D4.1 SPECIFICATION OF FLEXIBILITY NEED AND SERVICES

(UNDER TSO-DSO COORDINATION)

VERSION 1.0

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LIST OF ABBREVIATIONS

Abbreviation	Definition
ACER	Agency for the Cooperation of Energy Regulators
ANM	Active Network Management
AS	Ancillary Services
AVR	Automatic Voltage Regulator
BESS	Battery Energy Storage System
CC	Chance Constraints
CEER	Council of European Energy Regulators
DG	Distributed Generation
DLR	Dynamic Line Rating
DR	Demand Response
DSO	Distribution system operator
DSR	Demand Side Response
EDSO	European Distribution System Operators
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
EVs	Electric Vehicles
FACTS	Flexible AC Transmission Systems
FFR	Fast Frequency Response
HV	High Voltage
ICT	Information and Communication Technologies
IRENA	International Renewable Energy Agency
ISGAN	International Smart Grid Action Network
LV	Low Voltage
MO	Market Operator
MPC	Model Predictive Control
MV	Medium Voltage
OLTC	On-Load Tap Changer
OPF	Optimal Power Flow
PSS	Power System Stabilizer
PSTs	phase-shifting transformer
RES	Renewable Energy Sources
SC	Security Constrained
TSO	Transmission system operator
VRE	Variable Renewable Energy
WAMPAC	Wide-area Monitoring Protection and Control
WP	Work package

CONTENTS

1 INTRODUCTION

Widespread implementation of distributed generation, renewable energy resources, electric vehicles, and other modern technologies poses significant issues for future operation of power systems. Dealing with congestions, frequency and voltage control, and balancing in future power grids will become a more challenging task than ever before. The utilization of flexibility services plays a key role in resolving these challenges for transmission and distribution grids. The Distribution System Operators (DSOs) and Transmission System Operators (TSOs) will be beneficiaries of flexibility resources utilization, and therefore they have to assist implementation of flexibility services. A lack of coordination between the DSOs and TSOs may decrease profit from flexibility resources, affect grid security, power quality, increase the overall cost of grid operation to end-users, etc. In these conditions, the coordination between the DSOs and TSOs is crucial for a safe, reliable, and cost-effective implementation of flexibility-based services. The roles and responsibilities of participants in the flexibility market should be assigned so that DSOs and TSOs will be able to support each other efficiently, provide cost-efficient operation of the grid, and proper utilization of flexibility resources.

The HONOR project aims to develop and evaluate a trans-regional flexibility market mechanism, determine the optimal operation of flexible resources and their allocation, and integrate cross-sectoral energy flexibility at a community-wide level. One of the critical problems within the practical application of flexibility services is their harmonization with existing operational processes used by TSOs and DSOs. For this reason, the different visions, regulations, and approaches to flexibility utilization and TSO-DSO coordination were considered and systematized in this work. This investigation is essential for developing the HONOR solutions, which will link the new flexibility services to already established processes in the power system.

The document is organized as the following. Chapter 2 gives insight into power system structure. In Chapter 3, information about flexibility potential in the electrical power system was given. Chapter 4 considers the present and future roles of system operators, which will be affected by the widespread application of flexibility assets. In addition, the necessity for TSO-DSO coordination is explained. Next, Chapter 5 gives an in-depth literature review on projects and regulations dedicated to TSO-DSO coordination. The existing schemes for TSOs and DSOs coordination were presented in Chapter 6. Next, Chapter 7 provides a review of modelling approaches for TSO-DSO coordination. Finally, using information from Chapters 2-7, Chapter 8 concludes the current state of TSO-DSO coordination.

2 POWER SYSTEM STRUCTURE

The power system is a network that comprises generation, distribution, and transmission systems. It utilises the different forms of energy and converts them into electrical energy. The power system consists of many elements and devices connected to the network like the transformer, synchronous generator, motor, circuit breaker, and conductor, etc. As an illustration, the power system structure of Smart Grid is presented in Figure 1. The figure illustrates all active participants[1], such as energy providers, substation automation, grid operators, and electricity consumers.

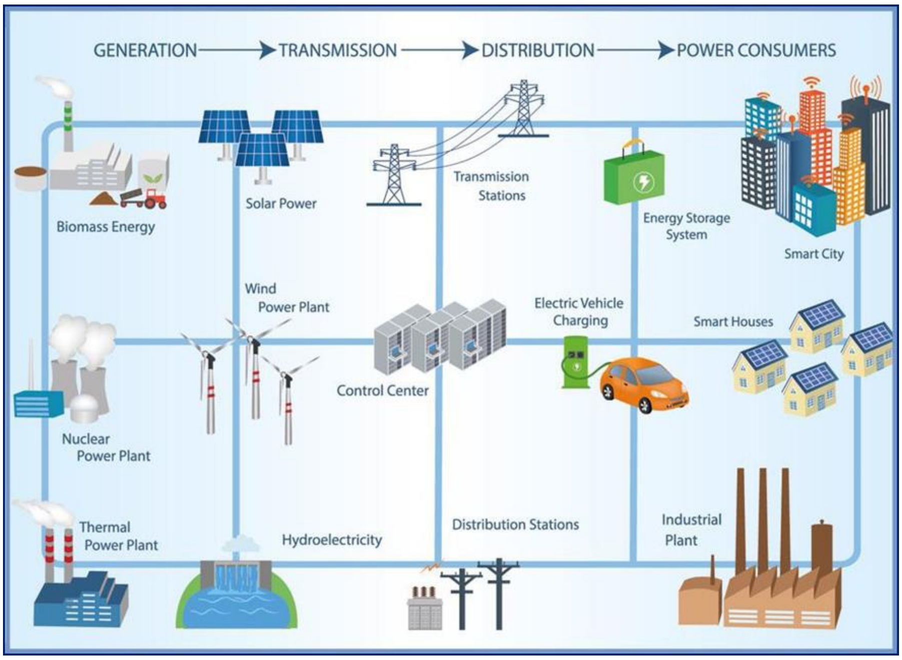

Figure 1. Electrical Power System Structure of Smart Grid[2]

The use of renewable energy leads to a reduction consumption of fossil fuels as well as reduction of nuclear waste. The infrastructure of modern power systems is optimised in order to achieve these goals. The generating units, transformers, transmission lines, substations, distribution lines, and distribution transformers are the six major components of the power system. The power stations produce electricity, which is step-up or step-down using the transformer for transmission.

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[1] Active participants in the Smart Grid is available at https://www.meinbergglobal.com/english/industries/smart- grid-timing.htm

[2] The source of the figure is https://www.meinbergglobal.com/english/industries/smart-grid-timing.htm.

2.1. Generation

Power plants convert the stored energy in non-renewable sources (oil, coal, natural gas) or renewable sources (solar, wind, water) into electric energy. Electrical energy is generated in the range of 11 – 25 kV or more, which is a step-up for transmission of long-distance. The power plant of the generating substation is categorised into three types: thermal power plant, hydropower plant, and nuclear power plant. Usually, the generator and the transformer are the central components of the generating station[3].

The dramatic increase of power generation from RES and DER is the critical target, which could positively contribute to a rise in energy autonomy and reduce CO_2 emissions. Based on the ownership and market structure in the power generation sector, it could also provide to further energy liberation market [1].

2.2. Transmission

The transmission system uses the overhead lines that transfer the generated electricity from generation to distribution substations. It only provides a vast bulk of electrical energy to bulk power substations or industrial consumers.

The transmission voltage is working at more than a given voltage level, which can be different from system to system, e.g., 33 kV in the Norwegian system. The system operators delineate resources with an aggregate capacity of a certain capacity, e.g, 1 MW in the Norwegian system or more than kV in their grid model for this level of resolution.

2.3. Distribution

The power system elements, including overhead lines, underground cables, service lines, electrical plant, control switchgear and meters connecting the end-users to the transmission system, is known as a distribution system

Given the increasing proliferation of resources at the distribution system level, transmission system operators tend to be able to mobilize these resources to support transmission systems. Moreover, utilities are concerned with the challenges that DER units could cause to the system operation. The IEEE 1547 standard only provides limited direction and emphasises only the essential prerequisites. The modern standards are being established towards more detailed DG and RES integration requirements with power distribution [2]. The coordination between TSO and DSO is required to overcome these challenges.

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[3] https://circuitglobe.com/power-system.html.

2.4. Power Market

The power market ensures the efficient use of resources and reasonable prices on electric energy. In Norway, power transmission and distribution are a natural monopoly and not expose to competition.

Presently, the Nordic countries are closely connected, both by economic market integration and by physical interconnectors. Nord Pool[4] is the interchange of physical power trade for the Nordic and Baltic Countries.

Unlike other goods, electric energy cannot easily be stored. Therefore, there must be a consistently accurate balance between production and consumption. When it comes to the wholesale market, prices are considered for every hour of the following 24-hour period, depending on bids and offers from several different participants, and provided the availability of capacity of the grid. The market adjustment of this short-term makes sure that the lowest cost-generation resources are utilised first. Electric energy prices also give the signals of investment as they point out where there may be a deficit of power supply. Market coupling makes sure that electrical power flows according to prices, hence making sure the optimal use of capacity and resources of generation [3].

2.5. System Operators

The TSO is responsible for dispatching, transmission, balancing of the whole electrical system, and dispatching of resources directly connected to the transmission grid and through aggregators of resources related to the distribution network. This usually includes the transmission system. Moreover, this contains controlling and monitoring the current grid topology (i.e., the position of switches and breakers within the grid) and the voltage in all parts of the transmission grid. The principal activity of interest is contracting ancillary services (AS) providers that decide the necessary control reserve capacity and the reserves when required [4].

The DSO is responsible for the secure operation of the distribution grids. Furthermore, DSOs are responsible for medium voltage (MV), low voltage (LV) grid operation, and metering. Sometimes they are responsible for high voltage (HV). They can control the voltage profile through on-load tap changer (OLTC), capacitor banks, and any other devices owned by themselves.

