, the incumbent. However, even after the liberalization of the electricity sector, which took place in Europe between the 1990s and the 2000s, the level of consumer-centricity in the way the products available to consumers are defined is typically rather low. Consumers can switch to a different supplier and can base their choice on some attributes of the product consumed, such as the generation mix of the electricity provided by that specific supplier. They can also see their preference reflected in different prices and contracts. However, they are typically unable to negotiate other attributes of the electricity supply, such as the level of reliability, or they typically face limits to the possibility of procuring the same product from different suppliers at the same time.[17]

Products that go beyond standard electricity supply, that is products for system services, are traditionally defined on the basis of the specific service requirements they are expected to satisfy. The possibility to "customize" these products is then inherently low. Consumer centricity for this set of products can then be better assessed in terms of the possibility, for consumers, to get involved in the relative markets and contribute to their provision, either directly or through some intermediary, such as an aggregator. Accessibility and aggregability are fundamental features to increase the level of consumer centricity of products for system services that, until recently, have been defined in ways that allowed only utility-scale electricity generators or large industrial consumers to provide them, basically excluding small-scale consumers from participating in their provision. From this point of view, it is then the responsibility of the intermediaries to develop commercial propositions that appeal to the various consumers and are able to accommodate their specific preferences and needs, to contribute to meeting consumer-centricity goals and standards.

3.3.3 What Makes a TSO-DSO Coordinated Flexibility Market Consumer-centric?

A consumer-centric TSO-DSO coordinated flexibility market is a market that is able to provide the system services required by the system operators at the transmission and distribution level, while generating additional value to consumers as flexibility providers. Such a market allows system operators to improve the secure and continuous supply of electricity in a cost-effective manner, it also gives consumers the opportunity to receive new offers which suit better their specific preferences and needs, both in terms of the reliability level of their energy supply and their willingness to invest in DERs and provide the system with flexibility from their assets located behind the meter (BTM). In a consumer-centric TSO-DSO coordinated flexibility market, consumers can

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[16] Reliability of the electricity service is typically not exactly uniform because network planning and contingency plans may allow for different treatments of consumers connected to different parts of the electricity network. A typical distinction is between consumers living in the countryside and consumers living in a densely populated neighbourhood or near a hospital or any other 'essential infrastructure', that is awarded priority in case of partial load-shedding.

[17] Collective self-consumption and peer-to-peer electricity trading are emerging energy models where consumers can access products with specific attributes, such as greenness or locality. However, regulation nowadays still restricts them to specific cases that limit the level of consumer-centricity of the product exchanged [38].

participate, directly or indirectly, in the provision of system services and be rewarded for that. Consistently with the concept of consumer-centricity, in such a market consumers can interact with several intermediaries, not just their electricity supplier, and select their level of participation, based on their ability to invest in DERs and their willingness to compromise in terms of comfort and service reliability. Consumer-centricity requires that participation is easy and that several markets can be accessed with the same resources. Stacking multiple revenue possibilities is an important aspect of this kind of markets, as the revenue a consumer can obtain for bidding in a specific market may be relatively low that it does not justify the initial investment in DER or the discomfort borne by the consumer for flexibility reservation or activation. Finally, a consumer-centric TSO-DSO coordinated flexibility market is a market where consumers, or their intermediaries, can have access to relevant information, while at the same time respecting consumer data privacy and ensuring data protection.

Based on this definition, it can be observed that consumer centricity has not been taken as a fundamental principle in the establishment of the mechanisms for the procurement of system services, until recently. When developing the rules governing markets for balancing and congestion management, more weight has been typically put on the needs of the system operation, which has decreased the focus on the possible participation of small-scale consumers. Flexible resources had to be visible and controllable by system operators, thereby minimizing any risk associated with non- or under-performance. This typically implied the exclusion of significant resources connected to the medium and low voltage networks, which were mostly opaque to system operators until the recent digitalization wave [65]. The lack of consumer centricity was visible also in the introduction of technology-specific requirements, excluding, for example until recently, most of the power plants running on intermittent renewables from the markets for system services, irrespective of their size and connection point to the network. Similarly, the trading of flexible resources and their final procurement by system operators had to fit specific procedures of operation by system operators and provide them with a certain room of controllability to be able to meet the pre-set grid operational and reliability requirements.

As already mentioned, the development of DERs and the digitalization of the electricity infrastructure, behind and in front of the meter at the consumer's premises, increasingly offer the possibility to design TSO-DSO coordinated flexibility markets that are more consumer-centric than the past mechanisms for the procurement of system services. Exploiting this possibility is fundamental to efficiently managing an electricity system with increasing shares of distributed and variable generation. It is also fundamental to offer additional value to consumers, incentivizing the provision of grid services rather than a complete disconnection from the public grid [43].

At the same time, it is important to note that the development of a more consumer-centric TSO-DSO flexibility market may also pose some challenges that require careful considerations by regulators and policy makers. In particular, the expansion of the set of choices available to consumers, which derives from the removal or relaxation of rules and requirements in existing flexibility markets, inevitably leads to a more complex and dynamic environment, where alternative and robust coordination mechanisms must be put in place [66]. If this is not the case, security of supply may be jeopardized and the cost of ensuring it may increase. In this context, certain network users may also disproportionally benefit to the detriment of others.

3.4 Consumer-centric TSO-DSO Coordinated Flexibility markets: Some Considerations on Products' Attributes and Coordination Schemes

Flexibility products and the coordination schemes that can be adopted to organize their trading can present different degrees of consumer centricity. Specific choices by the regulator or by the entity in charge of organizing and running a flexibility market can promote consumer centricity, while other choices may prioritize alternative considerations and lead to a less consumer-centric flexibility market. The implications can be relevant, as a less consumer-centric flexibility market may hinder the participation of DERs and make more expensive the procurement of system services by the system operator(s).

In what follows, we use the definitions developed in Section 3.3 to qualitatively explore the impact on consumer centricity of different choices regarding the attributes of flexibility products and the coordination schemes implemented in TSO-DSO coordinated flexibility markets, which have been defined in Chapter 2. While this analysis is far from being exhaustive given the large number of possible system services, product attributes and coordination schemes,[18] some useful considerations and insights may nonetheless be derived and could provide a relevant input to other tasks of the OneNet project or in future research projects. In particular, the analysis can highlight the importance of further investigating with quantitative tools the consequences of a choice regarding the attributes of a specific product or a certain coordination scheme.

In the following, we first look at the attributes of flexibility products and consider the implications of various choices for consumer centricity. Then, we turn to the coordination schemes that can be implemented in flexibility markets and we discuss the implications of the adoption of different schemes for consumer centricity.

3.4.1 Flexibility Product's Attributes

The report [3] identifies 25 different attributes of a generic flexibility product and gather them in two separate groups: the *technical dimensions* and the *bid-related dimensions* (Figure 3-1). The first group is further divided into the attributes that define the good traded (seven attributes), the attributes that specify the timing for delivery (seven attributes), and one attribute that indicates how the communication between the system operator and the flexibility service provider occurs. The second group is divided into the attributes that define

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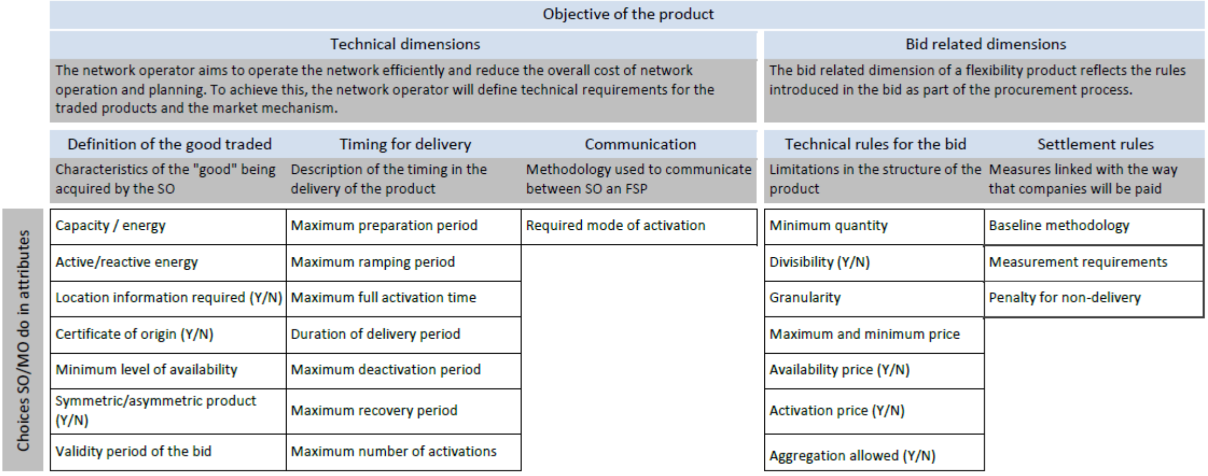
[18] [3] identify five system scarcities or needs, 12 system services that can address those system scarcities, and 25 attributes that can be relevant in the definition of the products that provide those system services. [8] identify seven fundamental coordination schemes for the market-based provision of system services.

the technical rules for the bids (seven attributes), and the attributes that specify the settlement rules (three attributes).



	Objective of the product				
	Technical dimensions			Bid related dimensions	
	The network operator aims to operate the network efficiently and reduce the overall cost of network operation and planning. To achieve this, the network operator will define technical requirements for the traded products and the market mechanism.			The bid related dimension of a flexibility product reflects the rules introduced in the bid as part of the procurement process.	
	Definition of the good traded	Timing for delivery	Communication	Technical rules for the bid	Settlement rules
	Characteristics of the "good" being acquired by the SO	Description of the timing in the delivery of the product	Methodology used to communicate between SO an FSP	Limitations in the structure of the product	Measures linked with the way that companies will be paid
Choices SO/MO do in attributes	Capacity / energy	Maximum preparation period	Required mode of activation	Minimum quantity	Baseline methodology
	Active/reactive energy	Maximum ramping period		Divisibility (Y/N)	Measurement requirements
	Location information required (Y/N)	Maximum full activation time		Granularity	Penalty for non-delivery
	Certificate of origin (Y/N)	Duration of delivery period		Maximum and minimum price	
	Minimum level of availability	Maximum deactivation period		Availability price (Y/N)	
	Symmetric/asymmetric product (Y/N)	Maximum recovery period		Activation price (Y/N)	
	Validity period of the bid	Maximum number of activations		Aggregation allowed (Y/N)	

Figure 3-1 - Attributes of a Generic Flexibility Product Set by a System/Market Operator [3, p. 35]

The values these 25 different attributes can assume influence the level of consumer centricity of a certain flexibility product. As stated in Section 3.3.2, a product is characterized by a higher degree of consumer-centricity if it provides the consumer with the possibility to express his or her preferences and needs. The values assigned to the attributes that characterize a certain flexibility product can limit, to a smaller or larger extent, that possibility, leading to a more, or less, consumer-centric product. In particular, the values assigned to the various attributes of a product can restrict the possibility for the ‘customization’ of the contribution by a consumer based on his or her preferences and needs. Possibly, the values assigned to the various attributes can define a product that makes the contribution of a consumer even impossible.

The harmonization or full standardization of flexibility products can be consumer-friendly, as it offers simplicity and other possible benefits to consumers. However, if the standard adopted for a product poses barriers to the participation of consumers, it then leads to a low degree of consumer centricity that can discourage participation in the market and undermine the efficient provision of system services.[19]

A detailed analysis is beyond the scope of this deliverable. In the following, we provide qualitative considerations for some of the most relevant attributes, divided according to the classification proposed in [3].

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[19] For a discussion of harmonisation and standardisation of system service products, see [3].

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3.4.1.1 Attributes Defining the Good Traded

Among the seven attributes that concur to the definition of the good traded, two are particularly interesting from a consumer-centric perspective. They are the product's symmetry and the validity period of the bid.

Symmetry determines whether only symmetric products or also asymmetric products are allowed. For symmetric products, upward and downward volumes must be equal, while for asymmetric products upward and downward volumes can be different. Imposing that only symmetric products can be traded in the market for a certain system service limits the level of consumer centricity. Some consumers may not value in a symmetric way the need to reduce or increase the amount of electricity withdrawn from the grid in a given time interval, for example because they do not have any storage capacity or a sufficient amount of other flexible loads. As a result of this constraint, some consumers may prefer to remain outside of the market and the liquidity of that market may decrease. In the case of capacity products in balancing markets, some previous research works argue that linking the upward and downward reserve requirements means excluding vRES and DR from participation [67, p. 69].

The validity period of the bid determines the period of time in which the bid offered by the flexibility service provider can be activated. The validity period has a start and end time, and its duration is at least equal to the delivery period. Imposing a specific validity period to the bids for a certain system service can reduce the participation potential of consumers. Its impact on consumer centricity is particularly negative when the duration of the validity period is very long. In this case, any consumer willing to offer a flexible resource has to agree on a potentially burdensome obligation. Of course, if properly remunerated, a consumer may be more incentivized to accept long validity periods. Still, this tends to require consumers investing in adequate flexibility resources and keeping them ready for a protracted period of time, which can increase the inconvenience of participation in the provision of flexibility.

3.4.1.2 Attributes Defining the Timing for Delivery

The seven attributes that specify the timing for delivery of a certain product have important implications for the consumer centricity of that product. Depending on the set of assets he or she has available and the level of discomfort he or she is ready to accept, a consumer can have different preferences with regard to the values these attributes can take. Let us consider the case of the full activation time and the delivery period.

The full activation time (FAT) is the sum of the preparation period and the ramping period and corresponds to the time between the activation request by the system operator and the corresponding full delivery of the concerned product. Consumers with automated management systems that can receive and implement the system operator's request almost instantaneously or consumers with very flexible loads, such a lithium-ion battery or an electric boiler, that can modulate their energy demand in a fraction of a second, will be ready to

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accept a relatively short FAT. On the contrary, consumers that must manually activate the relevant flexibility resources or that must adjust other processes in order to release a flexibility resource – take for instance the case of an industrial consumer that must ensure its production process is not damaged by a sudden change in its energy exchange with the grid – are likely to prefer a longer FAT. Therefore, setting a relatively short FAT can be expected to disregard the preferences and needs of several consumers and hinder their participation, at least individually, in flexibility markets.

The delivery period indicates the length of time during which the flexibility service provider delivers the full requested change of power in-feed to, or the full requested change of withdrawals from the system. Imposing a certain minimum duration of the delivery period can represent a barrier for the participation of some consumers. If the minimum duration of the delivery period is relatively long, some consumers may be discouraged from participating in a flexibility market. This is particularly the case if they do not possess adequate types and amounts of flexible resources. Indeed, a long delivery period means either that some assets (e.g., electric vehicles) or electric appliances may be not available for the consumer when needed or, to the contrary, that some consumption may be mandated, despite it being not useful for the consumer (except for securing the proceeds of the participation in the flexibility market). A consumer with limited flexibility resources that must accept long delivery periods will then face the risk of suffering excessive discomfort or pay for unneeded consumption if his or her bid is activated. Because of that, he or she may prefer to avoid any involvement in flexibility markets.

3.4.1.3 Attributes Defining the Technical Rules for the Bids

The seven attributes that define the technical rules for the bids introduce a series of limitations in the structure of the product and have important implications in terms of consumer centricity. Two of them are particularly relevant: the minimum quantity that can be bid and whether aggregation is allowed or not.

The minimum quantity is the smallest amount of power (or change in power) that must be included in a bid. In a market where a minimum quantity has been defined, transactions involving a smaller amount of power (or change in power) are not allowed. The adoption of a specific value for this attribute typically reflects some technical constraints faced by the system operator or the market operator, who can find convenient to limit the number of bids by imposing a minimum quantity. By doing so, some transaction and coordination costs can be reduced and efficiency in trade can be increased. However, the introduction of a minimum quantity can represent a barrier for the participation of consumers, especially the smaller ones, such as residential and (some) commercial customers. The resources they are able to mobilize are in the order of kW or tens of kW, an amount that is below the minimum quantity typically set, e.g., in balancing markets. For this reason, individual or even aggregated participation by many consumers can be hindered.

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Aggregation determines whether it is allowed or not to group several units and offer them in a single bid. This attribute plays a fundamental role in the determination of the product's level of consumer centricity. By allowing an intermediary to pool the resources of several consumers, aggregation ensures that many consumers, who would not be able to participate individually in a market, can do that and can do that according to their preferences and needs [68]. Indeed, if aggregation is allowed, then it is not necessary, for each consumer, to respect all the constraints and standards set by the product requirements. The task of ensuring the respect of those constraints and standards is left to the intermediary, who will rely on its portfolio of DERs to do that, while consumers can provide, up to a certain extent, a 'tailored' contribution that reflects an adequate (for them) balance between the inconvenience of changing consumption behavior and/or investing in DERs and the additional monetary revenue derived from the provision of flexibility. If aggregation can, on the one hand, foster customer engagement, it is important also to observe that for certain products there might be limits to preserve on the location and nature of the units that can be aggregated. Under certain conditions aggregation may in fact not deliver system benefits but only private benefits.[20] For instance, a product that is used only for the local management of congestion may not be efficiently provided by an aggregation of units that are not localized in a way to serve the alleviation of local congestions. On the contrary, a product that is used for balancing the frequency of the system may not present the same constraint: aggregation of units spread across the system may then not be a problem for the efficient delivery of the system service, especially when the grid from which this flexibility is delivered is not heavily constrained. Indeed, when providing, e.g., balancing services from distribution-level connected units, if the capacity of the distribution system is constrained (in terms of line flow limits, substation limits, voltage limits, etc.), the activation of this flexibility would have to consider the distribution level constraints to make sure the flexibility can be activated and delivered in a grid-safe manner. Hence, in these conditions, even when delivering balancing services, locational information would be required, which would limit the possibility of wide-scale aggregation.

3.4.2 TSO-DSO Coordination Schemes

The articles [8] and [1] introduce and discuss at length several coordination schemes and market models that can be adopted to organize the procurement and activation of system services at the transmission or distribution level on a market basis. These coordination schemes have led to the creation of a number of TSO-DSO coordinated flexibility market models, that were introduced and presented in Chapter 2. These schemes and models are classified based on the location of the relevant system scarcity or need (local, central or both), the identity of the primary buyer of flexibility (TSO, DSO, external stakeholders or peers), the number of markets utilized for trading flexibility products (one or more than one), and the possibility for the TSO to access resources located at the distribution level (Figure 2-2).

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[20] For a discussion of the fundamental and transitory values of aggregation vs its opportunistic value, see [68].

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This classification does not explicitly consider the point of view of consumers; nonetheless, by applying to the various schemes the definition of consumer-centric TSO-DSO coordinated flexibility markets presented in Section 3.3.3, it is possible to derive some general indications on the degree of consumer centricity of each of them and qualitatively "rank" them as more, or less, consumer-centric (Figure 3-2).

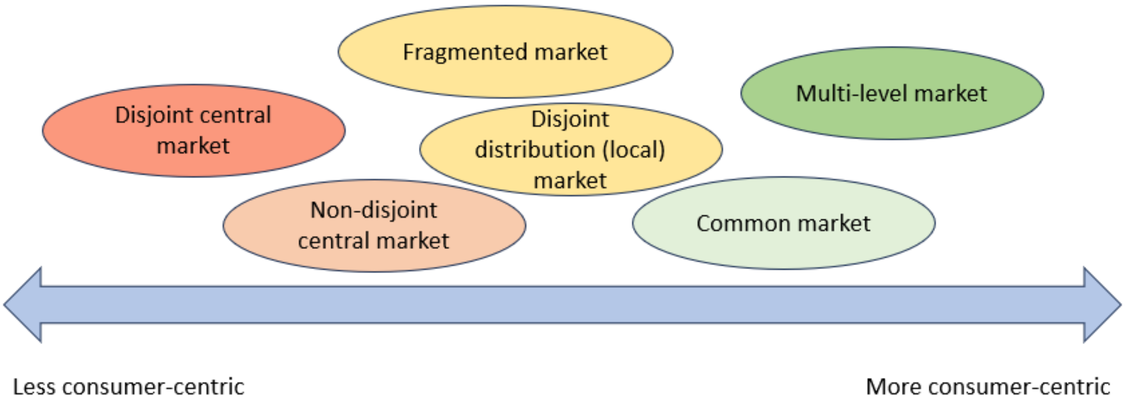

Figure 3-2 - Ranking of the TSO-DSO Coordination Schemes and Market Models in Terms of Their Consumer Centricity

The central market model aims to satisfy the needs located at the central level and qualifies as a monopsony, since the TSO is the only buyer present in the market. The flexibility needs of the interconnected DSOs are not considered in the market (even though their grid constraints might be considered depending on the central market structure as highlighted in Chapter 2), which means that the market value of the flexible resources owned by the consumers and the exploitation options they have available are somehow smaller, as the requirements of those markets at system level can be stricter for smaller-scale resources. Two variants of the central market model are possible: the disjoint and the non-disjoint. In the disjoint central market model, the TSO has access only to the resources connected to the transmission grid, typically big power plants and large industrial sites. The vast majority of the consumers with their resources connected to the distribution grid cannot provide any services to the TSO in this market model. The fact that only the needs of the TSO are taken into account and the fact that DERs cannot participate in the market suggest that the disjoint central market model has a particularly low degree of consumer centricity. In the non-disjoint central market model, the TSO has access also to the resources connected to the distribution grid, which is typically the case for smaller industrial sites and the entirety of residential and commercial consumers. The fact that DERs can participate in the market suggests that the non-disjoint central market has a higher degree of consumer centricity than the disjoint one. On the other hand, as the flexibility needs are central in that case, products traded in this market are likely to be defined in a way that still challenges consumers and may have a relatively low degree of consumer centricity. For instance, the bids of the products traded in this market can be characterized by a relatively high minimum quantity, as they have to satisfy the central needs of the system (at TSO level and beyond, for pan-

European applications, such as the case for MARI, PICASSO, and TERRE).[21] For this reason, we can assume that, overall, the non-disjoint central market model presents a low-to-medium degree of consumer centricity.

The disjoint distribution-level market, to which we refer as the local market model, aims to satisfy the needs located at the local level and qualifies as a monopsony, since the DSO is the only buyer present in the market. The needs of the TSO are not considered and revealed in the market, nor is any indirect sharing of flexibility resources between the transmission and the distribution grid allowed.[22] On the one hand, this feature is somehow symmetric to the one of the central market model and reduces the outlets for the flexibility resources owned by consumers, who are not able to provide flexibility outside their local markets in an integrated manner (as it is the case in other coordinated TSO-DSO markets, such as the common and multilevel markets, as we will highlight shortly). On the other hand, the fact that the markets are local (i.e., the buyer of flexibility is the DSO) suggests that the products traded in this market can be defined in a way that suits better the preferences and needs of small-scale consumers. In particular, product's attributes such as the minimum quantity may display values that are less demanding for consumers.[23] Moreover, the fact that the market aims to satisfy local needs and is open only to local resources means that its rules could be tailored and designed in a way that better reflects and suits the characteristics of the consumers involved. For these reasons, we can assume that, overall, the local market model presents a medium degree of consumer centricity.

The fragmented market model aims to satisfy the needs located both at the local and central level. It does so by establishing two or more separate markets that run sequentially (two-layer market model). First, the markets that aims to satisfy the needs of the DSOs are run. They are local markets open to the resources connected to the individual distribution grids. Second, the market that aims to satisfy the needs of the TSO and deal also with any imbalance created at the interface with the distribution grids is run. This is a central-type market and only resources connected to the transmission grid can participate in it. The fact that each resource can participate in only one flexibility market suggests that the degree of consumer centricity of this model is similar to that of the local market model described above. Indeed, most of the consumers and their assets, which are connected at the distribution level, will be able to participate only in the market procuring services for the DSO. This can be to some extent an advantage, as market rules and product's attributes can be tailored to the consumers' characteristics (as highlighted for the local market setting), but on the other hand it may limit the possibility of targeting more system needs and enabling value staking. The possibility to indirectly share some flexibility at the distribution level with the transmission level has an ambiguous impact on the amount of services

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[21] The possibility of aggregating resources from multiple consumers plays a key role in counteracting the fact that TSOs operate at a scale that is much larger than that of many consumers.

[22] The local market model is disjoint and the DSO must operate in a way to preserve the scheduled flow of energy at the interface with the transmission grid.

[23] It might be the case that the specific needs of the DSO call for other attributes being defined in a way that is less consumer centric. For instance, products for congestion management or voltage control may require the resources offering them being located in specific points of the grid. For this reason, aggregation may not be allowed or may be subject to more stringent requirements.

to be procured from consumers locally. For these reasons, we can conclude that the fragmented market model presents a medium degree of consumer centricity, as the disjoint-distribution level market.

The common market model aims to satisfy the needs located at the local as well as central level. It does so by establishing a single market where a single order book of the flexibility bids is created and is available to all the system operators of the interconnected system. In this model, all consumers can mobilize their assets to satisfy the needs of all the interconnected system operators. This clearly represents a positive element; however, the fact that there is just one market means that the market rules and the way in which the traded products are defined are not necessarily tailored to the needs and preferences of consumers, in particular the smaller ones. Attributes like aggregation play in this context a fundamental role in ensuring that consumers can still be at the center of the market and able to offer their resources to support the operation of the system. For these reasons, we can suppose that the common market model presents a medium or a medium-to-high degree of consumer centricity.

The multi-level market model aims to satisfy the needs located at the local and central level. Like the fragmented market model, it is characterized by a sequence of markets: first, one or more local markets are run; second, trading in a common or central-type market takes place. However, like the common market model, the multi-level model provides the TSO with access to the resources located at the distribution level. All the flexibility resources that bid in the local market and that are not used by the local system operator can be forwarded to the central layer of the market that aims to satisfy the TSO needs. Variants of the way in which unused bids are forwarded to this second layer of the market are possible (as introduced in Chapter 2). In one of them, the consumer or more likely his or her intermediary can adjust the bids before forwarding them on the basis of the results of the local market in the attempt to increase the chances of being selected in the TSO-level market. As described in [2], the overall economic efficiency of this model is not superior to that of the common market model (especially under low entry barriers, as will be shown in Chapter 5);[24] nonetheless, these above-mentioned characteristics suggest that the multi-level market model presents a relatively high degree of consumer centricity as it allows consumers to provide flexibility to the TSO while still being able to participate in a local market layer, which can be more tailored towards their needs.

3.5 Conclusions

European legislation does not provide a definition of consumer nor of consumer-centricity with regard to the electricity sector. What EU legislation defines is customer, which is a term that is used, practically, as a synonym of consumer (we keep this practice throughout the chapter). Over time, this concept has evolved to reflect the evolution of energy markets and the growing role that consumers can play in the sector. The

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[24] The opposite may be true due to higher transaction costs. See Chapter 5 in this report.

increasing attention to customers and consumers is visible in policy documents, stakeholder reports and the related academic literature. The active involvement of consumers is considered essential by many experts and policymakers to achieve the energy transition in an efficient and inclusive way. In particular, there is a growing consensus on the need for consumers to take part in all electricity markets (at times through the means of intermediaries and aggregators) and contribute to the provision of the system services that are increasingly needed by system operators to ensure the secure and continuous functioning of the system.

