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Market-Based TSO–DSO Coordination: A Comprehensive Theoretical Market Framework and Lessons from Real-World Implementations

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Abstract: This paper introduces a theoretical market framework (TMF) for conceptualizing and designing electricity markets, integrating transmission system operator and distribution system operator (TSO–DSO) coordination mechanisms. The TMF represents a comprehensive tool that formalizes new, innovative market concepts and their impact on existing markets, and outlines fundamental categories and decisions essential to market design. This paper, through the TMF, addresses the integration challenges posed by new mechanisms for system services. Utilizing the TMF, the study maps 13 European demonstrators' TSO–DSO coordination solutions, identifying real-world challenges in designing and implementing novel system services markets. Drawing on these real-world insights, the paper offers market design and policy recommendations to address and overcome the specific challenges in market-based TSO–DSO coordination.

Keywords: TSO–DSO coordination; real-world demonstrators; electricity market design; system services

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1. Introduction

The climate and policy goals driving the ongoing energy transition and decarbonization of our society call for the electricity sector to contribute through the massive use of renewable energy sources and energy efficiency [1]. With the considerable presence of intermittent energy sources and the need to maximize the use of existing infrastructure, it is increasingly important to adopt a more interactive approach to operating the electric power system [2]. Addressing the power system transformation at a reasonable cost, without harming the electricity supply security and quality, calls for unlocking the support from the already connected resources and fostering new resources availability [3–6]. In this context, cooperation and coordination among SOs are crucial for efficiently managing resources and infrastructures; nevertheless, the involved actors' coordination procedures must be carefully designed to strive for economic efficiency [7]. In order to promote investments in renewable energy sources (RESs) and enable coordinated procurement of system services by both DSOs and TSOs for secure system operation, efficient, integrated, coordinated, and scalable markets are essential in future power systems. These markets should include balancing services, non-frequency ancillary services, and congestion management services [8,9]. Ultimately, such markets aim to provide real choice for all end-customers and contribute to energy supply security and sustainability [10].

Market design is a complex task that encompasses the interplay of multiple markets and policy instruments [11–13]. The current market designs for electricity face barriers that hinder the efficient integration of renewable energy sources (RESs), leading to a slower and more expensive energy transition. Several studies in the literature have highlighted these barriers and proposed alternative market designs mainly focusing on wholesale electricity markets, capacity auctions for system adequacy, and balancing [11,14–23]. The identified hotspots mainly concern time and spatial granularity, market timing, market sequence, traded products, market power risks, and price settlement rules [11,15,17–19,24]. To outclass the identified challenges, a market architecture having a novel market sequence for electricity and balancing is proposed for Colombia [18], and improvements for the capacity markets of Chile, Brazil, and Europe are proposed in [14,19,21]. An alternative design for the European balancing market considering different timing is investigated in [20]. A novel market design for North America based on differentiating the wholesale transmission service and retail end-use service and introducing the concept of demand subscription service with fixed cost recovery is proposed in [23]. Auction design for congestion management markets is investigated in [16]. The reviewed proposals cover part of the entire electricity market architecture and consider the integration of large-scale RESs. The emergence of mid- and small-scale RES and new actors (i.e., prosumers, demand response customers, aggregators, and energy communities) and the operators' need for system services drive the creation of flexibility markets to engage them as FSPs. Hence, the consequent power system decentralization calls for integrating those markets into the entire electricity market architecture and enhancing TSO–DSO coordination.

To contribute to the design of integrated electricity markets, this paper proposes a theoretical market framework (TMF) for describing and designing innovative electricity markets. The TMF allows studying the market-based TSO–DSO coordination as well as the challenges of integrating the novel market mechanisms with existing energy and service markets. Regulatory frameworks, such as [10] promote market-based mechanisms for procuring system services, fostering the need for dedicated research on the market-based mechanism for TSO–DSO coordination. Previous work has been conducted on coordination between TSOs and DSOs. Researchers in [25] proposed five different service-agnostic coordination schemes (CSs) that define each system operator's roles and responsibilities when procuring and using system services provided by the distribution grid. This analysis was further extended by [26–28], who developed seven CS. Then, more specifically for the joint procurement of balancing ancillary services and congestion management services, [29] distinguished three market models for coordination while [30] identified five market design options. Finally, focused on congestion management, [31] describes TSO–DSO coordination under different systems states. However, while these papers and reports describe conceptual market designs concerning flexibility allocation, they do not describe the other market parameters and aspects that also need to be considered while designing a coordinated, integrated market, such as market optimization and operation options. Our framework attempts to fill that gap by adding several fundamental categories with possible choices that need to be made while designing a market, and hence defining a single and compact framework to support flexibility market design and analysis. Through the development of the TMF, the paper leverages 13 demonstrators' proposals to develop and test innovative market-based and technical mechanisms for TSO–DSO coordination. These proposals are framed within the European H2020 OneNet project, the largest project addressing TSO–DSO coordination to date [32]. The OneNet project core challenge is to unlock flexibility markets at all levels while considering and identifying the associated TSO–DSO operational challenges and proposing mechanisms to support the electricity system with flexibility services. In this context, 13 different market realities located all across Europe were assessed within the project demonstration activities.

The TMF proposed in this paper is adopted, within the OneNet project, to map the coordination schemes proposed by OneNet demonstrators to contribute to the definition of the building blocks for the demonstrator activities and, more importantly, to provide recommendations for the design of the novel European electricity market. Consequently, this mapping activity points out the real-world challenges of designing and implementing novel markets for system services. Moreover, it highlights and discusses market gaps, distortions, and inefficiencies that could arise when the novel markets are integrated into the existing electricity market architecture. The challenges that the paper describes regard structural aspects (e.g., number of sub-markets within a unique market architecture, size of the procurement areas, and roles and responsibilities of the market actors), coordination aspects (i.e., allocation of the available flexibility between buyers and sub-markets), optimization aspects (e.g., market optimization methodology and strategy, inclusion of the grid constraints), operational choices (e.g., remuneration schemes, clearing mechanism, timing of the procurement), and grid representation aspects (i.e., grid representation and corresponding market phases).

The main contributions of this paper can be summarized as follows:

1. Development of the TMF to formalize new, innovative market concepts and their impact on existing markets;
2. Application of this framework to the market design concepts proposed by the OneNet demonstrators;
3. Identification of real-world challenges of designing, implementing and integrating novel markets for system services into the existing market architecture.

The manuscript discusses the theoretical findings concerning TSO–DSO market-based coordination and the challenges emerging from the experience of the OneNet demonstrators. Moreover, it contributes to setting the basis for improving the evolution of the European electricity markets by providing recommendations on market design.

2. The Theoretical Market Framework

The TMF proposed in this paper aims to categorize market concepts, support the analysis of existing markets, and guide the design and integration of novel markets for procuring system services. Moreover, its adoption eases the communication of market concepts. The TMF describes and defines high-level coordination models and, more specifically, market architecture. In this paper, we consider electricity market architecture as the whole mechanism that allows the exchange of electricity products to operate a delimited power system (e.g., a country's power system). The concept of market architecture is further addressed in Section 3; more specifically, the TMF relies on the concept of interaction, and the set of interactions in the market architecture defines the coordination between actors. The TMF assumes the entire market architecture is composed of sub-markets that may interact, with the following definition for sub-markets: "a sub-market is assumed to be operated by one market operator responsible for the market-clearing of this specific market according to a specific objective" [33].

Following the experience of OneNet project demonstrators, the framework focuses on the market-based mechanisms to procure system services in which TSOs and DSOs are the primary buyers of system services. As shown in Figure 1, the framework consists of five pillars composed of different features. These pillars are the following: (i) entire market architecture, (ii) sub-market coordination, (iii) market optimization, (iv) market operation, and (v) grid representation. The first two pillars set up the entire market structure and define the coordination type, while the last three pillars describe the market clearing dimensions. Some features apply to the entire market to represent how the coordination and integration perform, while others apply to the individual sub-markets. Going through each pillar and selecting the desired attribute for each feature, the system service markets are designed while considering the context requirements. In what follows, each pillar is described in more detail.

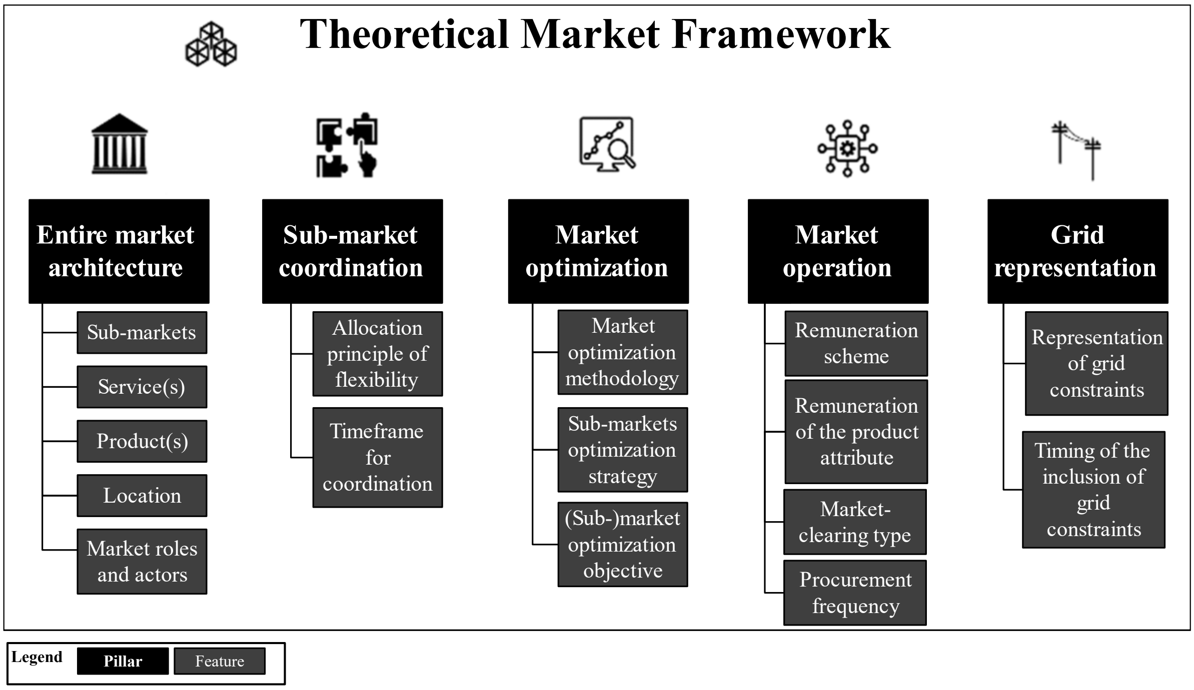

Figure 1. Key elements of the theoretical market framework.