In order to face the challenges of future power systems, using flexible assets become essential for both TSO and DSO. At the same time, the widespread application of flexible assets will lead to changes in DSO and DSO roles [5]. Thus, flexibility in electrical power system will be discussed in Chapter 3, and the present and future roles of system operators will be presented in Chapter 4.

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[4] Nord Pool is Europe's leading power market that delivers efficient, simple, and secure electricity trading across Europe. The reference is https://www.nordpoolgroup.com/.

3 Flexibility in Electrical Power System

The flexibility of the electrical power system has a central role in tackling some possible challenges of future power systems [6]. The availability of advanced solutions through flexibility is crucial for the power systems in the future, considering this being an increasingly significant issue for planning, operation, and policymakers. As described in [7], the rising demands for flexibility concern predominantly to the dramatic increase of variable renewable resources. Nordic TSOs have revealed the importance of flexibility as a significant challenge in the foreseeable future [8]. In the document [9], TSO-DSO coordination to employ flexibility resources is presented. A survey of flexibility for supporting the system is discussed in [10], and the forecast balancing of flexibility is performed in [11, 12].

Flexibility has both technical and financial measures, where the professional competencies may be employed to assist the grid and the system based on the financial capacities of the markets and their ordinances and management policies [6]. However, it may appear usually agreed that flexibility concerns the capability of the power system to conduct changes; flexibility is not a consolidated term and lacks a generally accepted definition. There are different opinions and meanings when it comes to the definition of flexibility, and some of them are compiled as follows [6]:

- The Council of European Energy Regulators (CEER) released a public consultation to submit the definitions of flexibility in 2017. In this regard, the European Transmission System Operators ETSO-E answered the meaning: “the active management of an asset that can impact system balance or grid power flows on a short-term basis, i.e., from day-ahead to real-time” [6].

- The European DSOs also proposed to the CEER consultation, basing their suggested definition on [13] and [14] and published this in [10] as: “the modification of generation injection and/or consumption patterns, on an individual or aggregated level, often in reaction to an external signal, to provide a service within the energy system or maintain stable grid operation” [10].

- The CEER published a final report in 2018 based on the suggested definition of flexibility: “the capacity of the electricity system to respond to changes that may affect the balance of supply and demand at all times” [15].

- In 2018, the International Renewable Energy Agency (IRENA) described flexibility as: “the capability of a power system to cope with the variability and uncertainty that variable renewable energy (VRE) generation introduces into the system in different time scales, from the very short to the long term, avoiding curtailment of VRE and reliably supplying all the demanded energy to customers” [7].

- The academy [16] reflects flexibility to present a system “ability to accommodate the variability and uncertainty in the load-generation balance while maintaining satisfactory performance levels for any time scale.”

In this context, the general statement mentions that the flexibility concept consists of several needs and features in the power system [6].

When the flexibility is considered for planning and operation of the power system, the flexibility is needed in a time-frame from fractions of a second for stability and frequency support to minutes and hours for thermal loadings and generation, to months and years for the planning of seasonal adequacy and planning for new investments [7].

The flexibility can be categorized into four groups:

- Flexibility for power
- Flexibility for energy
- Flexibility for transfer capacity and
- Flexibility for voltage

The correlation of the four classes in the measures of time and space are described in Figure 2, with a small number of examples of flexibility solutions for each group presented in Figure 3.

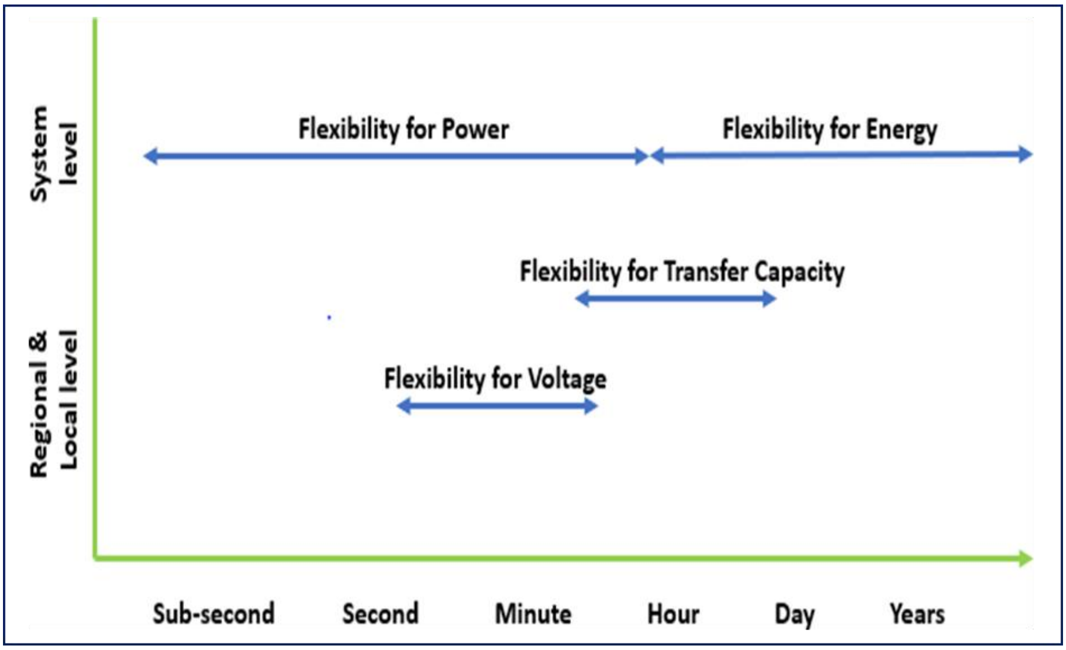

Figure 2. Correlation of flexibility needs in perspectives of space (local/regional to system level) and time [6]

Figure 2 for timescale presents activation time for the flexibility need. The ranges described for the four groups estimate and depend on the system's physical manner and regulations and requirements [6]. In space, the different groups are separating conditions that are local or regional flexibility for voltage and flexibility for transfer capacity from needs that are system-wide flexibility for energy and flexibility for power [6].

Figure 3 describes the examples of solutions for flexibility: a mixture range from services of system, responses based on control mechanisms, and methods of operations towards the implementation of new power elements in the system.

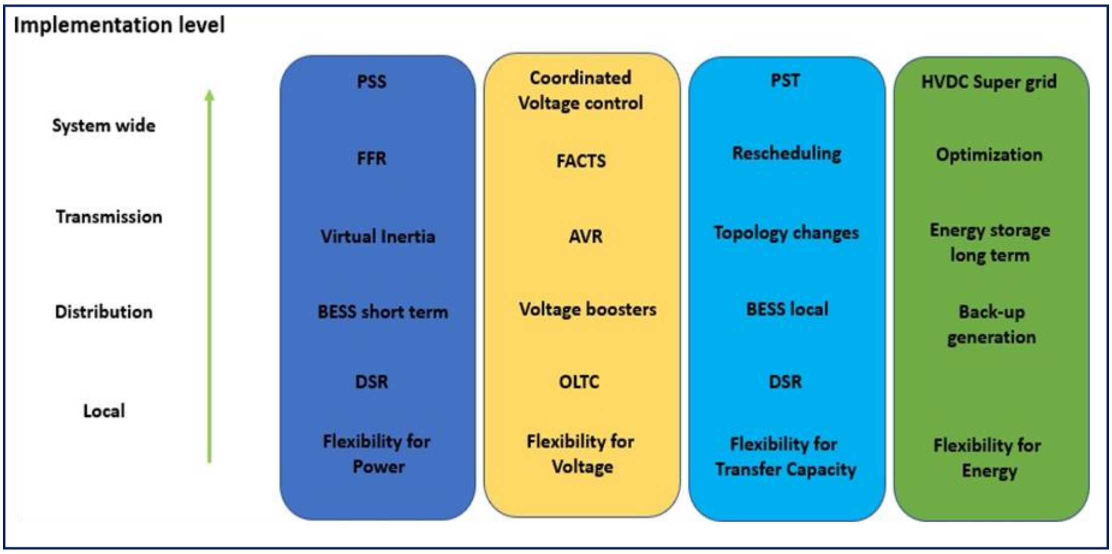

Figure 3. Examples of Flexibility solutions for each class with implementation levels from local to system-wide [6]

In Figure 3 the following abbreviations are used: PSS stands for Power System Stabilizer (PSS), Fast Frequency Response (FFR), Battery Energy Storage System (BESS), Demand Side Response (DSR), Flexible AC Transmission System (FACTS), Automatic Voltage Regulator (AVR), On- Load Tap-Changer (OLTC), and Phase-Shifting Transformer (PST).

The examples of flexibility solutions are completed on different hierarchical levels in the system, from the local level through transmission and distribution system levels to the system's broad standard. It can be noticed that the resources should be employed as the solutions of flexibility for more than one of the classes [6].

3.1. Flexibility Resources and Coordination

The electricity landscape in Europe is undergoing profound changes. The electrification of heat and transport sectors is experiencing significant expansion in many countries. The penetration of DER, located close to where electricity is consumed, e.g., households or commercial buildings is increasing considerably in the last years. Combining these effects poses significant challenges to the DSOs, and TSOs in this ecosystem. These challenges include the option between network upgrades or operating increasingly constrained networks, relying on the flexibility of distributed energy resources. In order to unlock flexibility from the consumer side, millions of small-scale and large-scale energy consumers and prosumers must be further incentivised to activate potential flexibility assets and offer flexibility on a new Flexibility Market, where TSOs and DSOs will be the most critical buyers. The ability of consumers and prosumers to play this role, however, is dependent on effective TSO-DSO-Consumer cooperation for the benefit of optimisation of grid services and utilisation of distributed flexibility assets at a large scale [6].

The European Commission has declared that on practically each grid part, such housing-level, low voltage, medium voltage, and high voltage storage are needed to mutate to the energy system of low carbon emission.

