Assessment of TSO-DSO coordination to enhance flexible grid operation

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Abstract.
The growing penetration of renewable energy sources (RES) and distributed energy resources (DERs) has introduced new challenges in power system stability voltage regulation, and congestion between Transmission System Operators (TSOs) and Distribution System Operators (DSOs). Effective TSO-DSO coordination is crucial for addressing these operational complexities and ensuring a reliable and flexible grid. This paper examines critical coordination domains, including voltage control, congestion management, frequency control, operational planning, system restoration, and ancillary services. We evaluate three principal coordination models—TSO-managed, DSO-managed, and hybrid TSO-DSO approaches—alongside six market schemes that define flexibility service procurement processes. Through analysis of centralized, distributed, and hierarchical technical solutions, we identify structural, regulatory, and technical gaps limiting effective coordination. Our examination of existing initiatives reveals that many projects treat balancing and congestion management as separate processes rather than integrated functions, overlooking potential synergies. Integrating these functions could enhance market efficiency, reduce system costs, and improve grid reliability, particularly within Nordic balancing market frameworks. The paper concludes by recommending innovative technologies, market designs, and operational strategies to enhance grid resilience, optimize DER integration, and promote efficient flexibility markets across transmission and distribution networks, contributing to the development of sustainable, reliable power systems.

Keywords: First Keyword, Second Keyword, Third Keyword.

1 Introduction

The global energy sector is undergoing a profound transformation, driven by the urgent need to mitigate climate change and achieve a more sustainable energy future [1]. This transition has led to the widespread adoption of renewable energy sources (RES) such as solar and wind power, alongside distributed energy resources (DERs) like battery energy storage systems (BESS) and electric vehicles (EVs) [2], [3]. These technologies not only reduce carbon emissions but also decentralize energy production. Prosumers—who both consume and produce energy—enhance grid flexibility by adjusting their demand, supplying excess energy, and supporting services like frequency regulation. However, integrating RES and DERs presents significant technical and operational challenges. The inherent intermittency of renewable energy sources, such as wind and solar power, increases the demand for balancing services to maintain the delicate equilibrium between generation and consumption [4]. Unlike conventional power plants, which provide stable and controllable energy output, renewable generation depends on fluctuating environmental conditions, creating additional complexities for system operators. At the same time, the electrification of sectors like transportation and heating places added stress on the grid, leading to issues such as voltage violations and thermal overloading of network components. These challenges are compounded by the proliferation of DERs at the distribution level, which has led to reverse power flows, voltage instability, and congestion in traditional networks which are not designed for bidirectional energy flows [5].

Addressing these challenges requires a holistic approach that leverages technological innovation and strategic collaboration. Advances in information and communication technology (ICT) now enable precise monitoring, real-time control, and improved dispatchability of DERs, allowing for greater flexibility in grid operations [6]. Meanwhile, regulatory frameworks in regions like the European Union encourage the development of flexibility markets, fostering the efficient utilization of DERs while incentivizing innovation in energy management. These measures lay the groundwork for overcoming the limitations of traditional grid management by integrating decentralized resources into the broader energy ecosystem [7].

In this context, effective coordination between Transmission System Operators (TSOs) and Distribution System Operators (DSOs) has emerged as a cornerstone of modern energy systems. As the penetration of RES and DERs increases, the traditional unidirectional flow of energy—from central generators through transmission networks to end consumers—is giving way to more dynamic and complex bidirectional flows. This shift demands a collaborative approach between TSOs and DSOs to optimize system-wide operations, balance supply and demand across all voltage levels, and ensure the resilience of the power grid [8].

Since both TSOs and DSOs can be interested in DERs flexibility, aggregators (AGGs) are particularly crucial in managing the interplay between local and system-wide energy markets [9]. DSOs support the participation of resources connected to the distribution grid to the flexibility market [10]. The DSO can be a contributor to system security, in supporting the TSO by providing local solutions for system-wide problems [11]. In November 2016, the European Commission issued the Clean Energy Package proposal that assigns DSOs to a role in local congestion management but not in balancing, which remains under the purview of TSOs. While this separation may align with short- to medium-term network evolution, maintaining a rigid decoupling between balancing and congestion management risks leading to inefficiencies in system operations [8]. Without effective communication and shared operational strategies, conflicts may arise, such as when DER activations for local needs disrupt transmission-level stability or vice versa. Furthermore, the lack of integrated planning can lead to inefficiencies, including over-investment in network infrastructure or suboptimal use of flexibility resources [12]. For example, uncoordinated investments in DER capacity may lead to stranded assets or exacerbate congestion issues in distribution networks. A unified planning framework that incorporates both transmission and distribution considerations can help optimize investment decisions and maximize the utility of existing infrastructure. Furthermore, TSO-DSO cooperation plays a vital role in addressing these challenges, encompassing various dimensions such as the time horizon (e.g., short-term or long-term), perspective (e.g., system operators, consumers, producers, flexibility service providers), and operational or investment viewpoints [13]. The application of short- or long-term coordination strategies depends on the specific context and objectives. Short-term coordination, such as TSO-DSO operational coordination for balancing and congestion management, focuses on immediate system stability and efficiency. In contrast, long-term coordination typically addresses strategic investments and planning, ensuring the grid's capacity and resilience align with future energy needs. Both approaches are essential and complementary, as they enable a comprehensive framework to manage the complexities introduced by the energy transition [14].