The need to put consumers at the center of the electricity system has led to the introduction of the concept of consumer centricity in the debate on electricity systems and markets. The concept, although widely used, has not been clearly defined. However, we argue that it can be associated with the practice or ability of putting the consumer at the center of all the decisions made by firms, regulators, and policymakers. Given this definition, one can see that the electricity sector has been characterized by a relatively low degree of consumer centricity over the past decades. Nonetheless, the situation is changing, due to the opportunities offered by technological development and the increasing awareness of consumers.

From the definition of consumer centricity, we maintain that a specific product is consumer centric when the consumer has the possibility to express his or her preferences and needs, which include not only the overall price, but also several other attributes. When looking at the case of electricity and the products to satisfy system needs, it is clear that there are limits to the possibility for consumers to express such preferences and needs, These limits can be alleviated through intermediaries, such as aggregators. By offering contracts tailored to the preferences and needs of consumers, these intermediaries enable the participation of consumers who otherwise would either not have the possibility to participate in the market or not enough interest in participating. As such, the role of aggregation for allowing increased participation of consumers in electricity and services market can improve the consumer centricity of those markets, as otherwise, such consumers can face barriers to entry. However, under this setting, the aggregator's role becomes increasingly essential for achieving the consumer-centric principles through providing adequate financial and contractual mechanisms to consumers to incentivize their participation, thus applying the consumer-centric characteristics defined in this chapter also to the aggregator-consumer dimension.

Finally, with regard to TSO-DSO coordinated flexibility markets, we claim that they are consumer centric if they are able to provide the system services required by the SO(s) at the transmission and distribution level, while generating adequate value to consumers and enabling their participation. This means providing consumers with the possibility to better reflect their preferences and needs, including the desire to contribute to the provision of system services and be rewarded for that. Consumer-centric TSO-DSO flexibility markets are increasingly possible and also increasingly necessary. Among the coordination schemes discussed in this deliverable, the disjoint central market presents the lowest degree of consumer centricity, while the common and multi-level markets are at the higher end of consumer-centricity levels.

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4 Entry Barriers in TSO-DSO Coordinated Flexibility Markets

4.1 Motivation of the Problem

Several products are exchanged in flexibility markets (such as the TSO-DSO coordinated flexibility market models introduced in Chapter 2) for the provision of services to the TSOs and DSOs. Several such standardized products for the procurement of flexibility services have been introduced and defined within OneNet's D2.2 [3] exploring their different attributes and uses for the delivery of different services (e.g., different balancing services, congestion management, among others). The implementation of these harmonized products may lead to certain entry barriers to different types of FSPs, leading to possible market exclusion, as some harmonized requirements may not be feasible to achieve by all types of FSPs. This is the case since different products for different services may have differing levels of strictness. Hence, when coordinating markets in a setting in which a product can be procured for different services, that product would in practice have to meet the most stringent requirements of those services, which can be difficult to achieve by some FSPs that might have been able to meet the less strict requirements of some of the services had they not been harmonized[25]. As such, different TSO-DSO coordination schemes, by combining or disjoining markets, can present different levels of entry requirements.

Understanding the different barriers that can result from the product attributes, depending on the coordination scheme chosen, provides us a basis for exploring the efficiency of the coordination schemes. The coordination schemes under consideration include local markets, central markets (in different forms), common markets, fragmented markets and multilevel markets, which were defined in Chapter 2. The analysis first starts by identifying barriers that can be introduced by different attributes. Then a reflection on whether these entry barriers can be different from one coordination scheme to the other is carried out.

Remark: *Note that the analysis carried out within this chapter should be seen in complement to the analyses already carried out in other OneNet deliverables, which dive further on specific entry barriers, such as in D2.2* [3], *D3.2* [69], *and D3.4* [70]. *The goal of those previous analyses had been to analyze product attributes, their harmonization, and the possible barriers that can exist. The goal within this chapter, on the other hand, is to rather provide an overview of what main barriers can result from the product attributes, the reason for their existence, and how they can manifest in different TSO-DSO coordination schemes, which can then feed into the*

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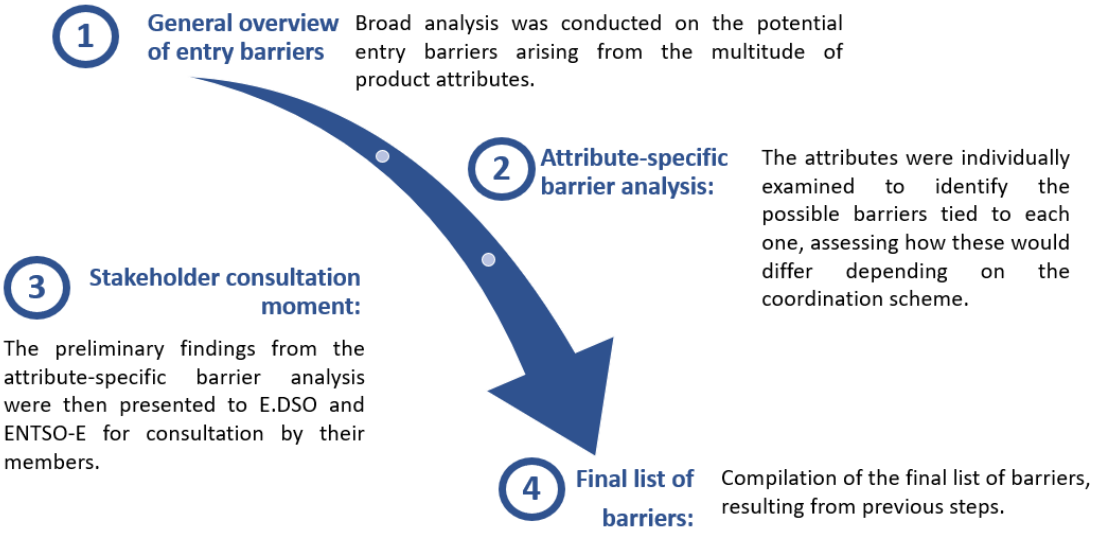
[25] Here, we note that what we mean by harmonization, is the use of a certain product to deliver multiple services (e.g., balancing and congestion management) as can be done using the different TSO-DSO coordination schemes introduced in Chapter 2. This is different than the harmonization of the requirements for the same services in different countries or geographical locations.

efficiency analysis in Chapter 5. Indeed, Chapter 5 considers, in the simulation analyses, the minimum bid entry requirement (i.e., minimum flexibility quantity requirement) as a proxy for those entry barriers to quantify their potential impact on efficiency. Chapter 4 then describes the underlying aspects and barriers that this proxy can encapsulate.

4.2 Framework for Entry Barriers Analysis

The assessment of entry barriers introduced by the different product attributes (and their link to different TSO-DSO coordination schemes) followed a four-step process, as presented in Figure 4-1. In a first stage, a broad analysis was conducted on the potential entry barriers arising from the product attributes (Step 1) defined and described in D2.2 [3]. The attributes were assessed based on their relevance and the likelihood of them causing potential entry barriers for FSPs.



1 General overview of entry barriers Broad analysis was conducted on the potential entry barriers arising from the multitude of product attributes.

2 Attribute-specific barrier analysis: The attributes were individually examined to identify the possible barriers tied to each one, assessing how these would differ depending on the coordination scheme.

3 Stakeholder consultation moment: The preliminary findings from the attribute-specific barrier analysis were then presented to E.DSO and ENTSO-E for consultation by their members.

4 Final list of barriers: Compilation of the final list of barriers, resulting from previous steps.

Figure 4-1 - Framework for Assessing the Entry Barriers Resulting from the Product Attributes and Linking Them to the Coordination Schemes.

Afterwards, the attributes were individually examined to identify the possible barriers tied to each one (Step 2). This analysis also studied whether the barriers varied depending on the coordination scheme. Different questions were addressed under this step to identify barriers related to each product attribute, ranging from the dependence on the technical capabilities of the FSPs' assets to the need to comply with stringent requirements when moving from one coordination scheme to the other. To ensure the accuracy of this analysis, a comprehensive review of relevant projects, a thorough literature review, and an in-depth analysis between the involved partners were undertaken. The preliminary findings from the attribute-specific barrier analysis were then presented to E.DSO and ENTSO-E for consultation (Step 3) to gather input from their members. Their

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expertise and insights were instrumental in verifying the accuracy of the identified barriers, understanding their practical implications, and refining the overall assessment.

The last step involved the compilation of the final list of barriers (Step 4). The list represents the product attributes that can potentially affect FSPs' entry into flexibility markets depending on the coordination scheme. This systematic approach allowed us to identify and validate the potential entry barriers in flexibility markets, to serve as input for the efficiency analysis of different TSO-DSO coordinated market schemes that is carried out in Section 5.3.1.

4.3 Analysis of Entry Barriers

This section presents an overarching analysis of potential entry barriers for flexibility markets that derive from the harmonized product attributes that have been defined in D2.2 [3], which are also listed in Annex A.

4.3.1 Framework of Analysis

There are several challenges that can be introduced by a certain product attribute. Each product attribute is designed in such a way to ensure reliability meeting the service requested by the SO. However, this puts restrictions on the FSP (and, as a result, the technologies providing this flexibility) to meet those requirements. The challenges introduced by an attribute can differ in origin and nature. To analyze those challenges (which can result in entry barriers) and identify their existence, several criteria were taken into account, which served as basis for this analysis:

- Compliance to most stringent requirements: *Would the definition of a common product that fulfills the most stringent requirements to meet both DSO and TSO needs lead to any market exclusion?*
- Technical capabilities of the FSPs assets: *Would the definition of attribute requirements for service provision limit the participation of an FSP asset (i.e., asset providing flexibility) due to its inherent technical capabilities?*
- Confidentiality requirements: *Would certain attribute requirements for service provision be difficult to fulfil due to data confidentiality and protection?*
- Timing: *Would the attribute impact the timing for bid forwarding to be used in sequential markets, requiring the fulfilment of strictest requirements to allow value stacking?*
- FSP interest and commitment: *Would the fulfilment of the product attribute requirements reduce the interest of participation from the FSP side?*
- Measurement requirements: *Would the fulfillment of the product attribute specifications require specific measuring devices and granularity that may not be envisioned in certain FSP assets?*

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Thus, the response to these questions for each of the product attributes under analysis guided the identification of these challenges. An in-depth analysis of the challenges posed by each product attribute is presented next.

4.3.2 Attribute-level Analysis

Following the criteria described under Section 4.3, several entry barriers were identified for the different product attributes defined in D2.2 [3], which are extensively described in Table 4-1. Note that the description for each of these attributes is found in Annex A.

Table 4-1 – Analysis of the Entry Barriers Identified for Each Product Attribute.

Attribute	Barriers' Description
Capacity / energy	A capacity-based product is focused on the maximum amount of energy that can be increased or reduced, during certain time periods within a defined time horizon, which is the opposite for an energy-based product. Some FSPs, depending on their technical characteristics, will have limitations in providing the minimum requirement, such as battery energy systems that are limited by their storage capacity, or even some demand response programs, which is the case for certain industries that are unable to sustain the demand reduction too long without disrupting their operations [71].
Active / reactive power	This requirement is related to the technical capabilities of the FSP assets. For example, the provision of reactive power services may not be possible to achieve for certain FSPs without requiring additional adaptation/investments. This is the case for generators that fit in the Type A RfG category, which do not have obligations (by design) related to reactive power [72]. On this matter it is important to emphasize, that within the current revision of the RfGs, ACER proposes the introduction of such requirements to new type A generators – existing generators will however be excluded from these requirements and would be unable to deliver reactive power services [73]. Also, it's important to add that reactive power-based services (due to the nature of the issues addressed) tend to require a quick reaction. For this reason, any participating unit must likely also have bidirectional communication allowing exchange of data concerning reactive power, Qmin/Qmax (P-Q-capability diagram), signaling of switch elements state, remote FSP control on service activation. In addition, based on the technical capabilities of some units, control of reactive power independently of active power outputs may also be challenging (enabling them to deliver reactive power without requiring significant changes to their active power outcomes within a certain control region). Unavailability

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	of these technical requirements would prevent relevant units from delivery some reactive-power related flexibility services.
Location information included	Barriers related to this attribute are specially related to some confidentiality requirements from the data managed by the SOs (metering and grid data), that limits the granularity of location data that is allowed to be shared to other parties (other SO, independent MO), which impacts the observability of the network to best evaluate the needs and optimize flexibility use [74]. In the end, this may also limit participation of FSPs. Examples of this are the compliance with regulations that may require anonymization of data (metering, procured services, grid availability), thus creating a barrier on incorporating detailed location information to be shared with parties. Specifically for metering data, this barrier can be solved if the customer is provided with easy ways to consent access by any concerned parties (FSP, SO, MO).
Certificate of origin	Certain FSPs may encounter difficulties in providing a certificate of origin for the energy transacted. This will potentially exclude them from offering services if a certificate of origin is a mandatory requirement. This is particularly relevant for smaller FSPs connected at the distribution level, especially those without sub-metering devices installed or those with mixed energy sources, which are not able to precisely report the origin of the energy/power being used for the provision of the service. The process of obtaining a certificate of origin may also include additional administrative burden and become cost-prohibitive. As a result, the potential benefits may not outweigh the effort required, causing these FSPs to abstain from participating in markets where a certificate of origin is required.
Level of Availability	This attribute is not only linked to the technical capabilities of the assets involved but also to the actual flexibility provider. It will represent different barriers if DSO/TSO have different technological requirements, depending on the service to be provided. For instance, a balancing service at TSO level may have different (possibly stricter) requirements for availability (which is also related to the frequency of availability) than a congestion management service at DSO level. At the same time, it is important to highlight that obligations to offer under specific terms to participate in specific sub-markets can lead to distortion of prices in the short-term [75].

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Symmetric / Asymmetric	Barriers related to this attribute will arise for certain FSPs that can't offer symmetric products if these are required for a specific service, leading to market exclusion. This is the case, for instance, for some RES power plants (e.g., wind) that are not capable of increasing production with the same flexibility as reducing it. This also takes place on the demand side. For example, certain industries may not be able to increase their manufacturing production (hence increase demand) but rather only to slow down or decrease manufacturing production (hence decreasing demand). The increase in demand may also not be possible to achieve due to limitations on the contracted power and electric installation power limitations, which is especially the case for residential consumers.
Validity period	For this attribute there is a barrier related to timing for bid forwarding, given that a bid to be used in a sequential market (forwarded) needs to comply with the strictest requirement in terms of validity period.
Preparation period / **Ramping Period /** **Full activation time (FAT)**	This attribute is linked to the technical capabilities of the flexibility assets and will represent different barriers if DSO/TSO have different technological requirements. For instance, for certain DSO services (e.g., reactive power services), a direct integration within the Supervisory Control and Data Acquisition (SCADA) system is required as the speed of reaction must be fast. This applies, e.g., for some balancing products or even for reactive power-based services where (due to the nature of the issues addressed) the problem requires a quick reaction, thus requiring specific and more stringent technical and communication capabilities (similar to the case for the Active / reactive power).
Delivery period / **Deactivation period /** **Recovery period**	The challenges introduced by this attribute are linked to the technical capabilities of the flexibility assets, thus, it may lead to market exclusion for certain FSPs that may not be able to meet the defined requirement. This is the case for example for: 1) certain energy storage systems, either small-scale battery storage systems (not able to sustain the response over a long period), or other battery technologies such as lead-acid batteries (longer recharge period), or even other storage technologies such as thermal and flywheels, depending on the design and control systems in place [76]; 2) demand response, in cases where a longer delivery period may affect the comfort and needs of the consumer (e.g., HVAC systems, EVs) or even for some industrial DR programs with more complex industrial processes [77], [71].

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	In addition, additional restriction on reaction times (similar to the case for the Preparation Period, Ramping Period and FAT attributes) which would also cause technical limitations. For this attribute there is also a barrier related to timing for bid forwarding, given that a bid to be used in a sequential market (forwarded) needs to comply with the delivery period requirements of both markets.
Maximum number of activations	This attribute is also linked with the technical capabilities of the FSP asset, as certain technologies may not be able to respond to stringent requirements for the maximum number of activations. This is the case, e.g., for battery storage systems, that see higher degradation with higher charge-discharge cycles, also, certain demand response programs may have operational restrictions (e.g., due to manufacturing processes) to respond multiple times. That is also the case for residential demand response as stringent number of activation requirements can cause higher levels of interference in the day-to-day operations and comfort levels of consumers [78]. Other technologies may also have operational imitations on the maximum number of activations that they are able to carry out during a time period due to one/off, ramp-up/down, and other operational constraints (which are either technical or financial through delivery contracts).
Mode of Activation	Automatic activation may be difficult to achieve for certain FSPs, limiting their participation - some technologies don't support automatic activation especially under strict reaction times (e.g., DR depending on technologies used, industry type, etc.). For example, as previously noted, from certain DSO services (e.g., reactive power services), a direct integration to the SCADA system is required. This will, e.g., apply for reactive power-based services that require quick and automated reactions (e.g., for voltage control). In this respect, any participating unit must have remote System Protection Unit (SPU) control on service activation. Unavailability of these technical requirements would prevent relevant units from offering their flexibility services.
Quantity	The barriers resulting from this attribute are especially related to the minimum quantity requirements for the provision of specific services. This is the case for smaller FSPs with more limited capacity that are connected at the distribution level, and that may not meet the minimum quantity requirement for services that normally require larger bid offers (e.g, balancing services), leading to possible market exclusion, and affecting the value stacking potential that these may provide to the FSP.

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Divisibility	There can be barriers related to this attribute due to aggregation or technology limitations. This is true when the division is limited to the capacity of different assets when aggregated, and on whether the technologies have full control over their consumption/production. This also applies when considering the aggregation of several non-divisible bids (this setting can take place when the TSO acquires bids from the distribution level that are non-divisible). In that case, the divisibility level corresponds to the sizes of each individual bid. However, it's important to note that it is rare to require non-divisibility (i.e., to have non-divisibility as a requirement), unless for capacity products [79]. At the same time, more markets (also for the provision of services, e.g., MARI) allow the option of submitting divisible or non-divisible bids [80]. As such, the level of applicability of this barrier is decreasing in practice.
Granularity	Barriers related to this attribute also arise due to aggregation or technology limitations (similarly to divisibility), especially when the granularity is limited to the capacity of the flexibility assets when aggregated. Apart from this, barriers related to this attribute will also arise depending on the technology of the FSP asset, which is the case of certain DR programs that may struggle to adjust their consumption in very fine increments due to the nature of their processes or limitations of their equipment [77], [71]. It is also the case for DERs such as rooftop solar or small-scale storage that may lack the required technical sophistication of their controls and inverters to meet the granularity requirements [81], [82].
Maximum and minimum prices / **Availability price /** **Activation price**	This attribute may turn to be a barrier if the prices are too low, limiting the business case for FSPs, when compared to the associated costs incurred in terms of investment and operational costs, and costs for market participation [83]. In addition, bid price limits could artificially constrain prices preventing markets from revealing the actual value of energy in a specific timeframe, which can discourage market participation (reflecting a barrier).
Aggregation	Aggregation enables increasing the participation from smaller resources in the provision of flexibility services for both TSOs and DSOs [84]. Hence, the lack of the possibility of aggregation for a certain service, will potentially prohibit the participation of smaller resources in delivering that service. It's important to highlight that the framework guidelines for the new network code on demand response has promoted smaller units' participation in wholesale, balancing or

	local markets through aggregation [85]. Along these lines, opening the possibility for smaller units to fulfil the System Operation Guideline (SO GL) requirements through aggregation (rather than on the level of each unit) would reduce the possible barriers.
Baseline methodology	The barriers created by different baseline techniques has been analyzed in [70], [86]. The baseline methodology requirements can be challenging for different providers, due to the requirements on metering and communication capabilities, especially for FSPs with several types of aggregated small-scale resources. This has impact on the accuracy of the baseline calculation and may have repercussions on the remuneration of the FSP, thus affecting their interest and participation [87]. Indeed, for higher accuracy, sub-metering devices may be needed which have associated costs that can discourage participation in service delivery. Finally, when the FSP is responsible for computing the baseline, specific technical capacities and expertise are required from the FSP side for that continuous computation, which may not be the case for certain FSPs that need to opt for other methodology [77]. A more extensive assessment on baseline methodologies and possible barriers can be found in [70], [86].
Measurement requirements	Measurement requirements will also constitute a challenge for certain FSPs, namely when several behind-the-meter devices are connected and where more complexity/dynamics are foreseen (rooftop PV, EV, heat pumps, storage system …) [74]. Sub-metering is helpful in addressing these issues, but their implementation will depend on aspects such as the cost the FSP is willing to bear, technical capabilities of the FSP, privacy-related issues, regulatory framework, and interoperability requirements [88]. Interoperability relates to the information and communication technology (ICT) requirements that are imposed for the provision of certain services [89].
Penalty for Non-delivery	This attribute can become a barrier specially for small-scale FSPs, which are less equipped to accurately forecast their variable consumption/generation levels, as well as baselines.

A summary of the salient factors driving the creation of entry barriers is presented next.

4.3.3 Summary of Main Findings from the Attribute-level Analysis

As such, the potential entry barriers that may arise can stem from different factors such as, location information needs, symmetry/asymmetry aspects, technical capabilities considerations, time-related requirements, price related specifications, as well as quantity requirements and aggregation measures.

Location information included

The primary barrier related to the attribute "location information included" stems from the confidentiality requirements of the data handled by SOs, namely, metering and grid data, which contains sensitive information, thus limiting the granularity of location data that is allowed to be shared with other parties (such as other SOs or IMOs).

The lack of detailed location information may limit network observability, thus, possibly reducing the ability to invest in and offer flexibility effectively. Examples of confidentiality requirements include regulations that mandate the anonymization of certain data types, such as metering data, procured services data, and grid availability information. A potential solution would be to provide customers with user-friendly mechanisms to consent to data sharing among concerned parties (FSP, SO, MO). This would require well-designed systems that respect individual privacy rights while also enabling the efficient use of flexibility resources.

Symmetry/Asymmetry

The "Symmetry/Asymmetry" attribute can also represent barriers for market participation of FSPs. For instance, when services require symmetric products, FSPs that cannot offer such products would be excluded. An example of this occurs in the case of certain variable RES power plants, which may not be able to flexibly ramp up production given their dependency on their variable energy resource, which limits controllability. This situation is mirrored on the demand side as well, with certain industries being unable to increase or decrease production with the same flexibility, due the limitations from the industrial process in place. Residential consumers may also face restrictions on demand increases due to contracted power limitations.

Technical capabilities

Several attributes are related to the technical capabilities of the FSPs, more specifically the active/reactive power, level of availability, FAT, preparation period, ramping period, delivery period, deactivation period, mode of activation and recovery period. In this sense, barriers may arise if DSOs and TSOs have differing requirements, which will depend on the specific service to be provided. For instance, automatically activated balancing services at TSO level may have stricter requirements regarding activation times than a congestion management service at the DSO level.

Combining services into a single product, therefore, must imply abiding by the most stringent requirements, which could create entry barriers in markets that allow the direct sharing[26] of flexibility between different SOs. For example, in multilevel sequential markets, the barriers may be more prominent if the DSO-level services have less strict requirements than those of the TSO. The need to meet the strictest conditions extend across preparation period, ramping period, delivery period, mode of activation, deactivation period, and recovery

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[26] Direct sharing of flexibility is the access of an SO to flexibility bids submitted from FSPs connected to a grid outside the operational area of this SO, as defined in Chapter 2.

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period. In this respect, these barriers could prevent relevant units from providing their flexibility services if they fail to meet the necessary technical requirements.

Time-related attributes

Several attributes are time-related, more specifically the validity period, the delivery period, the deactivation period, and ant the recovery period.

These attributes can introduce barriers associated with the timing of bid forwarding, specifically in sequential markets. To participate in sequential markets or in different timeframes from a same market (e.g., short-term and near real-time), a bid must meet the strictest requirement in terms of its validity period, thus, the timing coordination between those markets and timeframes may prohibit bid forwarding. Furthermore, different services may require different validity periods.

Price related attributes

Price-related attributes, such as the Maximum and Minimum Price, Availability Price, Activation Price, and Penalty for Non-Delivery may form barriers for market participants as they can jeopardize the profitability of FSPs and their business cases by failing to offset their incurred (investment and operational) costs and can in general hinder efficient price formation.

Penalties for Non-Delivery can also pose a significant challenge, especially for smaller FSPs, due to the limitation on their technical capabilities to accurately forecast future load and generation and their possible limited controllability over their assets (in terms of time response and volumetric adjustments). This, combined with potentially insufficient monetary benefits from market participation, may deter their involvement. However, mechanisms like flexibility value stacking can help FSPs enhance the value of their flexibility through diversified service provision, potentially reducing such entry barriers.

Quantity and Aggregation

The minimum quantity attribute clearly poses strong entry barriers, especially for smaller FSPs with more limited capacity. For instance, certain services such as balancing services often require higher minimum bid sizes, so that the resources being procured have meaningful impact on the stability and reliability of the grid. This barrier is prominent when aggregation is not allowed, thus limiting participation from smaller FSPs as well as their value stacking potential.

4.4 Entry Barriers Impact on the Different Coordination Schemes

This section analyses how the entry barriers described in Section 4.3.2 relate to the different coordination schemes described in Section 2, namely: central markets, local markets, common markets, multilevel markets and fragmented markets. In general, it can be observed that the different analyzed barriers can be present in

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any of the TSO-DSO coordination schemes (central, local, fragmented, multilevel, and common), as these barriers primarily stem from the requirements imposed by the attributes reflecting the needs of the services that a product aims to deliver. However, the organization of the different coordination schemes may serve at instances to reduce possible entry barriers.

Central markets

Here, we consider the variation of the central market, which allows the TSO to access distribution-level flexibility, presented at the end of Section 2.3 as a variation of the common market but including only the TSO as the flexibility buyer. The analysis of the barriers considering the central market formulation as a disjoint transmission-level market presented in Section 2.2 is rather trivial, as distribution-level FSPs are not permitted, by design, to participate in disjoint transmission-level markets, presenting a hard barrier to entry.

Central markets, as they are focused on solving transmission-level issues, may exhibit entry barriers for FSPs connected at the distribution level, especially for smaller FSPs that are unable – due to their technical characteristics and size – to meet the product attributes required to provide a certain service to the TSO, leading to possible market exclusion for these FSPs. This can be, for example, the case for product attributes related to the technical capabilities of the FSP and the quantity (amount of energy/capacity) the FSP is able to provide.

For the service provision, FSP and grid data may need to be exchanged between the DSO and TSO, hence, attributes related to the confidentiality of the data (e.g., location information) may also be applicable. However, for the purpose of solving issues in the transmission network, aggregated data at the TSO-DSO interconnection point can be sufficient, thus minimizing or even removing the impact from this barrier. This considers that the distribution-level flexibility ca be provided in a grid-safe manner also for the distribution grid, requiring only a monitoring of the aggregated DSO-TSO interconnection flows. Ensuring this aspect without requiring sharing of network information between the DSO and TSO is analyzed in Chapter 7. An additional element to consider, in terms of entry barriers for small-scale resources in central markets is possibility for aggregation. Indeed, aggregation is a pre-requisite for the majority of the FSPs from the distribution level to provide services to the TSO, thus, if not given the option, these FSPs would be excluded from the central market.