In addition to being the flexibility, resources are not still sufficiently available on the distribution network, the coordination approaches between TSO and DSO are critical. Presently, TSO is testing with the flexibility to balance the transmission network. Based on the results of several experiments, the flexibility resources are repeatedly withdrawn from the distribution network, affecting the expected loads of the grid [6].

3.1.1 Flexibility Resources available for TSO

The flexibility resources at TSO can be classified into demand and supply-side resources. The demand-side resources comprised accumulated clients that can regulate their need to deliver the flexibility to the transmission network and accumulated prosumers equipping with tremendous flexibility that includes renewable resources, Electric Vehicles (EVs) and storages [17].

The supply-side resources consist of conventional generators, wind turbines, virtual power plants, and any other massive generators that allow them to respond to the needs of the flexibility of TSO. Different flexibility resources in TSO networks are presented in Figure 4.

Generally, the conventional generators are responsible for providing flexible services to the transmission grid through complying with their available ramping, abilities, and operating limits towards the TSO.

Apart from the energy resources discussed above, some technologies and power electronic devices can also be used to increase flexibility. The Flexible AC Transmission System (FACTS) and high voltage DC (HVDC) devices enable expanding the flexibility and monitorability of TSO. HVDC combination with Wide-area Monitoring Protection and Control (WAMPAC) can promptly respond to the unusual changes in active and reactive power flows. Regulating electricity flows in transmission grids will also be operated using two other technologies, namely, OLTC transformers and PSTs [18].

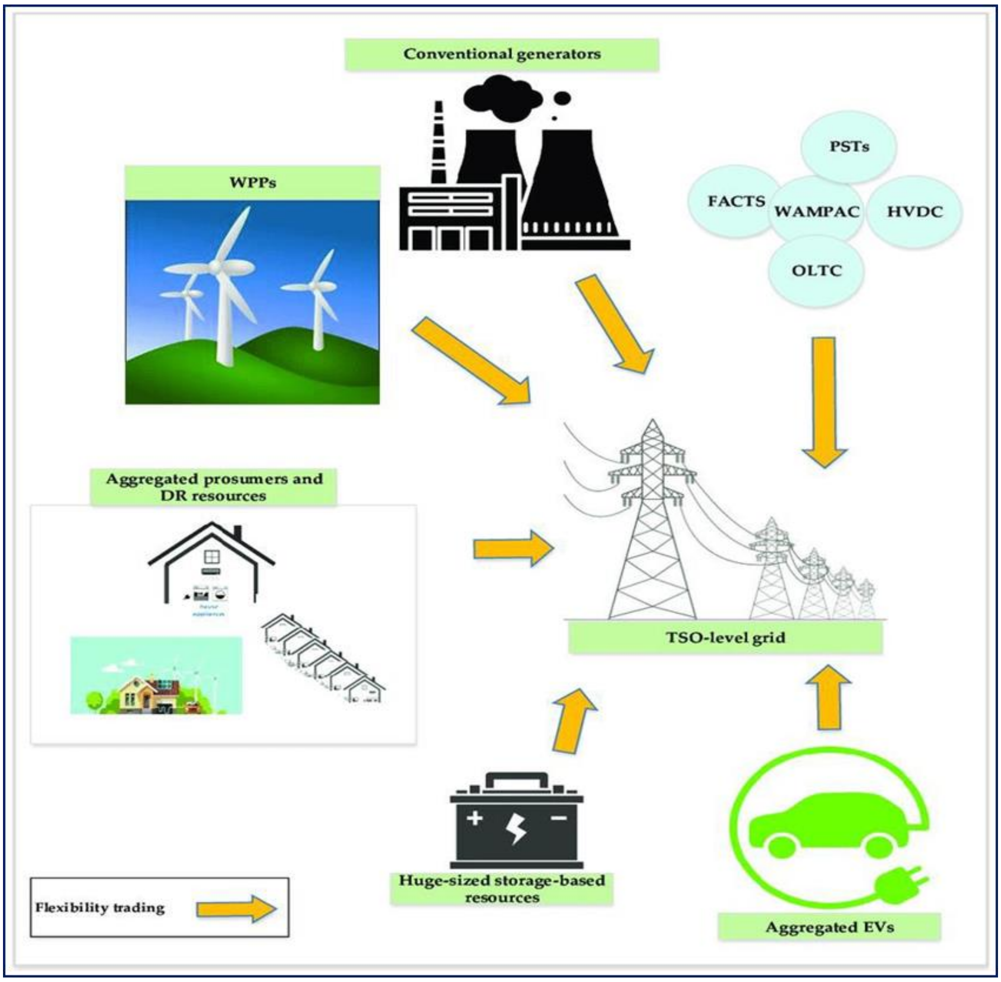

Figure 4. Flexibility resources for the transmission system operator [17]

3.1.2 Flexibility Resources available for DSO

Conventionally, DSOs spend significant investments in enhancing the distribution networks to overcome different grid challenges [19]. The electrical components like cables and transformers are modernized and replaced by high capacity limitations to escape possible grid congestion [20]. Apart from the capacitor banks, OLTC transformers are used for voltage control [19]. The varying topology of the network, termed grid reinforcement, is also one potential measure employed by DSOs to mitigate the congestion of the grid [21, 22]. The switches and circuit-breakers can be regulated together with shifting to resolve grid congestions of DSO [23]. The flexibility can also be achieved using advanced controlling strategies like Dynamic Line Rating (DLR) [24].

The DSO grid's efficient conduct, which is connected with DERs, can be covered as flexibility resources of DSO, decreasing the requirement for network reconfiguration and reinforcement. DERs can be curtailed eagerly to increase the flexibility of the system [25].

The resources of demand response are also enabled to provide the flexibility provision for DSOs. The document [26] has examined the DR resources effect on reducing the uncertainties appearing from the penetration of seasonal wind energy [17].

The storage-based resources of DSO are also consistent providers of flexibility for distribution grid needs through using different active network management (ANM) techniques. The paper [27] mentioned how to co-operate EV charging and load shedding by ANM in distribution grids for the future. In [28], the local marginal pricing was used to provide flexibility to the distribution grid.

As discussed in this chapter, the success of the future electricity grid is desperately dependent on establishing a flexible marketplace where flexibility aggregators and small-scale and large-scale producers and consumers (prosumers) can all openly participate. This marketplace must support real-time seamless collaboration between TSOs and DSOs, accommodate the future energy landscape (volatile renewable energies, DERs, etc.), and mobilise, incentivise and facilitate the participation of large numbers of consumers/prosumers, either directly or via aggregators.

The primary objective of this report lies in reviewing the existing practices to coordinate TSO and DSO interaction in order to reduce grid challenges (grid congestions and voltage issues) both in transmission and distribution networks. In the next chapter, there will be discussion on the present and future roles of system operators.

4 Present and Future Roles of System Operators

The main roles of both TSO and DSO are to ensure the safeguard operation of the power system at the transmission and distribution systems. In [29, 30] and [31], the authors described their anticipations for a role interpretation among TSOs and DSOs.

4.1. Present Roles of DSO

The present roles which DSO is focusing on are grid planning, maintenance, and verification of consumption. In general, DSO has three possible functions: service quality levels for the consumers, the facilitator of the market, and supply security for the system [31]. The present roles of DSO are described in Table 1.

Table 1. Present Roles of DSO

Roles	How is it controlled?	Tools
Service quality	Verifying the quality of wave and checking the supply continuity	Maintaining the distribution network and planning the network
Facilitator of market	Assessed by regulator	Generation of the clients, consumption verification and not discriminatory access and allowing transparent
Supply security	Checking voltages and overloading	Maintaining the distribution network and planning the network

4.2. Present Roles of TSO

TSOs perform similar roles to DSOs. However, TSO has different objectives within the same roles and various tools to reach those objectives. In Table 2, the present roles of TSO are presented.

Table 2. Present Roles of TSO

Roles	How is it controlled?	Tools
Service quality	Controlling the voltage	Maintenance of the transmission network, planning the system and utilize of the flexibility operational services of market
Facilitator of market	Assessed by regulator	Ensuring the use of the grid, flexibility operational market, not discriminatory access and exchange the borders
Supply security	Checking the voltage, frequency, and overloading of the transmission grid	Maintenance and distribution network, planning the system, utilize of exchange borders, utilize of the flexibility operational market services and technical monitoring of the electrical market

4.3. Difference between the Roles of TSO and DSO

Usually, the transmission and distribution grids have different brass tacks. The distribution network is designed at low voltages with a radial layout strategy where grid congestion and voltage variations are the primary concerns. However, the transmission network is designed with a meshing layout strategy. The differences between the systems make the differences in supply security and service quality roles that depend on the voltage level.

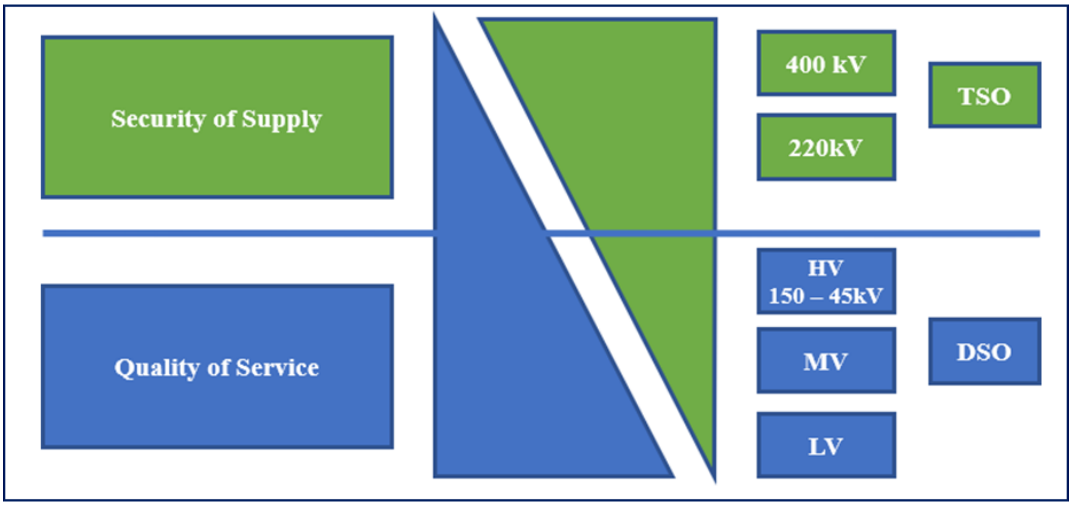

Figure 5. Security of supply and quality of service importance based on voltage level (the values are shown as an example, and they can be different in different systems) [32]

Figure 5 describes the main differences in roles of service quality and supply quality based on the different grid levels.