Previous studies have extensively explored various models, techniques, and frameworks for TSO-DSO coordination. For instance, the review paper in [15] provides a comprehensive review of TSO-DSO coordination models, categorizing them into centralized, decentralized, and hybrid approaches. The paper highlights the operational advantages and challenges associated with each model, along with optimization techniques for their implementation. Similarly, [8] presents a framework for market-based TSO-DSO coordination, emphasizing the design and requirements for flexibility markets at both the TSO and DSO levels, which aim to improve the deployment of flexibility services and address both local and system-wide energy needs. Further insights into the value of TSO-DSO collaboration are provided by the authors in [13]. This study evaluates the economic and operational impacts of coordinated re-dispatch strategies, particularly under scenarios with significant penetration of decentralized energy sources. Moreover, this study provides valuable insights into the interplay between flexibility, activation and market efficiency [16].

TSO-DSO coordination and market integration need key data, like where flexibility resources are located, their associated service providers, the technology they use, and their certifications. Effective data management is important to make these systems work smoothly. To help with this, a metadata register is used to collect, organize, and store this information. It allows different stakeholders to access the data they need based on their roles and permissions. This setup makes it easier to manage and share important information in a clear and efficient way. The study by [14] offers a systematic review of TSO-DSO coordination for renewable energy integration, outlining best practices and technological solutions to address operational, economic and computational challenges. The critical role of ICT in enabling seamless coordination is explored in [17] which reviews ICT architectures and data exchange protocols implemented in European coordination schemes. The paper analyzes the technologies used for communication and data sharing, providing a foundation for seamless real-time operational synchronization. Another notable study, [16] investigates the thresholds and scenarios where TSO-DSO coordination becomes essential, particularly in networks experiencing high load growth. The study quantifies the impacts of local flexibility activation on TSO responsibilities and identifies the operational boundaries for effective coordination.

These studies collectively highlight the multifaceted nature of TSO-DSO coordination, addressing technical, economic, and regulatory dimensions. They provide valuable insights into overcoming challenges such as integrating decentralized resources, addressing intermittency in renewable generation, and maintaining grid stability. In this paper, we build upon and expand previous review papers by offering a state-of-the-art analysis of the existing schemes for TSO-DSO coordination and a deeper exploration of the following key questions:

1- How do the roles of TSOs, DSOs, and other energy entities (e.g., aggregators, and prosumers) need to evolve to effectively manage the increasing complexity of bidirectional energy flows and the integration of renewable energy sources and distributed energy resources?
2- 2- What structural models, regulatory, and technical gaps currently limit the effectiveness of the TSODSO coordination?
3- 3- What methodologies and schemes are most effective for assessing the flexibility services provided through TSO-DSO cooperation? How can flexibility procurement schemes be systematically categorized? How can these services be optimized to enhance grid stability and efficiency?
4- 4- How can a structured interaction process be designed between the flexibility market and TSO-DSO to ensure efficient coordination? How do existing coordination approaches (centralized, distributed, and hierarchical) perform in practice and what are their key advantages and operational challenges?

2 An overview, Emerging Roles and Responsibilities

The increasing decentralization of energy systems and the integration of RES and distributed energy resources (DERs) have created new challenges and opportunities in electricity markets. These changes demand enhanced coordination between key stakeholders to ensure efficient system operation, market stability, and optimal use of flexibility. Among these stakeholders, the TSO and DSO play pivotal roles in balancing system-wide and local needs. Effective TSO-DSO coordination is essential to address emerging complexities, such as managing grid congestion, maintaining balance, and integrating DERs into the flexibility market. Additionally, Balance Responsible Parties (BRPs) and Aggregators (AGGs) contribute to this ecosystem by facilitating energy and flexibility trade. Figure 1 electricity distribution network hierarchy: From TSO to End-user. Figure 2 highlights the primary areas of TSO-DSO coordination, including voltage control congestion management, frequency control, operational planning,

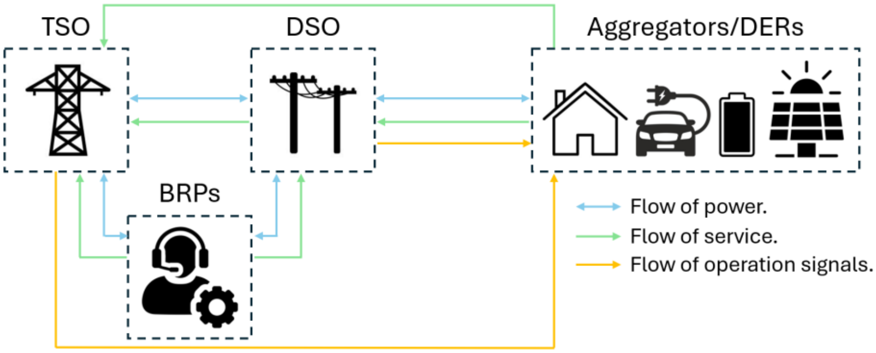

Fig. 1. Power flow framework for TSO-DSO and End-user interaction.

system restoration, and ancillary services. These coordination efforts ensure that grid operations remain efficient and reliable, even in the face of increasing complexity in the system.