Local markets

As for the disjoint distribution-level market (local markets), and since the product attributes can be designed taking into account possible local FSP characteristics, the barriers stated above could be minimized (albeit to the extent allowed for meeting the services' needs). On the other hand, some barrier levels can still persist, as in the case of those driven by locational information requirements.

However, even though local markets can reduce entry barriers, they also reduce the possibility of using local flexibility for meeting needs of other SOs (e.g., using forwarding of bids to other markets). This would then decrease the added value to the FSP, by removing the value stacking potential of their flexibility. This, in turn,

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may reduce their interest in participating in flexibility markets due to the reduction of possible financial return thereof.

Fragmented markets

Fragmented markets share several similarities with both local and central market (here, central in the sense of disjoint transmission-level markets introduced in Section 2.2), as Layer-1 of a fragmented market is equivalent to the disjoint distribution level market (local market) and the Layer-2 is comparable to the disjoint transmission level market (central market).

As distribution-level FSPs are not allowed to participate in Layer-2, this poses a firm entry barrier to this layer. The entry barriers reflections to local markets apply to Layer 1 of the fragmented market. One element to note is that, as fragmented markets allow the indirect sharing of flexibility between the DSO and TSO layers through induced aggregated changes to the interface DSO-TSO flows, this can provide additional valorization opportunities to the FSPs beyond meeting the local grid needs in the local market, even though direct access to their flexibility bids is not available to the TSO.

Common markets

Common markets foresee the participation of FSPs in the provisioning of services jointly to the TSOs and DSOs, having one responsible party managing the market, leading to the definition of common products to be procured within the overall market.

The creation of these common products would often require the most stringent product attributes to be met, in order to fulfill the needs of multiple services (both for TSOs and DSOs), which may be challenging if TSOs and DSOs have different product and service requirements. For instance, assuming that HV requires stricter product requirements to be met than lower voltage levels, this would cause entry barriers in the common market for certain resources, such as small-scale distributed resources and DER. These resources may struggle to comply with those stringent requirements, thus, possibly excluding their participation. This can be applicable to the majority of product attributes, not only the ones related to the technical capabilities and quantity, but also to the ones related to timing.

The barrier related to the location information product attribute can also be prominent in the common market scheme, since data from more FSPs will be exchanged between SOs, or between SOs and the MO, depending on who has the role of managing the common market. In addition, different services may require different needs on locational knowledge (e.g., balancing over a control area as compared to more locational congestion management or voltage control services). Hence, some SOs may not need storing or requiring the submission of granular grid data for their services when setting up their markets, but when engaged in a common market setting, this data would be required from all FSPs and SOs acting in this market.

It is worth noting, however, that allowing locational and network information exchange empowers the implementation of TSO-DSO schemes with higher levels of sharing of flexibility between the SOs, thus allowing higher valorization opportunities for all FSPs, and, in particular, for small-scale distribution-level FSPs (especially when aggregation is permitted). Indeed, one important upside of a common market setting is related to the overall efficiency of the market. As such, the sharing of flexibility among SOs allows further maximization of the market efficiency through the maximization of the value stacking potential of flexibility. On the other hand, when barriers exist for FSP participation in such markets, this would hinder exploiting the benefits of such markets leading to a drop in their efficiency (as showcased in Section 5.3.1).

Multilevel markets

Multilevel markets bring together local and central markets (which access of TSO to distribution-level flexibility), allowing bid forwarding between Layer 1 (the DSO level layer) and Layer-2 (the TSO level layer). This setting allows to gather benefits of both local and common markets, since smaller scale and DER resources can have higher chances of participation in Layer 1 of the multilevel market, even if they face restrictions in terms of technical characteristics and size to participate in Layer 2, thus reducing possible barriers related to the technical capabilities and quantity, which can arise under the purely common market. This is drive by the possibility of having Layer-1 be designed taking into consideration local FSP requirements and grid needs, while Layer 2 focuses on the transmission-level needs while still allowing the participation of distribution-level resources. As such, while allowing bid forwarding between one layer and the other, together with the reduced entry barriers for smaller FSPs, distribution level FSPs' market participation and value stacking potential can both be increased in comparison to the common market.

This is, for example, applicable to the minimum bid size attribute, which is particularly explored in the simulation environment described in Section 5.3.1. The original hypothesis typically aligns with the minimum bid size, implying that HV services often require larger flexibility volumes than services for lower voltage levels, which subsequently results in higher minimum quantity requirements compared to local grids.

Time-related product attributes can also pose barriers in multilevel markets related to bid forwarding, since the strictest requirement in terms of timing must be met by a bid for it to be forwarded from one layer to the other. This type of barrier existence is conditional on the assumption that services in Layer 1 of the multilevel market would require less stringent requirements in comparison to Layer 2. This is also applicable to other product attributes (e.g., attributes related to technical capabilities and quantity) if different product requirements are defined for each layer. If Layer 1 imposes more stringent requirements, the applicability of this barrier decreases or, at instances, is completely removed.

4.5 Conclusions

This chapter has provided an examination of the potential entry barriers that could result from different products attributes and their manifestation in the different TSO-DSO coordinated flexibility market models introduced in Section 2.

Our analysis has shown that different attributes (regardless of the coordination schemes) introduce different barriers, if the technical requirements imposed are challenging to meet to some types of flexibility providers. In addition, these barriers can be reflected differently depending on the coordination scheme.

In general, the different listed barriers exist in any market model (central, local, fragmented, multilevel, and common), as the barriers stem from the requirements imposed by the attributes themselves as a reflection of the services' needs (as shown in this chapter). The creation of local markets can lead to the creation of product attributes' requirements that are more cognizant of the technical capacities of local resources. However, some services needs of the SOs may still be challenging to meet even in the local market cases. Hence, those barriers may persist. Splitting the markets (e.g., moving from common markets to multilevel markets) may, on the one hand, alleviate some barriers to local resources but will, on the other hand, lead to an overall drop in market efficiency due to the lack of possibility for a co-optimized joint procurement of flexibility, in which the procured flexibility can jointly meet the needs of multiple SOs. Hence, the efficiency of a market is affected by the gain brought in through joint markets (as in the common market) or absence thereof, and the gain brought in by allowing additional market participation due to lower entry barriers, and the absence thereof. Analyzing the tradeoff between these two dimensions is one of the core aspects addressed in Section 5.

In other words, common markets can potentially include entry barriers, particularly for small-scale and DER resources due to service requirements that could be challenging to meet. These barriers can be alleviated either through aggregation, or when including a local market layer (e.g., Layer 1 of multilevel markets) in which the needs of the local grids and small-scale local FSPs can be taken into account. This improves the participation levels of small-scale resources, but this splitting of the common market can in turn lead to a reduction in efficiency (due to a foregone possibility of co-optimization and maximization of the value stacking potential of flexibility delivered to concurrently meet the needs of multiple SOs).

This chapter illustrates that while general barriers are observed across market schemes, the specific nature, prominence, and influence of these barriers can, indeed, vary depending on the product attributes and the selected coordination scheme. This detailed exploration underscores the need for careful consideration of market design and regulation, ensuring that market coordination schemes are tailored to the particular attributes and requirements of flexibility services, thus promoting accessibility and efficiency in the evolving energy landscape.

5 Efficiency Analyses of Different TSO-DSO Coordinated Flexibility Market Models

In this chapter, we study the efficiency of the four TSO-DSO coordinated flexibility market models presented in Chapter 2, namely: the common, disjoint[27], fragmented, and multilevel markets. For two use cases, we first present fundamental results on the efficiency of the procurement process of those different markets, to showcase which market models lead to lower costs for the system operators. Here, we note that by market efficiency, we refer to the incurred total cost of flexibility purchasing to meet the SOs' needs within each market model. Hence, the focus is on the economic efficiency of the flexibility procurement.[28]

We first present a set of fundamental analyses, in which we perform a total cost and inefficiency analysis of the different TSO-DSO coordinated market models while focusing on the impact of interface flow pricing, and the impact of different sequential bidding processes within sequential markets (as applicable, in particular, to the multilevel market).

We then perform sensitivity analyses to identify and analyze key further aspects that can have an impact on the markets' efficiency, and if this impact is less or more significant depending on the market design, i.e., the TSO-DSO coordinated market model. In this respect, we analyze the coordinated markets' sensitivity to entry barriers, to bid formats, and to strategic behavior, i.e., strategic bidding by FSPs.

In what follows, we first introduce the setting up of the simulation environment, then we explain the methods used to perform each of the efficiency and sensitivity analyses, and we present and analyze the obtained results.

5.1 Setting Up the Simulation Environment

In this section, we present the set-up of the simulation environment used to generate the results and showcase the efficiency analyses. We consider an interconnected system based on the IEEE 14-bus transmission system and the Matpower 69-bus and 141-bus distribution systems [90]. Two cases are created from this network, depending on the system balancing need:

- Case I: base injections and loads of the nodes are adapted to create an anticipated negative imbalance (total load surpassing total generation) in the interconnected system, which is resolved

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[27] The disjoint market considered in this chapter consider the parallel, concurrent existence of the disjoint-transmission and disjoint-distribution markets. In other words, all disjoint markets (for the transmission and all distribution systems) are run and the results presented here are the combination/summation of those individual results. As these individual markets are independent, and no coordination or resources sharing is allowed in these separate markets, the total result of the disjoint market is the summation of the individual ones.

[28] As such, other investment and operational costs related to, e.g., ICT costs, costs of setting up and operating the different platforms and modules, among others, are outside the scope of comparison.

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by upward flexibility. In addition, the lines' upper limits are adjusted to create anticipated congestion in the networks. Upward and downward flexibility bids are randomly generated and allocated to the nodes. Their quantities are aligned with the nodes' base injection/load and their prices are in the range [10, 25] €/MW (for downward) and [30, 55] €/MW (for upward). Additionally, the distribution-level bids are more expensive than the transmission-level ones. One artificial large and expensive upward bid is allocated to each distribution network, to represent the cost of an out-of-market solution, i.e., if the bids in the market are not sufficient to resolve the congestion, the DSO would resort to another technical and (assumed) more expensive solution to solve it.

- Case II: is similar to case I with respect to network parameters and bids, except that the base injections and loads in the transmission nodes are swapped, creating a positive total imbalance and, hence, a downward cumulative flexibility need in the system. The bids price rules are set the same as in case I.

5.2 Fundamental Analyses of Results

5.2.1 Initial Results

As a first analysis, we present the efficiency of the procurement process of the four fundamental TSO-DSO coordinated flexibility market models introduced in Chapter 2: the common, disjoint, fragmented, and multilevel markets. We run a market clearing algorithm for each of these markets, which were developed and implemented following the mathematical descriptions in Chapter 2. The algorithms were run using the data of case I and case II, and total cost results are shown in Table 5-1. The "inefficiency" element in Table 5-1 is defined with respect to the cost of the common market. In other words, the inefficiency is the difference between the total cost of a certain market (cost denoted by J) and the cost of the common market (denoted by J^*) normalized by the total cost of the common market (J^*), i.e.:

$$Inefficiency = \frac{J - J^*}{|J^*|} \times 100\% \,.$$

Table 5-1 – Total Cost of the TSO-DSO Coordinated Flexibility Markets

	Case I		Case II	
	Total Cost	Inefficiency	Total Cost	Inefficiency
Common	540.95	0.00	-9.22	0.00
Disjoint	553.10	2.25	-0.43	95.34
Fragmented	564.49	4.35	12.69	237.64
Multilevel	564.49	4.35	12.69	237.64

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The main result from Table 5-1 is that the common market is the most efficient one, for both treated cases. This is a generalizable result that have already been observed in [1] and proven in [2], [9]. Because the needs of the three system operators and the resources from the three systems are pooled together, the market clearing algorithm can find the least cost solution maximizing the value stacking potential of all available flexibility within the market, i.e., the one that most efficiently solves all congestions and balancing needs at the minimal procurement cost. The value stacking potential of the bids is, hence, maximized here, capitalizing on the settings in which a bid can concurrently (partially) solve multiple SOs' needs.

Another interesting result is that the fragmented and multilevel markets return more expensive procurement costs than the disjoint market, for both cases, which is initially counter-intuitive. Indeed, one would expect that any level of coordination should lead to more savings in flexibility purchasing than no coordination at all (as in the disjoint). The explanation for this result is that, in the first level of the two sequential markets (i.e., fragmented and multilevel), the distribution systems can select downward bids for a profit, as they are a revenue for the system operators (payment from FSP to SO). As such, as the interface flow can vary up to its thermal capacity (in both directions), Layer 1 (the DSOs' layer) of the multilevel and fragmented markets would tend to purchase more downward flexibility than needed to resolve grid congestions, as this purchasing leads to a reduced cost in Layer 1. However, this downward bid purchasing creates a balancing need in the second level of these markets, which needs to be resolved (e.g., by the TSO or a joint European platform) in Layer 2 (in case the imbalance is not netted by other created imbalances), increasing the total procurement costs of these markets. On the other hand, in the disjoint market, the interface flow is fixed, hence, the DSOs in Layer 1 would solve their local congestion needs in a balanced way not incurring any additional balancing need to be resolved in Layer 2. This means that in Layer 1, downward flexibility cannot be selected only to achieve profits (i.e., if they are not required to resolve congestions), as the DSO would need to purchase the same amount of upward and downward bids to keep the interface at the fixed value. As upward bids are more expensive than downward bids, purchasing more flexibility than required to solve the grid's congestions would not be economical. We propose different interface flow pricing methods aiming to price the imbalance caused by the procurement of flexibility in Layer 1 of the two sequential markets (fragmented and multilevel) and, hence, minimize the unnecessary procurement of downward flexibility in Layer 1. These methods are discussed in Section 5.2.2.

A final result from Table 5-1 is that the two sequential markets (i.e., fragmented and multilevel) returned the same total cost for both cases, which is also a counter-intuitive result. One would expect that the multilevel market is more efficient than the fragmented market because the TSO, in the second level, can use resources connected from the distribution systems in the multilevel scheme. Indeed, the observed result is due to the fact that, in this case study, the distribution network bids are considered to be more expensive than the transmission-level bids, which leads to distribution network (DN) bids not being used in the second level of the multilevel market, resulting in both markets having the same solution. In a case where distribution bids have the same price or are cheaper than transmission ones, the multilevel market can lead to more efficient solutions than the fragmented market, as shown in [1] and [2].

5.2.2 Impact of Interface Flow Pricing

As discussed in Section 5.2.1, in the fragmented and multilevel markets, DSOs in Layer 1 have the opportunity to select downward bids in the first layer for a profit, leading to an imbalance that must be resolved in Layer 2 (i.e., by the TSO or a European balancing platform) in the second level of those markets, which negatively impacts the markets' efficiency. To avoid unnecessary purchasing of downward flexibility, we re-run the two coordinated markets including an interface flow pricing in the total cost of their first level. More specifically, the interface flow changes caused by the DSOs' local flexibility procurement in the first layer are penalized using a price, and this "change times price" is included in the market clearing objective function. As a result, any extra flexibility purchased in Layer 1 (i.e., by the DSOs in this treated case), which would create extra imbalances to Layer 2 (i.e., to the TSO in this treated case), would represent a cost to be paid by the DSO to the TSO. More information about interface flow pricing is available at [2].

Two interface pricing methods are considered in this analysis:

- Midpoint ("_mid"): the price of the interface flow is defined at the midpoint between the most expensive downward flexibility bid and the least expensive upward flexibility bid of each distribution system. In that sense, the interface flow becomes more expensive than all downward flexibility bids, resulting in a situation in which there is no incentive to purchase downward flexibility in Layer 1 of the sequential market schemes unless this flexibility is needed for the grid (e.g., to solve congestion).
- Optimum ("_opt"): the price of the interface flow is optimally defined to capture the optimal marginal value for the entire system achieved by a marginal change to the interface flow. This optimal price can be obtained by a virtual run of the common market, which is able to capture the real optimal value to the system from providing flexibility through the connection points, as it solves the entire needs of the system in a joint, co-optimized way. This method is fully explained and its optimality is mathematically proven in [2].

The multilevel and fragmented markets are re-run for the two cases presented in Section 5.1 considering the different interface flow pricing methods, and the results are shown in Figure 5-1. The results of Table 5-1 are included in the plots, for comparison purposes. For easy of reading, the markets' labels are shortened in the plots (cm = common, dj = disjoint, fr = fragmented, ml = multilevel).

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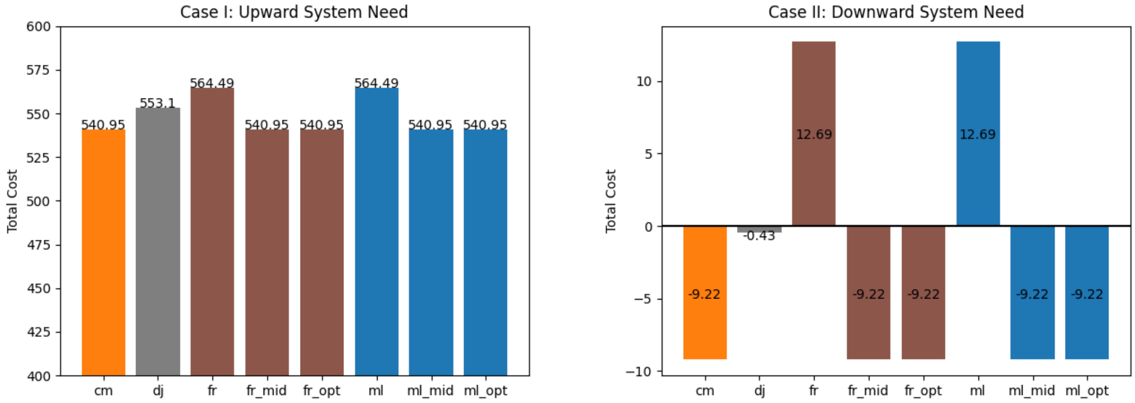

Figure 5-1 – Interface Pricing Results of the Fragmented and Multilevel Markets for the Two Cases.

As can be seen in Figure 5-1, both interface flow pricing methods are able to increase the efficiency of the two sequential markets. As expected, the optimal pricing method leads to an optimal total cost in both cases, for both fragmented and multilevel markets: “fr_opt” and “ml_opt” have the same total cost as “cm” in both plots. Indeed, as has been proven in [2], under optimal pricing, the sequential markets return the same market results as those under the most efficient scheme, i.e., the common market. However, as the optimal pricing method requires a virtual run of the common market to define the correct prices, its implementation in practice can be challenging and requires information sharing between the system operators and a third party for running the common market. In this regard, the midpoint pricing method can provide a simpler method to define the interface prices. For the two cases, the midpoint prices lead to solutions similar to the optimal ones (i.e., in the common market and the sequential markets with optimal interface flow pricing) for both markets: “fr_mid” and “ml_mid” have also the same total cost as “cm” in both plots. However, obtaining the optimal solution through midpoint pricing is specific the case study addressed here and is, hence, not generalizable. Indeed, the midpoint prices does not always lead to an optimal solution, as can be seen in [2].

5.2.3 Impact of Sequential Bidding Processes in the Multilevel Market

In this section, we analyze the impact of allowing distribution-level FSPs to diversify their bids in the multilevel market, as discussed in the multilevel market variations in Section 2.4 and following the process described in [4]. As FSPs participate in the two levels of this market, different bidding processes can be designed for those FSPs. For instance, in the original conceptualization of this market, the distribution-level participants submit one bid to the first level, with one price and one quantity, and any remaining quantity (not used to fulfill the DSOs needs) is automatically forwarded to the second level with the same original price. We further analyze two variations of the bidding process in this sequential market:

- “ml_p”: distribution-level FSPs make parallel, thus separate price-quantity bids to the two levels. This considers the case in which the FSPs can submit different bids in Layer 1 and Layer 2, but cannot

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observe the results of Layer 1 before bidding in Layer 2. Hence, this corresponds to a parallel bidding mechanism in the two layers, coined, *multilevel_parallel* and abbreviated to ml_p.

- "ml_s": The distribution level FSPs can change their bids in Layer 2 after observing the results of Layer 1. Hence, this is a form of sequential bidding coined as *multilevel_sequential* and abbreviated to ml_s. As such, in ml_s, distribution-level FSPs can change their bid prices after observing the result of the first layer, while their remaining flexibility bid quantities that were not used in Layer 1 are automatically forwarded to Layer 2, as in the original multilevel market.

To analyze the impact of the "ml_p" on the efficiency of the multilevel market, we split the distribution-level bids' offered quantities in two lists, keeping the same price in both. Then, we vary the price of the first level list by a control percentage. The goal is to represent one of the two situations where the distribution-level FSPs:

- Have lower marginal costs in Layer 1 (due to, for example, ease access to the local market of the first level), allowing them to reduce their bid prices in that level. The range of the control percentage is [-20% to -5%].
- Expect low competition in the first layer and/or that prices in the second layer will be lower, driving them to bid higher prices in Layer 1. The range of the control percentage is [+5% to +20%].

For the "ml_s", the quantities are the original offered quantities (given that remaining values are automatically forwarded), and the prices of the bids are varied in the same range as for the "ml_p" explained above. Case I and II are run for the two variations, with the different control percentages, and the total procurement cost is shown in Figure 5-2. For comparison, we include the results of the original multilevel (ml) and common (cm) markets in the plots.

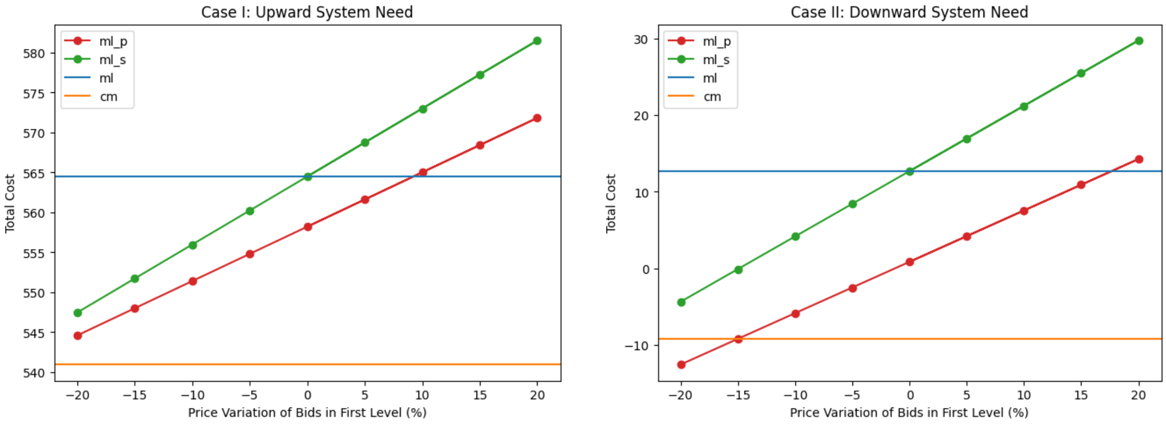

Figure 5-2 – Impact of different sequential bidding processes in the multilevel market, for the two cases. "ml_p" is the parallel bidding process, and "ml_s" is the sequential bidding process.

Since the muti-level and the "ml_s" have the same automatic forwarding process for remaining quantities, it is expected that they return the same result when the price variation of bids in the first level is 0%, which can

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be seen in both plots (green line crosses blue line at 0%). Moreover, for this multilevel variation, the total procurement cost is lower or higher than the original multilevel depending on whether the distribution-level FSPs have an incentive to reduce their bid prices in the first level. Therefore, the efficiency of the "ml_s" with regards to the original multilevel depends solely on the ability of those FSPs to reduce their prices in one (or both) levels when compared to the benchmark prices.

For the "ml_p", another aspect which also impacts the efficiency is the split of the quantity. For the two cases presented, splitting the quantities lead to increasing the efficiency of the "ml_p", if compared with the original multilevel, even when prices of the first level are higher than the original prices. This result is primarily attributed to allowing unpriced interface flow changes in Layer 1 (as analyzed in Section 5.2.2). Indeed, this is explained by the fact that splitting the bids' offered quantities between two levels reduces the amount of downward flexibility available in the first level to be purchased solely for a profit, after congestions have been alleviated (see Section 5.2.2). The "ml_p" can become even cheaper than the common market if distribution-level FSPs have incentives to reduce their prices significantly in the first level (as shown in the red line in the right-side plot of Figure 5-2).

5.3 Sensitivity Analyses to Market Specifications and Participants' Behavior

In this section, the impact of the product design and of market distortions on the TSO-DSO coordinated markets' efficiency is analyzed. One of the main objectives of the analysis in this report is to identify how consumer-centric products can be designed, and how efficient markets can be proposed for such products. One important question to be answered in order to fulfill this goal is what market distortions can impact the markets' efficiency and prevent consumers from participating in the markets under analysis. As a response, we identify three main aspects[29] that can distort the markets which we further analyze: market entry barriers, which have a direct link to product requirements; bid formats that are allowed by the markets; and the strategic behavior of the markets' participants. We note that the first distortion was conceptually analyzed in Chapter 4, with the identification of what market barriers can (negatively) impact the different markets. In this section, we further analyze the entry barriers, by means of simulation analyses, and we also analyze other possible distortions, as the bid formats and the strategic behavior of participants.

5.3.1 Sensitivity to Entry Barriers

One of the pillars of the OneNet project is the product harmonization. The idea is to have products with limited divergences enabling their use by multiple system operators when procuring system services to facilitate the participation of providers, reduce costs and complexities of the procurement process, facilitate TSO-DSO-consumers coordination, and provide value-stacking to consumers. Although this harmonization effort has been

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[29] We note, here, that this is naturally not a comprehensive list of aspects creating market distortions, but these are rather the aspects that the simulation-based analyses has focused on due to their identified practical significance.

successful within the project, as shown in [3], some barriers to certain TSO-DSO coordinated markets can still exist, because the different harmonized products have some divergent attributes/requirements. For instance, the mFRR product proposed in [3] has a minimum quantity requirement of 1 MW, which can hinder the participation of small resources connected to the distribution networks. On the other hand, the corrective local active product, also proposed in [3], has two different minimum quantity requirements, one for the resources located in the transmission systems (of 1 MW) and one for the resources located in the distribution systems (of 0.01 MW). In that case, small providers and consumers can more easily access the market where this product is traded.

As such, one can see that product requirements as the minimum quantity to participate can represent entry barriers to certain providers and consumers as has been detailed and analyzed in Chapter 4. In this regard, we next analyze how such entry barriers can impact the markets' efficiency using the methodology presented in Figure 5-3. From the initial set of bids of a certain use case, we apply filters according to the entry requirements of each of the products commercialized in each of the markets. This returns a partial set of bids, filtered based on the entry requirements, which is used to run the corresponding TSO-DSO coordinated market algorithm. As a result, we obtain the total cost of each of the markets, which allows the estimation and comparison of their efficiency.