2.1. Entire Market Architecture

The entire market architecture pillar is formed by five features: sub-markets, services(s), products(s), location, and market roles and actors. In Appendix A, Figure A1 depicts the structure of the entire market architecture pillar describing features, sub-features, and options.

The 'sub-markets' feature of the entire market architecture pillar applies to the entire market and describes the following attributes: the 'number of sub-markets'; the 'timing of the sub-markets' (i.e., when these sub-markets take place) which captures the temporal linkage between different sub-markets; and the sub-market type (i.e., the type of market-based solution) used to acquire flexibility (e.g., bilateral negotiation, auction, or exchange market).

The features service(s) and product(s) apply to each sub-market and concern the specific marketed product(s) (i.e., "a tradable unit that the network operator acquires from the flexibility providers and that entails the option to deliver a service in case of activation') and service(s) (i.e., 'the action, generally undertaken by the SO, which is needed to mitigate a technical scarcity or scarcities that otherwise would undermine network operation and may create stability risks") [34].

Similarly to service(s) and product(s), the feature 'location' is applied to every single sub-market. The 'level of spatial granularity' measures the size of the specific independent areas considered for flexibility procurement. In power systems, locational granularity can be in terms of nodes, voltage levels, and feeders. Then, for each market, the 'responsible SO' must be defined, i.e., the actor who takes up the role of SO. Finally, the voltage level(s) where flexibility is procured needs to be defined for each sub-market.

The fourth feature looks at 'market roles and actors' involved in each sub-market. It defines the actors who buy and sell flexibility and who take up the role of MO. In addition, it defines whether participation in the sub-market is optional, compulsory, or hybrid. Optional participation means that FSPs can choose to participate in the sub-market. Compulsory means that under certain circumstances, certain parties might be obligated to participate in the sub-market. For instance, in Italy, generators larger than 10 MW are obligated to participate in the ancillary services market. However, new sources of flexibility are also allowed to voluntarily participate in that same market [35]. In this case, participation is compulsory and optional, hence hybrid.

2.2. Sub-Market Coordination

The features in the sub-market coordination pillar are the allocation principle of flexibility and timeframe for coordination. In Appendix A, Figure A2 shows the structure of the sub-market coordination pillar depicting features, sub-features, and possible options.

The feature 'allocation principle of flexibility' of the sub-market coordination pillar determines how the amount of flexibility at the transmission or distribution level is divided between SOs and sub-markets. Hence, the allocation principle does not apply as one principle to the entire market, but forms a link between two sub-markets. Moreover, the allocation principle only applies when (i) resources are procured in the same time window, (ii) from both the transmission and distribution grid or distribution grid only, and (iii) by different SOs. When these conditions do not apply, the SO who needs flexibility has the exclusive use of this flexibility. In the TMF, we distinguish five options for 'system operator order' which are related to the 'commitment to bid selection' and the 'TSO access to DERs'. First, 'priority for the TSO' means that the TSO is the first to choose the sources of flexibility (at distribution or transmission level). Commitment to bid selection is formal, signifying that the offered flexibility can be used by the SO while respecting the constraints of the other SOs whose grid might be impacted. Therefore, formal commitment to bid selection implies the selection of the bids by the buyer (e.g., an SO), independent if, from a welfare perspective, it would be more beneficial to let another SO use the bids for another purpose. Additionally, bids are forwarded to other sub-markets as the TSO has priority but no exclusive use over the bids. A second option is 'priority for the DSO,' meaning that the DSO is the first to choose. These sources are located at the distribution level only. There is a formal commitment to bid selection. Bids can be forwarded to other sub-markets. The third option, 'exclusivity for the TSO', denotes that the TSO is the only one with access to the bids. Commitment to bid selection is formal, and rejected bids are not forwarded. Similarly, the option' exclusivity for the DSO' implies that the DSO is the only one with access to the bids, with a formal commitment to bid selection and no forwarding of rejected bids. The final option, 'no priority nor exclusivity for TSO or DSO', implies a conditional commitment to bid selection in a decentralized optimization (i.e., more than one sub-market) and a formal one in a centralized optimization (i.e., only one sub-market).

Conditional commitment refers to the fact that a particular local market with local grid constraints is run first, but without any formal commitment to the market participants. The preliminary results are then shared with the TSO market and integrated into a second market optimization that considers the system objectives. Based on the outcome of that second optimization, the local market is informed about the accepted bids and for whom (for the DSO or the TSO) [25]. For clarity purposes, this paper describes the TMF under the hypothesis of having one DSO and one TSO at the national level. For scenarios in which several local DSOs are connected to a regional DSO, and hence one additional layer exists (e.g., Sweden, Germany), the same principles apply to the relation between the local DSO and regional DSO and the relation DSO-TSO.

'Forwarding of bids', as proposed in [36], refers to transferring eligible bids not utilized in one market to another. This transfer may occur via an intermediary processing step managed by a designated agent.

The 'timeframe for the coordination' feature notes in which market phase of each sub-market the coordination will take place, i.e., prequalification, procurement, activation, measurement, activation, and settlement control.

2.3. Market Optimization

The market optimization pillar entails as features: market optimization methodology, sub-market optimization strategy, and (sub-)market optimization objective. In Appendix A, Figure A3 deals with the structure of the market optimization pillar.

The first feature of the market optimization pillar is the 'market optimization methodology' which describes the different options for market optimization between two sub-markets. We distinguish three possibilities, i.e., centralized and decentralized optimization, and distributed organization. In centralized optimization, one algorithm considers all voltage levels, including transmission and distribution. Therefore, one optimization for all SOs solves all their system needs. In decentralized optimization, several algorithms optimize for different levels, i.e., at least one for the transmission and one for the distribution levels, and require coordination. There is one optimization for each SO to procure its system needs. Then, coordination is needed between the different optimization levels. In a distributed market organization, there is no (externally driven) optimization [37].

The 'sub-market optimization strategy' feature looks at the market optimization applied to couples of sub-markets. This happens, for instance, in the case of more than one sub-market, or when one sub-market procures two products through separate optimization schemes. In simultaneous optimization, both sub-markets are optimized simultaneously while sharing resources. Sequential optimization means that one market is optimized before the other. Independent optimization means that markets are cleared simultaneously (i.e., in parallel, rather than jointly) while only sharing some clearing constraints (if needed) rather than sharing resources (i.e., bids).

The third feature is the '(sub-) market optimization objective'. Sub-markets can be optimized according to social welfare maximization or other objectives, such as reducing counter-activations. Maximizing social welfare means maximizing the producer (i.e., FSP) and buyer (i.e., SO) surplus. Markets may also have other objectives, such as reducing the counter-activations from another market, for instance, congestion management after the energy market.

2.4. Market Operation

The features of the market operation pillar are the following: remuneration scheme, remuneration of the product attribute, market-clearing type, and procurement frequency. In Appendix A, Figure A4 presents the structure of the market operation pillar showing the potential design options.

The first feature of the market operation pillar is the 'remuneration scheme'. Six options can be distinguished: no remuneration, negotiated price, pay-as-bid, uniform pay-as-clear, non-uniform pay-as-clear (i.e., nodal pricing), and cost-based remuneration. When the trade happens through bilateral negotiation, the price is negotiated. The remuneration method 'pay-as-bid' (i.e., discriminatory price auction) implies that each seller receives payment for the offered good or service equal to the requested selling price. Hence, the market price is different for each market participant if they bid at different prices [38]. The 'uniform pay-as-cleared' remuneration (i.e., uniform price auction) implies that all sellers receive the same per-unit price for the offered homogenous good or service which is equal to the lowest accepted bid, regardless of the sellers' actual selling price. Therefore, the market price is at the intersection of supply and demand curves, which also sets the cleared quantity, i.e., the traded volume [38,39]. Then, 'non-uniform pay-as-cleared' refers to nodal pricing, which method determines different clearing prices for the different grid nodes. The nodal price reflects energy's locational value, including energy and delivery costs (i.e., losses and congestion) [40]. Finally, remuneration is cost-based when based on a determined price or price curve the SO sets for buying a service and potentially agreeing with the FSP on the specified quantity [38]. It is important to note that the FSP may not be remunerated at all in case of mandatory requirements.

The second feature describes the 'remuneration of the product attribute'. Remuneration can be for availability, activation, or both, and for active, reactive, and apparent power.

The third feature looks at the 'market-clearing type'. In a continuous market, a market participant can buy and sell assets at any given time when the market is open. Following a discrete auction, market clearing is a recurring, scheduled, frequent batch auction market where the respective market is cleared at discrete intervals (e.g., each quarter-hour) through a uniform auction [26].

The 'procurement frequency' feature refers to how often the sub-market is run. The difference with the timing of the sub-markets is that, while the procurement frequency can be identical for different markets, they can still have different timing or GCT. For example, in Belgium, the FCR, aFRR, and mFRR capacity (availability) markets have a daily procurement frequency. However, the GCT of the FCR market is planned before that of the aFRR market, and the GCT of the aFRR market is planned before the one of mFRR market.

2.5. Grid Representation

The grid representation pillar includes the features representation of grid constraints and timing for the inclusions of grid constraints. In Appendix A, Figure A5 shows the structure of the grid representation pillar highlighting the possible design options.

The first feature in the grid representation pillar describes how the 'representation of grid constraints' is addressed. EU-SysFlex distinguishes three possible ways to represent grid constraints [37]. First, comprehensive grid data describes the electrical properties of the grid to depict its dynamics. This way, the optimization algorithm can calculate diverse grid phenomena and complete power flow calculations. Secondly, partial grid data uses the sensitivities of flexibilities towards critical V/I constraints and V/I margins in the grid, e.g., for one topology. Thirdly, bid limitations only are used when the SO reduces or rejects bids which, if accepted as submitted, would cause grid constraints to be violated. Bid limitations can be sent after a pre-selection step or before the selection led by the optimization operator responsible for selecting bids (clear the market or choose in an order book), considering grid data and switching measures [37]. The feature timing of the inclusion of grid constraints refers to the market phase in which grid constraints are included.