The other differences in roles are caused by the fact that the distribution system did not host large generation volumes in the recent past. However, this situation is changing, and an increasing number of renewable sources are integrating into the distribution grid. Such conditions will lead to further changes in TSO and DSO roles. The exiting system their roles are centered around the supply-centric system, and the roles will change by transforming the system into consumer-centric systems.

4.4. Future Roles of DSO and TSO

Reviewing the respective roles of system operators and adding appropriate changes will lead to the proper transition of the future roles for TSO and DSO.

The service quality, supply security, and market facilitator are the three different TSO and DSO roles. The objectives are evaluated to know whether the system operator is managing the different roles that are regulated.

Based on future TSO and DSO's roles, the responsibilities for the system operators may change. The DER will come up with new possibilities and challenges for the power system, which will assist in reaching the goals of the system operator.

4.4.1 Future Roles of DSO

Considering the current roles and the new incorporation of DER, there are some changes for the roles of DSO. The future objectives and tools to achieve them are described for the DSO in Table 3.

Table 3 Future Roles of DSO

Roles	How is it controlled?	Tools
Service quality	Checking the quality of waves and verifying the supply continuity.	Maintaining of the distribution network and planning the system. DER may provide the possibility of using operational tools to meet the quality of the desired service by the utility companies.
Facilitator of market	Assessed by regulator	Verification of the energy consumption and generation by the clients done in a transparent and non- discriminatory way. The accommodation of new agents as DER needs to be also taken into account for the regulatory assessment.
Supply security	Checking voltages and overloading	Maintaining of the distribution network and planning the system. Moreover, DER may give the possibility of using operational tools to obtain the quality of the desired service.

4.4.2 Future Roles of TSO

After developing and adding up the possibilities so that the new agents can come up to the TSO, the future roles of TSO with tools and actions are presented in Table 4.

Table 4. Future Roles of TSO

Roles	How is it controlled?	Tools
Service quality	Controlling the voltage	Maintaining the transmission network, planning the system, and utilizing the operational flexibility services of the market. The flexibility operational services of the market which are being performed by TSO should consider as the services given by DER.
Facilitator of market	Assessed by regulator	Transparent, utilize of exchange borders, and not discriminatory access to the transmission network that operates the flexibility market in an open and non-discriminatory way.
Supply security	Checking voltages, frequency, and overloading of the transmission network	Maintaining the distribution network, utilizing exchange borders, planning the system, utilization of the flexibility operational services of the market, and the technical monitoring of the electricity market. It may be considered a new logic control when running the operational flexibility market to reach a better quality with the new dubious that DER can carry.

4.4.3 The transition from Present to Future Roles

This is essential to recognize the transition elements emerging and changing the current roles to meet future roles. The changes may lead to new states of affairs for TSO and DSO operators, respectively. As discussed earlier, the electric flows were predictable since generation was situated at the transmission level, and the consumption was usually placed at lower voltages.

Due to distributed generation and the availability of modern technologies such as electrical storage and electric vehicles, the energy flows are no longer predictable. Consequently, the DSOs may have to introduce new flows, managing bidirectional flows, or allowing new connections with the consideration of third-party access.

The DER will provide the new services for TSO and DSO, which may be beneficial for the system to satisfy the objectives of the role. Moreover, the function changes go through the Information and Communication Technologies (ICT) development. There is a new prospect for TSO and DSO operators to operate the electrical system better since ICTs regulate the low voltage at an affordable cost.

4.5. Need for flexibility services and TSO-DSO coordination

The increase of DER in the distribution grid gives opportunities to use the resources for the overall benefit of both TSO and the DSO to settle down the problems related to frequency control and voltage control. As a result, coordination between system operators is needed for a safe, reliable, and cost-effective use of flexibility-based services [33].

The power market moves towards radical changes, led by the realisation of the European internal energy market on the one side and the increase of DER on the other side. The increase of DER impacts a more significant need for flexible services for system operators and delivers new opportunities for system operators [34, 35].

The TSO and DSO could assist with the use of flexible resources from the distribution grid. TSOs could use these resources for frequency control, voltage control, or congestion management, while DSOs could gain flexible resources for local congestion management and voltage control [36-38]. However, it is hard for TSOs and DSOs to make use of these flexibility services under the liberalisation regime achieved in the Third Energy Package as this imposed the separation between transmission and distribution (more details have been explained in section 5.1.1). For optimal use of these resources by TSOs and DSOs, coordination is necessary [39, 40]. The system operators will be able to efficiently support each other with the increase of the coordination and cost-efficient operation of their grids [41]. Furthermore, effective coordination will avoid that actions taken by one system operator that will oppose the efforts made by another system operator [42-44]. This means system operators could move combinedly to improve the grid's observability [45, 46].

The increased need for cooperation between system operators is extensively identified, principally when it comes to increasing RES and increasing the presence of DER to ancillary services [45, 47].

The European Union (EU) regulation provides a first framework that includes the different coordination concepts among system operators that could be further developed. The different Network Codes emphasise the need for system operator coordination concerning the exchange of data, operational procedures, and market design [48-51]. This concept considered as an important aspect within the HONOR project. The objective of the project is to develop and evaluate a trans-regional flexibility market mechanism, integrating cross-sectoral energy flexibility at a community-wide level. In order to pave the way for this objective, a regulatory framework should be established to exchange flexibility services between multiple DSOs and TSO.

A comprehensive review of existing projects on TSO-DSO coordination was given in Chapter 5.

5 LITERATURE REVIEW AND EXISTING PROJECTS ON TSO-DSO COORDINATION

The literature survey consists of policy and regulation of EU and Network Codes, reports of electrical associations, and research articles on TSO-DSO interactions.

The literature and project review are classified into four different sections: The first section considers the policy and regulatory documents of the EU. The second part presents procedure and network codes in a stage of Europe and network codes of local countries. The third part emphasises national and international actions that have approached the issues of this coordination before. The fourth one considers a review on TSO-DSO interaction.

5.1. Policy and Regulatory Documents from EU

5.1.1 EU Third Energy Package

Directive 2009/72/EC, the European Union energy market legislation, is called the third energy package for Europe’s internal electricity and gas market. The objective is to improve the functioning of the internal energy and to resolve the emerging structural issues - the legislation package deals with unbundling, Agency for the Cooperation of Energy Regulators (ACER), independent regulators, cross-border coordination, and retail markets.

According to this document, the responsibilities of DSO are to safeguard the longer-term capability of the system in order to cover the acceptable demands for the power distribution, maintenance, operation, and improvement of the actions based on the economic conditions [52]. This directive deals with the issues of the third party; it affirms that investment discrimination is less critical at the level of distribution than at the level of transmission wherever blockage and generation influence is more prominent than at the distribution level. Despite that, operational and legal unbundling is needed at the level of DSO. The agents must be observed to prevent them from benefiting from their vertical combination regarding their competitive position in the market, particularly concerning small non-household and household customers.

Following this document, member states should move towards innovation and evolution of distribution grids, using smart grids that will be applied to develop the efficiency of energy and decentralised power generation [52].

When a DSO is responsible for balancing the distributed system, the adapted rules in this regard should consider fair and transparent access. According to the article [53], contractual terms, including tariffs and regulations to supply such services by the DSO, should be set up in a fair and cost-efficient way.

Concerning the new conditions, the member states should impose on the companies of distribution a bond to link the customers to their grid covering the third party's access.

The member states should ensure special authorisation procedures that stand for connections of small distributed generation.

The third-party package declares that the DSO should provide the necessary information to the system users for efficient access. The data is termed a general matter, and therefore it is not identified any specific data that shall be concerned with the companies of distribution [52].

5.1.2 EG3 Report

EG3 Report represents valuable recommendations developed by Expert Group experts for Regulatory Recommendations for Smart Grids deployment (EG3). However, this document does not represent the official requirements of the European Commission.

The European Expert Group 3 has advised that transmission system operators and distribution system operators have to have the procedures for constraint management that cover the right to buy the services of flexibility in order to resolve the constraint on their grids [14].

This EG3 report[5] proposes new services with DER that would be useful for TSO and DSO to maximise investment in grids using the smart grids, including the flexibility services of the demand side. The DSO would potentially employ the services of flexibility, where offers advantages and profit to the grid and the consumer. Under proper regulation, the customers of DSO must have the opportunity of benefits from the services of flexibility.

TSOs and DSOs should approach the services of flexibility and other relevant information required to carry out their activities to ensure safe, secure, and cost-effective transmission and distribution network operation and improvement. Furthermore, this report states that TSO and DSO would exchange relevant operating data among themselves. Both TSO and DSO require to ensure the availability of relevant data to all related parties when unexpected blockage or congestion situations show up. This report highlights that the relationship between TSO and DSO should be applied for exchanging operational data and asking actions on the network of each other [14].

5.1.3 Energy Regulation: A Bridge to 2025

Agency for the Cooperation of Energy Regulators (ACER) is a European organisation that properly supports ensuring the European single market in electricity and gas functions. ACER supports national regulatory authorities in operating the supervisory tasks at the European level [30].