Voltage Control

The rise of DERs in distribution grids enables their use for voltage control in both transmission and distribution networks, driven by growing interdependence between TSOs and DSOs. Traditionally, TSOs managed transmission-level voltage, while DSOs handled local distribution levels. However, DER integration has transformed passive distribution networks into active systems, with reverse power flows and reactive power fluctuations affecting both grids. These demands coordinated voltage control, yet challenges remain lack of standardized TSO-DSO protocols, insufficient real-time data-sharing tools, limited DER participation due to regulatory and technical barriers, inadequate distribution grid modeling, and misaligned regulatory incentives. Addressing these gaps requires advanced coordination mechanisms, real-time communication infrastructure, and regulatory reforms. The need for TSO-DSO voltage

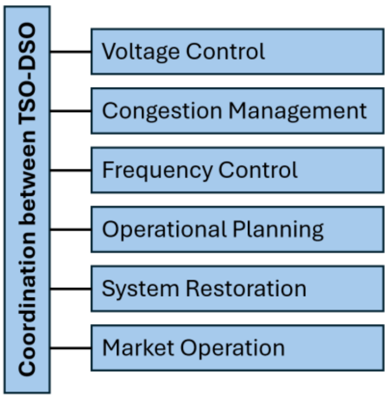

Fig.2. The primary areas of TSO-DSO coordination

control coordination is well-documented in the literature [18], [19], [20], [21], [22], [23].

Congestion Management

The growth of flexibility markets has complicated congestion management in transmission and distribution networks. Congestion stems from two sources: non-market-induced (e.g., load variations, maintenance, network faults) and market-induced (e.g., FSP actions in TSO markets causing DSO congestion) [13, 24]. Effective mitigation requires TSO-DSO coordination, leveraging advanced tools like local flexibility markets and real-time analytics [25]. However, gaps persist, particularly in predictive congestion forecasting and real-time data integration, leading to delayed responses. Recent studies highlight growing academic and industry focus on TSO-DSO coordination, with case studies in Greece, Spain, and Sweden exploring market-based solutions [26–29].

Frequency Control

Maintaining a stable frequency directly tied to power generation and consumption is critical in power systems. Traditionally, TSOs managed frequency stability using the inertia of large synchronous generators. However, high DER penetration, often connected via power electronics, has reduced system inertia, accelerating frequency disturbances. Small-scale DERs also lack sufficient capacity to provide meaningful inertia support. To mitigate this, aggregated or reduced order models are needed to accurately represent distribution network frequency response, simplifying analysis while preserving key dynamics. Frequency support can be managed locally by DSOs or through AGGs coordinating DERs and storage. Advanced modeling and TSO-DSO coordination enhance stability in low inertia systems, improving resilience [30–33]. However, gaps persist: many aggregation models oversimplify complex DER-rich distribution networks.

Operational Planning

Coordinated operational planning between TSOs and DSOs reduces system costs and improves resource efficiency. Integrating local flexibility management with centralized planning optimizes grid utilization while decreasing reliance on expensive balancing measures. Validating DER services increases their reliability, allowing TSOs to depend more on decentralized resources rather than costly infrastructure upgrades. Proactive DSO involvement in managing DER uncertainty and providing ancillary services further cuts costs by maximizing existing infrastructure instead of requiring high-capital solutions. Tools like grid equivalenting enable secure, simplified network model exchanges, improving operational alignment across voltage levels. While studies address technical challenges in TSO-DSO cooperation [34–36], gaps remain. Lack of standardized coordination frameworks creates inconsistencies in flexibility procurement, and DER forecasting uncertainties continue to challenge system reliability.

System Restoration

Extreme weather, disasters, and cyberattacks highlight the need for robust grid restoration strategies. While traditional top-down approaches rely on TSOs and black-start units, growing DER penetration enables decentralized, coordinated restoration [16, 37]. TSO-DSO coordination is crucial for leveraging DERs, which can form local microgrids during outages before re-synchronizing with the main grid. Restoration follows structured phases (black-start, re-energization, synchronization, load restoration), requiring joint planning to align transmission strategies with critical load needs. Real-time communication and situational awareness tools enable dynamic adjustments for unexpected failures or grid conditions. Integrating DERs and storage enhances recovery speed and resilience. Studies demonstrate these benefits [38–42], but challenges persist, including Lack of standardized TSO-DSO restoration frameworks, and uncertain DER availability during blackouts.