3. Application of the Theoretical Market Framework to the OneNet Demonstrators

The proposed TMF is used in this paper to describe the OneNet demonstrators' market architecture to support identifying the corresponding gaps and strengths. The TMF is a tool for bottom-up market architecture analysis and design. Starting from the description of every single market-based interaction, the TMF allows for a comprehensive description of the entire market architecture. This section describes the application of the TMF to OneNet demonstrators. This section provides proof of concept of the application of the TMF. The application of the TMF to the OneNet demonstrators follows the following five steps:

1. Identification of buyer–seller interactions;
2. Definition of sub-markets of the market architecture;
3. Description of each sub-market using the TMF features;
4. Description of the interactions between sub-markets using the TMF features;
5. High-level description of the market architecture.

System service procurement and provision require coordinating the power system actors involved (i.e., TSO, DSO, and FSP). The TMF studies this coordination by relying on the interaction concept since the set of interactions in the market architecture defines the coordination between actors. The interaction between provider and beneficiary can be classified as technical-based or market-based. As shown in Figure 2, in market-based interactions, the actors interact through a market architecture which may include the interaction with the actor that plays the market operator and, eventually, the market platform. The technical-based interaction is characterized by information exchange and control actions. These interactions are facilitated by a technical architecture, including interoperable platforms, communication protocols, etc., whose complexity may vary. This paper focuses on market-based coordination, hence, on the set of market-based interactions tested in the OneNet project.

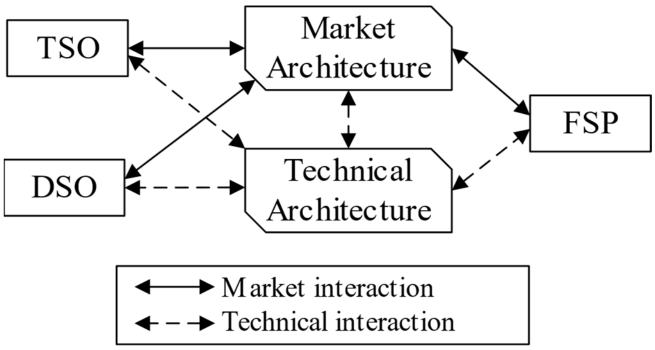

Figure 2. Scheme of the possible interactions between the actors involved in system service procurement and provision.

3.1. Procedure Adopted to Analyze the OneNet Demonstrators Using the TMF

The TMF starts analyzing the single buyer–seller interactions to describe the overall market architecture. Therefore, it constitutes a bottom-up approach to market design and analysis. As a first step, the market architecture's analysis (or design) requires studying the buyer–seller interactions in terms of generalized products (e.g., P, Q, availability, activation) and timing. More specifically, the identification and analysis of the market seller interactions part of the OneNet demonstrators is addressed considering the business use cases (BUCs) defined according to the standardized IEC 62559 methodology and described through the corresponding template [41]. In the second step, the sub-markets that form the market architecture are identified and located considering the buyer and temporal dimensions. The sub-markets are characterized by market-based interactions that differ in terms of actors involved, generalized products, and timing. The necessary information for accomplishing the second step has been obtained from the BUCs description and complemented through consultation moments with demonstrators' partners. Based on the information collected in the previous steps, the third step is devoted to processing the information to formalize a detailed description of each sub-market through the TMF features that apply to sub-markets individually (e.g., procurement frequency, responsible system operator). Similar to Step 3, in Step 4, the interaction between the couples of sub-markets is characterized in terms of TMF features (e.g., allocation principle of flexibility). Hence, in Steps 3 and 4, the collected information is organized into tables based on the pillars and the corresponding features that form the TMF, as defined in Section 2. These tables are tools for addressing the TMF-based analysis, and once filled, they represent the database that contains all the necessary information to describe the market architecture. Section 3.2 reports an excerpt of the TMF tables adopted for analyzing the OneNet demonstrators.

Moreover, the obtained TMF description can be represented graphically; Figure 3 depicts the outcome of applying Steps 1 to 4 of the TMF described in Section 2 to the OneNet demonstrators' market proposals. According to the TMF, Figure 3 describes the market architecture considering the allocation of flexibility according to the temporal and buyer dimensions. The temporal dimension describes the sequence of sub-markets, hence, the temporal allocation of flexibility from long-term to near-real-time. The buyer dimension describes the allocation of flexibility between the buyers. Hence, the outcome of Steps 1 to 4 allows transposing the market-based interactions into a market architecture formed by sub-markets that interact. Finally, to complement the TMF application and generalize the obtained description, elements from a top-down perspective are introduced in the fifth step, the outcome of which is depicted in Figure 4. This paper maps the TMF representations of the OneNet project demonstrators' market architectures towards the corresponding coordination schemes, as defined in the CoordiNet project [26,28].

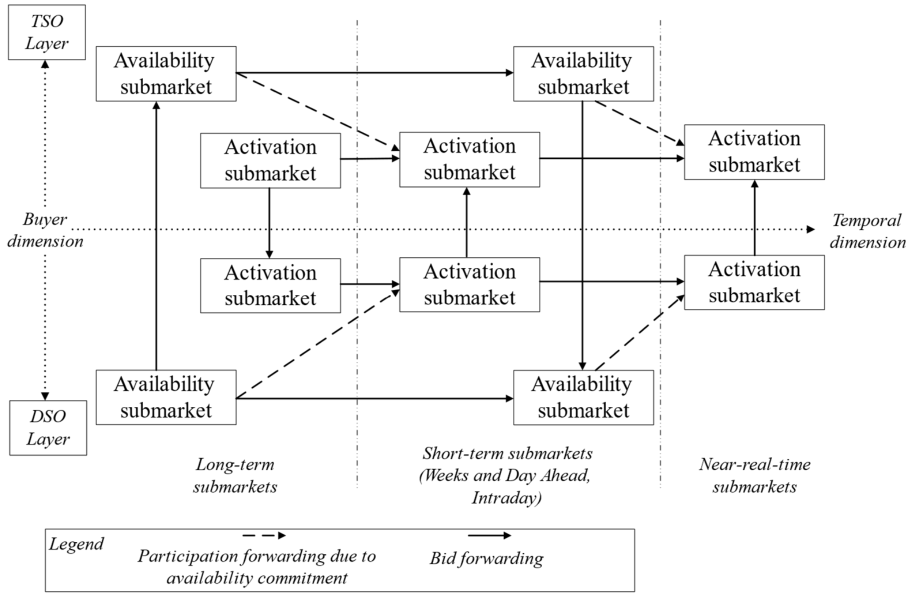

Figure 3. Generalized market architecture for the OneNet demonstrators described according to TMF.

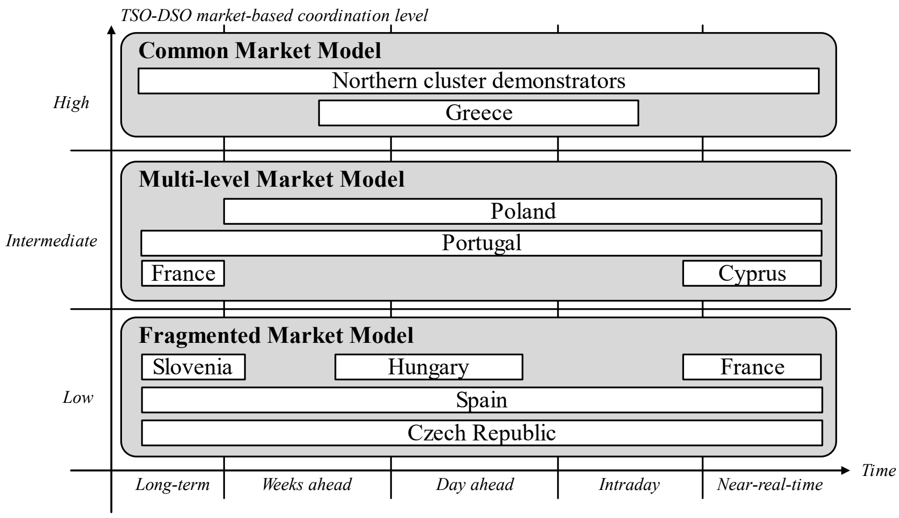

Figure 4. Market architectures of OneNet demonstrators in terms of TSO–DSO coordination schemes.

Figure 3 shows a generalized example of bidirectional interactions along the buyer dimension (i.e., the DSO sub-markets that trigger the TSO sub-markets and vice-versa); both directions can be described using the TMF. Figure 3 depicts the case where the buyers (TSO and DSO) act as single buyers in each sub-market. However, the TMF can also effectively describe the cases in which TSO and DSO are buyers in the same sub-market (common sub-market), as the two layers collapse in a single TSO–DSO layer; hence the common sub-market then holds on the horizontal axis shown in Figure 3. If all sub-markets of the market architecture have both TSO and DSO as buyers, the vertical axis collapses. Figure 3 shows that considering the generalized products exchanged, the market architecture is formed by two types of sub-markets: the availability and activation sub-markets. The availability of sub-markets can be linked to the activation ones with an interaction (dotted arrow) that commits the participants in the former to also participate in the latter. The bid forwarding interaction (full arrow) links sub-markets of the same type. Figure 3 describes the generalized market architecture of OneNet demonstrators; each specific market architecture adopted by the OneNet demonstrators can be obtained by customizing the diagram (deleting sub-markets and interactions, specifying common sub-markets).

Finally, according to Step 5 of the methodology adopted, a top-down descriptive approach is used to characterize the market architecture in terms of the global characteristics of the TSO–DSO coordination and complement the market architectures' description (the aforementioned Step 5). In this paper, the approach proposed in [26,28,29] is used to classify the OneNet market architectures analyzed through the TMF in terms of coordination schemes. Figure 4 depicts the outcome of this step concerning the OneNet demonstrators; each country block represents the corresponding market architecture obtainable from Figure 3. Figure 4 also describes the market architectures in terms of the timing of the TSO–DSO coordination and the corresponding level of market-based coordination. As a result, the OneNet demonstrators belong to three different market models that define specific TSO–DSO coordination schemas: common, multi-level, and fragmented [25–29]. The common market model defines a single TSO–DSO market to procure system services from resources connected to transmission and distribution grids. Unlike the common market model, the multi-level market model distinguishes the markets for TSO and DSO, where the TSO has access to DERs. In the fragmented market model, TSO and DSO have dedicated non-linked markets, the TSO does not have access to DERs.