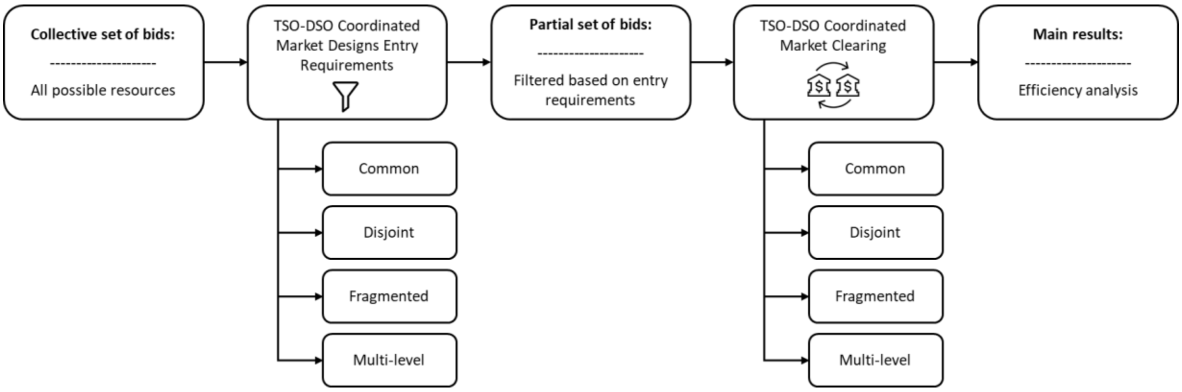

Figure 5-3 – Methodology Proposed to Analyze the Impact on TSO-DSO Coordinates Markets' Efficiency of Products Entry Requirements.

We use the minimum quantity entry requirement to perform such analysis, extending the results initially presented in [4] to all markets under analysis in this report. More specifically, for the cases I and II (described in Section 5.1), we run the methodology described above, considering that local markets, i.e., the first level of the fragmented and multilevel, and the disjoint-distribution markets, have less strict requirements, i.e., there is insignificant/no minimum quantity requirement. On the other hand, the transmission-level markets, i.e., the second level of the fragmented and multilevel, the disjoint-transmission, and the common markets, have more strict requirements, similar to the mFRR product proposed in [3]. For those transmission-level markets, bids with an offered quantity lower than this requirement cannot participate (these bids are filtered out of those markets).

We vary this required minimum quantity for transmission-level markets from 0 to 2.5 MW. The obtained results are shown in Figure 5-4 in which we use the following labels: cm = common, dj = disjoint, fr = fragmented, and ml = multilevel.

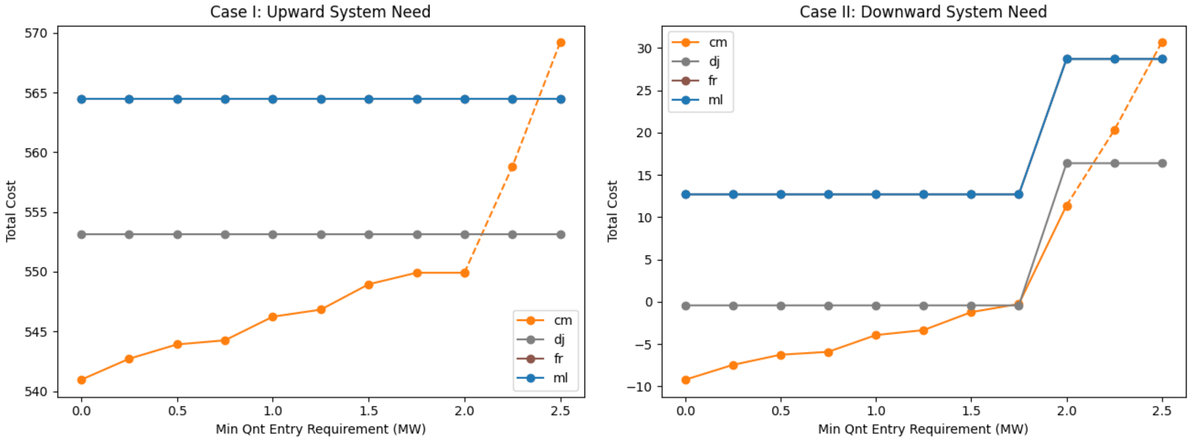

Figure 5-4 – Impact of the Minimum Quantity Entry Requirement on the Efficiency of the TSO-DSO Coordinated Markets. "ml" and "fr" Results are Equal in Both Plots (Brown Line behind Blue Line).

As shown in Figure 5-4, the bid minimum quantity requirement has a bigger impact on the common than on the other markets, as the common market excludes small distribution-level bids from participating, which are – in both treated cases, Case I and Case II – better suited to solve the local congestions while helping in balancing the system. This entry barrier reaches an extreme case starting at a threshold of 2.0 MW (orange dashed line in plots), when no bid larger than the minimum requirement is available in the distribution systems, and their congestion is then solved using the artificial big bid (out-of-market solution). At this point, the other markets can become more efficient than the common, given that their first layer/or the disjoint-distribution level (local congestion management) allows small bids to participate.

The multilevel and fragmented results are the same in both cases since, as discussed in Section 5.2.1, the first level of both markets are equal, and, in the second level, no bids from the distribution networks are selected in the multilevel market (given that they are more expensive than the transmission network bids), resulting in the same solution. In Figure 5-4, the brown line (representing the fragmented market result) is overlapping with the blue line (representing the multilevel market result).

In case I, none of the markets with a local level is impacted by the filtering of small bids. The reason behind this effect is that only transmission bids are filtered from the disjoint and fragmented markets (distribution-level bids are only allowed to participate in Layer 1 of the fragmented market and in the disjoint distribution-level markets and do not have bid quantity requirement for this participation), and those bids are mostly greater than 2.5 MW. The unique bid lower than 2.5 MW offered from the transmission-level resources is not cleared initially, which means it is not necessary for solving Layer 2 of the fragmented market and the disjoint transmission-level market, thus filtering it out does not impact those markets' efficiency. This explanation, together with our

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previous discussion on the fragmented and multilevel markets returning the same result, clarify the no-impact also on the multilevel. On the other hand, in Case II, a transmission bid of 1.75 MW is cleared when available. As soon as this bid is no longer available in the transmission-level of the disjoint, fragmented, and multilevel markets, i.e., when minimum quantity requirement is greater than 2 MW, those markets' efficiency is also impacted.

5.3.2 Sensitivity to Bid Formats

In a market, different bid formats can be allowed, to represent the FSPs' technical and economic constraints. So far, we have considered fully-divisible price-quantity pairs type of bids in the efficiency analysis of TSO-DSO coordinated markets, which are bids that can be cleared at any amount from zero to the offered quantity, at the stated unit price submitted in the bid. In this section, we include the possibility of FSPs to send partially divisible bids to the markets, to represent their own minimum bid clearing constraint, and we analyze the impact on the markets' efficiency of such bid format. Partially divisible bids have an additional attribute, which specifies the minimum level at which a bid can be cleared. Hence, on top of the price-quantity, this can represent either financial preferences of the FSP regarding the clearing of their bids or can represent the minimum amount that the resources linked to the bid can technically produce. In the market clearing algorithms, this technical constraint of such bids is represented by including a lower bound (other than 0) to their cleared quantity variable. Figure 5-5 showcases the difference between fully divisible bids (which can be cleared at any level from 0 to their maximum offered quantity) and partially divisible bids which cannot be cleared below their minimum quantity and can be cleared at any level between their minimum requirement and maximum offered quantity.

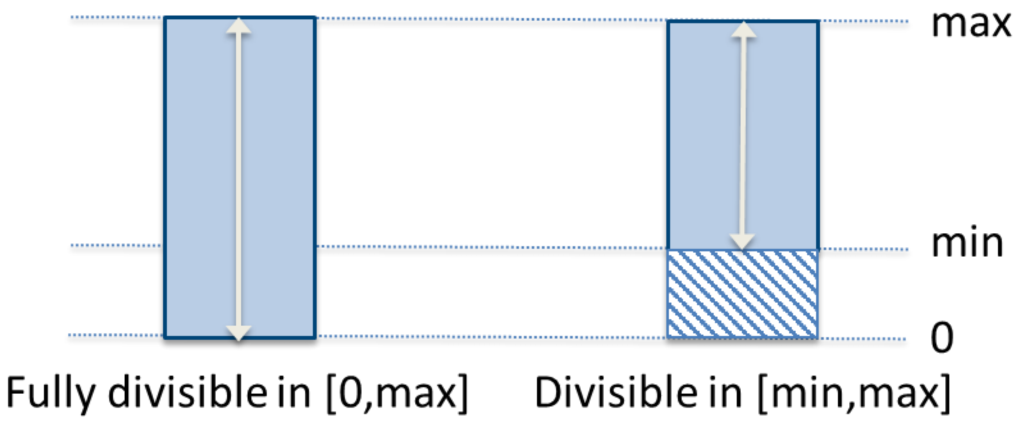

Figure 5-5 Fully Divisible and Partially Divisible Bids

To be able to perform the analysis, we follow the methodology detailed in [4], which is extended to all markets under analysis in this report. We apply a percentage of the bids' offered quantity (ranging from 0 to 50%) to represent their minimum clearing constraint. In this analysis, only bids with offered quantity greater than 1.5 MW can be partially divisible. These modified sets of bids are then submitted to the four markets, and the results are shown in Figure 5-6, in which the following labeling is used: cm = common, dj = disjoint, fr = fragmented, and ml = multilevel.

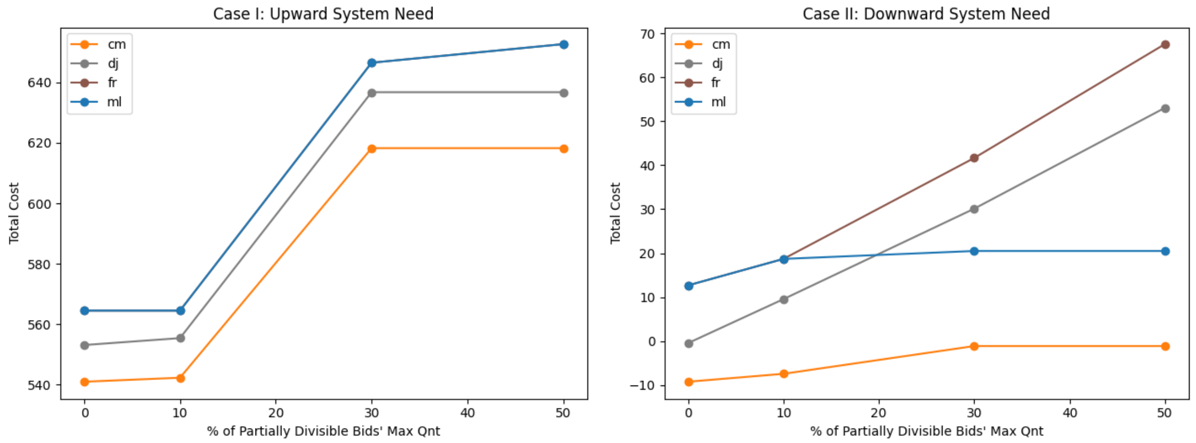

Figure 5-6 – Impact of the Partial Divisibility of Bids on the Efficiency of the TSO-DSO Coordinated Markets. "ml" and "fr" Results are Equal in the Left Plot – the Case I (Brown Overlapping with Blue Line).

Table 5-2 – Slopes of the Plots of Figure 5-6

Slopes	Case I			Case II		
	0 – 10%	10 – 30%	30 – 50%	0 – 10%	10 – 30%	30 – 50%
Common	13.2	379.9	0.0	18.0	31.5	0.0
Disjoint	22.9	406.9	0.0	99.9	102.8	114.6
Fragmented	0.0	410.3	30.7	60.1	114.7	129.5
Multilevel	0.0	410.2	30.8	60.1	9.0	0.0

The slopes of the lines in Figure 5-6 are presented in Table 5-2. As can be seen in Figure 5-6, partial bid divisibility impacts all markets, as a bid that was used for congestion management or balancing can become too expensive due to its minimum clearing constraint. For example, in the common market of case I, two bids in the transmission system are selected when they have 0 minimum clearing constraint, as they are positioned in the network in a way to solve both congestion and balancing needs in the most efficient way. When the minimum clearing constraint of those bids is increased to 10% of their offered quantity, the solution still selects both, but with a higher volume (to respect their clearing constraint), thus increasing the market cost. When this constraint is increased to 30%, another more expensive bid (but with a lower clearing constraint) is chosen instead, which explains the significant increase in cost from 10% to 30% for case I. For the disjoint, multilevel and fragmented markets, the impact is mostly higher (see slopes of blue, brown and grey curves in Table 5-2), as the congestion need of the distribution system is solved separately (in the first level), and a cheap partially divisible bid, which would have been able to solve congestion and balancing together, has now a minimum clearing constraint that is preventing it from being selected in the separate levels of those markets. In other words, the effect of partitioning the flexibility needs of the two systems due to the split in two levels can be exacerbated by the introduction of partially divisible bids.

So far, we have identified that the common market is more robust than the other markets when partial divisible bids are present. The pooling of resources allows cheap bids with high minimum clearing constraint to be used for solving the joint needs of the system operators, while in the separate markets (disjoint, fragmented, multilevel), the distribution-level needs and the transmission needs are split, making those bids too expensive to purchase. In case II, an additional robustness is verified for the multilevel market as compared to the disjoint and fragmented markets. In the second level of the multilevel market, bids from the distribution system are also available for solving the transmission needs, and they are potential substitutes to the cheap with high minimum clearing constraint bids of the transmission system. This is not the case for the disjoint and fragmented markets, which have to clear bids at higher quantities to solve the transmission congestion and balancing needs while respecting the bids' minimum clearing constraint.

5.3.3 Sensitivity to Strategic Behavior

In this section, the impact of the FSPs' strategic behavior on the efficiency of the TSO-DSO coordinated markets is analyzed. A methodology based on game theory and bounded rationality is used to model the FSPs bidding behavior when engaging in those markets, following and extending the analyses proposed in [1] and [5]. To perform such analysis, the market clearing problem must be examined from the point of view of the FSPs instead of from the point of view of the system or market operators. So far, we have analyzed the markets' efficiency considering that the system operators are procuring flexibility to solve their congestion and balancing needs at a minimum cost. We have included different aspects in this procurement process, i.e., interface flow pricing in Layer 1 (i.e., in the DSOs' objective function), different bidding processes in the multilevel market, entry barriers to the markets, different bid formats, and have run the markets to identify how their efficiency is impacted. For the strategic behavior analysis, this methodology first considers how FSPs can strategically compute their best, most optimal bids in those markets, and then we run the markets considering those optimal bids and compare the resulting market efficiencies. This enables highlighting and comparing the effects of the FSPs strategic bidding on the efficiency of each TSO-DSO coordinated market model.

The FSPs, when entering the TSO-DSO coordinated markets and offering their flexibility as bids, are expected to aim at maximizing their profits, which constitutes a rational economic behavior. Moreover, their revenue, as well as their best bids, will depend on what other FSPs are bidding, the market structure, and the network configuration. For instance, if an FSP offers a very expensive upward flexibility bid, the market clearing will select another bid if available, or if an FSP offering downward flexibility is located in a grid without a downward balancing or congestion need, this bid would not be cleared. As their revenue depends on those aspects, the FSPs behavior can be modelled as a game (using the principles of game theory), which is explained in Figure 5-7.

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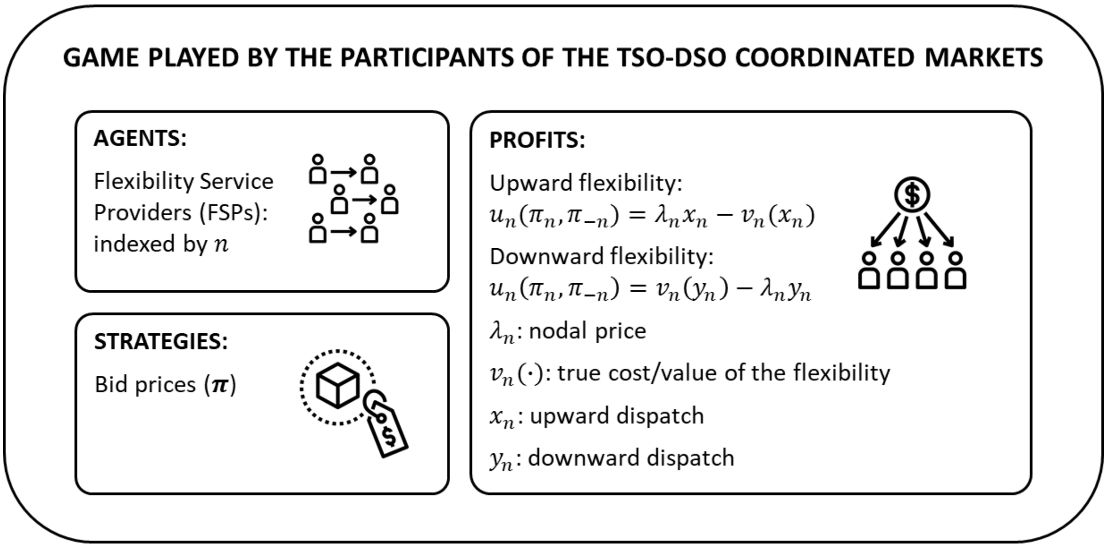

Figure 5-7 – Building Blocks of the Game Played by FSPs when Offering Bids to the TSO-DSO Coordinated Markets.

As shown in Figure 5-7, the FSPs are the agents of this game, and their strategies are the bid prices, following the proposition in [1]. The agents' profit when joining the TSO-DSO coordinated markets depends on the market solution when a bid vector $\boldsymbol{\pi} = (\pi_n, \pi_{-n})$ is sent to the market, and this solution is described by the resulting nodal prices (λ_n) and the cleared quantities (x_n for upward bids, y_n for downward bids). The index $-n$ is used to represent all bids but the one of agent n. The FSPs' profit depends on their flexibility direction: if upward, they are paid by the SO the nodal price times the cleared quantity, and their cost of providing flexibility is a function of the cleared quantity $v_n(x_n)$; if downward, they receive a value from the flexibility provision, which is also a function of the cleared quantity $v_n(y_n)$, and they pay to the SO the nodal price times the cleared quantity.

For an FSP to determine its best bid price (strategy), it needs to consider the impact of a bid vector on the cleared nodal prices and quantities, to identify and compare the resulting profits from different bidding strategies that it can implement. We use best response (BR) models in which FSPs heuristically determine the best bid as a response to a vector of the opponents' bids. More specifically, given a vector of opponents' bids, an FSP would run the TSO-DSO coordinated markets multiple times, while varying its bid price and estimating the profit it receives from each bid price, and pick the price leading to the higher profit. Mathematically, this is represented by the following optimization model:

$$BR_n^\sigma(\pi_{-n}^\sigma) = \pi_n^{\sigma^*} = \operatorname*{argmax}_{\pi_n^\sigma} u_n^\sigma(\pi_n^\sigma, \pi_{-n}^\sigma),$$

Subject to:

$$\pi_n^\sigma = [\pi_{n,1}^\sigma, \pi_{n,2}^\sigma, \cdots, \pi_{n,\Pi}^\sigma],$$

$$\lambda_n^\sigma, y_n^\sigma \text{ or } x_n^\sigma = f^\sigma(\pi_n^\sigma, \pi_{-n}^\sigma).$$

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In the model, the index σ is added to represent each of the four TSO-DSO coordinated markets $\sigma = \{\mathrm{cm}, \mathrm{dj}, \mathrm{fg}, \mathrm{ml}\}$, π_n^σ is the vector of possible bids of FSP n, $u_n^\sigma(\pi_n^\sigma, \pi_{-n}^\sigma)$ is the profit function of FSP n when submitting one of the π_n^σ bids to market σ, and $f^\sigma(\pi_n^\sigma, \pi_{-n}^\sigma)$ is the result of the market σ when a vector of bids $(\pi_n^\sigma, \pi_{-n}^\sigma)$ is sent. The result of this optimization model is the best response of FSP n (denoted by $\pi_n^{\sigma^*}$).

If each FSP can determine the best responses (strategies) of their opponents and apply the optimization model to estimate their own best response to the opponents' best responses, a Nash Equilibrium (NE) is reached, from which no FSP has an incentive to unilaterally deviate. However, computing such NE strategies can be computationally challenging for the FSPs, especially given the requirement of estimating the opponents' best responses. In this respect, we consider that FSPs can have limited computational capabilities to estimate each other's best responses, and thus the equilibrium vector of strategies. In that setting, the strategic bidding behavior of the FSPs and its impact on the markets' efficiency is assessed using the k-level approach [91], which is a form of bounded rationality in game-theoretic terminology. The approach is inspired by k-level reasoning, in which players are rational and best respond to opponents who they believe are (k-1) rational. Following this logic, an FSP's strategic bid is derived based on its observation of the bids submitted by the opponents in the previous market round. Under this approach, at each level k the FSPs choose the bid that optimizes their profit (solve the above optimization model), considering what the other FSPs bid at the previous level (i.e., at level k − 1). As such, this provides gradual levels of rationality in the derivation of the optimal bidding strategy, through the increase in k. After K levels of thinking, the set of strategic bids for the FSPs are obtained, for which we can

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run the market models to determine the impact of the strategic bidding behavior on the markets' efficiency. This full process is illustrated in the flowchart of Figure 5-8.

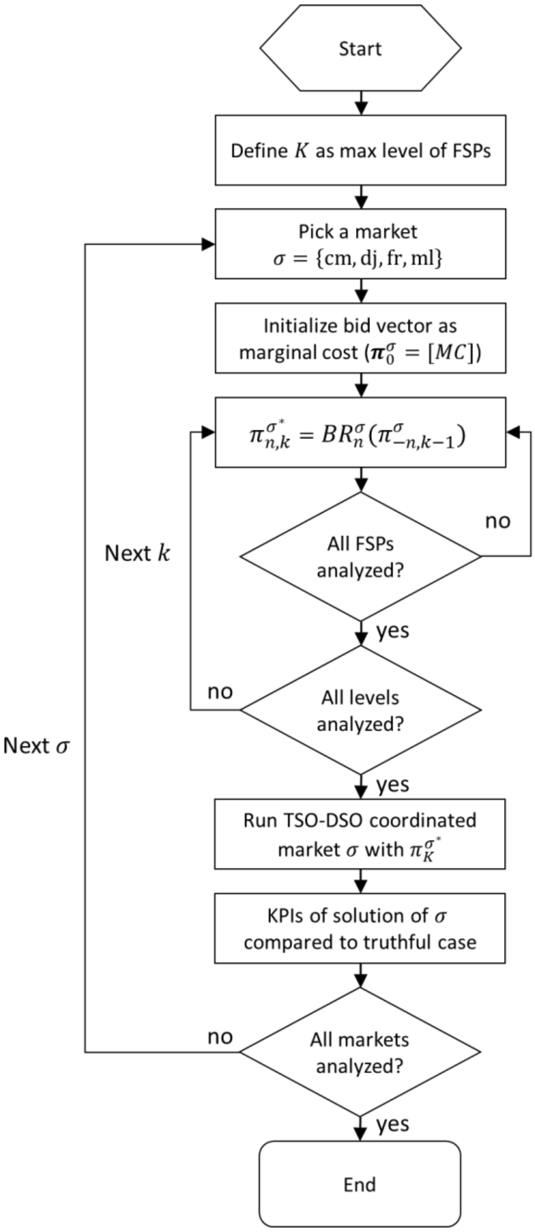

Figure 5-8 – k-level Approach to Estimate the Impact of FSPs Bidding Behavior on the Efficiency of the TSO-DSO Coordinated Markets.

The proposed k-level approach is applied to Case I, which was introduced in Section 5.1, and to three variations of this case:

- Case I.1: 40% of the bids located in the transmission system are considered to be unavailable for purchase, representing a case with low liquidity in the transmission system.

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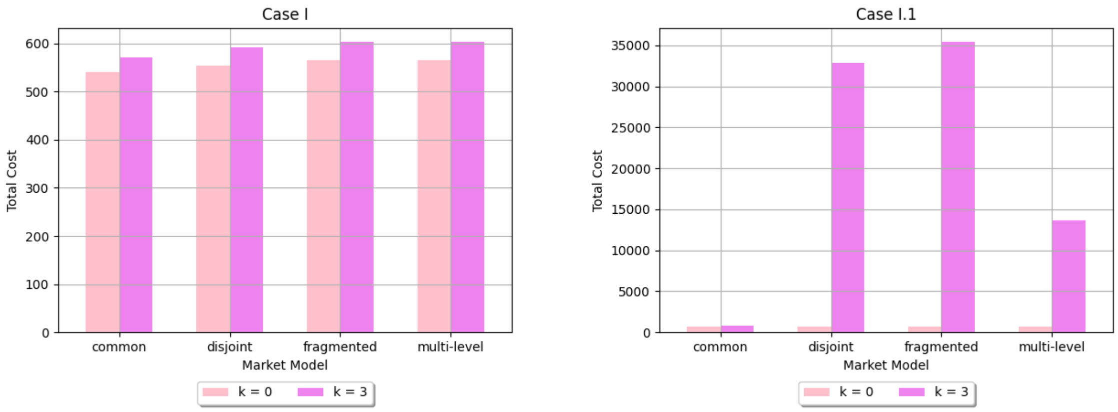
- Case I.2: 98% of the bids in the distribution systems are considered unavailable for purchase, representing a case with limited liquidity in the distribution systems.
- Case I.3: only the necessary bids to solve congestion in the distribution systems are available for purchase, representing a case with extreme low liquidity in the distribution systems, leading to a “market power” situation.

We consider three levels of thinking, following experiments in [92] which had shown most agents typically employ a level $k = 3$ reasoning (however, the approach can be extended to any number of levels). Moreover, we consider that the possible bid prices vector π_n^σ of each FSP n, which are the possible best responses used in the optimization model abovementioned, are defined according to its opponents’ best bid prices with the same sense (upward or downward) in $k - 1$ as follows:

- For an upward FSP n, the vector of possible bid prices includes all upward opponents’ prices that are higher than its marginal cost, together with those values minus a small decrement, epsilon of 0.10, a price cap for upward offers of 3,000 (which is an artificial limit for bid prices) and this cap minus epsilon;
- For a downward FSP n, the vector of possible bid prices also includes all downward opponents’ prices that are lower than its marginal value, together with those values plus an epsilon of 0.10, a price cap for downward offers of 0, and this cap plus epsilon.

We note that the addition of values plus or minus epsilon to the vector of possible best responses is done as a tie-break rule, i.e., when two FSPs are bidding the same value, only one of them might be selected, which can encourage them to bid a slightly lower (for upward) or higher (for downward) price than the opponents. Considering these simulation settings, the results of the four cases are shown in Figure 5-9 and Table 5-3. In all plots, the truthful scenario ($k = 0$) represents the situation that FSPs bid their marginal cost/value, i.e., the original bid prices of Case I in Section 5.1. In Table 5-3, the values are calculated by dividing the total cost of the $k = 3$ by the total cost of the truthful scenario ($k = 0$).