A Bridge to 2025 has recommended improving the energy field and regulation in the next five years. Various measures are proposed based on extensive consultation. This

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[5] EG3 Report (The Expert Group 3, 'Regulatory Recommendations for Smart Grids Deployment') of the Smart Grids Task Force and is a product of intensive work and discussions amongst EG3 stakeholders during 2014 [3].

document consists of a scheme of actions for the regulators, European Commission, member states, the agents of the energy market. The main considered issues in the document are outlined as follows:

- DSOs will require developing their networks to cover demands such as DG, charging stations of electric vehicles, and consumer services of demand response.
- DSO should need to conduct their systems proactively through service investment and smart grid. TSO-DSO coordination is first and foremost essential to identify the specific role and responsibilities of DSO and TSO so that it can define the bases. Operational data exchange and interaction with each other will be needed.

It is essential to specify the main functions of DSO to support the improvement of ambitious services. This document clarifies it is vital to make a toolbox based on the DSO regulation, which is pliable, adjustable towards the conditions of the nation, and contains a group of persistent choices in order to ensure a sufficient level of the business environment. In this respect, several important elements should be taken into account ranging from the new structures of network tariffs and develop a smart grid to meet the investments in change, achieve novelty and effective management regarding the distribution. According to ACER, smart meters play a crucial role in developing and assisting the actions of the system operators [30].

5.2. Procedure and codes

The secure system operation is the main activity of any transmission system operator. It meets the requirements made to ensure the stable and optimal real-time operation of the network, including flexibility of the transmission system. The activities of system operations, such as a Network Code development, are carried out by the European Network of Transmission System Operators for Electricity (ENTSO-E). The operational framework focuses on developing, performing, and controlling the sufficient structure of system operation for the European transmission system while ensuring durable further development and management changes of this framework based on the needs of security of supply, transmission system operators, and transmission network users' needs [54]. In the following subsection, some of the existing network codes in Europe are discussed.

5.2.1 ENTSO-E Nordic Synchronous Area

The Nordic Synchronous Area (former NORDEL network) comprises four different countries: Norway, Denmark, Finland, and Sweden. For voltage control in its grid, each system operator is responsible. The Nordic countries do not have any provision for payments towards reactive power services. The generators provide reactive power on a compulsory basis and without any financial compensation in Sweden. There is an obligation for reactive power supply within the cosφ range of 0.93 to 0.98, without having any benefit of finance in Norway [53].

Furthermore, the cooperation between the system operators is treated as intercommunication between the operator of Sweden and Norway. The regional and national centres maintain the voltage regulation of Norway. The national centres will be approached when the regional centres do not have adequate resources in order to regulate the voltage within the given limits. There are two operating systems in Sweden: the southern and northern parts of the grid, responsible for voltage control. They communicate from one region to another when the operation centers do not have enough resources to regulate the voltage within the given limits. In the normal operation, the joint target is to keep the voltage within the range of regular activity. Under the abnormal situations, Norway and Sweden may agree on actions to regulate the voltage within the given interval through respective operation centers, respectively. The operational security standard of Nordic Synchronous Area mentions that there must be a reactive power reserve within each subsystem. This must be formed when it comes to the size, localisation, and regulation to hinder the possible system collapse [55].

5.2.2 Network Codes, Spain

These Network Codes presents the technical and operational information required for proper and suitable professional management of the electrical power system in Spain.

In the Network Code 3.2, the DSO specifies a security challenge on the network to be handled. The DSO will request TSO in order to make changes in the schedule of generation to maintain security in the affected distribution grid. The TSO would make the necessary amendment required in the base program and send the modification to the DSO [56]. For all procedures, TSO acts as the principal contractor that can resolve the encountered problems. In that sense, DSO does not have the opportunity to maintain the constraints on the distribution grid. It is described that in cases when DSO finds out the real-time grid limitations and the system should go through the changes of programs of production, the distribution system operator may take the distribution grid measures and will inform to TSO, as fast as possible so that it can adapt with several modifications.

In the Network Code 7.4, it is determined that the voltage control is situated at the voltage level of the transmission grid. At present, the voltage control includes operations on resources of generation, consumption of reactive power, and voltage control of tap changer of the transformer to ensure the conformity with quality and safety norm. This code also settles the absorption and transfer of reactive power at the edge of the transmission and distribution networks.

In the Spanish Code 9, data exchange is performed by TSO, where it finds that the companies of distribution need to provide the TSO with the necessary data of the elements of its grid so that it can have a balance of energy. According to this, TSO is the principal counterparty in the operations of the network. Furthermore, the transmission system operator can operate over the customer of the grid, and this is the TSO that receives the information from DSO [56].

5.2.3 Network Codes, Germany

The TSO is responsible for the maintenance of the power balance within its control area. The responsibility of network operators regarding the maintenance of voltage limits and loading of equipment rests with every network operator within the network run by him in operational terms [57]. All the necessary network-related measures are conducted using cascading overall voltage levels of the network, appearing at the transmission system. By the command of the TSO, the DSO performs the actions of backup. The distributed system operators are needed to supply assistance to the TSO through their users of the grid. The TSO creates proper arrangements with the DSOs, based on the voltage level where the consumer is connected, and the TSO and DSO conduct manually local disconnection [57].

Power producers and suppliers, DSOs are needed to have available data to the TSO to achieve the necessary data for the system [57].

5.3. National and International Activities and Actions

The electrical power associations are the several electrical companies that are based in the European Union. These organisations are essential to consider as they serve a large number of companies of generation, transmission, distribution, and retail trading, respectively.

5.3.1 ISGAN

International Smart Grid Action Network (ISGAN) makes the multinational collaboration of government-to-government in order to proceed with the improvement and deployment of smart grid techniques, traineeship, and systems. ISGAN is a global platform for improving and exchanging acquaintance and expertise on intelligent, cleaner, flexible, and stiff smart grids. The objective of ISGAN is to increase clean and flexible electricity across the world using smart grid technologies. It also promotes the adoption of government policies and innovation of industry technology to assist the larger national purpose of developing smart grids in member states and regions of ISGAN [58].

The ISGAN has published a report on TSO-DSO coordination. This report declares a clear explanation for TSO and DSO’s roles and meets interaction between both system operators. Modification of models, roles, and cooperation emerge due to the need to dispense all the distributed generation, which appears at the distribution level. The report finds a model where DSO sets for the distribution networks, and TSO manages the transmission grid for TSO-DSO coordination. The recommendation of ISGAN for TSO-DSO is emphasised on the primary substation values, which connect TSO and DSO networks. The report studies the actions of different countries based on various issues such as congestion, overloading, grid voltage, grid balance, and resynchronisation. The organisation finds out DSO requires two communication methods: communication with the customers of flexibility and interaction with the TSO. DSO should expand to have more roles than TSO [58]. The congestions are resolved while planning to utilise n-1 criteria. Usually, the TSO either disconnects or curtail in case of an emergency. The report recommends that data exchanging and network maintenance should apply the grid flexibility to decrease the load when required.

Furthermore, the report covers the issues of voltage. Presently, the TSO handles the voltage matters. Though the voltage issues appear at DSO, TSO is settled down using a tap changer transformer on TSO-DSO coupling point. Moreover, DSO can employ capacitor banks to assist the voltage at the transmission. It has been expected that DSO may widely use capacitor banks to cooperate with reactive power from DG to facilitate the voltages of the transmission system. The report also gives recommendations on resynchronisation, islanding, and black start. Currently, islanding is prevented using suitable devices for protection. When it comes to the black start, there must be created coordination between TSO and DSO. In order to restore the grid, distributed generation should be considered in the present schemes.

The overloading can be covered through flexibility[6] of TSO or flexibility of DSO. When a local voltage issue appears, the DSO will apply active and reactive power flexibility by the users of distribution and capacitor banks to get back typical situations in the grid. The report has clearly described that TSO is responsible for maintaining the transmission network, while DSO must always be used to support the distribution network [58].

5.3.2 GEODE

GEODE is the EU voice of local energy distributors of gas and electricity in Europe. The objective is to make equal possible access to European energy infrastructures for all those included in providing the customer needs on energy to create a favourable competitive energy market in Europe. It represents more than 1200 companies in 15 countries, both privately and publicly owned.

GEODE has published a report that strengthens the potential use of Demand Side Response (DSR) to benefit flexibility. The report emphasises how DSR can provide advantages to the complete power system: it brings the possibility to maximise the utilisation and grid balancing, and energy generation and consumption, low grid cost, reasonable prices, development of security supply, or the efficiency of the whole system are some of the advantages of DSR [59]. The report specifies significant impediments for the flexibility of the demand-side due to the DSO tariff's present structure in Europe. The structure of the current DSO tariff targeted the consumed energy, which does not create feasible fiscal incentives for the consumers to adapt their energy consumption based on the network's capacity. The structures of the present DSO tariff do not respond to the cost suitably. The structure of the current DSO tariff should develop more so that it can address insufficient costs. DSOs must be allowed with a legal framework to play an essential role in developing technology. The report recommends a ground rule that the market operators can perform independently as far as the distribution network is not at risk. When it comes to Distributed Generation, GEODE considers that distributed generators can support local distribution grid balancing. In this regard, the report develops a DSO form with flexibility service; DSOs are a fundamental element to have

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[6] According to ENTSO-E, Flexibility in a power system is the active management of an asset that can affect system balance, or grid power flows on a short-term basis, i.e., from day-ahead to real-time. The reference is https://www.entsoe.eu/2012/07/04/entso-e-response-to-acer-public-consultation-on-the-draft-framework-guidelines- on-electricity-balanc/.

regular grid operation and grid stability. The report also defines that if DSO requires a direct market, it will be essential to raise the ability of real-time maintenance and handleability in the distribution network. In order to overcome the future challenge of the power system, the DSO needs to make dynamic data to bring jointly decentralised production and consumption [59].

5.3.3 Eurelectric

Eurelectric is the sector association representing the common interests of the electrical power industry at a European level. This association affiliates and associates in many other parts of the world out of Europe. Eurelectric presently has over 30 full members representing the electrical power industry in 32 different EU countries [60].