Figure 4 shows that the northern and Greek demonstrators implement the common market model. The Polish, Portuguese, Cypriot, and French (for LT) market architectures implement a multi-level market model. The common and multi-level market models include both market-based and technical-based TSO–DSO coordination. The Hungarian, Slovenian, Spanish, Czech, and French demonstrators proposed a fragmented market architecture. For clarity, the following paragraphs describe the TMF application to the market architectures demonstrated in the OneNet project.

3.2. TMF Analysis of the Northern and Polish Demonstrators' Market Architectures

To present the capability of TMF, the Polish and northern OneNet demonstrators (The Polish and northern OneNet demonstrators are described in detail in deliverables D7.1, D7.2, D7.4, D10.2, D10.3 [32]) are discussed in more detail to present how the TMF applies to market architectures characterized by a market-based TSO–DSO coordination based on opposing design principles. Figures 5 and 6, respectively, represent the application of the TMF to the northern and Polish demonstrators. These figures depict the market architecture of the demonstrators mentioned; they represent a particularization of the generalized market architecture in Figure 3. Table 1 reports the nomenclature used in this paper to describe the sub-markets of the analyzed demonstrators. Moreover, Table 2 contains an excerpt of the tables used to elaborate the TMF description of the market architectures of the OneNet northern and Polish demonstrators.

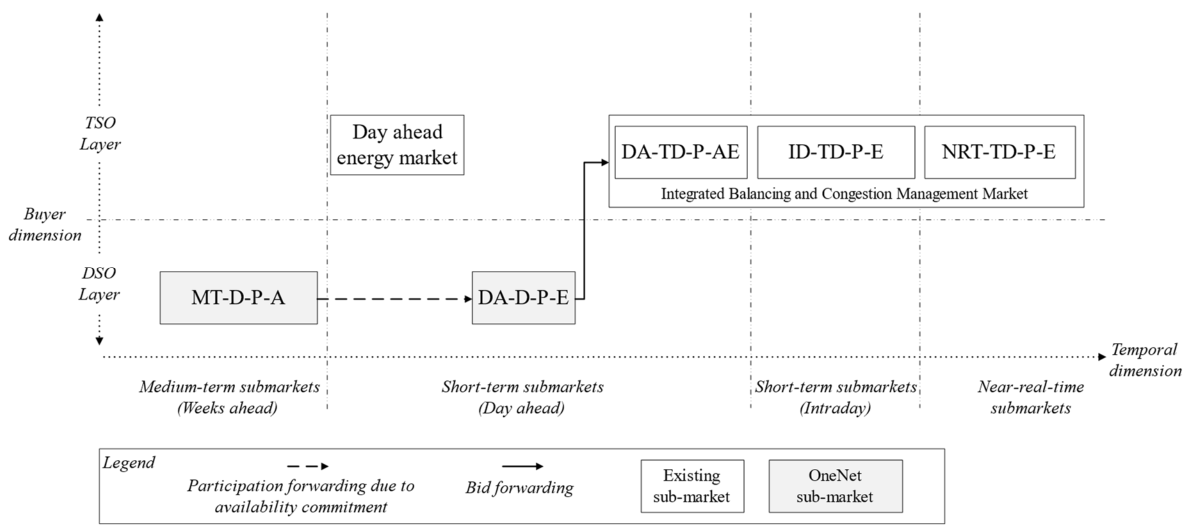

Figure 5. Schematic representation of the market architecture for the Polish demonstrator.

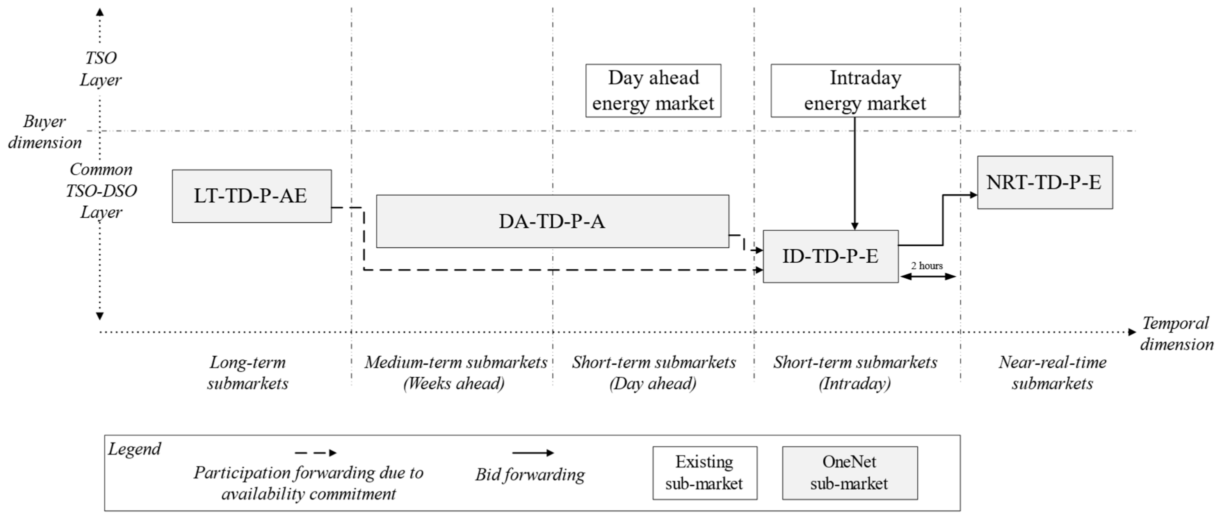

Figure 6. Schematic representation of the market architecture for the northern demonstrator.

Table 1. Nomenclature adopted for naming the sub-markets.

Element	First	Second	Third	Fourth
Meaning	Timing (considering gate closure time)	Grid connection of service providers	Electric variable of the product traded	Generalized product traded
Options	LT (Long-term)	T (Transmission)	P (Active power)	A (Availability)
	MT (Medium-term)	D (Distribution)	Q (Reactive power)	E (Activation)
	DA (Day-ahead)	TD (Transmission and distribution)	PQ (Active and reactive power)	AE (Availability and activation)
	ID (intraday)			
	NRT (Near-real-time)			

Table 2. 'Entire market architecture' pillar applied to OneNet demonstrators.

Attribute	Polish DA-D-P-E	Polish DA-TD-P-AE	Northern LT-TD-P-AE	Northern ID-TD-P-E	Northern NRT-TD-P-E
Feature: Sub-market dimension					
Timing of the sub-markets	Day-ahead	Day-ahead	More than month ahead, event-based	From weeks ahead to intraday	Near-real-time
Sub-market type	Auction market	Auction market	Auction market	Auction market	Auction market
Feature: Service(s)					
Service	Congestion management, voltage control	Congestion management, frequency control	Service agnostic	Congestion management, frequency control	Congestion management, frequency control
Feature: Product(s)					
Product procured	Active power activation	Active power activation	Active power availability and activation	Active power activation	Active power activation

Table 2. *Cont.*

Attribute	Polish DA-D-P-E	Polish DA-TD-P-AE	Northern LT-TD-P-AE	Northern ID-TD-P-E	Northern NRT-TD-P-E
Feature: Location					
Level of spatial granularity	Distribution grid	National, transmission grid distribution grid interface nodes	National, transmission grid distribution grid	National, transmission grid distribution grid	National, transmission grid distribution grid
Responsible system operator	DSO	TSO	TSO, DSO	TSO, DSO	TSO, DSO
Voltage level for resources	MV, LV	HV, MV, LV (frequency control only)	HV, MV, LV	HV, MV, LV	HV, MV, LV
Feature: Market roles and actors					
Who is the buyer(s)	DSO	TSO	TSO, DSO	TSO, DSO	TSO, DSO
Who is the seller(s)	FSP	FSP	FSP	FSP	FSP
Who is the MO	DSO	TSO	DSO, TSO, IMO	DSO, TSO, IMO	DSO, TSO, IMO
Participation in sub-market	Hybrid	Hybrid	Optional	Hybrid	Optional

The proposed Polish demonstrator's market architecture has a multilayer TSO–DSO structure. As generalized by Figure 3, TSO and DSO are alternatively the only buyers in the sub-markets belonging to the respective layer; several sub-markets form each layer that spans from weeks ahead to near-real-time, as shown in Figure 5. The OneNet sub-markets are the new ones developed in the project: the MT-D-P-A and the DA-D-P-E (colored in grey). Both sub-markets have the DSO as the only buyer and the resources connected to the distribution network are allowed to bid. The generalized product of the MT-D-P-A is active power availability (i.e., capacity), while the DA-D-P-E deals with active power activation (i.e., energy). The capacity bids cleared in the first market determine the obligation to participate with energy bids in the second market. The leftover bids of the DA-D-P-E are forwarded to the integrated balancing and congestion management market through a bid filtering and aggregation process that considers the DSO grid constraints compliance, the point of connection of the resources, and the bid characteristics.

The northern demonstrator, on the contrary, proposes a common TSO–DSO market architecture in which all sub-markets involve both the TSO and DSO as buyers. Hence, considering Figure 6, a common TSO–DSO layer characterizes the market architecture of the OneNet demonstrator. As depicted in Figure 6, the sub-markets in the market architecture of the northern demonstrator span from long-term to near-real-time procurement. The OneNet sub-markets developed by the northern demonstrator are colored in grey in Figure 6. In all these markets, both the TSO and DSO are buyers, and all the resources connected to the transmission and distribution grid can participate. The LT-TD-P-AE submarket is a long-term submarket in which the resources submit active power availability bids (i.e., capacity) with an active power activation (i.e., energy) price. The DA-TD-P-A is a day-ahead sub-market concerning the active power availability product, while ID-TD-P-E and the NRT-TD-P-E are respectively an intraday and a near-real-time sub-market in which active power activation products are exchanged. As shown in Figure 6, the sub-markets concerning availability products determine for the cleared bids the participation forwarding towards the related sub-markets dealing with activation products. Moreover, bid forwarding exists among the intraday energy market, ID-TD-P-E and NRT-TD-P-E sub-markets.

For brevity, the main aspects of the market architecture characterizing the Polish and the northern demonstrators are presented in the following the TMF pillars and features. This section focuses on a set of sub-markets and interactions; this set has been selected to describe the greatest variety of circumstances observed in the OneNetžlinebreak demonstration activities.

Considering the Polish demonstrator, the first sub-market of interest is the DA-D-P-E, the second sub-market considered is the DA-TD-P-AE sub-market of the integrated balancing and congestion management market which takes place DA and includes bids from resources from transmission and distribution grids (TD). From the northern demonstrator, the sub-markets described in this paper are the LT-TD-P-AE, the ID-TD-P-E, and the NRT-TD-P-E.