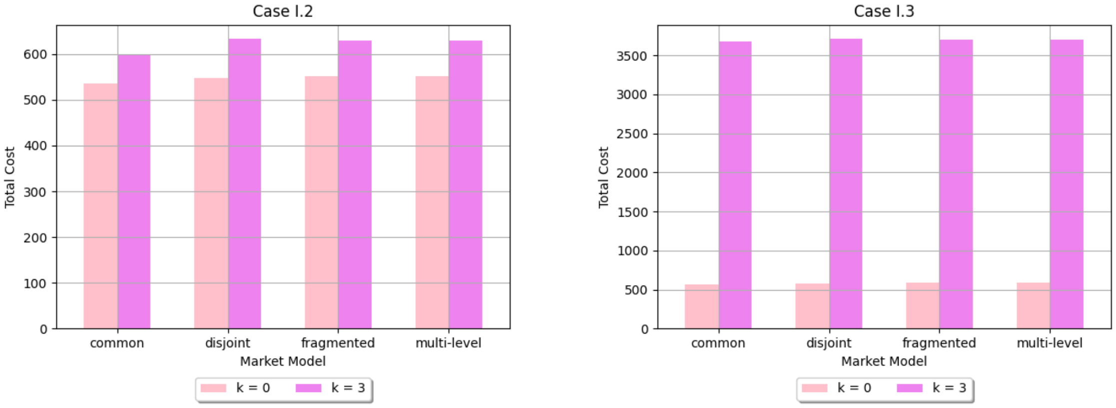


Figure 5-9 – Impact of Strategic Bidding Behavior of FSPs on the Efficiency of the TSO-DSO Coordinated Markets.

Table 5-3 – Efficiency of the TSO-DSO Coordinated Market Models when FSPs Behave Strategically: the Factor by which the Total Cost of k=3 is Higher than the Truthful Case (k=0)

	Case I	Case I.1	Case I.2	Case I.3
Common	1.05	1.17	1.12	6.47
Disjoint	1.07	48.05	1.16	6.40
Fragmented	1.07	50.45	1.14	6.35
Multilevel	1.07	19.39	1.14	6.35

In Case I, all 536 bids from the different systems are kept, which represents a situation with high liquidity. As can be seen in the top left plot of Figure 5-9, the strategic behavior of the FSPs leads to an increased cost in all market models, as some in-the-money FSPs can bid higher than their marginal cost (or lower than their marginal value). However, this increase is limited by the high liquidity available in the markets: the last in-the-money FSPs are prevented to bid higher (for upward) or lower (for downward) than the next opponent's bid price, as they would otherwise no longer be cleared. As shown in Table 5-3, the total cost of the SOs when FSPs behave strategically ($k = 3$) is 1.05 times higher than the truthful case ($k = 0$) in the common market, and 1.07 times higher in the disjoint, fragmented, and multilevel markets.

In Case I.1, several bids from the transmission system were unavailable, leading to a high impact on the markets' efficiency, as can be seen in the top right plot of Figure 5-9. As shown in Table 5-3, the total cost to the SOs when FSPs behave strategically ($k = 3$) is 1.17 times higher than the truthful case ($k = 0$) in the common market, 48.05 times higher in the disjoint market, 50.45 times higher in the fragmented market, and 19.39 times higher in the multilevel market. The impact is more pronounced in the disjoint and fragmented markets due to the additional market fragmentation, which creates opportunities to some FSPs to exert market power (e.g., bid at price cap) in the second (transmission) layer. Although the multilevel market is also a two-layer market, the effect is reduced if compared to the disjoint and fragmented markets, given that its second level pools bids from the different grids, which increases its liquidity. Nonetheless, the impact is higher than if all needs were solved jointly, as in the common market.

In Case I.2, the unavailability of 98% of the distribution level bids leads to a limited level of liquidity in the distribution systems, increasing the effect of strategic behavior on the markets' efficiency, when compared to Case I. This can be seen in the bottom left plot of Figure 5-9. As shown in Table 5-3, the total cost to the system operators when FSPs behave strategically ($k = 3$) is 1.12 times higher than the truthful case ($k = 0$) in the common market, 1.16 times higher in the disjoint, and 1.14 times higher in the fragmented and multilevel. However, this increase is not as high as compared to the increase in cost at low liquidity in the transmission system (Case I.1). In the transmission with low liquidity case (Case I.1), the lack of competing bids to solve both the congestion and balancing needs leads to an opportunity for FSPs located in the transmission network to exert market power and bid the price cap, while in the distribution with low liquidity case (Case I.2) there are still enough competing FSPs available, located in the distribution networks, to avoid market power exertion. This is not a general conclusion, as there can be situations in which distribution FSPs can exert market power and impact all market models, which we show next.

Lastly, in Case I.3, depicted in the bottom right plot of Figure 5-9, the market liquidity at distribution level is critically low, leading to an increased impact on all market models. As shown in Table 5-3, the total cost to the SOs when FSPs behave strategically ($k = 3$) is 6.47 times higher than the truthful case ($k = 0$) in the common market, 6.40 times higher in the disjoint market, and 6.35 times higher in the fragmented and multilevel markets. In this case, the impact is more pronounced in the common market due to the fact that: 1) it is the most efficient market when FSPs bid truthfully (leading to a lower denominator in the calculation of the inefficiency), and 2) the FSPs which are necessary for the congestion management of the distribution systems strategically bid at the price cap (exerting market power) in all market models, which means that the final cost is comparable in all the markets. The common market is still slightly more efficient under $k = 3$ than the rest of the market models, but the difference is less pronounced as compared to the case under truthful bidding.

As a general conclusion, we can see that all markets can be negatively affected by the FSPs' strategic behavior, but the common market is more robust to such behavior, due to its resources pooling nature that increases the market liquidity. Moreover, the impact of strategic behavior can be significant in situations with restrained liquidity, especially in the transmission system. Finally, congestions can lead to a "market power" situation, which can significantly reduce the markets' efficiency.

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5.4 Conclusion

In this chapter, we have analyzed the economic efficiency of the TSO-DSO coordinated flexibility market models. We have initially performed a fundamental analysis by showcasing that the common market model theoretically leads to the lower costs to the system operators, using two use cases and results reported in previous projects and the scientific literature. We have also illustrated the sub-efficiency which can be achieved by the other three market models (disjoint, fragmented, and multilevel). However, we have identified several practical key factors which can directly impact, at different levels, the efficiency of each market model, which can impact the theoretically derived efficiencies, driving their convergence or divergence. Indeed, as part of this fundamental analysis, we have simulated the impact of the interface flow pricing on the markets' efficiency and of different sequential bidding processes on the multilevel market's efficiency. For the first, we have discussed how adding an interface flow price in sequential markets (i.e., fragmented and multilevel) can avoid situations in which excessive downward flexibility is purchased in the first level, which would have, otherwise, led to a significant drop in the efficiency of these market schemes. Two pricing mechanisms were studied: midpoint and optimal. In the simulation results, we have shown that, although the optimal pricing method will always be able to lead to the most efficient solution in sequential markets, the midpoint method can also reach (near-) optimal solutions (the closeness of the result to the optimal result is case-dependent). Regarding the FSPs' bidding processes, we have shown that different bidding processes can be implemented in the multilevel market, given that FSPs located in distribution networks participate in the two levels of this market. Two types of sequential bidding were studied (in addition to the original bidding process of forwarding remaining bids with same price): one in which FSPs make parallel bids to both layers (thus being able to split their quantities between those markets and to select different prices for both), and one in which those FSPs can bid a different price in the second level (after observing the result of the first). By simulating the two processes in the two use cases, we were able to show their impact on the overall efficiency. In addition, we have observed that the parallel bidding process can help reduce the purchase of unneeded downward flexibility in level 1 (when no interface flow pricing is employed) due to the reduced downward capacity available in the first level.

We have then performed sensitivity analyses of the market models to market specifications and participants' behavior. Three key further aspects that can have an impact on the markets' efficiency were studied: entry barriers, bid formats, and FSPs' strategic behavior. For the first key aspect, following the analysis of Chapter 4, we have studied the impact of the minimum quantity attribute of a product on the markets' efficiency. We have considered the case in which markets with a transmission system need (i.e., the disjoint-transmission market, the second level of the fragmented and multilevel markets, and the common market) have more stringent requirements than the markets with only distribution system needs (i.e., the disjoint-distribution and the first level of the fragmented and multilevel markets). We have simulated different minimum quantities for a bid to participate in transmission-level markets and concluded that this entry barrier can have a negative impact on

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the efficiencies, to the extreme of having the common market potentially be less efficient (more costly) than the others (given that the others still have a distribution level market without a minimum quantity barrier). For the analysis on bid formats, we have included partially divisible bids in the markets, each with a minimum clearing constraint: those bids can only be cleared at their minimum clearing value (or more). Simulation results of the inclusion of such bids have shown that the common market can be more robust to (less impacted by) the inclusion of partially divisible bids, given that it has a bigger pool of bids available to replace bids that become too expensive due to their minimum clearing constraint. For the third and last key aspect, focusing on FSPs' strategic behavior, we have analyzed the impact of strategic behavior on the markets' efficiency. We have proposed a game-theoretic methodology and simulated the bidding behaviors of the FSPs in the markets using this methodology. We have shown that, when FSPs are aware of the markets' set-up and of their opponents, they can "game" the markets and bid higher than their marginal cost (in the case of upward provision) or lower than their marginal value (in the case of downward provision). This effect is more pronounced in markets with fragmentation (e.g., disjoint and fragmented markets), because of the reduced liquidity leading to a higher opportunity for FSPs to exert market power (and still be cleared).

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6 Linking Flexibility Markets Through Bid Forwarding: Regulatory Analysis

Deep integration of flexible resources in an electric system requires proper incentivization of the services provided by these resources. Considering small-sized resources, the revenues that FSPs can earn just by participating in the energy markets will be very low, as illustrated in studies such as [93] [94] [95]. However, most FSPs owning generation, consumption and/or storage units can provide energy as well as ancillary services. Hence, the profitability of the FSPs will be based on diversifying the revenue streams by participating in different eligible markets, or in other words, by revenue-stacking [95].

In the European markets, procurement of energy and different ancillary services take place separately. In certain cases, the same or similar products are procured in different markets due to a difference in market area, market operator, timeline of procurement etc. If these markets trading similar products are not coordinated with each other, the revenue-stacking potential of the FSPs will be affected by their level of expertise, market transaction fees, etc. An obvious solution is to connect these markets by creating market coordination channels. Sequential procurement of products, as done in the European markets, can also be conducted in a coordinated manner. When the same product is procured in two different timeframes, certain cases can be identified where the second market uses unselected bids from the first market instead of having a separate bidding session. For instance, in a previous model of the ancillary service market used by the California independent system operator (CAISO), the unused bids from the day-ahead ancillary service markets were carried over for real-time ancillary service markets [96]. Similarly, in the current Spanish electricity markets, the unused bids submitted to the day-ahead (DA) congestion management market are considered for real-time congestion management [97]. In both cases, the second stage (real-time ancillary in case of CAISO and real-time congestion management market in case of Spain) mainly use the same bids from the first stage markets (day-ahead ancillary services and day-ahead congestion management respectively), with limited or no bidding in the second stage.

Considering the same mechanism and applying it to two isolated markets (separate market phases and distinct prices), a channel for coordination can be created. In electricity systems where markets are organized at different voltage levels, such a process can help accumulate residual bids from the lower-level markets to meet demands from higher-level markets. Optionally, a bid processing stage might be needed if the second market has different entry requirements or bidding formats. In that case, a predefined market participant should convert the bid into an acceptable format and forward it to the second market. Thus, we define bid forwarding as the process of forwarding unused eligible bids from one market to another through an optional processing stage by a predefined market agent. A simplified representation of bid forwarding is shown in Figure 6-1.

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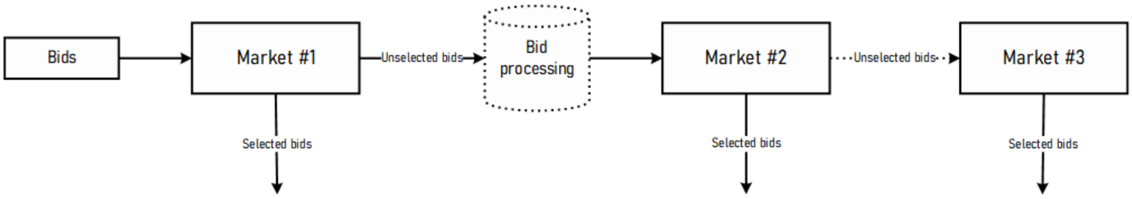

Figure 6-1 – General Scheme of a Bid Forwarding Process

The bid forwarding process can act as a coordination channel between local flexibility markets and wholesale electricity markets. The recently published European Framework Guideline on Demand Response (FGDR) establishes some preliminary regulations on the bid forwarding process between local and wholesale markets [85]. Norflex, a pilot flexibility project in Norway, has recently successfully implemented the forwarding of unused bids from the local flexibility platform to the balancing markets [98]. Another European project, CoordiNet, also developed solutions for forwarding bids from local markets to wholesale electricity markets to increase the value-stacking potential of the flexibility service providers (FSPs) [99].

The main focus of this chapter is to define the conditions for bid forwarding process and discuss the main regulatory barriers that hinder this process. In Section 6.1, the bid forwarding process is discussed conceptually, focusing on the main enabling factors. In Section 6.2, the methodology for the analysis is presented, along with an application of this methodology in Section 6.3. Further, in Section 6.4, the main regulatory barriers to the bid forwarding process are described, focusing on the European electricity markets. As an illustrative example, Section 6.5 discusses the main regulatory barriers for forwarding bids from local distribution-level markets to MARI platform. Finally, Section 6.6 provides the main conclusions from this chapter.

6.1 Bid Forwarding Process

Electricity markets trade different products with different technical characteristics to deliver different system services. Among the available portfolio of products and services in an electricity market, certain pairs can be identified where product attribute requirements are similar or one has a stricter product attribute requirement than the other. For instance, if a market player is eligible to participate in the day-ahead energy market, they are more likely to be eligible for intraday (ID) energy markets as well, as the product requirements are similar (for instance, the product requirements for the Spanish ID and DA markets can be found in [100]). Further, considering the case of Spanish balancing markets, if a market player is eligible for providing automatic frequency response (aFRR) with a full activation time (FAT) of 5 minutes, they might also be eligible for offering manual frequency response reserve (mFRR) with a FAT of 12.5 minutes (if other attributes meet the requirements) [101]. In the latter case, aFRR markets can be said to have stricter entry requirements than RR markets.

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In FGDR, such relationships between markets are expressed through product compatibility, i.e., if a product meets all entry requirements to a specific market, it is said to be compatible. If an unused product in one market is compatible with use in another market, the corresponding bid can be forwarded from the first market to the second with the consent of the market player [85]. For the market players, the automatic forwarding of bids reduces the transaction fees and increases their value-stacking potential, whereas, for market operators, the increased participation potentially reduces the cost of procurement and gaming possibilities. Bid forwarding is also interesting from a market design perspective as the link between different markets, especially between different voltage levels, increases the synergies between them and opens new ways for coordination. The main enabling factors for the bid forwarding process are discussed next.

6.1.1 Responsible Agent for Bid Forwarding

To implement a bid forwarding process between two compatible markets, a key element to be defined is the responsible agent for bid forwarding. In FGDR, the responsibility of operating local markets falls under the SO of the grid for which the service is procured, different SOs, or a third-party [85]. When a third-party market operator (MO) operates the markets, whether they can forward bids into wholesale markets should be stated in national terms and conditions. When the SO or MO forwards the bids from the market under their responsibility to another market, their role changes. For example, in the NorFlex project, the third-party local market operator, NorFlex, aggregates the remaining bids after the local market gate closure time (GCT) and forwards the aggregated bids to the balancing market. In the balancing market, NorFlex becomes the balance service provider (BSP) and undertakes associated responsibilities such as bidding and settlement [98].

6.1.2 Bid Processing for Increasing Compatibility

A necessary condition that enables bid forwarding is the product compatibility. Only products that are compatible for use in the second market can be forwarded from the first market. However, certain level of product incompatibilities can be addressed through additional bid processing stages. For instance, an important barrier to the participation of distributed resources in wholesale electricity markets is the minimum bid size condition [102] [103]. If a set of unused bids meets all other technical requirements for participation in the second market, then an aggregation stage can help to meet the size requirement. Similarly, if a set of bids fall short only in certain entry requirements, the predefined responsible agent (SO of the grid, a different SO/SOs, or a third-party MO) can regroup or recombine the bids before forwarding it to another market as mentioned in FGDR [85][30]. However, there are also cases of bid forwarding where a filter for certain attributes (e.g.,

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[30] This may require the need for updating the roles of such responsible agents as they engage not only in system/market operation, but also in the forwarding of bids as well as in bid aggregation and regrouping.

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divisibility or symmetry) might be needed, to filter out incompatible bids, instead of recombining bids. Hence, we call the intermediary step for bid forwarding a bid processing stage.

A requirement in the FGDR is to allow the SO to establish pricing mechanisms and bid processing conditions consistent with European and national regulations [85].[31] A clear description of the pricing and bid selection mechanisms is important to preserve the system's transparency while maintaining the MOs' position as market facilitators.

Although the roles in a local market operation are clearly defined in FGDR, limitations to the bid processing mechanism might naturally emerge from the limitations set for the role of a system and/or market operator. System operators and market operators should be neutral market facilitators, and they must not interfere with market activities [18]. Hence, once the bid is submitted, there are very limited possibilities for any changes before forwarding it to the next market. This is similar to the TSO's balancing market bid forwarding procedure, where changes are permitted only under exceptional conditions after gate closure time for BSPs [104]. Nevertheless, compared to balancing markets closer to the real-time operation, if a local market might be taking place in DA or ID timeframe, the changes would be useful for reducing the prediction errors (the difference between the predicted output and real output). This is especially relevant for FSPs dependent on intermittent resources, whose accuracy of predictions show significant improvements closer to the real-time.

6.2 Methodology for Bid Forwarding Process Analysis

The methodology used to analyze the bid forwarding potential of markets couples is formed by three steps [105], as shown in Figure 6-2. By following this methodology, we can effectively assess the bid forwarding potential and address any barriers that may hinder its implementation in the studied markets. The three steps of the methodology are discussed in detail in this section.

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[31] According to the FGDR regulation , the establish pricing mechanisms and bid processing conditions responsibility is solely under the role of an SO. Once these conditions are established, the MOs or third-party operators can follow these rules for procurement or for bid processing.

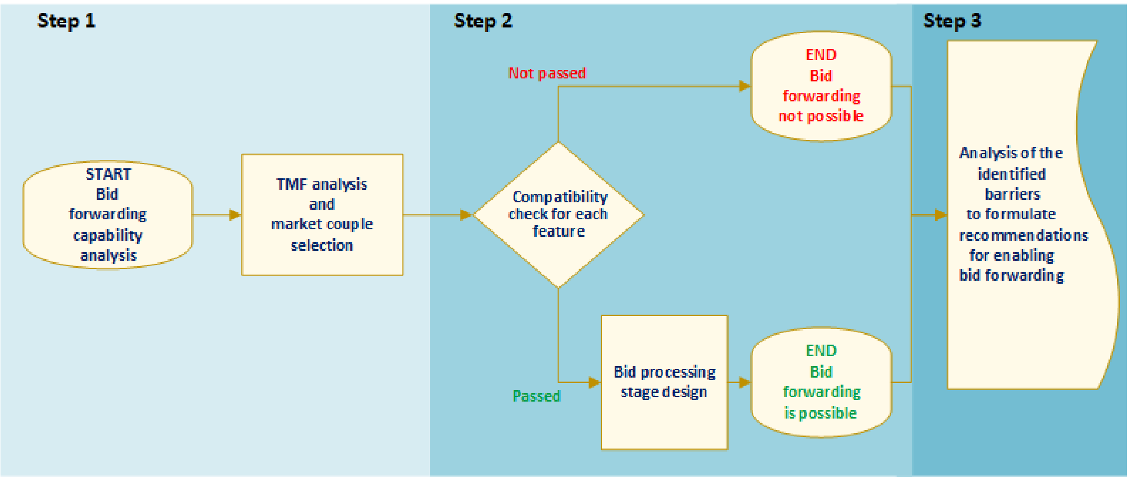

Figure 6-2 – Flow Diagram of the Adopted Methodology for Bid Forwarding Potential Analysis (source: [44])

Step 1: Identification of markets of interest within the national electricity market architecture.

To begin, a comprehensive description of the market architecture in terms of design features is required. We utilize the Theoretical Market Framework (TMF) [106] [107], a systematic market design and analysis tool developed in the OneNet project, to capture the necessary information for analyzing bid forwarding potential and barriers. The TMF enables a comprehensive description of the market architecture using a set of market design pillars and features. In this step, the TMF is applied to identify and describe the markets of interest for the bid forwarding assessment. More details about the TMF can be found in [106].

Step 2: Analysis of market design features and identification of bid forwarding barriers.

In this step, we analyze the market design features relevant to bid forwarding between the identified market pairs from Step 1. The goal of Step 2 analysis is twofold:

1. Checking bid forwarding feasibility: We examine whether the market design features comply with the compatibility conditions necessary for bid forwarding.
2. Identifying bid forwarding barriers: If any barriers exist within the market architecture, we identify and document them as part of the analysis.

The analysis focuses on the bid processing process and identifies several salient features, as defined in Table 6-1. The market design features that facilitate bid forwarding in Table 6-1 can be categorized into two types based on the enabling conditions:

- Necessary Features (**N**): These features require strict compliance from both markets involved in bid forwarding. When any of such feature's condition is not met, bid forwarding becomes unfeasible, as no bid modification step can overcome the non-compatibility issue

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- Conditional Features (**C**): These features do not demand strict compliance from both markets. Instead, they allow for a bid processing stage, acting as a "market connector." This stage filters and/or converts leftover bids from the first market to align them with the requirements of the second market. Hence, for conditional features a bid processing stage for enabling bid forwarding can be designed considering the case specific conditions that characterize the problem of forwarding the bids between the two selected market. It is not always assured that the specific case conditions will permit a successful design of the bid processing stage.

Figure 6-3 presents the summary of conditions that exist between two markets for bid forwarding, these market design features are classified into four categories, roles and actors, market units, product attributes, and bid characteristics. Furthermore, considering bid forwarding enabling conditions, two types of market design features can be defined. The arrows in Figure 6-3 also display the rationale that the bid processing stage design has to follow to enable bid forwarding between the two selected markets.

It is important to note that while this selection is not exhaustive, the identified feature set is considered sufficient and suitable for the analysis discussed in this section. The design features may also be modified to better align with the unique characteristics of the markets under consideration.

Table 6-1 Design Features for Bid Forwarding and Condition Types: Necessary ('N') and Conditional ('C') (Source: [105]).

Design feature	**Definition of the design feature**	**Type**	**Required bid processing stage**
Technical requirements	Set of technical conditions for the product must meet to participate in the market.	N	Filter out bids that do not meet the technical requirements and forward bids meeting the requirements.
Gate closure time (GCT)	Instant when submitting or updating bids is no longer permitted [106] [107].	N	No bid forwarding possible.
Market time unit (MTU)	Period for which a market price is established [100]. Minimum duration of a sell or a buy bid.	C	Splitting divisible products or merging (subsequent) divisible or indivisible products to meet the new MTU conditions.
Local granularity (LG)	Level of detail to represent the grid location of a buying unit or a selling unit [100]	C	Allow voluntary additional locational information and filter only bids that contain it.
Type of product	Type of product traded in a market (e.g., capacity or energy, or energy with capacity reservation obligation) [3]	C	Predefine conditions for capacity-energy bid conversion. Forwarding bids to a market with capacity reservation obligation is not possible.
Allowed technology	Type of generation, consumption, or storage units eligible to participate in a market.	C	Filter out bids composed (even if partially) from technologies not allowed to participate and keep bids from allowed technologies.
Aggregation condition	Conditions to combine multiple resources in a buy or sell offer [3]	C	Regroup or recombine the assets according to the new aggregation conditions.
Minimum bid size	Minimum volume (capacity or energy) that can be offered/asked by a bid in a market [108].	C	Aggregate the bids to meet the minimum bid size and bid granularity requirements.
Bid structure	Level of complexity allowed in a bid (e.g. simple or complex bid, types of complex bid, symmetry conditions, divisibility conditions) [109]	C	Filter the bids that meet the bid requirements.

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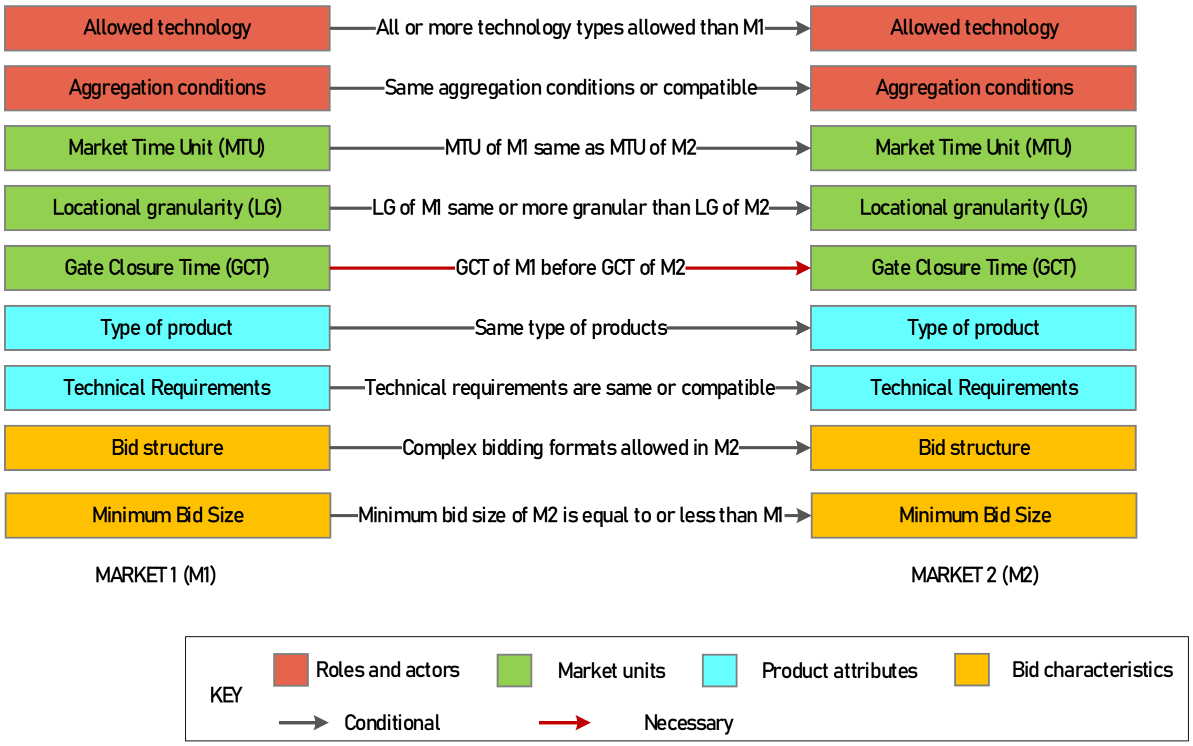

Figure 6-3 Summary of Conditions that Exist Between Two Markets for Bid Forwarding

Step 3: Formalization of recommendations to overcome identified barriers.