At present, when the voltage of the grid is low, the grid's maintaining level moves to very low. This case can be overcome, considering RES's benefits with the Information and Communication Technologies (ICT) upgrade. The Eurelectric association advises DSOs to set aside the conventional inert distribution networks based on fit-and-forget strategy. The fit-and-forget approach considers that distribution networks have to be designed to meet all possible combinations of production and load situations, even those that occur only for a few hours per year.

The document clarifies that a cost-efficient unification of DER needs to reconsider how distribution networks are designed and performed. The cooperation between all related stakeholders is a crucial issue when this type of problem is encountered. When it comes to the clarification of roles and responsibilities, Eurelectric sees that DSO should be allowed to perform constraints if the safe operation of the distribution system is at risk. In order to do so, DSO must be enabled to obtain the relevant information of DER. DSOs must have access to receive data.

In [61], this association elucidates that DSR shall be one of the essential elements for wholesale and retail trade in the future, providing the grid users with the possibility to achieve the full advantages of their potential flexibility. The improvement of innovative services will offer customers several options for control over electrical power consumption. This document proposes a traffic light system that will inform about network stability considering no congestions or emergencies. This system should give the relevant data to the respective parties of the market along with transparency. DSO must ensure that aggregators' intervention will not affect the safety of TSO or DSO networks through the traffic light system. DSOs must also have access to the process of constraints to handle the limitations in the systems.

5.3.4 EDSO

European Distribution System Operators (EDSO) for smart grids gather DSOs for electrical energy, cooperating to implement the vision of smart grids in the electric system of Europe. It is mainly focused on guiding European Union RD&D, policy, and regulation for member states to facilitate development [31].

The principal tool applied by DSOs to surpass the high demand for electricity consumption in their grids is to enhance the network using electric cables, modernisation of transformers, substations, etc. However, an alternative strategy creates the use of the flexibility provided by the users of the grid. The new approach gains prominence. This document recommends that with the increase of DER, the flexibility services connected with the distribution network will rise. Furthermore, DER connections may cause less predictable flows of energy in the distribution networks [31].

According to EDSO, the DER development is enormously affecting the networks having low and medium voltages. Generally, DER needs a high degree of control over the service parameters.

This document highlights that DSOs may obtain flexibility services in all timeframes. The DSOs should be allowed to determine which circumstances require a market solution and which conditions need to develop a grid while retaining a quality service.

The system's flexibility services will need a widespread interaction and explicit constraint between TSO and DSO. The DSO should always be allowed to coordinate and accept TSO’s action so it cannot make subsequent limitations in the DSO grid. The data exchanging between TSO and DSO will ensure that the system operators have completed data to sustain network stability. For this purpose, the system operators should need to improve explicit definitions of hierarchical processes and network management plans to each other and the markets. This is required to adjust the current legislation and accommodate it to the new environment. However, there is a network code to overview the roles and responsibilities and cooperation between TSO and DSO. The legislative framework should be able to make the new service system at the level of distribution. These system services may lead to the possibility of being obtained as ancillary services. The EDSO document proposes the DSO obligation through the different system operators to perform as the market facilitators for other new appearing market-based services [31].

5.4. Literature review on TSO-DSO interaction

The increasing importance of renewable energy generation connected to distribution networks needs better coordination among TSOs and DSOs to manage reactive power. The authors in [62] recommend a realistic and efficient cooperation strategy based on continuous optimisations to determine the reactive flexibility of distribution grids and dispatch them through the conventional synchronous generator, holding to minimum data exchange. In this paper, a consistent optimal power flow (OPF) mechanism having multi-objective optimisation is made to achieve this goal. The proposed strategy is applied for a real example of 110 kV network model with 1.6 GW on wind power capacity and a mitigated model of the transmission system. It verifies the advantage of including wind farms to reduce reactive power losses at transmission and distribution levels.

In the Power system, the reactive power is primarily maintained by the units of large generation in the transmission network, along with compensating apparatus and Flexible AC Transmission Systems (FACTS). The TSO is responsible for cooperating with different reactive resources to ensure the balance of reactive power supply by DG will attain a vital role. The distribution system performed primarily as passive grids and the potential use of OLTC transformers, and power factor correction of load are the primary strategies for DSO to maintain local voltage control [62]. A coordination method among DSO and TSO based on the Optimal Power Flow (OPF) tool characterising multi-objective and Model Predictive Control (MPC) optimisation is considered. The technique involves the cooperation between two real-time OPF performing in the DSO and TSO premises. The coordination chain based on the following optimisations and relevant information exchange, and the setpoint is specified [62]. This paper proposes a mechanism to achieve optimal control of wind power parks for an interacted management of reactive power among DSO and TSO takes into account the constraints and benefits of both system operators [62].

5.4.1 Redefining the new role and procedures of power network operators for efficient exploitation of demand-side response

The authors in [47] have described the presence of a large number of approximately small generation units connected to the distribution network concerning the transmission system operators as they have no opportunity to control and monitor areas and are invisible for them. The reason is that both TSO and DSO concern only with their networks and the control of network data. It could not be possible for TSO to conduct all the DGs that may be linked to the grid.

The article clarifies that any procedures where DSO’s activity impacts the independent users of the market should undergo managerial supervision. This legislation must be carried out to ensure security and transparency of outcomes every time. The paper indicates that the motivations given to the DSOs shall be sufficient to support them to take benefits of the added value of the services DER may provide to the planning and operation process. However, in the meantime, it could be adequately temperate to make sure by no means DSOs should be induced to allocate economic stability at stake [47].

5.4.2 The new role of DSOs: Ancillary services from RES towards a local dispatch

It is essential to clarify that system operators of transmission and distribution would have the possibility to provide effective use of the services that allocated energy resources may provide using a new electrical network [63]. This document mentions that there are no systems planted for data acquisition from distributed generation if the model of Italy is taken into account. In some instances, TSO acquires information from renewable energy sources in real-time. Considering the future, well-ordered and systematised exchanging data between appropriate agents is necessary. The DSO would need data about the forecast of distributed generation, active and schedules dispatch to promote their emergence, and to attain a near to management of real-time distribution grid comprising the constraints of the local network.

Three different methods of cooperation models are proposed based on the management of various services:

- In the first proposed model, it is an extension of a conventional model for coordination. The units of RES connected to low voltage, medium voltage, and high voltage networks would have to provide an injection forecast into the grid one day earlier than the delivery day. The distributed system operator resolves local constraints through that forecast. Regarding the real information, it should be provided to DSO utilising TSO so that DSO can finally respond consequently in emergency circumstances and select the most suitable distributed generation. Furthermore, any measure on distribution grid users asked by the TSO shall be satisfied over with appropriate DSO to gather new resources of dispatching; if the DSO figures out the limit of the network are being surpassed, it should inform the TSO so that it can adapt the plan of production [63].

- The second model comes up with the opportunity to DSO of managing a functional market of flexibility. The DSO may procure the services to meet its own needs and provide resources accumulative way in the interest of TSO. The DSO can purchase flexibility afforded by different aggregators or DGs. TSOs take offers from conventional plants and DSOs so that they can perform the power system operation. Furthermore, TSO resolves the transmission congestion and makes secondary and tertiary retains at the lowest cost.
- DSO is responsible for keeping the scheduled program at a medium voltage - high voltage interface in the third model. For curtailment of unbalances at every primary substation, the DSO should apply all balancing resources on the distribution grid. At the same time, TSO will conduct the system with the central dispatch containing all the users connected to the high voltage network. The TSO would manage the services of the system, and DSO would lead the local services individually [63].

5.4.3 Market approaches for TSO-DSO coordination in Norway (joint project between Statnett and N-SIDE)

This project investigates how to exploit flexible assets at both the transmission and distribution levels close to real-time for balancing and congestion management purposes.

Several pilot or commercial projects on similar objectives are investigated in the project (Enera, Gopacs, Nodes, Piclo, Cornwall, Soteria, Coordinet, Smartnet). A key outcome of these analyses is that some of these projects often segment balancing and congestion management rather than consider them an integrated process. The integration of balancing and congestion management is an attractive feature from an economic standpoint and is well-aligned with the Nordic balancing philosophy and present practice.

The project concludes that a marginal local balancing price (i.e. BSPs can have different prices depending on their location) would be the ideal solution, preferably if imbalance prices can also be set locally. As a practical alternative, maintaining a different settlement scheme depending on the activation purpose (i.e. paid-as-cleared for balancing and cost-based paid-as-bid for congestion management) as a way to reduce gaming (in line with the currently applied paid-as-cleared for balancing and paid-as-bid for “special regulation”) deserves further investigations [64].

6 SCHEMES FOR TSOs AND DSOs COORDINATION

According to Chapter 5, the coordination between TSOs and DSOs in the context of services based on flexibility is not abundant yet [65-67]. Furthermore, the presumption of a more decentralised energy system in the future supports the idea that DSOs play a role in collecting and providing small-scale generation to the TSO in a coordinated manner [68].

The proposed coordination schemes may take into account current and potential future needs of network operators [40, 47, 69], new concepts for the supply of services based on flexibility from and to the distribution network [37, 70, 71]. It also includes the potential approaches and considerations for coordinated system operation [58, 63, 72, 73] and the need for data exchange between system operators [66, 74, 75]. In the following sub-sections, we review the proposed schemes available in the literature.

6.1. Existing Coordination Schemes

The coordination between TSOs and DSOs, in the context of the procurement of ancillary services (AS) and local services, could be organised according to SmartNet project [76]. The SmartNet project proposed a new classification of coordination schemes between the TSO and DSO divided into five different coordination schemes. These coordination schemes are described as the result of choices made on multiple layers:

- The needs (from which SO does the need for flexibility come from?)
- The buyers (which stakeholders are going to be buyers in the flexibility market(s)?)
- The market (how many flexibility markets are organized?)
- Resource accessibility (does the TSO have access to flexibility resources connected to the DSO grid?)