For brevity, only the application of the most significant pillars is discussed in this paper; details can be found in OneNet deliverable 3.1 [42] and updated in OneNet Deliverable 11.2. Table 2 describes the three selected sub-markets in terms of the features and attributes defined by the corresponding TMF pillar outlining the structural aspects that characterize the selected sub-markets pointing out similarities and differences.

As shown in Table 2, all sub-markets are auction markets in which active power activation is procured to address different operational issues. The three sub-markets encompass different market areas considering the power system (i.e., distribution, transmission, and distribution and transmission), buyers, sellers' participation, and market operators (MO). While in the Polish demonstrator, the MO role is assigned to the relevant SO, in the case of the northern sub-market, the MO role can be assigned to the TSO, DSO, or an independent MO if available in the sub-market area. It is worth mentioning that discussing the role assignment task performed by the demonstrators is out of this paper's scope. Table 3 shows the TMF application to the linkages between the sub-markets that form one market architecture through the features of the market optimization and sub-markets coordination pillars. More specifically, it describes the linkage between the Polish demonstrator's sub-markets and the linkage between the northern demonstrator's sub-markets described in this paper.

Table 3. TMF sub-market linkage applied to OneNet demonstrators.

		Polish Demonstrator	**Northern Demonstrator**	**Northern Demonstrator**
Sub-markets	A	DA-D-P-E	Intraday energy	ID-TD-P-E
	B	DA-TD-P-E	ID-TD-P-E	NRT-TD-P-E
Market optimization pillar				
Feature: Market optimization methodology		Decentralized	Centralized	Centralized
Feature: Sub-markets optimization strategy		Sequential	Simultaneous	Sequential
Sub-markets coordination pillar				
Feature: Allocation principle of	Forwarding of bids	Yes (only for frequency control)	Yes (only for congestion management)	Yes
	Commitment to bid selection	Conditional (forwarded bids are aggregated)	Conditional (bids with locational information)	Formal
	System operators order	Priority for DSO	No Priority	No Priority

Considering the market optimization pillar, the Polish demonstrator's sub-markets in Table 3 show a decentralized optimization methodology since the procurement of system services is addressed first at the local level, prioritizing the DSO. On the contrary, the sub-markets of the northern demonstrator are characterized by a centralized procurement of system services. Concerning the optimization methodology, the two Polish sub-markets are optimized (i.e., cleared) sequentially; conversely, the northern demonstrator's sub-markets are simultaneously optimized. Considering the sub-market optimization pillar, the feature concerning the overall allocation principle of flexibility is discussed. In the Polish demonstrator's sub-markets, the bids are forwarded from the local market (DA-

D-P-E) to the national one (DA-D-P-E). In the latter, the forwarded bids can only be used for energy balancing services. The commitment to bid selection is conditional since the bids are forwarded in an aggregated way with a prior distribution grid constraint check. The aggregated bids represent a balancing offer at the TSO–DSO coupling point that does not endanger the operation of the DSO network. As described in Table 3, the Polish demonstrator's sub-markets linkage prioritizes the DSO in allocating flexibility. Moreover, Table 3 shows that the sub-markets linkage in the northern demonstrator's market architecture regards the intraday energy market and the short-term congestion management market (ID-TD-P-E). A centralized market optimization methodology is adopted while the two sub-markets are simultaneously optimized. The ID-TD-P-E and NRT-TD-P-E sub-markets linkage is characterized by a sequential optimization strategy since the ID-TD-P-E closes before forwarding the leftover bids to the NRT-TD-P-E submarket. Considering the sub-market coordination pillar, the bids submitted to the intraday energy market are also made available for the ID-TD-P-E sub-market if they include locational information. Consequently, those bids can also be used for congestion management in addition to those already submitted to the ID-TD-P-E sub-market only. Hence, the intraday energy market and the ID-TD-P-E sub-market share a set of bids: the former is a continuous trading market, while the latter is an auction market with a GCT of 2 h ahead of the activation time. In this case, bid forwarding is conditional since it requires the bids to include locational information, the grid constraints compliance check, and a checking process involving the market platforms to ensure the uniqueness of bid selection among the sub-markets and avoid double clearing. The bid forwarding that links the ID-TD-P-E and NRT-TD-P-E sub-markets is formal since no procedures are required to transfer the bids across the sub-markets. The in-depth analysis of the formal and conditional bid forwarding characteristics for the analyzed market architectures is out of this paper's scope and is part of further research within the OneNet project in OneNet Deliverables 3.3 and 11.2.

Regarding the overall allocation principle of flexibility between the intraday energy and the ID-TD-P-E sub-market, the linkage features in Table 3 show no priority or exclusivity for TSO or DSO. Tables 2 and 3 prove the TMF capability to capture the characteristics of the sub-markets delivering a concise but comprehensive market aspects description. Moreover, the TMF adoption allows for an effective comparative analysis of different sub-markets. In particular, the analysis based on the TMF allows observing the OneNet market architectures from different dimensions: time allocation of flexibility, buyer allocation of flexibility, and TSO–DSO interaction level.

Overall, the two demonstrators' market architectures described in this paper differ despite the common ambition of achieving liquid markets for system services. Implementing specific design choices depends on the specific ambitions and boundary conditions [38]. Both demonstrators aim to achieve a high level of liquidity thanks to the market scope and trading volume. It is worth nothing that, as stated in [43] the liquidity concept is slippery and elusive, mainly because it includes a number of transactional properties of the market. In [44] in financial markets, liquidity considers three dimensions: tightness, depth and resiliency. Tightness refers to the cost of turning a position over a short time; it is referred to transaction costs and usually measured with the bid-ask spread. Depth refers to the size that the bid order flow requires to change prices. Resiliency indicates the speed at which prices recover from shocks. Therefore, if positions in the market can be changed with small changes in prices and prices can be recovered from shocks then the market are called liquid. High trading volumes and competition can contribute to high liquidity levels. The demonstrators unlock DERs' potential by creating multiple business opportunities for DERs. The northern demonstrator aims to integrate local and national markets in one cross-border market architecture involving multiple TSOs and DSOs. Therefore, DERs will provide system services to multiple system operators to solve cross-border needs. The Polish demonstrator aims to enhance the TSO–DSO cooperation at the national level by enabling DERs to support the power system operation. Participation in the balancing market contributes to increase the liquidity in local markets.

It is worth noting that in the OneNet demonstration activities, to avoid interfering with the existing electricity market functioning, the Polish demonstrator considers an emulated integrated balancing and congestion management market, while the northern demonstrator considers an emulated intraday energy market. However, the analysis presented in this paper conceptually extends the boundaries determined by the limits imposed on the demonstration activities that, by definition, have demonstrative scope.

The TMF assists in evaluating and comparing market design choices which insights can inform policy decisions, guide market reforms, or shape the development of new market architectures. Table 4 resumes and compares the OneNet Polish and northern demonstrators market designs based on the TMF pillars.

Table 4. Comparison of the TMF application to the OneNet Polish and northern demonstrators considering the TMF pillars.

	Polish Demonstrator	Northern Demonstrator
Entire market architecture	Multi-layered TSO–DSO market architecture for congestion management and voltage control with active power activation products.	Common TSO–DSO market architecture characterized by service-agnostic products for congestion management and frequency control with active power activation and availability products.
Sub-market coordination	Forwarding of bids from local to national market with priority to DSO for flexibility allocation. Bid forwarding considers aggregation with grid constraint check.	Bids from intraday energy markets can be forwarded to other markets if bids include locational information and pass grid constraints check. No priority to TSO or DSO for flexibility allocation.
Market optimization	Decentralized optimization with sequential strategy. The local market (DA-D-P-E) has priority, bids may be forwarded to the national level (DA-TD-P-AE).	Centralized market optimization and simultaneous markets optimization. Bid sharing between intraday energy market and other sub-markets, given certain conditions.
Market operation	Day-ahead operational procedures with specific auction mechanisms for congestion management and voltage control.	From long-term to near-real-time, with auction mechanisms for multiple services.
Grid representation	Grid constraints check at the DSO level with detailed representation of grid. Forwarded bids undergo aggregation considering DSO grid constraints.	Bids including locational information are checked for grid constraints compliance. Moreover, bid forwarding and selection checks the uniqueness of bids among sub-markets to prevent double clearing

Overall, the Polish demonstrator's design offers a localized approach with multiple layers and DSO priority, which might be more suitable for regions with distinct local challenges but may face sub-optimal allocation of resources when integrating with broader grids. While the northern demonstrator's design which could be more efficient for regions aiming for wider grid integration but that might overlook specific local needs. The modular approach of the Polish demonstrator design has a reduced need for data sharing between TSO and DSOs and implementation complexity. The northern demonstrator presents an integrated design that requires joint TSO–DSO operations and increased data sharing requirements.

4. Real-World Challenges of Implementing TSO–DSO Market-Based Coordination

In OneNet project activities, the TMF application has supported and encouraged market design through an iterative process. Furthermore, the application of the TMF to the OneNet demonstrators, thanks to the process of translating the demonstration activities into the TMF-based description by checking every feature that forms the TMF pillars (see Section 3.1), allowed us to identify the challenges for the real-world implementation of a market architecture devoted to system service procurement. In fact, each TMF feature represents a design aspect to be defined when devising a market architecture; these design aspects are not independent; mutual influence exists, as noticeable in the discussion in this section. The TMF application points out similarities and differences among the different market architectures proposed in OneNet. The process described in Section 3.1 of formalizing the market architectures according to the TMF pillars and features led us to discover a non-exhaustive (and non-prioritized) set of real-world challenges concerning the design of integrated TSO–DSO markets. Basically, each TMF feature has different options; in the addressed market design and analysis process, the pros and cons of the different solutions are assessed, leading to the identification of the challenges that characterize the deployment of TSO–DSO market-based coordination in the real world. Adopting the TMF allows identifying all necessary dimensions and features for electricity market design, by providing a comprehensive overview of the possible options the TMF supports market design to avoid incoherent choices and highlights the impacts of the trade-off choices allowing mitigating market distortions and inefficiencies.

This section focuses on the outcome of the TMF application to the OneNet demonstrators by discussing the challenges identified thanks to the analysis of the TMF features. Moreover, the solutions proposed within the OneNet project to address the identified challenges are presented. The presented outcome has been possible thanks to the high frequency and great variety of interactions and consultation moments among the stakeholders and the variety of market architectures proposed by the OneNet demonstrators that cover different system service needs.