Step 3 of the methodology focuses on analyzing the identified barriers. Based on the analysis conducted in Step 2, recommendations are formulated to address and overcome the identified bid forwarding barriers and develop design solutions and the necessary market connectors. These recommendations aim to enhance bid forwarding potential, promote best practices, and remove any obstacles encountered in the market architecture.

6.3 Example of Applications of the Methodology for Bid Forwarding Process Analysis

In this section, the case of the Spanish OneNet demonstrator (OneNet DSO Congestion Management Markets and Intraday Markets) is provided as an example of applications of the methodology for bid forwarding process analysis. A detailed discussion on these two examples is available in [7].

6.3.1 Description of the Spanish System

The OneNet Spanish demonstrator market deals with leveraging the flexibility of resources connected to the distribution grid to address distribution-level congestion [110]. The market of interest consists of two local submarkets: the long-term congestion management capacity (or availability) market and the short-term congestion management (CM) energy (or activation) market. Though long-term procured capacity mandates energy bid submissions in the short-term market, participants have the option to also provide free bids. Our study specifically concentrates on the short-term CM energy markets.

This example focuses on the Spanish intraday (ID) energy market, which is comprised of six distinct intraday auction sessions and a concurrently running continuous intraday trading market (single intraday coupling) [111]. Geographically, the two ID energy markets vary. The ID auction market facilitates cross-border trade exclusively between Spain, Morocco, Portugal, and Andorra. In contrast, the continuous trading sessions connect to the broader continental European markets [112]. Given that both ID markets trade in compatible products, we explore the feasibility of forwarding unused bids from the local CM to the intraday auction (ID-a) and then onto the continuous intraday trading (ID-c) markets.

In this case, the Spanish Nominated Electricity Market Operator (NEMO), OMIE, oversees both the intraday and local markets. The MO is aware of the structure of the markets to which the bids are forwarded and their requirements. Also, it can be assumed that data sharing and communications will be easier compared to a case where two MOs are involved. A detailed comparison of the design features of the OneNet local short-term market, Spanish ID-a, and Spanish ID-c market can be found in Table 6-2 [110], [111], [112], [107] (adopted from [105]). Utilizing the methodology outlined in this, we pinpoint the bid forwarding potential of these markets and determine the necessary bid processing steps.

Table 6-2 Market Design Features of Spanish OneNet Local CM and Intraday Markets. Source: [105].

Market design feature	**Spanish OneNet local CM market**	**Spanish intraday auction market**	**Spanish intraday continuous trading market**
Allowed technology	No restriction by technology type	No restriction by technology type	No restriction by technology type
Aggregation conditions	Upward and downward flexibility cannot be aggregated together	Generation and consumption cannot be aggregated in a single bid	Generation and consumption cannot be aggregated in a single bid
Market time unit (MTU)	1 hour (15 min in near future)	1 hour (15 min in near future)	1 hour (15 min in near future)
Locational granularity	Nodal	Zonal	Zonal
Gate Closure Time	Day-ahead (D-1) 14:45	D-1: 15:00, 17:50, 21:50 Intraday: 01:50, 04:50, 09:50	Trading allowed up to 2 hours before delivery period
Type of product	Energy	Energy	Energy
Technical requirements	FAT < 1 hour	No specific technical requirements	No specific technical requirements
Bid structure	Simple bids	Complex conditions allowed including maximum income condition and load gradient	Certain types of complexity can be expressed through execution conditions
Minimum bid size	0.01 MW	0.1 MW	0.1 MW

6.3.2 Bid Forwarding Potential in the Spanish Markets

Table 6-2 illustrates that the local short-term market's gate closure time is earlier than both the ID-a and ID-c markets. No technical constraints restrict distributed resources from participating in the ID markets [111]. Additionally, the locational granularity of the local markets surpasses that of the ID markets, while the MTUs remain consistent [107].

The potential barriers to bid forwarding from the local short-term market to the Spanish ID-a are the aggregation conditions and the minimum bid size. In intraday markets, aggregation is based on whether the technology type is for generation or consumption. Moreover, the local market's minimum bid size is 0.01 MW, compared to the intraday markets' 0.1 MW. Both issues can be tackled through aggregation—distinguishing production units from consumption units to align with the ID markets' aggregation criteria. As such, this situation involves conditional bid forwarding.

Bids left unused from the ID-a can be further redirected to the ID-c markets, either as a continuation from local markets or as an independent action. For bids originating from the ID-a market, the intricacies within the bid structure, such as indivisibility, minimum income, scheduled stops, and load gradients, need to be scrutinized and made compatible for use in ID-c markets. The complexities permissible in ID-c include conditions like fill-or-kill, session-based validity, and basket order conditions such as linked orders [111]. If the bids initially come from

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local markets, this isn't a concern, as all such bids will be straightforward. Figure 6-4 illustrates a suggested procedure for bid forwarding between the local and ID markets in Spain [105].

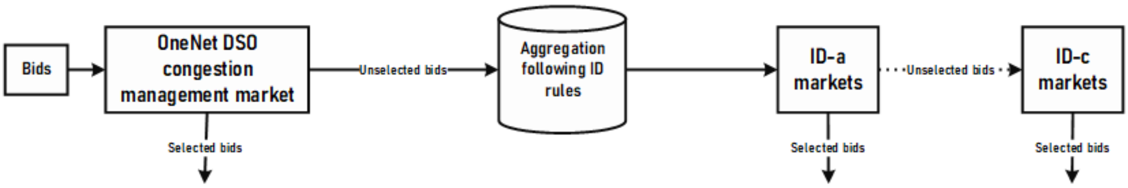

Figure 6-4. An Option for Implementing Bid Forwarding between OneNet Local Flexibility Market and Intraday Markets in Spain [105].

6.4 Regulatory Barriers to the Bid Forwarding Process

Despite the recognition of the bid forwarding process in the European regulations, there can be many factors that prevent the implementation of this process. As mentioned in Section 4, in certain cases, the bid forwarding process may be hindered due to product attributes or market time constraints. For example, consider an FSP who is prequalified in both aFRR and mFRR market. However, if their mFRR energy bid is unselected, it cannot be forwarded to the aFRR energy market, as their gate closure times are extremely close (harmonized gate closure time for both MARI and PICASSO are ~ 25 minutes before delivery) [113]. Moving aFRR procurement closer to real-time operation is not a feasible option due to the time constraints imposed by the product activation and the platform computational requirements. While these conditions are a justifiable reason for searching for other coordination mechanisms, in many other markets, the barriers to bid forwarding exist only due to unsupportive institutional and regulatory frameworks. In the following section, we discuss some of the main regulatory barriers to the bid forwarding process and, as an extension, to similar market coordination schemes.

6.4.1 Participation Conditions (Market Entry Conditions)

A competitive market should allow the free entry and exit of participants. In electricity markets, such entry-exit conditions will be restricted if the markets are not designed to be technology-agnostic. As bid forwarding is the transfer of bids from one market to another, entry barriers in the second market can affect the potential bid forwarding process. By comparing the ENTSO-e survey on ancillary service procurement over the years, we can observe a trend where the types of technologies permitted to participate in European balancing markets have been expanding since the survey's edition [114] [115] [116]. This suggests a potential shift towards the development of more technology-agnostic markets, accommodating a broader range of technologies. However, compared to the conventional generation units, new technologies like battery storage and demand response may require additional provisions for market participation, such as modifications in bidding formats and the development of baselining methods [117]. Hence, newer technologies may face delays in accessing the market unless the regulations are proactively modified for their participation.

A related concern is the lack of maturity of technologies like storage and demand response in market participation. Considering battery energy storage, the prerequisites for participation in the markets, such as minimum service duration in the balancing markets could be too long, or the minimum bid size allowed could be too large [118]. Accordingly, special channels and procedures may need to be designed to integrate them into the market, which should be removed once they gain sufficient maturity.

Apart from the technology-specific entry barriers, other conditions, such as lack of free bids, specifically in balancing markets, can also prevent the entry of eligible market participants. Free bids are energy bids that are submitted to a market without an associated capacity reservation condition [119]. For example, if a market player can bid into the balancing energy market only if their balancing capacity bid is previously accepted, then free bidding would not be allowed in the balancing energy market. If such conditions exist in the forwarded market, only bids with a capacity reservation obligation will be able to access that market[32]. Hence, a clear way to make bid forwarding feasible between local and balancing markets is to allow free bids in the latter. Although European regulation mandates the participation of free bids in the balancing markets, some countries are still in the process of making that change [116].

6.4.2 Aggregation Conditions

In bid forwarding processes, aggregation plays a major role as the local markets generally have minimum bid size requirements (in the OneNet project, it ranges from 0.001 - 0.01 MW) much lesser than the wholesale markets (e.g., 0.1 MW) [120] [3]. Therefore, in markets where aggregation of resources is not allowed, bid forwarding can only be done bid-by-bid, filtering small-sized bids that are eligible but do not meet the size requirements. However, due to the strong emphasis on market access facilitation for independent aggregators placed by the European regulations (such as Internal Energy Directive and Energy Efficiency Directive), the entry of aggregators now faces significantly fewer barriers than earlier [121] [18]. Nevertheless, even if their participation is encouraged, if prevailing market rules are not friendly toward unlocking their full potential, complete integration will not be possible. A good example is the aggregation rules of the Spanish markets, where generation and consumption cannot be aggregated together in one bid [101]. Such conditions may cause unnecessary barrier among owners of non-conventional technologies like storage and demand response facilities, which can be grouped in both categories.

Similar concerns arise from balancing markets with a central-dispatching model, where the scheduling and dispatching take place at the unit level, essentially limiting the scope of aggregation [122]. Italy, a country with a central-dispatching balancing market model, addressed this barrier by allowing the participation of aggregators through a pilot project called *Unità Virtuali Abilitate Miste*/Mixed Virtually Aggregated Units

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[32] In this case, the market players are obliged to submit energy bids in any case (with or without bid forwarding)

(UVAM) [123] [124]. The prequalification of units participating in this pilot takes place at the group level instead of the unit level. However, as these pilot projects are conducted as a phase separate from the balancing markets, bid forwarding may not be possible from local markets to balancing markets. Hence, the aggregation rules of the forwarded market can play a major role in determining the volume of bids that can be forwarded.

Apart from the general restrictions to the aggregation processes, bid forwarding can also be hindered by the differences between aggregation conditions between the markets. For instance, if the aggregation is set at zonal level in the first market and nodal level in the second, the already aggregated bids have to be disaggregated and regrouped into nodal level bids. Similarly, stricter aggregation conditions in the second market (compared to the first one) increases the complexity of the bid processing stage required, which, in turn, will act as a barrier to the implementation of bid forwarding process.

Aggregation in a bid forwarding process is also subject to the terms and conditions set specifically for the bid forwarding processes between local flexibility markets and wholesale markets [85]. These conditions, set at the national level (following the FGDR conditions), determine whether unused bids from local flexibility markets can be forwarded to the wholesale markets, who can forward them, and how they can be combined (or recombined). Unclear conditions regarding the roles and responsibilities of the aggregating party and aggregated parties can severely hinder the implementation of bid forwarding processes.

6.4.3 Prequalification Conditions

Prequalification is the testing and validation of a unit's ability to provide a specific service to the grid. It consists of grid prequalification, service provider (SP) prequalification, and product prequalification, as shown in Figure 6-5 [85]. Grid prequalification aims at verifying whether the delivery of the product or service can be technically supported by the grid. SP prequalification verifies the capability of an SP to deliver a service, have adequate communication tools, have the SP data registered correctly, among others. Product prequalification aims at verifying the compliance of the assets of the SP with the required technical requirements for that service (specified in the product’s technical requirements). The new FDGR rules also differentiate between ex-ante product prequalification and ex-ante grid prequalification, and ex-post verification, consisting of ex-post product verification and ex-ante grid prequalification [125].

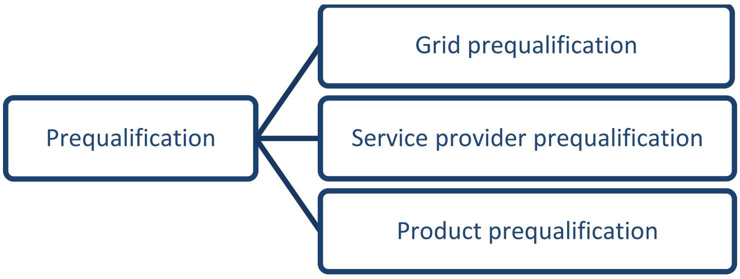

Figure 6-5 Concepts Associated with Prequalification in FDGR [1]

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When bids are forwarded from local markets to another market (like balancing), where only prequalified units are allowed to bid, the prequalification conditions become a determining factor. A report from ACER on prequalification processes for the provision of balancing services shows that many European countries still conduct prequalification at reserve providing unit (RPU) or reserve-providing group (RPG) level instead of the portfolio level [124]. Additionally, central-dispatching balancing markets like Poland, Italy and Greece do not allow prequalification at the group level. Such restrictions towards prequalification can affect the volume of bids that can be forwarded from one market to another, especially when an aggregation stage is involved. Simplified prequalification processes can lower the high barriers to market entry for small market players as well as for market coordination processes like bid forwarding. However, simplified prequalification processes may not always be feasible as more complex prequalification can be required to guarantee the ability of providers to provide the service, and hence, meet the reliability requirements of the grid. An example of a simplified prequalification is the ex-ante administrative validation used in French mFRR and FRR markets and Norwegian mFRR markets [62].

Furthermore, the group of bids forwarded from one market to another is subject to changes, depending on which bids are accepted and which are not accepted in the first market. Hence, even if prequalification is allowed at the group level, but if when changes occur to the group a new prequalification process is required, this can hinder the forwarding of bids between markets. The ACER report shows that many European countries require detailed re-prequalification if there are changes to the already prequalified groups [62]. However, some initial implementations in different European countries have aimed at simplifying or reducing the need for this re-prequalification step. For example, Austria is attempting to implement a registration process whereby small units of already prequalified types or technologies can be added to the prequalified group just by registering them [62]. Sweden and the Netherlands use type-approval for small units, a form of simplified prequalification for units with similar technical requirements to those already included in the group [62].

Simplified prequalification and requalification conditions, along with the reduction in process redundancy, can enhance the bid forwarding potential of the markets. Close examination of the existing regulations to ease these processes and sharing best practices among system operators is a necessary condition to achieve it.

6.4.4 Market Timing

Bid forwarding, by definition, takes place after the market clearing of the first market. As discussed in the introduction to this chapter, in certain cases, market timing can be constrained by product attributes. For example, consider the mFRR direct activation products. Although mFRR products can be used for real-time congestion management, due to the direct activation condition, the market players will not be able to know beforehand whether their product will get activated. Thus, direct mFRR bids cannot be forwarded to other markets. However, when market timing is not motivated by such reasons and, rather, is a regulatory decision, it can be treated as a regulatory barrier.

Consider the case of a local flexibility market for capacity (M1) and a balancing capacity market (M2), given in Figure 6-6. If M1 takes place weeks ahead of delivery, but M2 takes place months ahead of delivery, bid forwarding is not possible in the direction of M1 to M2. Bids rejected from M2 can be forwarded to M1, but due to the local nature of M1, the number of bids that can be forwarded in that direction may only be small. Hence, the development of local markets should consider the timing of the existing wholesale markets, particularly compatible markets for trading products, when aiming at maximizing the value stacking potential of the locally available flexibility.

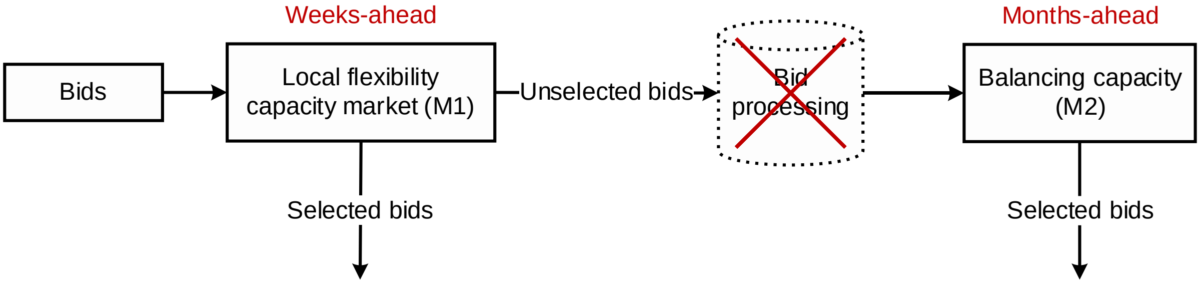

Figure 6-6 Case for Demonstrating the Barrier Posed by Market Timing. Here, as the Gate Closure Time for M1 is Weeks-ahead Compared to the Gate Closure Time of M2 (Months-ahead), Bid Forwarding is not Possible in the Direction of M1 to M2.

6.5 Conclusions

Bid forwarding is a promising way to connect different markets trading similar products in a multi-market setup. Realizing its potential to integrate distributed resources into the wholesale market, the framework guidelines on demand response has set out few preliminary suggestions to facilitate this process. However, these regulations are still under development and many aspects that enable the bid forwarding process still remains unclear. These barriers include lack of clear definitions surrounding the role of bid forwarding responsible agent and bid forwarding processes such as aggregation and recombination of bids. Even while these aspects are clarified in the regulation, there are underlying regulations of individual markets that can affect the bid forwarding possibilities.

In this chapter, some of these regulatory barriers are briefly discussed. Removing high entry barriers to the markets, such as removal of capacity reservation conditions and allowing the aggregation of resources, can increase the liquidity of markets and increase the number of bids that can be forwarded to the markets. Simplified prequalification and reduction in redundancies are other ways to increase the volume of forwarded bids. Clear, non-discriminatory regulations on aggregation (and the role of aggregators) can also enable the bid forwarding process. Finally, the design of the markets should try to maximize the bid forwarding potential between the markets by closely considering the existing wholesale market designs.

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Although these recommendations are important for a strong development of the bid forwarding process, it should be acknowledged that some of these regulations (such as capacity reservation conditions or aggregation conditions) exist for ensuring system adequacy and reliability. Hence, these recommendations should be considered on a case-by-case basis, weighing their benefits with the potential system costs.

7 Linking Flexibility Markets Through Bid Forwarding: Grid-impact Aware Bid Forwarding and Efficiency Implications

A multilevel market structure (see Section 2.4) emerges naturally when FSPs participate sequentially in multiple flexibility markets. For instance, distribution-level FSPs can engage in the congestion management of their distribution systems and then the balancing and/or congestion management of the transmission system. A similar setting can be found in the interconnection between congestion management markets in the regional/national levels and the MARI platform [126]. In this chapter, our focus is on enabling such participations in a grid-safe manner. Specifically, first, in Section 7.1, we discuss a potential issue that can arise due to the participation of FSPs in multiple markets through bid forwarding: when bids are forwarded from one market to the next, the cleared bids in the subsequent market can jeopardize the safe operation of the grid in which the FSP's assets are located if the constraints of that grid are not taken into account during market clearing of that subsequent market (as showcased in Figure 2-7). Then, we discuss three bid-forwarding approaches that can potentially mitigate this issue in Section 7.2. We compare the performance of these approaches by numerically evaluating the market efficiency in Section 7.3 and discuss potential regulatory barriers of each method in Section 7.4.

7.1 Unsafe Bids in Multilevel Markets

In the ideal multilevel market scheme presented in Chapter 2 and further studied in Chapter 5, the second-level market formulation includes the grid constraints of local networks in which FSPs operate (as can be seen, e.g., in Figure 2-7). However, in practice, the second-level market operator does not necessarily know the network constraints of these local networks. This situation can arise due to data privacy concerns, technical challenges, or simply the unwillingness of the market operators to share such information. For example, the transmission-level balancing market operator might not be aware of the grid constraints and parameters of distribution systems connected to its transmission network. However, when FSPs physically located within the lower-level market domain can also participate in the higher-level market, there is a risk that their bids, if accepted, may not be aligned with the local grid constraints, potentially jeopardizing the operation of the local electrical system.

A simple illustration of the above situation is provided in the following example, presented in Figure 7-1. Suppose that an interconnected transmission and distribution network have upward balancing needs, which can be met by purchasing flexibility from FSPs in both networks. Suppose also that FSP A, operating in the distribution network, has the cheapest price and a large quantity of flexibility. Therefore, first the DSO procures flexibility from FSP A to meet the upward need at node 1, resulting in full capacity usage of the line between

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nodes 2 and 4. However, FSP A still possesses remaining flexibility. Consequently, when the remaining flexibility of FSP A is made available in a subsequent market to the TSO, the TSO would request it after clearing its market as it is unaware of the physical constraints and states of the distribution network. In turn, this solution causes congestion in the distribution system.

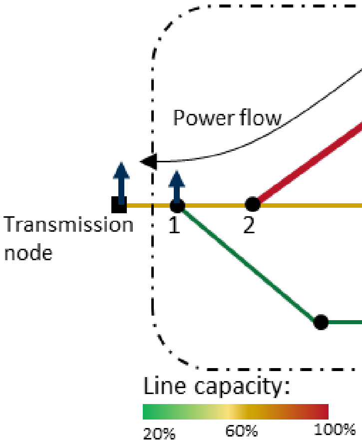

Figure 7-1 - Illustration of Unsafe Purchase of Distribution-level Bids.

Finally, let us recall from Section 5.2.2 (and Section III of [2]) that under the optimal pricing technique of the interface flow, which is the power flow between the root node of the distribution network (node 1 in the example of Figure 7-1) and the transmission node connected to the former, the *ideal* multilevel market scheme achieves the efficiency of the common market scheme. In this regard, the ideal multilevel market scheme is equivalent to the fragmented market one and therefore there is no explicit need to forward bids from one layer to another as the clearing of Layer 1 of the multilevel market, under optimal pricing, generates the optimal flexibility needed at that DSO-TSO interface by the transmission system. Nevertheless, obtaining an optimal price is not always practical as, technically, it requires solving the common market problem, which assumes that all network information is available and can be shared to a central platform that can perform a virtual run of the common market. This partly opposes the underlying confidentiality motivations of splitting the market into two layers in the multilevel market, where in the latter, local network representations would not be needed to be externally shared[33]. Therefore, in practice, if the ideal pricing mechanism (i.e., optimal pricing) is not possible, and if the DSO is unable to share its network representation with Layer 2 of the multilevel market to be included in its market clearing, running Layer 2 of the multilevel market would likely lead to violations of the local grids' operational constraints when these networks run at restrictive capacity (e.g., tight line flow limits or transformer

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[33] Additionally, if the DSO grid constraints can be shared externally to perform a virtual run of the common market to generate the ideal optimal interface flow prices, those constraints can then also be shared with Layer 2 of the multilevel market to be included in its market clearing, thus attenuating the risk of creating local grid issues upon activation.

capacity usage, voltage magnitudes nearing operational limits, etc.). These possible network violations have been showcased in [1].

7.2 Bid Forwarding Methods

To ensure that cleared bids participating in multiple sequential flexibility markets are safe for the electrical grids, three solution methods are analyzed (these solutions are inspired by different propositions in previous European projects, (H2020 CoordiNet [1], H2020 Interrface [127], and H2020 SmartNet [128], [129]), namely:

i. Three-layer market scheme,
ii. Bid pre-qualification method,
iii. Bid aggregation method.

We describe and discuss in detail these three methods along with their advantages, disadvantages, and challenges. For clarity of exposition, in the remainder of the chapter, we use the two-level market example of congestion management markets in the distribution systems, handled by the DSO, and the balancing market in the transmission system, handled by the TSO, as previously illustrated in Figure 7-1. We emphasize that the second-level market is a central market which includes all FSPs in the transmission and distribution networks but the network constraints of the distribution systems are not considered (as opposed to the ideal multilevel market scheme described in Section 2.4). Note that, in practice, these methods can be adapted to any multilevel or sequential flexibility markets.

7.2.1 Three-layer Market Scheme

The first method that can mitigate the impact of unsafe bids to distribution systems is a three-layer market scheme, depicted in Figure 7-2. In this approach, all remaining bids from the first layer market are forwarded to the second layer. After the distribution and transmission level markets are cleared, DSOs have an additional market layer to purchase extra flexibility from the remaining bids so that they can resolve any potential congestion caused by the second layer. This method is essentially a corrective approach and was initially proposed in the H2020 CoordiNet project [1]. A further discussion on the link of this approach with a common practice of redispatch is given in Section 7.4.

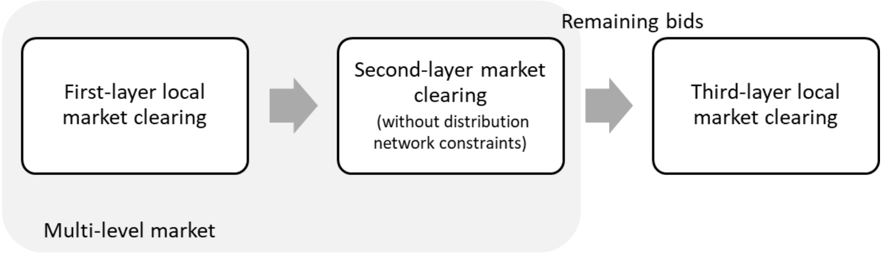

Figure 7-2 – Three-layer Market Scheme.

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The additional (third-layer) local markets of this approach resembles the first layer markets, taking into account the cleared bids (i.e., excluding the portions of the bids that have been cleared in the first two layers) and the interface flow decision from the first two layers and the grid constraints [6]. We also note that, in this market formulation, the interface flow of the additional layer is fixed based on the outcome of the second layer. Obviously, by having this formulation, when at least a feasible solution exists, we guarantee that the multilevel market scheme obtains outcomes that are grid safe. Consequently, if this problem is infeasible, the corresponding DSO cannot resolve its congestion caused by the bids cleared in the second layer. This fact immediately suggests that the distribution systems must be liquid enough. By having an additional layer of market per DSO, implementing this method requires solving the same number of extra optimization problems as that of the DSOs in the network. Nevertheless, this additional computational burden is divided among the DSOs, and, for each DSO, the extra optimization is of the same complexity as the first layer market problem.

7.2.2 Bid Pre-qualification Method

To avoid inducing congestion after the TSO clears its market (i.e., in Layer 2), the DSO can pre-qualify the bids that will be forwarded to the second market layer/transmission-level market (see Figure 7-3). The objective of this pre-qualification[34] process is to obtain a set of bids to be forwarded which are deemed ex-ante to be grid-safe for the distribution systems if they are cleared in the transmission-level market. This method is based on an initial proposition made in the INTERRFACE project [127].

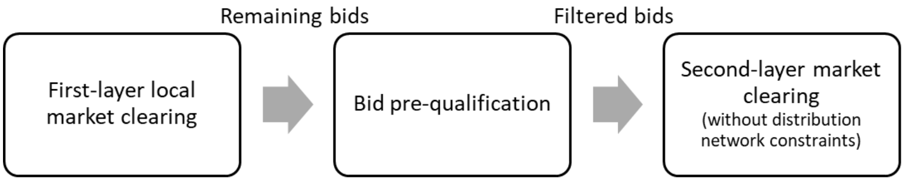

Figure 7-3 – Multilevel Market Scheme with Bid Pre-qualification.