The classification considering the above criteria results in five coordination schemes:

6.1.1 Centralised AS market model

The TSO is the market operator who performs a market for both resources connected at the distribution and transmission level. TSO operates all resources located at the transmission and distribution level, with no or little involvement of the DSO (which can possibly be involved in some prequalification steps, if needed).

6.1.2 Local AS market model

the DSO organizes a local flexibility market with the resources connected to its grid, with no cooperation with the TSO. The TSO does not have access to the resources that are connected to the DSO grid.

6.1.3 Shared balancing responsibility model

The balancing responsibilities are called separately by DSO and TSO, each on their grid separately. The DSO manages a local market while considering a schedule of power exchange accepted with the TSO. The remaining flexibility bids accessible from the DSO are ultimately aggregated and offered to the TSO market

6.1.4 Common TSO-DSO AS market model

both the DSO and the TSO buy flexibility on one single market platform, which centralizes all the flexibility bids and the network constraints from both SOs. Both TSO and DSO have a common goal to reduce resource cost. They both operate a common market to ensure optimal use of the available resources. The DSOs will ensure the local distribution grid constraints are integrated into the market processes.

6.1.5 Integrated flexibility market model

This scheme is similar to the previous scheme, except that commercial parties such as BRPs can also buy flexibility from the market, e.g., in order to balance their portfolio. An independent market operator operates the market platform, and both TSO and DSO have to share data with the market operator. This market platform increases the possibilities for BRP to solve imbalances in their portfolio.

Each of the coordination schemes is defined above as the relation between TSO and DSO that specifies the roles and responsibilities of each system operation [33]. A role is defined as an intended behaviour of a specific market party, with particular unique responsibilities and cannot be shared [69]. Some system operators' roles might be added, modified, or shifted based on the coordination scheme. The specific purpose of the DSO is subject to evolution [77]. DSOs could play a role as active system managers, technological enablers, data managers, and innovators [14]. Furthermore, DSOs could be involved in the development of local markets as neutral market facilitators, market operators, and contributors to system security [69]. The DSOs support the participation of distribution grid-connected resources to the flexibility market as neutral market facilitators.

The processes should be in the right place to ensure proper justification and transparency around restrictive actions made by the DSO or TSO. The integration of local grid constraints could be carried out based on different concepts. The distributed system operator could allow in advance the presence of flexible resources to the flexibility market through a process of the prequalification system. Furthermore, the DSO will turn into a competent buyer of flexibility as a TSO.

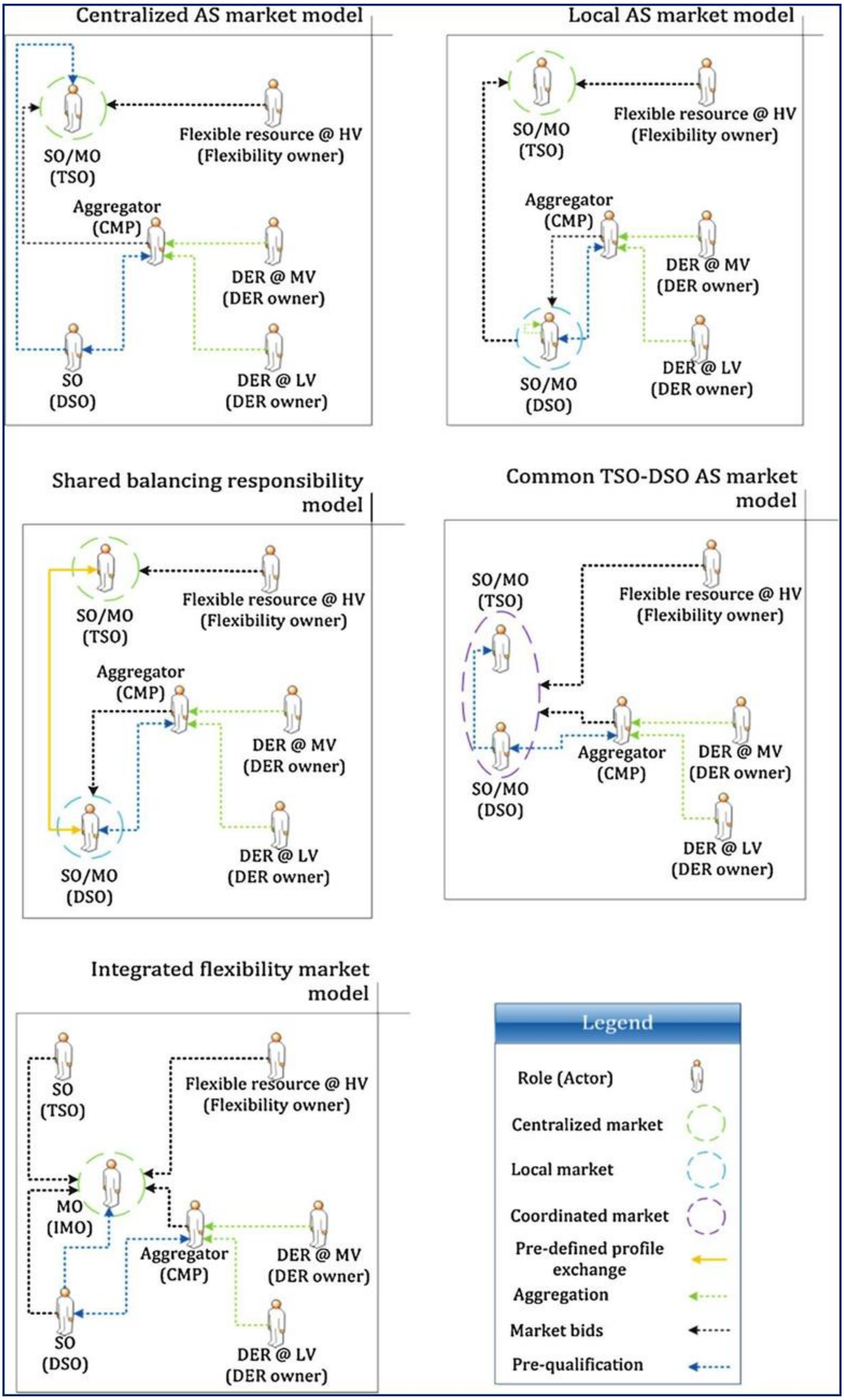

Figure 6. Five different coordination schemes [76]

6.2. Roles and Responsibilities of TSO and DSO

The TSOs and DSOs are responsible for the secure operation of their network, including managing voltage on their grid and congestion [73]. However, the system operators' current roles are subjected to development under the increasing amount of distributed energy resources connected to the distribution grid. More particularly for the DSO, the current roles might be expanded, and new roles could appear. When it comes to grid operation, DSOs could play a significant role as active system managers, data managers, innovators, and technological enablers. Furthermore, DSOs could be engaged in the evolution of the local market as both market operators, neutral market facilitators, and contributors to the security system [69, 73]. The DSOs act as a neutral market facilitator to assist in distributing grid-connected resources to the flexibility market. As a contributor to system security, the DSOs will uphold the TSOs by supplying the local solutions for the problem. When it comes to the role of the market officer, the DSOs can contract the flexibility resources both in the short and long term for the local goals, for instance, management for congestion. At present, DSOs are not commonly employing contract and/or use flexibility-based services as an alternative to delay or escape network reinforcements to deal with the increasing intermittent generation [69, 73].

In the same vein as the rules specified for TSOs, DSOs cannot be on both sides of the market as both market facilitators and service providers. TSOs and DSOs should not actively operate as commercial service providers if they are buying or demanding a system service [73, 78]. The roles of TSOs and DSOs are subject to development, but also, the roles and responsibilities of other market parties are affected by recent market evolution [76].

The policymakers will require subsidiarity in the development of roles and responsibilities for DSOs and TSOs [78]. There is no one-fits-all solution that could be applicable for every country or balancing area due to the substantial heterogeneity in roles and responsibilities of system operators [76].

6.3. The Coordination Scheme Feasibility

In Figure 6, the different coordination schemes are classified based on the feasibility of implementation. Some coordination schemes can be easily adopted through simple modifications to the existing market design. However, most coordination schemes require radical changes to the regulatory framework and market design before implementation. Furthermore, the feasibility of a particular coordination scheme is affected by the current organisation and cooperation of national TSOs and DSOs on one side and the present initial movements for harmonisation and integration of ancillary services markets on the other side [33]. The existing national systems of organisation and cooperation among TSO and DSO will affect any coordination scheme [33]. This might be a relevant feature to consider the different coordination schemes regarding the existence of several comparatively small distributed system operator DSOs, for instance, in Norway or Germany. For designing the instruments and requirements to deliver the policy objective to avoid negative cost/benefit impacts or disproportionate, the nature and type of DSOs (size, TSO-connected, or DSO-connected) should be considered properly [33].

The different visions and approaches of interaction between TSOs and DSOs describe a framework for policymakers to decide how the current market structure and regulation could be adjusted. The analysis indicates that each of the models can develop into a different or more advanced coordination scheme. This makes it easy for policymakers to put forward measures to enhance the coordination between TSO and DSO operators.

6.4. TSO-DSO Interaction

The TSOs and DSOs need to co-operate jointly to utilize flexibility to achieve their goals as presented in regulation while creating conditions for the uptake of new services without putting the reliable provision of electricity at risk. When the appropriate coordination mechanisms are in the right place, and the required data are exchanged between TSOs and DSOs, the flexibility is the modification of generation injection to an external signal such as activation or price signal to provide a service within the power system. As we have commented previously, the efficient TSO-DSO interaction is essential to ensure cost-efficient, reliable system and grid operation and sustainable energy use and facilitate the power markets throughout Europe. Apart from the TSO-DSO coordination with the parties of the market, co-operation with the consumer organizations also plays a vital role in securing the development of engaging and trustworthy market patterns. The provision of ancillary services connected to the distributed system has been the focus of several development projects and researches and the recent regulatory developments in some European countries. For the moment, many pilot projects are ongoing, reflecting that they are still in the learning stage, which is encouraged by the European Commission and the member countries [79]. In the next, chapter we review the theoretical basis and modelling approaches for TSO-DSO coordination.