Market Operation

Market operation including frequency regulation (FCR, FFR, mFRR), voltage control, and congestion management are increasingly vital as renewable integration grows grid variability [44]. DERs and demand response programs enable consumers to participate in these markets through flexible load adjustments, creating revenue streams while supporting grid stability. Current limitations persist in DER participation, with TSOs often accessing distribution-level resources without DSO coordination. While flexibility markets align with existing energy market structures [44], improved TSO-DSO coordination through real-time data sharing could enhance DER integration, reduce conventional generation reliance and optimize flexibility procurement. Key studies highlight this potential [45–48], though current market designs often overlook DSO operational needs when utilizing distributed flexibility.

3 TSO-DSO Coordination Mechanisms

This section examines various TSO-DSO coordination models that, although presented through simplified scenarios, reveal key challenges and opportunities in designing efficient and practical coordination mechanisms. These models highlight critical aspects of aligning the roles and responsibilities of stakeholders across TSO and DSO [49]. Various coordination frameworks have been proposed to address the technical, economic, and operational challenges arising from decentralized energy systems. In previous studies, three primary TSO-DSO coordination models have been identified: TSO-managed model, DSO-managed model, and the TSO-DSO managed model [15]. Each model reflects different levels of authority, responsibility distribution, and decision-making processes, impacting the efficiency of flexibility procurement, congestion management, and ancillary service provision. To illustrate the key differences between these coordination frameworks, Figure 3 presents a comparative visualization of the TSO-Managed Model, DSO-Managed Model, and Hybrid TSO-DSO Model, highlighting the bid submission, DSO-TSO interaction, and control signal in each case. These diagrams provide a structured overview of how flexibility resources

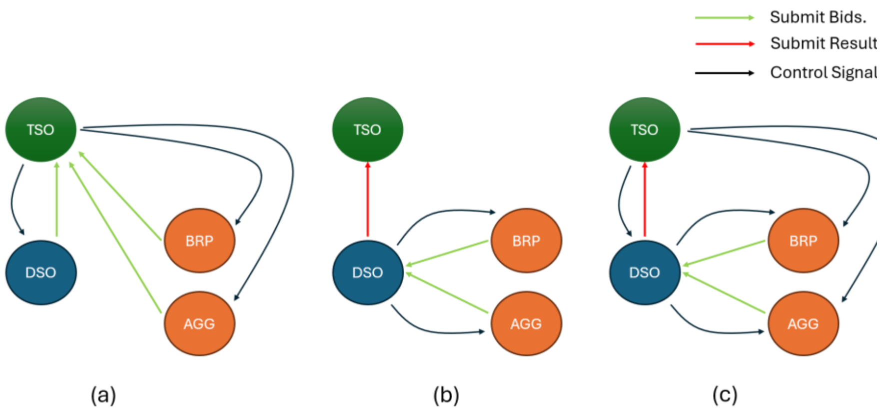

Fig.3. TSO-DSO Coordination Mechanisms: TSO-managed model, DSO-managed Model, and TSO-DSO coordinated model.

are managed across transmission and distribution networks under different operational paradigms.

1. **TSO Managed model**: In this model, the TSO retains full control over the dispatch of DERs for the DSO, BRPs, and AGGs. The TSO centrally optimizes flexibility services while ensuring that both transmission and distribution grid constraints are managed effectively. The DSO plays a supporting role, primarily by providing real-time operational data on distribution network conditions, but it does not have direct control over DER dispatch.
2. **DSO Managed model**: In this model, the DSO takes full responsibility for managing DER dispatch within its network. AGGs and BRPs give their bids to the DSO, which then validates and aggregates them before forwarding bids to the TSO. The TSO only interacts with the DSO, instead of coordinating individual DERs. This approach ensures that distribution network constraints are properly accounted for before flexibility resources are activated.
3. **TSO-DSO Managed model**: The Hybrid Model balances centralized and decentralized control by allowing both TSOs and DSOs to participate in DER dispatch coordination. The DSO first validates the bids from AGGs and BRPs to ensure that they do not cause local congestion or voltage issues. The validated bids are then shared with the TSO for final dispatch decisions. The model also allows DSOs to procure flexibility services independently for local network management while ensuring that the TSO still has access to systemwide flexibility. Table 1 provides a detailed comparison of the three TSO-DSO coordination models, outlining their decision authority, roles of the DSO and TSO, advantages, and limitations.