As proposed in the INTERRFACE project, the pre-qualification method iteratively discards the most expensive bids as long as the set of available bids still causes congestion in the distribution system when fully cleared. In this method, each DSO separately evaluates the upward and downward bids. When evaluating the upward bids, each DSO assumes that no downward bids exist and then solves a feasibility problem based on its grid constraints (i.e., perform a *grid check*). Starting from the full set of upward bids, if the problem is infeasible (i.e., if the set

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[34] This bid pre-qualification process concerns a filtering mechanism to allow or prevent bids from being forwarded from Layer 1 to Layer 2. This does not impact the prequalification process of resources for market participation in either Layer 1 or Layer 2. These resources are assumed to have been prequalified for participation in both markets (as highlighted in Chapter 6), otherwise, they cannot be considered for bid forwarding.

of bids considered caused congestions in the distribution system), then the DSO discards the most expensive bid. These steps are iterated, and the iterations stop when the set of remaining upward bids passes the *grid check*, i.e., the problem is feasible and the set of bids remaining would not cause distribution system constraint violation if these bids are fully and jointly cleared by the TSO. Then, the DSO performs the same iterations for the set of downward bids, assuming there are no upward bids. The pre-qualification method is summarized in Figure 7-4.

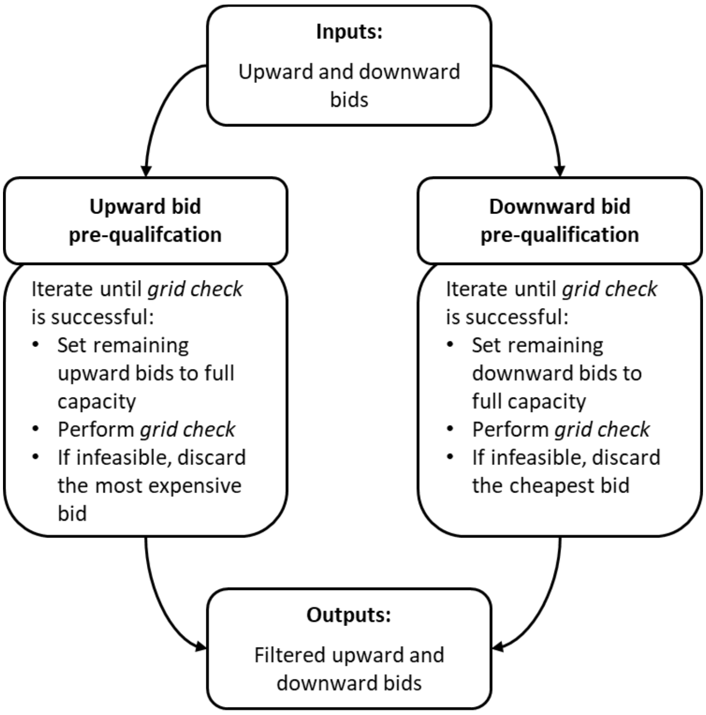

Figure 7-4 - Flowchart of the Bid Pre-qualification Method.

The bid pre-qualification algorithm requires each DSO to solve feasibility problems (to perform *grid check*) multiple times, i.e., at least twice and at most the same number of the available bids. These problems are of the same complexity as the first layer market problem. Therefore, this approach is more computationally intensive than the three-layer market approach. However, the forwarded bids can be generally safe (i.e., the forwarded bids can be cleared by the transmission layer market without a significant risk for distribution system network constraint violations) under (mild) assumptions on the distribution network structure (i.e., radial distribution network) and flexibility prices (i.e., the upward flexibility bids are more expensive than the downward ones). Additionally, the outcome of the multilevel market under this method is in general suboptimal since some bids are discarded, implying a smaller space of flexibility resources that are at the disposal of Layer 2 compared to the standard multilevel market, which may lead to higher system costs.

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There are a few features of this method that must be highlighted. In the filtering technique, upward and downward bids are filtered separately while in the second layer, the forwarded upward and downward bids can be cleared jointly. If the flexibility price assumption is not satisfied (i.e., not all upward flexibility bids are more expensive than downward bids), the grid-safe outcome can no longer be guaranteed. Additionally, these bids are evaluated in the grid check step by considering that they are fully cleared. This is indeed an extreme/worst-case scenario in a radial network under PTDF power flow representation, which can imply that partial clearing is grid-feasible when the full clearing of the bids is also feasible. However, this might not be the case when a different power flow representation (e.g., AC power flow formulations, second-order cone or linear approximations [10]) or network structure (e.g., a meshed network) is considered. Therefore, under these cases, the risk of observing congestion in the distribution systems from prequalified bids may still persist under this filtering mechanism.

7.2.3 Bid Aggregation Method

The third method available for safely forwarding bids is through bid aggregation, which is initially developed in the Smartnet project [130]. In this approach, instead of forwarding individual bids, each DSO forwards different aggregation of the bids in the form of steps (which would be translated in the form of a step-wise change to the interface flow) to the second-layer market, which the DSO considers to be safe for its grid. To do so, the DSO creates a step-wise function that includes different steps of flexibility that the DSO can offer to the TSO and the price for each step. Each step is created by the DSO while taking into account its grid constraints. Hence, when this step is cleared, the DSO envisions a grid-safe way to serve this step through a grid-safe dispatch of flexibility resources within its own grid. This step-wise function is the, so-called, residual supply function (RSF), and is, hence, created taking into account the base state of the distribution network and the network constraints of the distribution grid in an optimization process to generate each step of the RSF and the associated price. Subsequently, the DSOs forward the RSF to the second-layer market. In the second layer, the TSO selects the optimal step of the RSFs received from each DSO to be cleared. Consequently, for the selected RSF step for each DSO, the DSO then dispatches the optimal set of bids from its grid to deliver the RSF step in a grid-safe manner. This process is depicted in Figure 7-5.

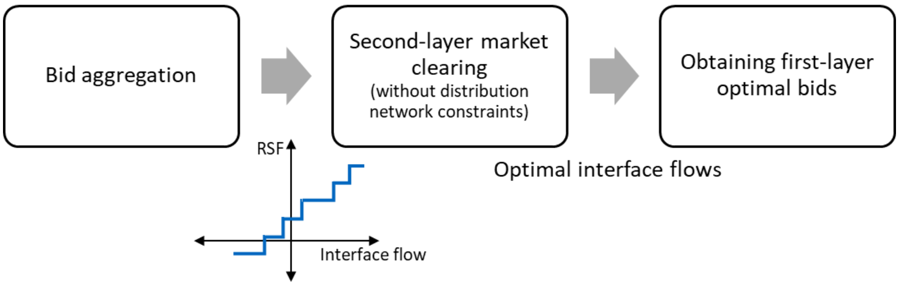

Figure 7-5 - Multilevel Market Scheme with Bid Aggregation.

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To construct the residual step-wise function, each DSO solves the first layer market problem for a fixed value of interface flow (the bid aggregate step). Note that this problem includes grid constraints as previously mentioned. In [129] and [128], an optimal dual value associated with the equality constraint of fixing this interface flow value is then considered as the price of this bid aggregate step. This dual solution corresponds to the marginal contribution of the interface flow in the local market. The residual supply function is obtained by performing the above task iteratively for a finite number of aggregate steps within the feasible region of the interface flow. We highlight that the pricing mechanism of the bid aggregate via the dual solution is quite practical but does not reflect the actual marginal price of the interface flow. Therefore, differently from [129] and [128], we consider a variant that uses the optimal cost of the DSO generating the corresponding bid aggregate value (interface flow value) [6]. The bid aggregation process with both pricing mechanisms is summarized in Figure 7-6.

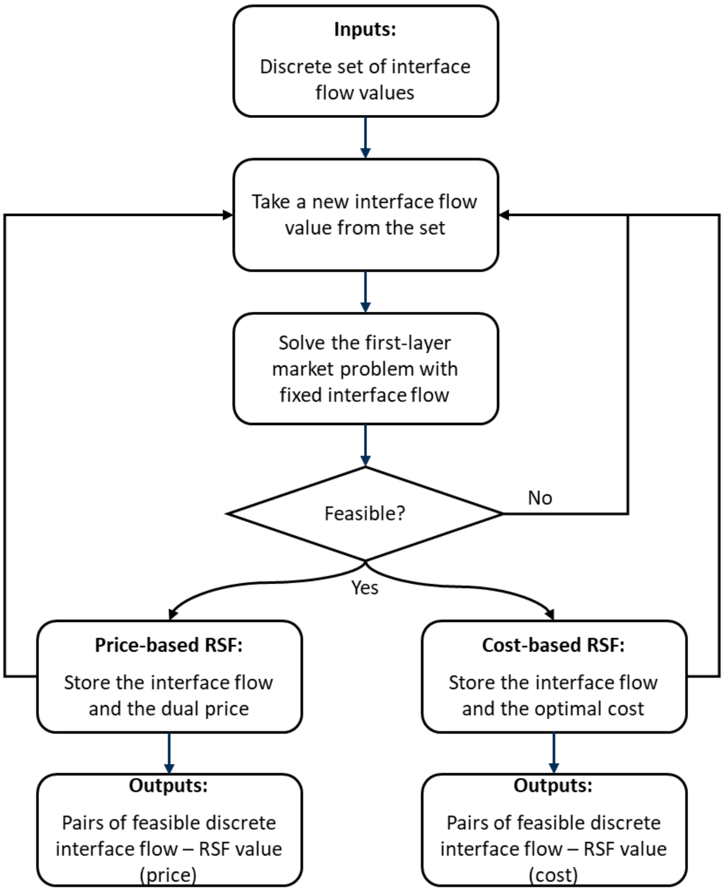

Figure 7-6 - Bid Aggregation Process Based on the RSF Methods. Both Price-based and Cost-based RSF Variants are Shown.

It can be theoretically guaranteed that all bids cleared in this approach are grid safe with any pricing mechanism for the bid aggregate [6]. While the transmission-level bids are cleared in the second layer by taking into account the transmission system's constraints, a cleared (i.e., optimal) distribution-level bid aggregate has a one-to-one correspondence with a set of grid-safe and optimal distribution-level individual bids. Therefore, compared to the three-layer-market and bid pre-qualifying methods, this approach provides the most general guarantee in ensuring grid-safe solutions. Furthermore, for the cost-based RSF method, the suboptimality of the outcome can be bounded by the step size that defines the residual supply function [6]. This fact implies that better efficiency tends to be achieved by using smaller step size. However, when the cost-based RSF is used, it is not clear how the total cost should be divided between the TSO and DSOs, while the price-based RSF can be immediately used as the price of using the interface flow, i.e., the TSO and DSOs exchange interface flow with a certain price while the bids forming that interface follow change are locally settled.

The bid aggregation method is the most computationally intensive among the three methods. To construct the residual supply function, the number of optimization problems that must be solved by each DSO is equal to the number of aggregate steps, which tends to grow in size when aiming to achieve more efficient market solutions. More importantly, the second layer market problem becomes a mixed integer problem (to be able to integrate the RSF in the market clearing process), where the dimension of the integer decision variables is proportional to the number of aggregate steps.

7.3 Efficiency Comparison via Numerical Simulations

In this section, we perform numerical analyses on the implication of the bid forwarding methods to the efficiency of the multilevel market scheme. To that end, we consider the interconnected system based on the IEEE 14-bus transmission system and the Matpower 69-bus and 141-bus distribution systems [90], as in Section 5.1. We generate the following four different cases that allow us to provide a comprehensive analysis on the performance of the three bid forwarding methods:

- Case A (Case I in Chapter 5): The networks have anticipated line congestions and cumulative negative imbalances that must be resolved by upward bids. The prices of the downward bids are in the range [10, 25] €/MW while those of the upward bids are in the range [30, 55] €/MW. Additionally, the distribution-level bids are more expensive than the transmission-level ones.
- Case B: The networks have the same negative imbalances, anticipated congestions, and FSPs as in case A. However, here the transmission-level upward bids are more expensive than the distribution-level ones, i.e., their prices are in the range [90, 165] €/MW, while the prices of the other bids are the same as in case A.
- Case C: The networks have negative imbalances and anticipated congestions, as in Case A. The transmission-level upward bids are more expensive than those in the distribution systems, as in Case B. Additionally, we add several new upward bids in the distribution systems whose prices are more expensive than those in the transmission level and new downward bids in the distribution

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systems whose prices follow the rules of downward bid prices in Case A. These extra bids are selectively located in critical nodes as we discuss later in the simulation results.

- Case D (Case II in Chapter 5): The networks have anticipated congestions, as in Case A, but positive imbalances that must be resolved by downward bids. The price rules are set the same as Case A.

Cases B and C are variants of case A (which is taken from the numerical study in Chapter 5), created to better illustrate the performance of these bid forwarding methods. In the simulations, we also consider the different pricing mechanisms of the interface flow that can be applied to the multilevel market (some discussed in Section 5.2.2), namely: 1) no interface, i.e., when the interface flows are fixed to their original values (i.e., their anticipated values prior to the run of the flexibility markets) not allowing any changes to the interface flows to be induced by the flexibility market clearing; 2) no pricing, i.e., when the interface flows are not priced; 3) optimal, i.e., when the interface flow is priced by the marginal price (dual optimal solution) of the corresponding power balance constraints; 4) midpoint, i.e., when the price is the average of the most expensive downward bid and the least expensive upward bid. We test the three-layer and bid pre-qualification methods under these four pricing techniques. On the other hand, in the bid aggregation method, the interface flow follows a different pricing mechanism, i.e., by using the RSFs. As discussed, we consider both variants of RSFs, namely 1) RSFs constructed by optimal dual solutions (price-based RSF) and 2) RSFs constructed by optimal primal costs (cost-based RSF). For each variant, we use ten different step sizes within the range of [0.03, 1.3].

The simulation results are summarized in Table 7-1. We use the optimal cost of the common market as the benchmark since it is the most efficient market scheme (see Section 5.2.1). Therefore, inefficiency is defined, similarly to the definition in Chapter 5, as the difference between the total cost of the multilevel market (J) and the common market normalized by the total cost of the common market (J^*), i.e.

$$Inefficiency = \frac{J - J^*}{|J^*|} \times 100\% \,.$$

In this regard, the smaller the inefficiency, the more cost-efficient the bid forwarding method is. Let us also recall that the common market solution is equal to those of the ideal multilevel (with full information in both layers) and fragmented markets when these markets price the interface flows optimally [2]. We also run the fragmented market model for comparison purposes since this model represents a scheme where no distribution-level bids are forwarded to the second layer. Finally, we remark that the inefficiencies of the RSF method (rows 8 and 9) are given in a range to accommodate the different step sizes used. We show the inefficiencies of this method with varying step sizes in Figure 7-7 and Figure 7-8.

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Table 7-1 - Inefficiency of the Multilevel Market under Different Bid Forwarding Methods

No.	Method	Inefficiency (proportional %)			
		Case A	Case B	Case C	Case D
1	Three-layer (no interface)	2.25	infeasible	16.06	95.36
2	Three-layer (no pricing)	4.35	infeasible	22.50	237.67
3	Three-layer (optimal pricing)	0.00	infeasible	7.17	0.00
4	Three-layer (midpoint)	0.00	infeasible	10.36	0.00
5	Bid pre-qualification (no interface)	2.25	67.28	67.28	95.36
6	Bid pre-qualification (no pricing)	4.35	31.67	31.67	237.67
7	Bid pre-qualification (optimal price)	0.00	0.00	0.00	0.00
8	Bid pre-qualification (midpoint)	0.00	17.03	17.03	0.00
9	Bid aggregation with price-based RSF*	[0.06, 3.15]	[1.53, 5.19]	[1.53, 5.19]	[3.66, 222.91]
10	Bid aggregation with cost-based RSF*	[0.04, 1.78]	[0.03, 5.19]	[0.09, 3.59]	[1.70, 77.29]
11	Fragmented (midpoint)	0.00	59.17	59.17	0.00

🟨 : cleared bids cause congestion but resolvable
🟧 : unsafe bids (congestion is not resolvable)
*: the RSF steps are in the range of [0.03, 1.3]

From Table 7-1, we can observe that the bid pre-qualification and bid aggregation methods can obtain grid-safe cleared bids in all the cases. The bid pre-qualification method generates grid safe results as the numerical case considers radial distribution systems and abides by the assumption of upward flexibility bids being cheaper than downward flexibility ones (i.e., meets the considerations for grid safety highlighted in Section 7.2.2). The three-layer scheme results in a grid-safe outcomes in cases A, C, and D but return infeasibility for case B (due to low liquidity in Layer 1 implying unavailability of enough flexibility in Layer 3 to rectify congestions caused in Layer 2). In terms of efficiency, we can observe that the performance of the three methods is case-dependent. Except for the optimal pricing scenarios and the midpoint pricing for cases A and D, the bid aggregation method results in a higher efficiency, but this efficiency is dependent on the step size used. We elaborate on the discussion of each case next.

In cases A and D, both the three-layer and bid pre-qualification methods obtain equal solutions. These results can be explained by the fact that the bid prices in the distribution systems are more expensive than those in the transmission system; thus, no distribution level bids are cleared in the second layer, while the first layer market solutions are equal for both methods. Coincidentally, for these two cases, the midpoint pricing results in an optimal solution as can be observed in rows 4, 8, and 11. As for the bid aggregation method, the inefficiency can be remarkably low, especially for the variant with primal cost RSF (rows 9 and 10).

In case B, the infeasibility results obtained by the three-layer market scheme can be explained by evaluating the case itself. In this case, we have set the transmission-level bids to be more expensive. Thus, in the second layer, the TSO is more likely to procure larger amount of flexibility from the distribution systems (as distribution-

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layer bids are significantly cheaper). However, since the TSO does not know/have access to the grid constraints of the distribution layers, this larger procurement can result in larger congestions in the distribution systems, which cannot be resolved by the third layer. It is worth noting that under optimal pricing, the outcomes of the first-layer markets should have been optimal, i.e., no more first-layer bids should be cleared in the second layer. However, under the three-layer scheme, all remaining bids are forwarded. Subsequently, the TSO, due to the lack of information on the state of the distribution networks, purchases extra bids from the distribution networks which have caused congestion. This observation also applies to case C. However, in case C, the distribution systems are more liquid and, therefore, the congestion can be resolved. On the other hand, as can been in cases A and D, in those cases, the three-layer approach has resulted in optimal and grid-safe solutions (similar to the common market). Hence, the performance of the method should be assessed with respect to the case for which it is implemented. That can also be generally the case for the other two approaches. Table 7-1 shows that the bid prequalification method is able to forward only feasible bids to the second layer (as the conditions for that are met by the case analyzed, as mentioned earlier). In turn, it obtains grid-safe but suboptimal solutions. However, the efficiency of the bid pre-qualification method is outperformed by the bid aggregation method.

Additionally, we construct case C, obtained by modifying case B, to show that forwarding bids can be beneficial. In this case, the inefficiencies of the three methods (rows 4, 8, 9, and 10) are smaller than the fragmented market (row 11). In fact, the same observation is also observed in case B, in which the bid prequalification and the bid aggregation method outperforms the fragmented market (compare rows 8-11). Another interesting observation from case C is the comparison of the three-layer and bid pre-qualification methods. In this case, the three-layer method outperforms the bid prequalification method in any pricing scenario, even though the former obtains additional cost from resolving congestion in the third layer. It is also worth reiterating that under the optimal interface-flow pricing, the distribution-level bids should not be forwarded to the second-level market, as numerically shown in cases B and C that doing so could lead to inefficiency and even infeasibility.

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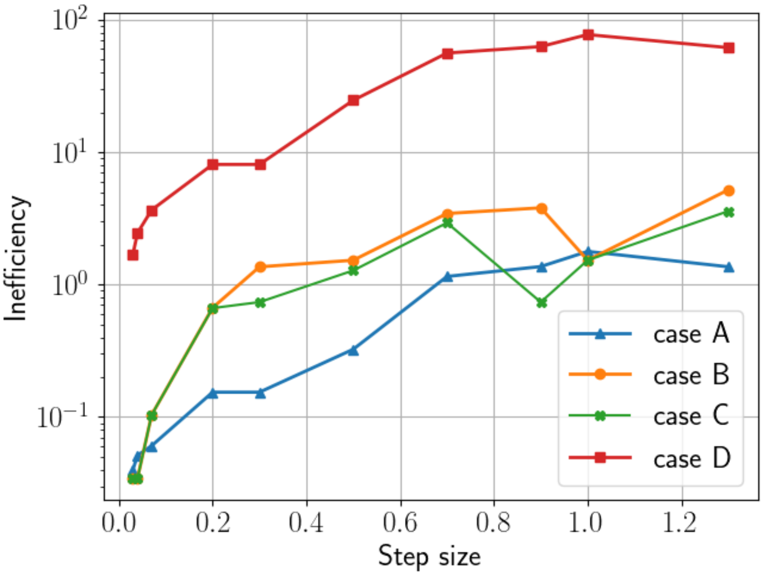

Figure 7-7 - Inefficiency of Bid Aggregation Method with Cost-based RSF

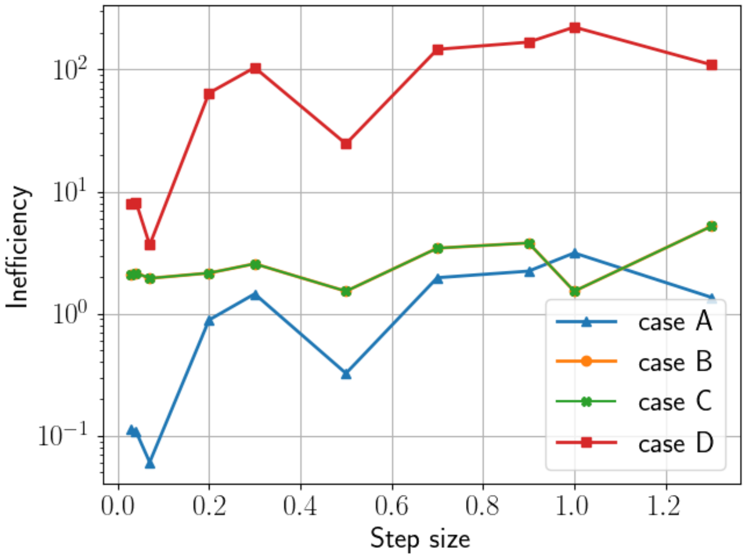

Figure 7-8 - Inefficiency of Bid Aggregation Method with Price-based RSF

Finally, we focus our discussion on the bid aggregation method. As shown in Table 7-1, the price-based RSF [129] and [128] performs worse than the cost-based RSF, which we propose. This numerical observation corroborates our mathematical analysis in [6] that shows that, by using the cost-based RSF, the bid aggregation method solves a restricted version of the common market and, thus, its performance approximate that of the common market solution. On the other hand, when constructing the RSF with the dual solution of the first layer problem, the prices obtained do not match the marginal prices of the interface flows in the second-layer market. This deviation is reflected by a worse performance than the cost-based RSF. Additionally, as shown in Figure 7-7, we can observe a decreasing trend of inefficiency as the step size decreases when the cost-based RSF is used.

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This result agrees with the theoretical suboptimality bounds of this method that is proportional to the step size. On the other hand, from Figure 7-8, we do not observe a similar trend for the price-based RSF (see cases C and D).

7.4 Potential Regulatory Challenges

After analyzing the efficiency of the multilevel market with the three bid-forwarding methodologies, we now evaluate regulatory challenges that may arise on their implementation.

In the three-layer market scheme, the third-layer market does not directly interact with the second-level market. EU regulations state that if enough competitive resources are available for redispatch, redispatch processes should be market-based [131], as suggested in the third layer of this scheme. When competitive conditions do not exist, the DSO (or TSO in the transmission grid) can procure resources for redispatch in a fair, transparent, rule-based mechanism. Hence, if these conditions are respected, the three-layer market scheme is more compatible with European regulations, especially on balancing, than the other methodologies. However, such schemes are prone to market arbitrage attempts, especially when the congestion is predictable and frequent [132]. Moreover, there is a mismatch between the source of congestion and the actors paying for the resulting congestion [96]. When congestion occurs as a result of activations in the balancing market, the costs of congestion should ideally be allocated to the market players who created the congestions. However, in this case, when congestion is treated separately in another market, it leads to the socialization of costs among users of a system different from the system from which the congestions might have been caused.

Proactive filtering, as in the bid pre-qualification method, is accepted within the Electricity Balancing Guideline (EBGL) regulations to reduce the need for real-time congestion management. It can be speculated that such methodologies can be employed by DSOs as well. Here, the important concern would be the accuracy at which the congestion can be forecasted [133]. If a low-cost bid is proactively filtered due to forecasted congestion, and the congestion does not materialize in real-time, then procurement efficiency will be reduced. Additionally, factors such as the threshold for filtering (i.e., at what sensitivity level will the units be filtered for causing congestion), remuneration for filtered units, and the severity of congestion can influence the efficiency of the system as well as the regulatory barriers it will face. In general, if the constraint violations are not severe but predictable and the same units are not repeatedly filtered out, these types of solutions can be implemented without high regulatory or institutional barriers.

The implementation of the bid-aggregation method is subject to the condition that the financial neutrality of the DSO (or TSO in the transmission grid) is maintained. If the revenues obtained from the TSO or DSO do not match the costs incurred in procurement (i.e., during the disaggregation of bids and reallocation of the cleared volume to the non-constraining competitive bids are not equal), then, the TSO or DSO will have a deficit or a surplus. Furthermore, it is not clear whether the creation of a new residual bid by an SO or an MO is permitted within the current European regulations. A similar approach is discussed for the Norwegian transmission grid congestion, where the TSO creates a residual function for their grid after considering the network constraints. The authors acknowledge the lack of clarity regarding the legality of this process and questions whether the bid conversion provisions allowed by EBGL to central-dispatching systems[35] can be applied to self-dispatching systems [50]. According to the EBGL, the TSOs can proactively filter out some bids for possible grid congestion or for reserving some bids for direct activation, but converting non-standard bids (e.g., detailed complex bids in central-dispatching systems) to standard balancing bids (the harmonized bidding formats allowed in European balancing platforms) is an exception allowed only for central-dispatching TSOs [55]. Additionally, the creation of residual functions by the SOs or MOs can raise significant transparency concerns among the stakeholders, as the FSPs may not understand the bid selection process. Therefore, compared to the first two, this methodology can face severe regulatory barriers toward its implementation.