7 Review of modelling approaches in TSO-DSO coordination

The authors in [28] explore the economically optimal use of DSO-based flexibility resources for power system benefits. Flexibility supports re-dispatch measures and serves as secondary reserves for the given ancillary services scheme. The TSO shares its capacity needs and pays the DSO for providing flexibility through DERs aggregated by types such as demand response, storage and PV. The scenarios implemented consider possible developments in TSO-DSO communication, and a price-sensitive function reveals fixed flexibility prices and a variable price-demand curve. The results in [28] show that re-dispatch support is not beneficial compared to secondary reserves, which can considerably lower the TSO cost.

Similarly, the authors in [67] apply hierarchical coordination of economic dispatch for the TSO and DSO based on the Benders decomposition and by defining generalized bid functions. The hierarchy is composed of two levels. The second level is the DSO, where the output is packed into generalized bid functions, approximating the dispatch cost of the distribution system holding distributed generation (DG) units represented individually. The bid functions are communicated to the TSO level, ensuring the information exchange between the TSO and DSO, which is limited in the current power system structure. The modelling framework is compared to centralized dispatch, and the effect of DERs on voltage magnitudes and angles is discussed. This shows that compared to [28] the work of [67] is focused on the difference between the coordinated and non-coordinated case, rather than a comparison of the potential ways of exploiting flexibility from DERs.

In [80] the authors investigate the optimal investment and operation of aggregated DERs including DR, PV, storage and thermal units. They perform analysis in the distribution system with market participation in both deterministic and stochastic contexts. The uncertainty in the day-ahead wholesale market is considered in the stochastic program. Unlike [28] and [67] there is no TSO-DSO coordination mechanism implemented by [80]. A price-maker approach is developed based on representing the market competitors with residual demand curves. The impact of the aggregators on the price is assessed to help the decision to use price-maker or price-taker approaches for the aggregated resources. With the objective to maximize prosumer benefits, [80] shows a significantly increased economic benefit if the aggregators are large enough to follow a price-maker approach compared to the case where DERs are not integrated. This requires that the size of the aggregated DERs surpasses the bid size limits of the market. Also, the stochastic model is more robust against price changes than the deterministic.

Along with [80], [81] develops a stochastic model. However, [81] implements a scheduling model with a day-ahead market structure minimizing costs where there are no DERs and uncertainty is related to RES, load and component outages in the transmission system. The set of single outages and contingency dispatch is pre-selected. The reserve requirements and line flow limits are formulated as chance constraints (CC). The power system reliability requirements are to be satisfied with a presumed level of high probability. The CC stochastic programming formulation provided by [81] is converted into a linear deterministic problem, and a decomposition-based method is applied to solve it.

A two-stage stochastic program is also defined by [82]. In this case, the goal is to handle the intermittency of RES, both solar and wind power, while minimizing the system costs. In the first stage, the operating points for conventional generation based on the forecasts of demand and generation from renewables are determined. In the second stage, the realizations of generation from RES as well as demand are incorporated. Hence, it is solved by exploiting demand-side flexibility and recourse decisions available because of the flexibility from conventional generation sources. The DR program holds demand shifting, while, at the same time, the conservation of demand for specific time periods must be fulfilled. Furthermore, DR is calculated from a flexibility interval based on the proportion of load delivered for shifting and aggregated for each distribution system.

Uncertainty in generation from wind power and demand response as the DER is incorporated in [83]. Reference [83] develops a robust chance-constrained model. Only the transmission system is considered, like in [67], but the TSO is able to use demand response to provide flexibility. Furthermore, DR is allocated to effective buses and aggregated in each node where it is present. The model is defined in two stages, where the first stage contains here and now decisions determining the generation cost and start-up and utility function of demand response at the base case. The second stage, wait and see, includes the cost of power amendments for generation units and demand response and involuntary load curtailments in response to uncertainty sources.

The reference [84] develops a two-stage modelling framework, where both the transmission and distribution networks are solved separately. The transmission system feeds the distribution system through the distribution substation, which is represented as one node. The framework determines the locational marginal prices in the first stage by implementing unit commitment and dispatch problems. DR, as in [82] and [83], is the DER providing flexibility, and it is used to minimize the total cost of providing energy for the consumers in the distribution system. However, in the case of [84], prices are modelled as the uncertainty parameters through robust optimization. The unpredictable behaviour of the market participants is analysed, taking into account a worst-case scenario [84] .

The reference [85] develop a two-stage adaptive robust model for the security-constrained (SC) unit commitment problem in the presence of nodal net injection uncertainty. In practice, this uncertainty is related to RES and demand. The uncertainty set is defined deterministically, and, like in [84], the solutions are robust against all possible realizations of the modelled uncertainty. As in [81], no DERs are considered. The model is a two-level decomposition approach, including Benders decomposition and outer approximation. A first-stage commitment and a second-stage adaptive dispatch minimize the sum of the unit commitment and dispatch cost under the worst-case realization of uncertain nodal net injections.

Lastly, in [86], the authors proposed a coordinated modelling approach that tests the presence of TSO-DSO coordination versus the lack of coordination. The objective is to integrate DSO models into TSO models while also considering the value of coordination from the operators perspective. To accomplish this, a bilevel objective function test various sensitivity costs to calculate a Pareto front for DSO vs TSO costs.

Table 5 summarizes the comparison of the presented literature in this section on modelling approaches in TSO-DSO coordination. Moreover, we mapped the coordination schemes presented in chapter 6 in bold under the “Coordination mechanism” column.

Table 5 Comparison of the presented literature

Paper	Coordination mechanism	Uncertainty	Source of uncertainty
Tran et al. (2016) [28]	TSO shares need for capacity and pays DSO and aggregators for using DERs for AS (**Shared balancing responsibility model)**	-	-
Yuan and Hesamzadeh (2017) [67]	DSO share generalized bid functions with TSO **(Common TSO-DSO AS market model)**	-	-
Calvillo et al. (2016) [80]	Only DS with aggregators **(Local AS market model)**	Deterministic and 2-stage and stochastic	Electricity prices
Wu et al. (2014) [81]	Only TSO (**Centralised AS market model)**	CC stochastic	RES, load and component outages
Bukhsh et al. (2015) [82]	DSO shares info about demand and flexibility (DR) to TSO (**Local AS market model**)	2-stage stochastic	RES
Nikoobakht et al. (2018) [83]	Only TS, but TSO can use DR (**Centralised AS market model**)	Robust CC	Wind and component outages
Mahboubi Moghaddam et al. (2016) [84]	TSO shares nodal prices with DSO, and DSO shares demand with TSO iteratively **(Common TSO-DSO AS market model)**	Robust	Market prices
Bertsimas et al. (2013) [84]	Only TSO (**Centralised AS market model)**	2-stage adaptive robust, SC	RES and demand
Grottum et al. (2018) [85]	Power balance constraints and prices for power procurement are coordinated (**Integrated flexibility market model**)	2-stage stochastic	RES

From Table 5, it can be noticed that currently, there is no unique modelling approach used for the TSO-DSO coordination. Several alternatives exist, each of them has certain advantages and disadvantages. The most suitable modelling approach is selected and applied based on specific Local/National priorities and constraints.

8 Conclusion

Using flexibility services is an intelligent way to tackle the challenges that the increasing penetration of renewable and distributed energy resources will create in power systems. The central task of the HONOR project is to investigate the smart energy systems integration with a full picture of how flexibility is operated, generates value at local, regional and national levels, and based on this investigation to propose the holistic flexibility marketplace concept. In order to develop the flexibility marketplace concept, which will be in consensus with already established processes in the power system, a deep understanding of existing flexibility solutions, regulations, and ways of TSO-DSOs coordination is required. Therefore, this document presents research findings based on a literature review emphasising the current state of the art in the flexibility utilization and coordination of TSO-DSOs. The appropriate study creates the basis for developing flexibility market solution within the HONOR project.

Most of the existing publications define that flexibility correlates to the power system’s capability to conduct the changes. Flexibility can be achieved through different services of the system, responses based on control mechanisms, methods of operations towards the implementation of new power elements in the system. The demand response, energy and heat storage, electric vehicles have tremendous potential for future flexibility market. In addition to the flexibility resources, the coordination between TSO and DSO is critical in the practical implementation of flexibility services and flexibility market mechanisms. This problem is reflected in policy and regulatory documents, procedures and codes, national and international projects. However, the literature review showed that the coordination between TSOs and DSOs in the context of services based on flexibility is not abundant yet, and this concept is still under development.

Traditionally, the TSOs and DSOs are in charge of their network's secure operation, including managing voltage, frequency and congestion problems. Renewable and distributed energy resources, electrical storage and other modern technologies introduce new bidirectional and less predictable energy flows in the distribution system. These changes affecting the system operators’ roles, and therefore new responsibilities for system operators might be added. For example, DSOs could be involved in developing local flexibility markets, market operators, and contributors to system security. The roles and responsibilities of participants in the flexibility market should be organized so that DSOs and TSOs will be able to efficiently support each other, provide cost-efficient operation of the grid, and proper utilization of flexibility resources. Furthermore, effective TSO-DSO coordination will guarantee that actions taken by one system operator will have no negative impact on another system operator and the overall operation of the power system.

The literature review showed several possible schemes for TSO-DSO coordination in the flexibility market. The publication states that the existing coordination schemes need extensive modifications to the regulatory framework and market design before implementation. The feasibility of a particular coordination scheme is affected by the current organisation and cooperation of national TSOs and DSOs on one side and the local initiatives to integrate ancillary services markets on the other side. Therefore, it might be required to consider the different coordination schemes and select the best one for the national/local conditions when it comes to TSO-DSO coordination. A similar situation can be noticed for the modelling for the TSO-DSO coordination. Several alternative modelling approaches are presented in publications. Each of them has certain advantages and disadvantages. The most suitable modelling approach is selected and applied based on specific priorities and constraints for flexibility utilization.

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