Table 1. Comparison of TSO-DSO Coordination Model

Model	Decision Authority	DSO Role	TSO Role	Pros	Cons
TSO Managed Model	TSO has full control over DER and TER dispatch	Limited to data sharing, monitoring, and network maintenance.	Manages all dispatch decisions and ensures system-wide stability	• Simplifies coordination with a single entity (TSO) controlling system-wide dispatch. • Fast adoption of new standards and market regulations. • Leverages TSO expertise in market operations and dispatch. • No conflict of interest, as the TSO does not own distribution assets.	• Does not consider local grid constraints, potentially leading to congestion issues. • High computational complexity, as the TSO must manage both transmission and distribution networks. • Requires significant Realtime data exchange between TSOs and DSOs. • Difficult to scale with increasing DER penetration
DSO Managed Model	DSO has full control over DER dispatch and validation	Manages DER dispatch and flexibility, ensuring grid integrity before engaging with TSO.	Receives aggregated DER bids from the DSO but has no direct control over distribution-level resources.	• Optimized local grid operations, as DSOs manage distribution-level constraints. • Reduces TSO's computational burden, since dispatch decisions are distributed. • No need for extensive Realtime data transfer between TSOs and DSOs. • Enables local flexibility markets, ensuring DER participation at the distribution level.	• Potential conflict of interest, as DSOs may avoid using flexibility services aggressively to protect their assets. • Limited system-wide visibility for the TSO, potentially leading to inefficient dispatch. • Fragmented market operations, as different DSOs may have inconsistent approaches. • Complex coordination when multiple DSOs interact with the same TSO.
TSO-DSO Managed Model	Shared responsibility between TSO and DSO, with coordination mechanisms.	Validates and manages local flexibility, ensuring network stability before submitting bids to the TSO.	Optimizes system-wide dispatch based on validated bids from DSOs.	• Balances system-wide and local flexibility, optimizing both TSO and DSO objectives. • Enhances network efficiency, reducing unnecessary grid investments. • Better market integration, allowing DERs to participate at both distribution and transmission levels. • Lower computational burden, as decision-making is distributed. • Clear priority structure to allocate flexibility based on technical and economic needs.	• Requires complex coordination mechanisms, including real-time data exchange. • Regulatory and market design challenges, as responsibilities must be well-defined. • Potential dispatch conflicts, as both TSOs and DSOs may compete for the same flexibility resources. • Requires significant investment in market platforms and digital infrastructure.

4 Assessment of the Flexibility Services through TSO-DSO Market Schemes

To facilitate the procurement of flexibility among system operators, various TSO-DSO coordination market schemes have been proposed. These market schemes define the roles and responsibilities of TSOs and DSOs when procuring and using system services provided by the distribution grid. This assessment has provided valuable insights into the design and implementation of flexibility mechanisms, helping to refine the problem definition and highlight key challenges [50].

There are six primary TSO-DSO coordination market schemes for system services, as defined in the SmartNet project. Each coordination scheme is defined by a unique set of roles for system operators and a specific market design. These schemes determine the operational processes and information exchanges between TSOs and DSOs, covering prequalification, procurement, activation, and settlement of flexibility services that impact both transmission and distribution systems [51].

In the Centralized Market Model, the TSO leads the ancillary services market with minimal DSO involvement. The Local Market Model enables DSOs to prioritize local flexibility before offering it to the TSO. Under the Shared Balancing Responsibility Model, DSOs and TSOs operate independently, each managing their own balancing needs. The Common TSO-DSO Market Model promotes joint participation without prioritizing either network, aiming for total system cost minimization. Finally, the Integrated Flexibility Market Model opens participation to both regulated and non-regulated entities through a neutral market operator, enhancing competition and market liquidity. These schemes highlight key trade-offs between centralization, autonomy, and the effective integration of distributed energy resources.

The choice of a suitable market scheme depends on local market maturity, regulatory frameworks, and operational needs, as no single approach fits all scenarios. To categorize these schemes, four key dimensions have been considered:

1. Flexibility Needs: Differentiating between Local (DSO), System (TSO), or combined needs.

2. Flexibility Buyers: Identifying the stakeholders procuring flexibility.

3. Market Structure: Determining if flexibility is procured in a single market or multiple parallel/sequential markets.

4. Resources accessibility: Assessing whether the TSO can directly procure flexibility from distribution level resources.

Each market scheme offers unique advantages and considerations for TSO and DSO grid operations, market participants, and overall market efficiency. The effectiveness of a given scheme depends on factors such as grid constraints, regulatory frameworks, and the degree of market integration. Table 2 provides an overview of these coordination schemes, detailing their structural and operational characteristics, computational complexity, and market roles [51].

Table 2. The key elements of the TSO-DSO coordination market schemes.