The research activities described in this paper point out that one of the main concerns related to system service procurement is achieving a satisfactory level of participation that gives TSOs and DSOs certainty on service providers' reliability at competitive costs. This aspect represents the main real-world challenge for market-based mechanisms for procuring system services. Solving this challenge requires devising mechanisms that guarantee liquidity and a high level of competition. This paper adopts a generalized liquidity definition, a mechanism is "liquid" if the price related to the sellers' willingness to sell is close to the price related to the buyers' willingness to buy, and the quantity offered is enough to satisfy the need of the buyer(s) [45]. Moreover, we consider a mechanism "competitive" if the participation of buyers and sellers determines final prices that reflect the marginal costs related to the product provision [46]. The achievement of satisfactory levels of liquidity and competition represents a challenge that can be addressed by considering the different design choices pointed out by the TMF.

4.1. Challenges Related to the Design of Market Architecture Structural Aspects

The 'entire market architecture' pillar, through the features 'number of sub-markets', 'timing of sub-markets', and 'locational granularity', concerns structural aspects such as the temporal and spatial dimensions that influence the market architecture's liquidity and competition. In terms of temporal dimension, a large market window increases the chance of more FSPs participating. Similarly, considering the spatial dimension, a larger market area allows for encompassing more FSPs. As observed in the context of OneNet, setting-up the number and the spatial and temporal dimensions of the sub-markets is a market design challenge since no solution of general validity exists; market design has to identify the best-case specific compromising solutions. The OneNet demonstrators described in this paper address this challenge by pursuing an expanded spatial dimension for the market. The northern demonstrator considers a market area that includes several countries. Due to bid forwarding, the Polish demonstrator forwards the products offered in the local markets to the national level. Considering the temporal dimension, both demonstrators exploit a short-term procurement for the sub-markets described in this paper; hence, the contribution of this design aspect to liquidity and competition is limited.

The 'service' and 'product' TMF features highlight the market design challenge concerning the optimal compromise between standardized service-agnostic and dedicated products. Product standardization and substitutability influence the liquidity and competition achieved by the market. A standardized or harmonized product definition enhances market interoperability, hence liquidity and competition. Moreover, these aspects are also strengthened if the same product can be exploited to solve the different system needs of both TSOs and DSOs. However, the benefits of increased harmonization and standardization of flexibility products should be compared to the advantages that tailored product features might have to address local needs. The demonstrators described in this paper address this challenge similarly by considering service-agnostic products instead of service-specific products; this influences the number of sub-markets in the market architecture and increases liquidity since different system service needs are solved using the same product. Moreover, cross-border and cross-SO markets are enabled in the northern demonstrator due to the achieved product interoperability.

Interoperability of products across markets and SOs poses a challenge related to defining boundaries for the activity of the different actors to avoid inefficiencies and conflicts. This challenge is related to the 'market roles and actors' TMF feature. The northern demonstrator addresses this challenge by involving an IMO for the common TSO and DSO markets. The Polish demonstrator addresses this challenge differently by adopting separate markets for TSOs and DSOs and establishing technical rules for aggregating the bids forwarded from the DSO market (DA-D-P-E) to the TSO one (DA-TD-P-E).

4.2. Challenges Related to Sub-Market Coordination Aspects

The TMF 'sub-market coordination' pillar points out the design aspects to address the challenges for achieving effective coordination among the sub-markets and then among TSOs and DSOs for procuring system services from the same pool of FSPs. The 'allocation principle of flexibility' feature highlights the market design challenge of allowing TSO–DSO coordination for procuring system services from the same pool of resources by avoiding inefficiencies, conflictive overlapping, and gaming. The optimal allocation of resources and products between sub-markets leads to an efficient market architecture; an effective allocation of flexibility across sub-markets can be achieved by devising a sub-markets' time sequence that avoids conflictive overlapping and room for gaming (e.g., creating artificial congestions by overbidding in one market to be called in another one). Moreover, market operational processes such as bid forwarding represent a valuable measure to distribute the available resources across the sub-markets. However, it has to be carefully designed to enhance market liquidity and competition by avoiding technical issues between TSO and DSO (e.g., conflictive activation) and gaming (e.g., artificial congestion due to overbidding). The northern demonstrator deals with the challenge of effectively allocating flexibility among sub-markets by defining bid forwarding from the intraday energy sub-market to the ID-TD-P-E sub-market for the bids that embed locational information. Differently, the Polish demonstrator defines aggregation rules at the TSO/DSO interface before bid forwarding from the local (DA-D-P-E) sub-market to the integrating balancing and congestion management sub-markets.

Overall, the allocation of flexibility among sub-markets defines the priorities in the TSO–DSO coordination. In common markets (northern demonstrator), no priority nor exclusivity is pre-established but rather overall economic efficiency. While in the multi-level market model adopted by the Polish demonstrator, the DSO prioritizes the allocation of the flexibility available from the same pool of resources. In terms of economic efficiency, this option can lead to sub-optimal results considering the overall national power system. However, the multi-level market model is less complex, leading to lower implementation costs and time and better suits local conditions due to the higher granularity (e.g., it allows adopting smaller bid size, less demanding ramps, and tailored market clearing timeframes).

The 'timeframe for coordination' feature regards the efficient resource allocation by considering the design aspects related to the coordination of the market phases from prequalification to settlement that the sub-market can share (e.g., the prequalification process can be addressed once for all sub-markets, settlement coordination across sub-markets can avoid unnecessary cash flows). This feature highlights a market design challenge since the overall market efficiency is enhanced if duplication of procedures across sub-markets is avoided; however, a dedicated process may be preferred in some cases to address peculiarities and specific needs (e.g., a sub-market may require very restrictive prequalification procedures that are not necessary for participating to the other sub-markets). In addition, in this case, a solution of general validity does not exist; identifying the solution that best fits is a market design challenge. The solutions developed by the OneNet demonstrators concern the prequalification phase coordination to decrease the barriers to FSPs market participation. The definition of a common procedure for prequalification has been discussed to find a compromise among the requirements of the different parties involved (i.e., TSOs, DSOs, and MOs) and define a shared flexibility register; further information is available in [41]. Cross-country prequalification procedures are also proposed and demonstrated in OneNet.

4.3. Challenges Related to Market Optimization Design Aspects

The challenges related to the 'market optimization' pillar concern the overall procurement economic efficiency, the flexibility allocation among sub-markets, the TSO–DSO coordination timing and information exchange, and the market gaming risk. The 'market optimization methodology' feature highlights the market design challenge of adopting a centralized or decentralized optimization methodology (i.e., common TSO–DSO model or disjoint DSO and TSO markets), which choice determines the requirements in terms of timing and content of TSO–DSO coordination and the related requirements for information and corresponding data availability concerning grid representation and power flow calculation. The 'submarket optimization strategy' feature regards the market design challenge of activating the FSPs considering the effect on the overall system operation costs (e.g., solving a local network congestion may create a power imbalance that requires an expensive countermeasure). This feature's choices influence the overall economic efficiency achieved; moreover, they have an implication on the countermeasures to avoid double procurements and discourage gaming. The northern and Polish demonstrators address these challenges differently. The northern demonstrator defines a centralized procurement where local operational issues can be solved by activating bids with locational information. In this case, the central and local needs are simultaneously addressed and the TSO–DSO coordination is embedded in the market clearing, preventing the need for additional countermeasures and double procurements. However, this design choice increases the requirement for grid representation and network information sharing among TSOs and DSOs. The Polish demonstrator proposes a decentralized procurement characterized by a sequential optimization strategy in which the local needs are solved first; then, the central needs are addressed with the contribution of the forwarded aggregated leftover bids. The TSO–DSO coordination is embedded in the bid aggregation rules since the DSO checks the FSPs activation to avoid distribution network constraint violation. In the Polish demonstrator, double procurement is avoided by designing a decentralized and sequential optimization in which a local market is solved before a central market in which DER bids are submitted in an aggregated way if there are local market leftovers. This design choice is characterized by a lower requirement for grid representation and network information sharing among TSOs and DSOs. However, sub-markets decentralized optimization may lead to sub-optimal solutions in terms of overall economic efficiency.

4.4. Challenges Related to Market Operation Design Aspects

Regarding the 'market operation' pillar design choices, the main challenges concerning the effectiveness of the remuneration scheme (related to the 'remuneration scheme' feature), the coordination of availability and activation procurement from FSPs (related to the 'remuneration of the product attribute' feature) and the corresponding timing for procurement (related 'procurement frequency' features), and the cost-effectiveness of the market related to the 'market-clearing type' feature choices are discussed in this section.

Considering the 'remuneration scheme' feature, the OneNet demonstrators alternatively propose pay-as-bid and pay-as-cleared for remunerating similar products. The market design challenge identified by this choice relates to the impact on market efficiency; in-depth research involving real-world demonstrators is needed to identify the factors relevant to the local and central electricity market that can lead to the design of effective case-specific solutions. The 'remuneration of the product attribute' feature leads to the market design challenge of setting up, or not, an availability sub-market related to an activation sub-market to enhance the overall liquidity and competition in providing the related system service. Setting up availability and activation sub-markets increases the temporal dimension for procurement and increases the confidence of TSOs and DSOs towards the availability of FSPs. However, no solutions of general validity exist and the most suitable timeframe for procuring flexibility has to be found depending on the system service need and context [38]. This aspect also influences the temporal size of the market; as pointed out by the 'procurement frequency' feature, timeframes can vary from year ahead until near-real-time. As observed while analyzing the OneNet demonstrators, TSOs, DSOs, and FSPs may have a conflictive perspective since SOs may prefer, in some situations, to procure flexibility at time frames closer to service delivery (e.g., when more information on the system conditions is available), while FSPs may prefer to be informed long in advance (i.e., to reschedule the core business activities optimally). However, in other scenarios, SOs may prefer to procure system services long in advance (e.g., in the case of planned maintenance), while FSPs would prefer to commit the system service provision closer to the time of delivery (e.g., to decrease the burden of forecasting generation or load patterns). In the OneNet project, the challenges related to identifying the most suitable correlation between availability and activation markets and timing of system service procurement are addressed by proposing and testing, thanks to a large number of demonstrators, a great variety of solutions. However, the analysis of the obtained outcome has to consider the impact of the initial and local conditions and the specific demonstrator's objective, as reflected in the differences among the OneNet demonstrators. The 'market-clearing type' feature concerns the market design challenge of adopting a continuous trading or a discrete auction scheme. The design choice is case-specific and has to be based on the need for designing the markets, finding a compromise between the timing with respect to the time of service delivery and the cost-effectiveness.