The analysis of the three methodologies has been focused predominantly on DSOs with implications to TSOs. If we apply the analysis of the multilevel market to the case in which DSO and TSOs run jointly layer one for a regional congestion management, where unused bids can then be forwarded to subsequent European balancing markets (e.g., MARI), then the analysis would have also to take into account the roles of DSOs and TSOs in such European-scale balancing platforms. Focusing on balancing markets, the regulations are clearer about the role of TSOs than that of DSOs. Once the implementation of European balancing platforms is complete, the TSOs are in charge of collecting the bids from their control area and forwarding them to the balancing platforms [16]. Although EBGL states that TSOs should cooperate with DSOs to ensure efficient and effective balancing, the role of DSOs in balancing the market is unclear. A clear definition of their role is especially relevant if distribution-grid-connected resources are participating in the balancing market. The main list of responsibilities for DSOs regarding the service provision recommended in EBGL is given below:

- The DSOs shall provide all necessary information to perform imbalance settlement to the TSO.
- The DSOs shall coordinate with the TSOs to ensure efficient operation across all voltage levels and regions.
- If the BSP has a connection point to a DSO, if required by the DSO, the BSP has to declare any unavailable volumes of balancing energy bids to the DSO.

The EBGL does not explicitly allow the DSOs to forward the bids to the European platform, and hence, for the time being, the DSOs can only forward it to the TSO of its control area, who will then forward it to the balancing platform.

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[35] Central-dispatch system is an alternative to the prominent self-dispatch balancing market model used in Europe. The TSO in a central-dispatch system schedule and dispatch the balance service providing units through an integrated scheduling process (ISP) considering a comprehensive set of information such as the network constraints, techno-economic data provided by the units, international exchanges etc. To enable ISP, the BSPs have to provide detailed technical and economic data through complex bids known as ISP bids, which are different from the standard bids allowed in balancing platforms such as MARI and PICASSO.

7.5 Conclusions

This chapter focuses on the multilevel market scheme where FSPs can participate in a flexibility market of their local network and subsequently a flexibility market of a larger network through bid forwarding. We delve into methodologies that enable such a multilevel structure, especially focusing on the case where the higher-level market has limited information on the local networks where the FSPs are located. As this limitation can cause network constraint violations for the local networks, we propose and discuss three approaches to either rectify or prevent the occurrence of such network issues.

The first approach is a corrective method where a third-layer market is introduced to resolve any issue caused by clearing the multilevel market. This approach is the least computationally demanding and is the one that abides existing regulatory frameworks the most as it enables the procurement of flexibility using market mechanisms and limits the external interference in the market process. However, this method can only guarantee grid-safe solutions at all times only when enough flexibility (liquidity) is offered from the distribution systems to allow the corrections of any network issues cause by the central markets, as evidently shown in the numerical simulations.

The second approach is a bid pre-qualification method where the first-layer market operator filters bids that will be forwarded to the second layer such that only feasible ones can be cleared. In our numerical simulations, this method effectively performs the filtering process, resulting in grid-safe (but possibly suboptimal) cleared bids. In addition, the extent up to which the grid-safety of the forwarded bids is guaranteed depends on the nature of the systems involved and the prices of the flexibility bids submitted. Hence, the approach may not always provide a robust grid-safe mechanism. In terms of regulation, when bid filtering currently available to TSOs is also extended to DSOs, the approach can generally fit within the space of applicable regulations.

The third approach is a bid aggregation method, where the second-layer market only considers the aggregates of first-layer bids. The price function of the bid aggregate is obtained by the residual supply function method, which either uses the dual solutions or the primal costs of local markets. In general, the bid aggregation results in obtaining grid-safe cleared bids and maximized efficiency, as compared to the other methods. However, the superior performance of this method comes at the cost of high computational demand both for the DSOs and TSO. In addition, this method can face regulatory barriers given the implied changes to the roles of DSOs and TSOs.

Our numerical results also show that forwarding bids from one market to another, despite the potential risks from the lack of awareness of grid constraints, can be beneficial if executed properly, e.g., by employing one of the three bid forwarding methods, as it can result in a more efficient solution than simply limiting FSPs to participate only in their local market.

8 Conclusions

This report has focused on the proposition and evaluation of varying TSO-DSO coordination schemes and market models for the provision of (a combination of) flexibility services for TSOs and DSOs. The analysis has followed a structured methodology based on quantitative analysis (based on rigorously developed mathematical models and simulation environments) and conceptual, qualitative and regulatory analyses.

8.1 TSO-DSO Coordination Aspects

The work has first presented a set of TSO-DSO coordinated flexibility market schemes, incorporating different ways in which flexibility can be procured in a coordinated way among TSOs and DSOs. These schemes have been initially proposed in the H2020 CoordiNet project, where the drivers of the differentiation between the different schemes stem from several factors, including: (i) the system(s) requiring flexibility to meet system services (which can include, e.g., a TSO-level requirement, a DSO-level requirement, or requirements in several SOs) which would then indicate the SO(s) that would be the primary buyers of flexibility, (ii) the systems (transmission or distribution) in which flexibility assets are connected and from which flexibility is offered through FSP market participation, (iii) the number of markets, to which we refer as market layers, that are in place and through which the SOs can independently, jointly, or sequentially purchase flexibility, (iv) the possibly differing access-levels of the different SOs to flexibility available from within or from outside their grids, (v) the differing ways in which FSPs can offer their flexibility in the markets, especially in the situation of the existence of multiple (sequential) markets in which they are authorized to participate and offer their flexibility, (vi) the way the flow of power between systems, or the changes to the volume thereof, which would capture the use of cross-grid flexibility requiring possible correction mechanisms is priced (i.e., interface flow pricing), (vii) the need (or absence thereof) for an SO to share information about its network representation and constraints with the market platforms operated to meet the flexibility needs of other SOs. These different options give rise to a number of fundamental TSO-DSO coordinated flexibility market models, namely: the disjoint distribution-level markets (or local markets), the disjoint transmission level markets (a form of central markets), the common markets (in which flexibility is jointly procured among the SOs in a co-optimized way), the multilevel markets, and the fragmented markets – where the multilevel and fragmented markets introduce sequential market layers – in addition to different variations thereof.

The evaluation of the different TSO-DSO coordinated schemes and flexibility market models has taken into account several factors and dimensions, which have resulted in several key insights on the adequacy of the different market formulations.

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8.2 Efficiency of Different TSO-DSO Coordinated Market Alternatives

First focusing on efficiency, we have quantitatively evaluated and compared the economic efficiency of each TSO-DSO coordinated market model, reflecting their ability to procure the flexibility needs of the SOs at lowest cost. We have first identified that the common market can achieve the maximum possible theoretical efficiency, as it allows a joint and co-optimized procurement of flexibility by all SOs from a common pool of flexibility resources while abiding by all the network constraints of all the grids involved. This corroborates similar previous observations in previous studies, such as in [1, 2]. However, several other factors can affect this efficiency as well as the efficiency of the other market schemes, driving their efficiencies to change, converge, or diverge. The first element of key effect is the pricing of the interface flow between systems (i.e., between the distribution and transmission systems), which enables the pricing of the indirect sharing of flexibility in sequential markets. We have first observed that unpriced interface flow can lead to a direct reduction in efficiency of the multilevel and fragmented markets as it drives the purchasing of unneeded downward flexibility in the local layer of those markets (i.e., Layer 1) creating an imbalance which would be rectified at an additional cost in the subsequent layer (i.e., Layer 2). However, a pricing of the interface flow can reduce this mechanism. This pricing can be done in several ways, whose effects were analyzed and showcased. In fact, we have showcased that when the interface flow is priced optimally, the efficiency of the multilevel and fragmented markets can equate that of the common market, hence, achieving maximized efficiency. However, the derivation of such optimal pricing can face practical limitations. Next, we have explored the effects that entry barriers can have on the market efficiency of each TSO-DSO coordinated market models. For example, by focusing on minimum bid requirements, small-scale resources might be excluded from common markets while being able to participate, for example, in the local layer of the multilevel market (i.e., Layer 1). This aspect can have a direct impact on the achieved efficiency. On the one hand, the coupling of the markets in a common market can increase efficiency through pooling and co-optimizing, but can reduce market participation due to potential barriers (especially if not being able to be met through aggregation). The multilevel market, on the other hand, due to market fragmentation, would lead to a reduction of efficiency as compared to the common market. However, through the combination of a local and central market layers, some resources that would have otherwise been excluded from centralized markets, may be able to participate in the local layers of the multilevel market (that similar logic applies to the fragmented and the disjoint distribution-level markets) hence improving the overall market participation, which would also induce efficiency gains. This increase in efficiency does not fully materialize in fragmented and disjoint distribution distribution-level markets as, even though participation of local resources can be enhanced, such local resources are only limited in participation to the local markets layers, hence not being able to deliver services, e.g., to the TSO, which would directly impact their efficiency. In this respect, our results have shown that even though the common market is the most efficient, that efficiency can experience a drop due to potential entry barriers, which would then reduce the gap in efficiency between the common and, e.g., the multilevel market, where the latter can benefit from an increased efficiency driven by small-resource

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participation. The ranking of the efficiencies of the different market schemes under entry barriers would depend on the case involved and the level of entry barriers that may exhibit in the studied case, as has been showcased through our sensitivity analysis.

The efficiency can also be impacted by the bid formats allowed in the market. In that respect, we have analyzed the efficiencies of the different TSO-DSO coordinated market models when considering the inclusion of not only fully divisible bids (in the form of a price-quantity pair) but also partially divisible bids, which impose a minimum clearing requirement. In other words, partially divisible bids cannot be cleared below their indicated minimum clearing level. Our analysis has showcased that the common market efficiency can be less impacted by the existence and introduced requirements of partially divisible bids, since it considers a large pool of resources than other markets, which would allow the ability to more easily replace bids that can become increasingly expensive due to their minimum clearing constraint with possible alternatives. O n the other hand, due to the fragmentation of the flexibility needs and offers among different market layers in the other market schemes, the minimum clearing requirements of partially divisible bids can have a higher negative impact on their efficiencies.

Moreover, another dimension which can have a direct impact, in particular, on the efficiency of the multilevel market is the bidding process that the FSPs can employ when participating in sequential market layers. Indeed, as the FSPs located in distribution networks are able to participate in the two layers of the multilevel market, they can have different bidding processes. For example, a standard bidding process is to automatically forward unused (portions of) flexibility bids from Layer 1 to Layer 2, without enabling the FSP to modify their bids before being forwarded. Other types of sequential bidding can also be considered, and which have been studied in our analysis, which would allow the FSPs to submit different bids in the two layers. The first alternative is one in which the FSP can submit different bids in the two layers (i.e., the distribution-level market layer and the transmission-level market layer) but without being able to observe the results of Layer 1 before bidding in Layer 2 due to, e.g., having the market clearing time of Layer 1 extend beyond the gate closure time of Layer 2. As such, in this alternative, the FSPs would need to submit parallel bids in the two market layers, through which they can decide to split their available flexibility quantity to be submitted in each market and can decide on different submitted prices for their flexibility in each of the markets. Another alternative which can be envisioned (and which has also been considered in our analysis) is one in which the FSPs can have different bids in Layer 1 and Layer 2, while also being able to observe the results of Layer 1 before bidding in Layer 2, which renders it a form of sequential bidding. Due to the ability to submit different quantities and different prices in the two sequential market layers, these bidding processes can directly impact the efficiency of the multilevel market. Indeed, if FSPs are incentivized, through low cost requirements of local markets' participation, to submit lower prices in Layer 1 than in Layer 2, this can induce lower flexibility procurement costs as compared to the standard automatic forwarding, and, hence a higher efficiency. This would, however, be the opposite case if the FSPs envision lower competition in Layer 1, which incentivizes them to bid higher prices in Layer 1 than they

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would have in case of automatic forwarding. Our numerical results have also highlighted that the parallel bidding process can reduce the level of available downward flexibility in Layer 1 of the multilevel market as compared to sequential bidding and the standard automatic forwarding alternatives, which can lead to a reduction in total cost in the case where no pricing of the interface flow is considered, as this can reduce the likelihood of unneeded purchasing of downward flexibility, which we have characterized in the earlier part of the efficiency analysis.

Another key element analyzed and which can direct impact the efficiency of each TSO-DSO coordinated market models is the strategic bidding of the FSPs in each market model, and which can be incentivized by the structure of each market. In our analysis of the impact of strategic behavior on the different market models' efficiency, we have introduced a game-theoretic analysis to identify and simulate the optimal bidding behaviors/strategies that the FSPs can implement in each market scheme. The obtained results demonstrated that each TSO-DSO coordinated flexibility market can incentivize different levels of strategic bidding or can have different level of sensitivity to strategic bidding when it occurs. Indeed, through our analysis, we have shown that, when having relevant information on the market set-up and previous opponents' bids, they can bid higher than their marginal cost (in the case of upward flexibility) or lower than their marginal value (in the case of downward flexibility), and successfully improve their revenues, hence incentivizing the deviation from the truthful bidding strategies. Moreover, this effect can be more pronounced in market schemes with fragmentation (such as the disjoint markets and fragmented markets), due to their reduced liquidity, which enables FSPs to exert market power impacting the resulting market prices.

8.3 Consumer-centricity in TSO-DSO Coordinated Flexibility Markets

This work has also evaluated the different TSO-DSO coordinated market schemes from a consumer-centricity perspective. In this respect, we have first aimed to identify how consumer-centricity can be defined and what it can entail in existing and emerging electricity markets, and then applied this concept to TSO-DSO coordinated flexibility markets. The first identified observation is that there is no commonly agreed-upon definition of consumer-centricity. Consequently, we have tracked and identified definitions introduced by different stakeholders to synthesis a concrete definition. As such, consumer-centricity can reflect the practice and aim of putting the consumer at the center of all the decisions and design choices made by firms, regulators and policymakers. Based on this definition, a specific product traded can be considered to be consumer-centric (or at least capturing a higher level of consumer-centricity) when a consumer can express his/her preferences and needs, reflecting not only price preferences but also preferences with respect to other attributes of the product. When applied to electricity systems and markets, there is a limit – which can be imposed by the electrical characteristics of the products traded and requirements for system services – which can limit the possibility for consumers to express such preferences and needs and have them reflected in product options, especially when

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considering small-scale consumers. However, those limitations can potentially be attenuated through the use of intermediaries and aggregators, which can first open up market participation opportunities for small-scale consumers by decreasing the hurdles that individual consumers may face for meeting strict service requirements of the traded products. Then, by offering contracts, which can be tailored to the preferences and needs of consumers, aggregators can then increase the engagement possibility of consumers and improve the consumer-centricity of the electricity or flexibility market. When projected to the different TSO-DSO coordinated flexibility market models, their level of consumer-centricity depends on their ability to allow participation opportunities for consumers (in a manner cognizant of their preferences and needs), generating additional value to them, while ensuring the ability to deliver the required services to the SO(s) at the transmission and distribution levels. The different TSO-DSO coordinated market alternatives introduced can exhibit different levels of consumer-centricity. Indeed, it can be argued that the disjoint central market presents the lowest level of consumer centricity as it excludes the participation of distribution-level resources. On the other hand, disjoint distribution-level and fragmented markets do allow the participation of distribution-level resources, but strictly to meet the needs of DSOs. This allows such markets to take into account – in a more easy way than centralized markets – the technical requirements of local resources and consumers, which increase their potential level of consumer-centricity. However, as it excludes distribution-level resources form providing services outside the distribution grid, e.g., for the TSO, their consumer-centricity potential is not maximized. The common market, on the other hand, allows distribution-level resources to provide flexibility too all the SOs involved in the joint procurement of flexibility (i.e., the set of DSOs and TSOs). This element increases the opportunity to deliver flexibility and the potential value received, which reflects a good level of consumer-centricity. However, as the common market includes a joint procurement by all SOs, some central level needs can require a relatively stringent product requirement that can less-easily accommodate all the needs of local resources, which can lead to a reduction of consumer-centricity. However, if that aspect can be met through aggregation, this can improve the consumer-centricity potential of common markets. Lastly, the multi-level market can potentially provide an advanced level of consumer-centricity, as similarly to the common market, it allows distribution-level resources to provide flexibility to the DSO as well as to the TSO. In addition, as the market is formed by a sequential DSO-level followed by a TSO-level market – even though this can lead to a drop in overall efficiency of the flexibility market – it can allow the DSO-layer markets to more easily accommodates the needs and requirements of local resources, thereby increasing the overall consumer centricity of the multilevel markets. On the other hand, as its efficiency can be lower than, e.g., the common market, this can also have an impact on the consumer-centricity of the multilevel market, as additional costs would then be reflected on the consumers' bills.

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8.4 Entry Barriers in TSO-DSO Coordinated Flexibility Markets

As previously mentioned in the efficiency analysis, different TSO-DSO coordination schemes can exhibit different levels of entry barriers. As such, our analysis has also focused on first identifying the entry barriers that can be induced by the different products' attributes, which are the reflection of the services' technical requirements. Indeed, different attributes can (regardless of the coordination schemes) lead to the introduction of different types and levels of barriers to different types of flexibility providers, if the technical requirements imposed are challenging to meet for those providers. As such, the different identified barriers can exist in any TSO-DSO coordinated market model (i.e., disjoint-transmission/central, disjoint-distribution/local, fragmented, multilevel, and common), as these barriers originally stem from the requirements imposed by the attributes themselves as a function of the needs of the services that those products aim to deliver (i.e., different balancing services, congestion management at different grid levels, voltage control, among others). In this respect, the creation of a local market layer can theoretically enable the definition of product attributes that can be more cognizant of the technical capacities and requirements of the local resources. Nonetheless, some grid services' requirements may still be challenging to meet even in such tailored local market cases, in which case such barriers would persist. In general, splitting the markets in different layers (e.g., a multilevel market as compared to the common market) may, on the one hand, alleviate the severity of some barriers that can be experienced by local resources (hence, enhancing their participation potential and, as a result, the potential market efficiency), but, on the other hand, as mentioned in the efficiency analysis, this market fragmentation can lead to an overall drop in market efficiency (as compared, e.g., to the common market) due to the absence of the capability to jointly co-optimize the purchasing of flexibility in a way to maximize the flexibility's value stacking potential and, thus, minimize the total resulting cost. Hence, this represents a key tradeoff as both aspects can have a direct impact on the markets' efficiency. Overall, the overarching conclusion of the analyses on the entry barriers showcase that general barriers can materialize across different market schemes, while the specific nature, prominence, and influence of these barriers may vary depending on the product attributes, the availability of remedial solutions (e.g., through aggregation), and the selected coordination scheme, thereby necessitating a careful consideration of the market design and available regulations, to lower such possible entry barriers.

8.5 Linking between Flexibility markets through Bid Forwarding

Our analysis has also focused on another key aspect, focusing on the linking between markets through bid forwarding, which is a mechanism in which unused bids in one market for a specific service can be forwarded to another subsequent market to potentially meet other services. This enables an increase in the value stacking potential of flexibility, similar to the multilevel market, but in a setting in which the markets are not otherwise connected through their market clearing processes. A practical example of such settings is having a regional

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market for congestion management in which regional flexibility resources can offer their flexibility. The portions of the unused bids in this market can then be forwarded to a subsequent market for the procurement, e.g., of balancing resources (such as mFRR through the MARI platform). The forwarding of these bids require compatibility of the products (and their attributes) traded in the two markets, compatibility of the bids formats in the two markets, as well as a mechanisms for ensuring that the bids forwarded, when cleared in the subsequent market, would not cause network violations in their respective grids as the subsequent market may not have the capability to constraint its market clearing to account for local or regional market constraints. For example, local, regional, or intrazonal network representation and constraints would not be available to the MARI platform to take them into account when procuring flexibility from those grids to ensure that this flexibility does not lead to network constraint violations within those grids.

As such, we have analyzed these processes for bid forwarding and investigated the regulatory frameworks which can impact their implementation potential (in the form of incentives or barriers). For example, the reduction of entry barriers (e.g., through the reduction or removal of capacity reservation conditions), the ability and permission to aggregate resources, as well as the development of adequate market designs and market timings can enhance the bid forwarding potential, as is similarly the case for including simplified prequalification methods in the different markets. Nonetheless, these aspects, even though can enhance the bid forwarding potential, they can face other practical obstacles driven by the requirements of the services to be implemented, which may limit their practical implementation potential. Indeed, although these recommendations are important drivers for enabling bid forwarding, it should be acknowledged that some of these regulations (such as, e.g., capacity reservation requirements, aggregation conditions, simplified pre-qualification processes) exist for ensuring system adequacy and reliability. Therefore, a weighing of the risks, potential benefits, and possible incurred system costs should be in place when considering adjustments to those mechanisms.

Another key element in the analysis of bid forwarding, as previously mentioned, is the risk that the forwarded bids, when procured, can cause network issues in the grids from which they originate. This risks stems from the inability of the subsequent markets to adequately constraint their market clearing to abide by local/regional/intra-zonal network constraints. This is, for example, not the case in the standard multilevel market that we have introduced and explored, in which Layer 2 does explicitly take the different grid constraints into account in its market clearing. As such, we have explored variations to the multilevel market to analyze possible methods to explore whether bids can be forwarded in a grid-safe manner, even when the subsequent, higher-level market cannot include all relative grid constraints of the local/regional grids in their market clearing. We have explored and compared three different approaches inspired by previous European projects, namely, the H2020 CoordiNet project, the H2020 Interrface project, and the H2020 SmartNet project. The first approach considers a corrective mechanism in which a third-layer market is introduced to the multilevel market to resolve any issues that can be caused by the clearing of the second market layer, as this second layer does not include first layer grid constraints. This approach is the least computationally demanding and is the one in most harmonization with most existing regulatory frameworks, as it enables the grid-safe procurement of flexibility using market mechanisms while limiting the external interference in the market process. However, our analysis showcased that this method would guarantee grid-safe solutions only when enough flexibility (liquidity) is available from distribution systems to enable the corrections of any network issues using the introduced third market layer. The second investigated approach constitutes a bid pre-qualification mechanism, in which, the first-layer operator (e.g., the DSO or the local market operator) implements a bid filtering processes aiming at filtering out bids, preventing them from being forwarded in case they are deemed to be risky for the local grids through a grid-check mechanism. The grid-safety level of this approach would naturally depend on the sophistication and precision of this grid-check method. In our numerical simulations, the developed grid-check method (driven by the nature of the grids and flexibility considered) has effectively performed the filtering process, resulting in grid-safe cleared bids, but which have resulted in possible suboptimal solutions (i.e., sub-optimal efficiency). Indeed, the level of guarantee of grid-safety of the forwarded bids depends on the nature of the systems involved and the submitted prices of the flexibility bids. Therefore, the approach is not guaranteed, in the general, sense to always provide a robust grid-safe mechanism, but in many practical situations, it can successfully achieve this goal. With respect to its level of harmony with current regulations, if bid filtering which is currently possible to TSOs can be considered also for DSOs, the approach can generally fit within the space of applicable regulations. The third investigated approach consists of a bid aggregation method, in which the first layer operator (DSO or local market operator) forms an aggregated step-wise bid curve (known as the residual supply function) to be offered to the second layer. Each step of this curve is computed taking the local grid constraints into account, so that when a step is chosen in the next market layer, local resources can be securely dispatched to deliver the required flexibility. In general, our analysis has shown that this bid aggregation method can result in obtaining grid-safe cleared bids and maximized efficiency if the step-wise function is properly derived in terms of step-sizes and properly priced. However, this method is computationally expensive, as it requires repeated market clearing runs to generate the required step-wise curves. Moreover, this method can also face regulatory challenges as it implies changes to the roles of the system operators (in particular, the DSO) as well as changes in aggregation mechanisms/rules (i.e., aggregating bids possibly submitted by different FSPs). Overall, our analysis has showcased that the forwarding of bids, even though can introduce potential risks due to potential violation of local grid constraints, can be beneficial if implemented adequately, as introduced and analyzed in the three investigated methods, since it can yield an increased efficiency of the markets as compared to the case of limiting FSPs to merely participate in their local markets.

Overall, our analysis has captured key elements highlighting the different advantages and disadvantages that each possible TSO-DSO coordination scheme and market mechanism can introduce, thereby providing key insights on their adequacy for implementation under different practical settings and scenarios.

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Annex A Product Attributes in OneNet

This annex presents a comprehensive description of the product attributes of OneNet, as defined in [3].

Attribute	Definition
Capacity / energy	This attribute determines whether the product accounts for the possible acquisition of capacity (in MW) or energy (in MWh).
Active / reactive power	Type of power that will be acquired by the SO.
Location information included	This attribute determines whether certain locational information needs to be included in the bid (e.g. identification of Load Frequency Control (LFC) area, congested area...).
Certificate of origin	This attribute determines whether the FSP would be required to deliver a certificate of origin of the energy they sell.
Level of availability	When there is uncertainty about the capacity of an FSP, this attribute would determine the percentage of time or the committed flexibility that the FSP would be able to deliver the product.
Symmetric / asymmetric product	This attribute determines whether only symmetric products or also asymmetric products are allowed. For a symmetric product upward and downward volumes have to be equal. For asymmetric products, upward and downward regulation volumes can be different. Two particular cases of asymmetric product are: • when either upward or downward regulation volume is set equal to zero (i.e. the product only covers downward or upwards offers). • When there is a rule linked upwards and downwards offers (e.g. upwards adjustment is 2/3 of downward adjustments).
Validity period of the bid	The period when the bid offered by the FSP can be activated, where all the characteristics of the product are respected. The validity period is defined by a start and end time. The duration should be, at least, the full delivery period of the bid but it could extend over longer periods of time.
Preparation period	The period between the SO request and the start of the ramping period.

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Ramping period	The period during which the input and/or output of power will be increased or decreased until the requested amount of power is reached.
Full activation time	The period between the SO activation request and the corresponding full delivery of the concerned product. This attribute is the result of adding preparation time and ramping time.
Delivery period	Period of delivery during which the service provider delivers the full requested change of power in-feed to, or the full requested change of withdrawals from the system.
Deactivation period	The period for ramping from full delivery to a set (pre-agreed) point, or full withdrawal back to a set point.
Recovery period	Minimum duration between the end of the deactivation period and the following activation.
Maximum number of activations	Maximum number of times a SO can activate an FSP during a period of time.
Mode of activation	The mode of activation of bids, i.e. manual or automatic. Automatic activation is done automatically during the validity period (with little or no direct human control), whereas a manual activation is done at the SO's request.
Quantity	The power (or change in power) offered and will be reached at the end of the full activation time. This quantity can be limited by a minimum and/or maximum amount of power to be included in a bid. The minimum quantity represents the minimum amount of power for one bid. The maximum quantity represents the maximum amount of power for one bid. These values could reflect technical constraints faced by the SO and/or the MO as well as the FSPs.
Divisibility	The possibility for a SO to use only part of the bids offered by the service provider, either in terms of power activation or time duration. A distinction is made between divisible and indivisible bids.
Granularity	The smallest increment in volume of a bid.
Maximum / minimum price	Maximum and minimum price the market operator accepts for the clearance of the market.
Availability price	Price for keeping the flexibility available (mostly expressed in €/MW/hour of availability).

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Activation price	Price for the flexibility actually delivered (mostly expressed in € /MWh).
Aggregation	This attribute determines whether a grouped offering of power by covering several units via an aggregator is allowed.
Baseline methodology	Methodology used to estimate the volume of energy delivered by an FSP compared to the case if the product would not have been activated.
Measurement requirements	This attribute describes the systems to be used to measure the unit traded as a result of the product.
Penalty for non-delivery	This attribute would determine the penalty that the FSP would face if they fail to deliver the energy agreed on the product.

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