Coordination market scheme	Architecture	Interaction between system operators	Grid operation	Market operation	Computation complexity	Flexibility buyers	Need of flexibility	Does the TSO have access to DER?	Markets per bidding zone/area	Aggregation rules	DER provision of services to TSOs	DER provision of services to DSO
Centralized market	Centralized	High	Low	Medium	Very low	TSO	TSO need only	Yes and NO	1	Low	Low	Very low
Local market	Decentralized	Medium	Medium	Low	Medium	DSO	DSO need only	\	>1	Low	Very low	Low
Common TSO- DSO centralized market model	Centralized	Low	High	Low	High	DSO and TSO	DSO and TSO	Yes	1	Low	Low	Low
Common TSO- DSO decentralized market model	Decentralized	Low	High	Low	Medium	DSO and TSO	DSO and TSO	Yes	1	Low	Low	Low
Shared balancing responsibility model	Decentralized	Medium	High	Medium	Low	DSO and TSO	DSO and TSO	No	>1	Low	Low	Low

Integrated flexibility market	Centralized	Medium	High	High	High	DSO and TSO	DSO and TSO	Yes	1	Low	Low	Low

Table 3. Assessment of flexibility market characteristics of selected TSO-DSO coordination projects

	Enera	**GOPACS**	**NODES**	**PICLO**	**Cornwall**	**Soteria**	**Coordinet**	**Smartnet**	**OneNet**
Integrated in EU markets	✗	✓	✓	✗	✗	✓	✓\✗	✓	✓
Market operator	✓	✓	✓	✓	✗	✗	✓	✓	✓
TSO-DSO Cooperation	✓	✓	✓	✗	✓	✓	✓	✓	✓
DSO-DSO Cooperation	✓	✓	✓	✓	✓	✓	✓	✓	✓
Trading Type (B: Pay as bid or C: Pay as clear)	B	B	B	C	C	C	C	C	C
Congestion Management	Local	Local\System	Local\System	NA	NA	System	Local\System	System	Local\System
Voltage support	✓	✓	✓	✗	✗	✓	✓	✓	✓
DERs provide voltage support	✗	✗	✗	✗	✗	✗	✓	✗	✓
Regulation provides cost recovery for flexibility procurement?	✓	✓	✓	✓	✗	✗	✓	✗	✓
DERs be aggregated in the different markets	✓	✓	✓	✓	✓	✓	✓	✓	✓

Several pilot projects and commercial initiatives, such as Enera, GOPACS, NODES, Piclo, Cornwall, Soteria, Coordinet, and Smartnet, have been assessed to evaluate their approaches to flexibility markets [49]. One significant observation from this assessment is that many existing projects tend to treat balancing and congestion management as separate processes rather than integrating them into a unified framework. While this segmentation simplifies market operations, it may lead to inefficiencies by overlooking potential synergies between the two services [52].

The integration of balancing and congestion management is particularly relevant from an economic and operational perspective. By coordinating these functions, system operators can enhance market efficiency, reduce overall system costs, and improve grid reliability. This approach aligns well with the Nordic balancing philosophy, which emphasizes market-based solutions and proactive coordination between system operators. Table 3 provides an assessment of the key characteristics of these flexibility markets, highlighting their market integration, operator structure, and trading mechanisms.

Recent developments, such as the Nordic Balancing Model and transition to 15-minute mFRR (manual frequency restoration reserve) energy activation market, has a potential to support the integration of flexibility resources in the Balancing Markets. These changes enhance the temporal granularity of bids, allowing DERs, AGGs, and demand response, to better align with system needs and participate more actively in balancing services. As flexibility becomes an increasingly valuable grid resource, aligning technical capabilities with market design will be crucial for achieving efficient and resilient power system operations [51].

Also, the integration of the flexibility market into the existing market presents significant advantages from both an economic and operational perspective. By coordinating these functions, system operators can enhance market efficiency, reduce overall system costs, and improve grid reliability. This integrated approach is well aligned with the Nordic balancing market such as FCR (Frequency Containment Reserve), aFRR (auto-frequency restoration reserve) ,and mFRR. To facilitate this coordination, a structured interaction process between the flexibility market and balancing market is required, ensuring seamless communication between DSOs, TSOs, and all market participants. The Nordic balancing market's 15-minute mFRR bid framework exemplifies this synergy, where automated bid selection—optimized via the Nordic Activation Optimization Function (AOF) enhances DER participation by aligning local flexibility procurement with system-wide balancing needs. Key features like dynamic pricing (using day-ahead prices as bid floors/caps) and cross-border capacity constraints mirror the integrated TSO-DSO market model, demonstrating how standardized high-frequency markets can harmonize balancing and congestion management. This approach not only prioritizes cost-efficiency through algorithmic bid clearing but also strengthens grid reliability by ensuring flexibility activations that respect both DSO-local and TSO-transmission constraints, as evidenced in the Swedish Coordinet project's alignment with Nordic market mechanisms.

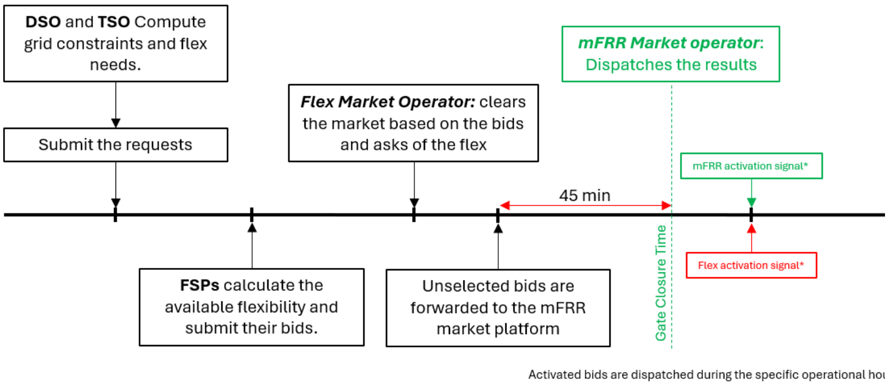

Fig.4. Flexibility Market and mFRR Coordination Process.