4.5. Challenges Related to Grid Representation in the Market Architecture

Electricity markets have to deal with power system network constraints; how and in which phase to include the grid representation in the market architecture represents an open challenge for integrated TSO–DSO markets pointed out by the 'grid representation' TMF pillar. The grid representation comprehensiveness has implications on the grid information availability, computational requirement for power flow calculation, data exchange timing requirements, and cyber security and data privacy issues related to network and user data gathering, storage, and sharing among the different stakeholders such as TSOs and DSOs. The 'representation of grid constraints' feature deals with the market design challenge of achieving an adequate level of comprehensiveness for the grid representation. Different levels of comprehensiveness for the grid representation can be exploited, influencing the compliance of the market-clearing results with grid constraints and the need for further corrective procedures to ensure the feasibility of the final market result. Moreover, the 'timing of grid constraints inclusion' feature highlights the market design challenge of identifying the market phases to embed the network with the service procurement (i.e., definition of procurement areas, prequalification, procurement, monitoring, activation, and settlement). Achieving a satisfactory level of techno-economic effectiveness is a market design challenge since identifying the most effective level of comprehensiveness for grid representation in the different market phases for integrated TSO–DSO markets is case-specific and depends on the perspective of the involved actors and relevant stakeholders. The challenges related to the grid representation pillar will be further investigated in

OneNet project activities. The northern demonstrator aims to address this challenge by relying on comprehensive grid data and detailed power flow analysis; the Polish demonstrator exploits partial grid data (i.e., sensitivity indicators) and DSO grid constraints check for bid aggregation before forwarding.

4.6. Analysis of Challenges and Recommendations across the Analyzed Demonstrators

The analysis of the northern and Polish demonstrators highlights common themes such as the importance of effective TSO–DSO coordination, product standardization, and the grid representation challenges. Considering the two demonstrators whose TMF application is described in Section 3, both the Polish and northern OneNet demonstrators address distinct challenges in market design, offering valuable insights into crafting efficient and responsive energy markets. Table 5 lists the main market design challenges by highlighting the specific demonstrator's challenge and the corresponding solution adopted.

Table 5. Comparative analysis of challenges, recommendations, and solutions from the Polish and northern OneNet demonstrators.

Market Design Challenge	Demonstrator's Challenge	Demonstrator's Solution
Market Integration	The Polish demonstrator aims at enhancing TSO–DSO cooperation at the national level. The complexity arises in achieving an efficient multi-layered TSO–DSO structure.	In Polish demonstrator prioritization is given to local markets, with flexibility allocations from local markets to national ones. Decentralized optimization to ensure local constraints are accounted for before scaling to a national perspective.
	The northern demonstrator seeks to integrate local and national markets in one cross-border architecture involving multiple TSOs and DSOs. The complexity here is in managing interactions across borders.	The northern demonstrator adopted a common TSO–DSO market architecture, integrating both TSO and DSO as buyers in a single coordination platform that realizes a centralized market optimization.
Liquidity and DERs participation	For the Polish demonstrator: ensuring market liquidity while focusing primarily on local markets and TSO–DSO interactions at the national level.	Polish demonstrator solution: unlock DERs' potential by creating multiple business opportunities with value staking from the local to the national level.
	For the northern demonstrator: ensuring market liquidity with cross-border markets integration.	For the northern demonstrator: a common TSO–DSO market, ensuring all stakeholders, regardless of region, operate on a single platform unlocking cross-border and cross-service market participation.
Ensuring proper allocation of flexibility	For both Polish and northern demonstrators: ensure adequate coordination between sub-markets that realizes a proper flow and prioritization of bids and optimizes flexibility allocation.	Polish demonstrator: sequential optimization and forwarding of bids from local to national markets, with prioritization for DSOs.
		Northern demonstrator: centralized optimization with shared bids between sub-markets without TSO or DSO priority.

Table 5. *Cont.*

Market Design Challenge	Demonstrator's Challenge	Demonstrator's Solution
Maintaining grid security with DERs	For both Polish and northern demonstrators: with increasing distributed energy resources participating in the market, maintaining the security of the electricity supply becomes more complex.	Polish demonstrator: bid filtering and aggregation at DSO level with grid constraints check before bid forwarding to the TSO market.
		Northern demonstrator: flexibility register with prequalification to ensure grid constraints are respected and the uniqueness of bid selection among the sub-markets avoiding double clearing.

4.7. Policy Recommendations and Insights Emerged from the Applicationof the TMF

Applying the TMF provides a structured and systematic approach to understanding and designing market architectures. Hence, the TMF offers a framework that policymakers can leverage to derive specific, actionable insights for policy formulation. More specifically, the TMF analysis supports policymakers in identifying systemic and specific challenges in market design (e.g., the trade-offs between centralized vs. decentralized procurement mechanisms, the extent of grid representation required, or the intricacies of TSO–DSO coordination) that allow formulating policies that set clear guidelines.

Applying the TMF to the OneNet demonstrators sheds light on factors influencing market liquidity and competition, such as product interoperability, spatial and temporal dimensions of sub-markets, and a coordinated allocation of available flexibility. As a practical implementation, the policies may promote product standardization across markets or mandate service-agnostic products. Similarly, guidelines setting coherent spatial and temporal dimensions of sub-markets to ensure their coordination and promote value staking for system service providers to foster higher participation and better competition, as highlighted by the OneNet demonstrators in which the TMF description of market features supports establishing coherent temporal coordination across energy markets, ensuring consistency in auction timings, bid submission deadlines, and settlement periods.

The TMF application underlines the challenge of identifying the level of grid representation in market architecture depending on the adopted market design requirements. To address this challenge, considering the features of the adopted market architecture, policymakers can set standards on grid data collection, storage, and sharing, ensuring that while grid representation is comprehensive, it is also operationally viable.

The application of the TMF promoted the use of precise and common market nomenclatures and definitions, easing the interaction of the relevant stakeholders in the demonstrators and facilitating the market design process. The TMF for the OneNet demonstrators support facilitated a comprehensive market description. TMF's method of providing a detailed, structured breakdown of market interactions, from individual buyer–seller dynamics to broader market architectures, offers a blueprint for comprehensive market analysis. The TFM supports policymakers in promoting standardized market definitions and nomenclatures, ensuring clarity and minimizing ambiguities across regional markets. Moreover, TMF provides policymakers with a systematic framework to base stakeholder consultations.

Each analyzed demonstrator offers unique insights into how these challenges can be approached, the diversity of possible solutions allows appreciating the need for adaptability in policy design. However, several common broad themes relevant to policy-making can be identified from the OneNet demonstrator analysis.

Emphasize TSO–DSO Coordination: Effective coordination between TSOs and DSOs is pivotal. Regardless of the method, the importance of TSO–DSO synergy cannot be understated.

Clear Definitions and Nomenclature: Given the intricacies involved, especially with diverse stakeholders interacting, maintaining a clear database of definitions and nomenclature is essential. This ensures consistent communication, reduces ambiguities, and aids in the smooth implementation of market mechanisms.

Robust Technology and Data Management: Bid forwarding, grid constraints checks, and ensuring bid uniqueness across sub-markets are critical processes that require robust technological solutions. Investing in data management and technological platforms will streamline operations and ensure market efficiency.

Scalability vs. Specificity: While the northern demonstrator leans towards a broader, more-integrated approach (cross-border markets), the Polish demonstrator focuses on a more localized approach, tailoring solutions to the specific needs of regions. Both are valid, emphasizing that market design should be adapted to specific ambitions and regional conditions. This trade-off between scalability and specificity is a key insight for policymakers.

Interoperability vs. Complexity: The northern demonstrator's emphasis on product interoperability suggests a vision for a more interconnected European energy market. However, the Polish approach, which separates TSO and DSO markets, points out that simplicity can sometimes be preferred on integration, especially when dealing with complex systems.

Adaptive Design: Both demonstrators provide valuable insights into the need for a flexible design for market architectures. While standardization and harmonization are crucial, structures must be adapted to local conditions and needs.

5. Conclusions

This paper contributes to the power system evolution by addressing the perspective of integrating markets for system service products (also known as flexibility markets) into the electricity market architecture. The proposed TMF is an instrument to guide market design activities. Furthermore, the TMF supports policymakers in identifying challenges, barriers, and gaps that characterize a particular electricity market architecture. The TMF is a descriptive tool to analyze the market-based TSO–DSO coordination and a valuable prescriptive tool to guide market design and integration. It represents a single tool to describe the great variety of TSO–DSO markets by using fundamental parameters and aspects for designing coordinated and integrated markets. The TMF supports market analysts and designers by pointing out a comprehensive set of categories with possible choices that need to be made while devising an electricity market architecture.

This paper describes the application of the TMF to support the real-world demonstrators of the OneNet project, proving the TMF's capability in delivering a systematic description of the fundamental market design aspects of the TSO–DSO coordination. The adoption of the TMF supported and encouraged the market design, engaging the electricity actors in the demonstrators (TSOs, DSOs, and IMOs). Therefore, adopting the TMF is beneficial for the electricity market designers since its concise but comprehensive structure eases the communication on market concepts and market design.

Furthermore, applying the TMF to the OneNet demonstrators allowed us to identify a set of challenges for the real-world implementation of market-based TSO–DSO coordination devoted to system service procurement. The dimension of the OneNet project favored reaching this outcome since the great variety of scenarios and involved actors led to diverse demonstrators. The application of the TMF points out similarities and differences among the proposed market architectures. This paper presents the analysis of the solutions adopted by the OneNet demonstrators to address the identified challenges and, on this basis, delivers recommendations on the possible design choices whose beneficiaries are TSOs, DSOs, MOs, regulatory bodies, and policy decision-makers.

The analysis of the identified challenges highlights that "one solution does not fill all"; depending on the context, the same service need can be solved by adopting different TSO–DSO market design choices. The application of the TMF supports market-efficiency assessment by providing a general framework that harmonizes concepts useful also for a broader market assessment that complements quantitative market-efficiency evaluation. On the one hand, the TMF offers a systematic approach that comprehensively dissects complex market architectures, reducing potential biases. It allows categorizing markets into TSO–DSO-Customer models, ensuring both macro- and micro-level analyses. The standardized nature of the TMF enables easier comparisons of different market architectures and clearer communication between stakeholders. It aids in pinpointing specific areas of concern, promoting an iterative approach to market design that remains relevant over time. Furthermore, the TMF is adaptable to various market structures, showcasing its versatility.