The study in [43] presents an actual implementation of the interaction between the flexibility market and the mFRR market. The proposed framework begins with the DSO identifying its flexibility needs and submitting a request for flexibility services from Flexibility Service Providers (FSPs) (e.g., BRPs, AGGs, prosumers, etc.) to address local grid constraints and operational challenges. In response, FSPs submit their bids to the flexibility market, specifying the amount of flexibility they can provide, the activation price, and their availability. In the next step, the market tool clears the flexibility market, selecting the most cost-effective and technically feasible bids that meet the DSO's needs. If there are unused bids that remain eligible, these bids are forwarded to the TSO's mFRR (Manual Frequency Restoration Reserve) market, allowing surplus flexibility to contribute to system-wide balancing. Once the mFRR market is cleared, the TSO determines which bids to activate, ensuring system-wide grid stability while respecting network constraints. The activation signals are then sent to the market tool, which in turn forwards them to the relevant FSPs, ensuring seamless communication and coordination. Upon receiving these activation instructions, the FSPs deliver the required flexibility services, either by adjusting generation, modifying consumption, or dispatching storage assets according to the agreed flexibility contract. By design, this coordination process ensures that local flexibility is prioritized to meet distribution-level needs, while excess flexibility is efficiently integrated into system-wide balancing through the TSO's market. This structured approach enhances grid reliability, improves market efficiency, and strengthens collaboration between DSOs, TSOs, and market participants. Figure 4 illustrates the steps above for the coordination process between the flexibility market and the mFRR market.

5 Methods of TSO-DSO Coordination

Several coordination frameworks have been developed to address this challenge, each offering different balances between centralization, autonomy, scalability, and operational efficiency.

1. Centralized Method: the centralized method treats the entire power grid transmission and distribution networks as a single integrated system. A central authority (e.g. the TSO or a joint entity) makes all operational decisions, such as dispatching resources or resolving congestion, using a unified model that incorporates data from both networks. This approach ensures globally optimal solutions by harmonizing grid-wide objectives, such as minimizing operational costs or maximizing renewable integration. It eliminates conflicting priorities between TSOs and DSOs, as decisions are made with full visibility of transmission and distribution constraints. Centralized frameworks are particularly effective for small- to medium-scale systems, where computational resources can handle the complexity of simultaneous optimization across all network layers. However, scalability becomes a critical limitation in large or ultra-large systems (e.g., networks with thousands of nodes or deeply nested distribution feeders), as computational complexity grows exponentially, hindering real-time applications. Centralized methods also require exhaustive data sharing, raising concerns about privacy, communication reliability, and dependency on accurate models, and often oversimplify distribution networks by neglecting three-phase imbalances or excluding small-scale DERs, reducing their practical applicability.

2. Distributed Method: the distributed method divides the power grid into smaller subsystems (e.g., transmission and distribution networks), each managed independently by TSOs or DSOs, where local operational challenges are solved autonomously while coordinating through iterative exchanges of boundary conditions (e.g., power flow limits, voltage thresholds) to ensure system-wide feasibility. This approach reduces computational complexity by decentralizing decision-making and enabling parallel processing of sub-problems while preserving operator autonomy and data privacy (e.g., DSOs retain control over local DER data), and accommodating heterogeneous network architectures (e.g., unbalanced feeders, mixed AC/DC grids) for scalability in large systems. However, achieving globally feasible solutions relies heavily on consistent communication and alignment between subsystems; discrepancies in data granularity (e.g., detailed distribution models vs. simplified transmission models) or delays in iterative negotiations can lead to suboptimal outcomes. Additionally, distributed methods may struggle with dynamic reconfigurations (e.g., sudden faults, DER disconnections) and often exclude practical elements like controllable grid devices (e.g., tap-changing transformers) or small residential DERs, limiting their applicability in real-world scenarios.

3. Hierarchical Method: the hierarchical method organizes grid operations into tiers, where higher levels (e.g., transmission networks managed by TSOs) set overarching objectives, such as power injection limits, which guide lower levels (e.g., distribution networks managed by DSOs) in translating these goals into localized actions while adhering to network constraints. This framework aligns with the inherent structure of power systems, balancing global priorities like transmission stability with local optimization of DERs for voltage regulation, and offering scalability for multi-level networks (e.g., nested transmission, medium-voltage, and low-voltage systems) and reducing computational complexity through tiered problem decomposition. However, its effectiveness depends on robust communication protocols to synchronize objectives across hierarchical levels, and simplified representations of lower-tier networks (e.g., aggregated distribution feeders) may neglect critical dynamics like voltage fluctuations or phase imbalances. Additionally, challenges persist in integrating small-scale DERs and adapting to real-time variability, such as sudden load shifts or renewable generation changes, limiting practical responsiveness in dynamic grid environments.