On the other hand, the TMF's detailed nature might be challenging for those unfamiliar with electricity market topics. While it aims to be comprehensive, it might sometimes miss out on specific nuances, suggesting a need for regular updates. The framework is resource-intensive, demanding both expertise and time, and its effectiveness relies on accurate and detailed information. Though the TMF emphasizes qualitative assessments, a subsequent step involving quantitative analysis becomes crucial to ensure the efficiency of the designed market.

Further research will focus on an in-depth analysis of the identified challenges related to market integration and harmonization and assessing the proposed solutions. Moreover, quantitative approaches to assess market functioning will be developed based on the TMF qualitative modeling of the market architecture designs.

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Abbreviations

aFRR	automatic frequency restoration reserves
CS	coordination schemes
D	distribution network
DA	day-ahead
DSO	distribution system operator
FCR	frequency containment reserves
FSP	flexible service provider
GCT	gate closure time
H2020	Horizon 2020
HV	high voltage
ID	intraday
IMO	independent market operator
LT	long-term
LV	low voltage
mFRR	manual frequency restoration reserves
MO	market operator
MV	medium voltage
NRT	near-real-time

P	active power
Q	reactive power
RES	renewable energy source
SO	system operator
ST	short-term
T	transmission network
TMF	theoretical market framework
TSO	transmission system operator
V/I	voltage or current

Appendix A

In Appendix A, the detailed structure (i.e., pillar, feature, sub-features, and possible options) of each pillar of the theoretical market framework is depicted. Figure A1 depicts the structure of the entire market architecture pillar, Figure A2 shows the structure of the sub-market coordination pillar, Figure A3 deals with the structure of the market optimization pillar, Figure A4 presents the structure of the market operation pillar, and finally Figure A5 shows the structure of the grid representation pillar.

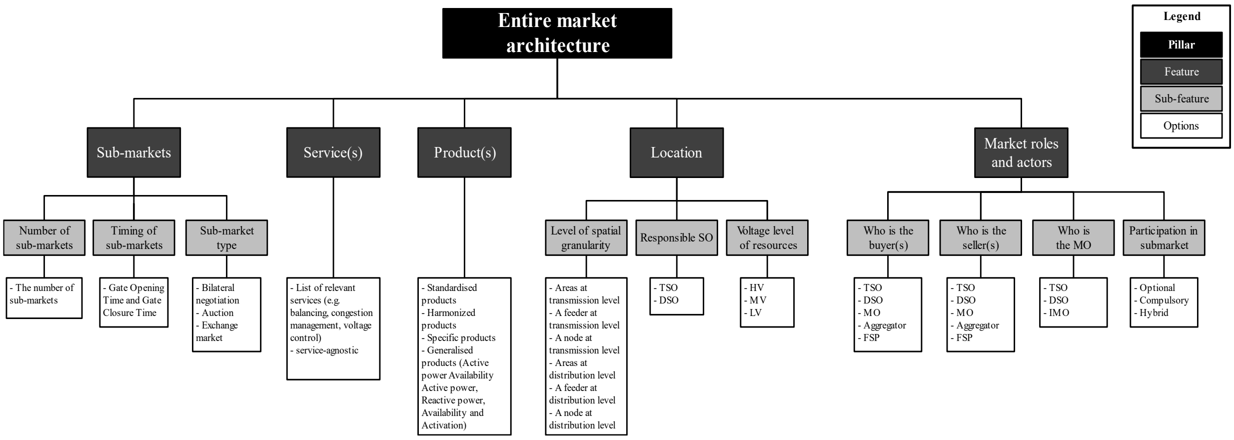

Figure A1. Structure of the entire market architecture pillar.

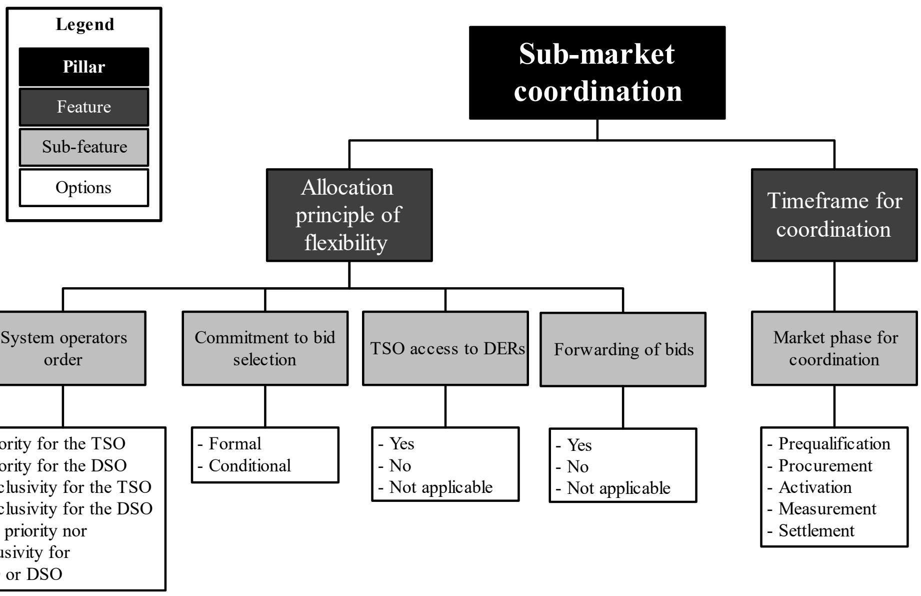

Figure A2. Structure of the sub-market coordination pillar.

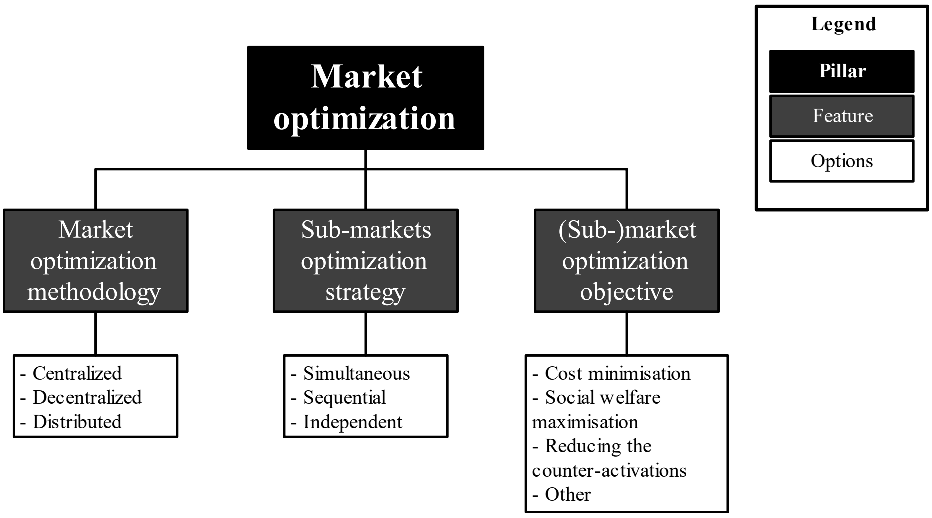

Figure A3. Structure of the market optimization pillar.

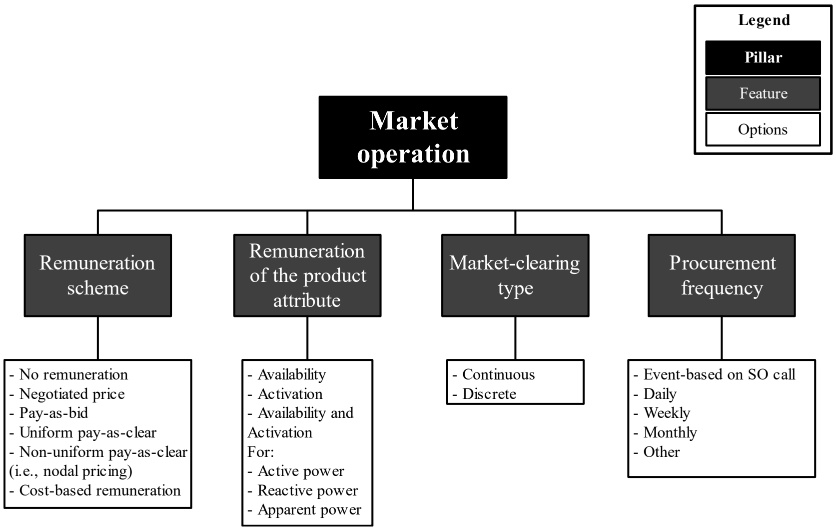

Figure A4. Structure of the market operation pillar.

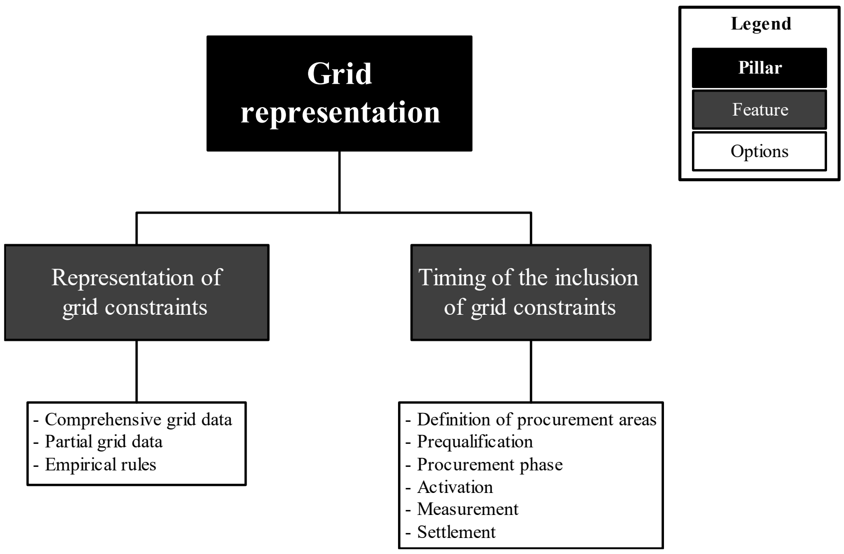

Figure A5. Structure of the grid representation pillar.

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