Table 4 presents an overview of selected studies that have proposed mathematical formulations for TSODSO coordination. The table summarizes the approach type, mathematical formulation, optimization objectives, and key constraints used in each method. These studies highlight the trade-offs between computational complexity, optimality, and practical feasibility in different coordination frameworks.

Table 4. Overview of TSO-DSO Coordination Models and Their Mathematical Formulation

Ref	Approach Type	Mathematical Formulation	Optimization Objective	Key Constraints
[47]	Centralized method	nonconvex nonlinear programming (NLP) problem	maximize the power injected/exported into the transmission system.	Optimal power flow, Active and reactive power balance
[45]	Centralized method	Mixed-Integer Linear Program (MILP)	Minimize the operation cost	Market clearing condition, Nodal power balance constraint, distribution network limits
[40]	Hierarchical method	Linear programming approximation	Maximize the total restored loads and minimize voltage deviation	Power flow constraints, Security constraints, Boundary variables constraints
[13]	Centralized method	Non-Linear Programming (NLP)	Minimize the operation cost	Market clearing, Power limits, Load shifting, Nodal balance and Power injection.
[23]	Centralized method	Non-Linear Programming (NLP)	Minimize the maximum frequency deviation	Current transfer, Current unbalance
[44]	Centralized method	Non-Linear Programming (NLP)	Minimize the cost of the Ancillary Service	Active, Reactive power limits, Lines losses, Remuneration of DER.
[19]	Distributed method	Multi-agent deep reinforcement learning Approach	Minimize the accumulated Frequency and Voltage deviations	Voltage and frequency regulation, DERs Limits, Operational constraints

[46]	Centralized method	Linear Programming (LP)	Minimize the cost of reserve activation	transmission constraints, distribution constraints, and Ancillary Service market
[53]	Distributed method	Mixed-Integer Linear Program (MILP)	Minimize the cost of generation and the cost of providing the flexibility services	DER Limits, Line limits, turn-up and down the service, start-up limits.
[27]	Centralized method	Non-approximate selecting (NAS) method	Minimize Power loss	Congestion management, Power flow, DERs limits.
20]	Centralized method	Non-Linear Programming (NLP)	Minimize the operating cost of the DSO by contracting reactive power flexibility	Upward and downward reactive power flexibility, Active power flow, DERs limits
[26]	Centralized method	Non-Linear Programming (NLP)	Minimize the generation cost and Minimizes the total cost of the Flexibility Service Providers	DERs limits, Market clearing, Supply–demand balance constraint.
[21]	Centralized method	Non-Linear Programming (NLP)	Minimize the total cost of flexibility activation	Regulatory limit of reactive to active power ratio, Upper limit of line flows, Market clearing
[48]	Centralized method	Mixed-Integer Linear Program (MILP)	Minimize the daily cost of electricity	Frequency and voltage deviation limit, Load flexibility limit, up- and down-ramp-rate limits.
[41]	Distributed method	Analytical target cascading (ATC)	Maximize the load recovery and Minimize the load pickup/operation	DERs limits, Power flow constraints.
[34]	Distributed method	Alternating direction method of multipliers (ADMM)	Maximize the flexibility volume of feasible regions	DERs limits, Power flow constraints, and investment constraints.

6 Conclusion

The transition to decentralized energy systems requires effective TSO-DSO coordination to maintain grid stability and optimize flexibility markets. This paper analyzed the coordination models and the market schemes, such as centralized, local, and integrated markets, demonstrating their varying effectiveness depending on system needs and regulatory frameworks.

Key findings from projects like Enera, GOPACS, SmartNet and OneNet reveal that most current implementations treat balancing and congestion management separately, missing potential synergies. The Nordic Balancing Model's 15-minute mFRR market demonstrates the benefits of integrated approaches, where local flexibility can simultaneously address distribution constraints and support system-wide balancing. The Swedish case study further illustrates how coordinated flexibility markets between TSOs, and DSOs can enhance both economic efficiency and grid reliability.

To advance TSO-DSO coordination, it is essential to develop clear regulatory frameworks that define operator roles and responsibilities, implement standardized data-sharing protocols, and adopt high-resolution markets that align local and system-wide needs. Future research should focus on dynamic pricing mechanisms and AI-driven optimization to further improve coordination efficiency.

These improvements will enable power systems to integrate renewable energy better while maintaining reliability and cost-effectiveness, supporting the global transition to sustainable energy. The experiences from European projects provide valuable insights for implementing effective TSO-DSO coordination worldwide.

Declarations

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