CLEAN ENERGY MINISTERIAL

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ISGAN INTERNATIONAL SMART GRID ACTION NETWORK

Power Transmission & Distribution Systems

Flexibility harvesting and its impact on stakeholder interaction

Discussion paper

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About ISGAN Discussion Papers

ISGAN discussion papers are meant as input documents to the global discussion about smart grids. Each is a statement by the author(s) regarding a topic of international interest. They reflect works in progress in the development of smart grids in different regions of the world. Their aim is not to communicate a final outcome or to advise decision-makers, but rather to lay the groundwork for further research and analysis.

Disclaimer

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List of Acronyms

AC	Alternating Current
aFFR	automatic Frequency Restoration Reserve
API	Application Programming Interface
BESS	Battery Energy Storage System
BRP	Balance responsible party
CAPEX	Capital Expenditure
CEP	Clean Energy Package
CIM	Common information model
DEP	Data exchange platform
DER	Distributed Energy Resource
DG	Distributed Generator
D-NDP	Distribution network development plan
DNO	Distribution network operator
DSM	Demand Side Management
DSO	Distribution System Operator
EMS	Energy Management System
ENTSO(-E)	European network of Transmission System Operators (for electricity)
ESG	Environmental social governance
ESO	Electricity system operator
EU	European Union
EV	Electric vehicle
FACTS	Flexible Alternating Current Transmission System
FCFS	First come first serve
FERC	Federal Energy regulatory commission
FSP	Flexibility service provider
G2V	Grid to vehicle
HEMRM	Harmonised Electricity Market Role Model
HP	Heat pump
HTTPS	Hypertext Transfer Protocol Secure
HV	High voltage
ICCP	Inter-control Centre Communications Protocol
ICT	Information and Communication Technology
IESO	Independent Electricity System Operator
IPPs	Independent power producer
ISGAN	International Smart Grid Action Network
IT	Information technology
LV	Low voltage
mFFR	manual Frequency Restoration Reserve
MV	Medium voltage
MW	Megawatt
MWh	Megawatt-hour
NRA	National regulatory authority
NWA	Non-Wires Alternatives

OPEX	Operational Expenditure
PV	Photovoltaic
RAE	Regulatory Authority for Energy
RES	Renewable energy resources
REST	REpresentational State Transfer
RR	Restoration Reserve
RTO	Regional transmission organisation
SCADA	Supervisory Control and Data Acquisition
SO	System operator
TNO	Transmission network operator
TSO	Transmission system operator
TYNDP	Ten-Year Network Development Plan
UK	United Kingdom
V2G	Vehicle to grid
VRES	variable Renewable Energy Resource

Executive Summary

Power system flexibility

Power system flexibility has become an important component of many modern power systems around the world. However, the term “flexibility” is highly challenging and complex and can offer a different meaning, depending on the perspective of the stakeholder (e.g., flexibility provider, user etc). Furthermore, as the power system transitions towards the increase in existing and new sources of flexibility (such as distributed energy resources), their unique characteristics can provide many services to system operators who can utilise them in order to ensure the safe, reliable and cost-effective supply of electricity. Within this report, the needs, services and requirements of the power system flexibility from the perspectives of the TSO and DSO are presented, based on the outlook of network operation and planning.

Stakeholders and stakeholder interaction

Within the electrical energy supply chain there are many different stakeholders who play an active role in order to ensure the safe and reliable and secure supply of electricity. Within the European Union, the Harmonise Electricity Role Model provides an overview of the various roles and responsibilities of stakeholders related to information exchange. Within this report, the most common actors and their roles are presented and discussed. An example of representative stakeholders from various countries are provided to show case the current situation respectively. Additionally, a summary of the current boundary conditions. which further distinguishes the focus areas and responsibilities between these stakeholders, from an international perspective is given. In order to facilitate the interaction between these stakeholders, it is necessary to design and develop a coordination scheme/mechanism which provides a structured framework for each stakeholder. In doing so, the relationship between the stakeholders and their respective roles and responsibilities are clearly defined. This is particularly important when procuring and utilising flexibilities for system services connected in the distribution grid. To demonstrate this, example coordination schemes from North America and Europe are provided. However, it was noted that, while many coordination schemes differ slightly, they are, for the most part, based on a similar framework, with differentiating nomenclature.

Benefits of flexibility and stakeholder interaction

There are many benefits that flexibility harvesting may provide respective stakeholders within the electrical power system. In order to maximise the benefits of these flexibilities, it is essential that stakeholder interaction is well defined and implemented. In general, the benefits of the increased interaction between TSOs and DSOs include 1) Increased system flexibility due to DER participation 2) Increase system flexibility and 3) Optimised investments in grid infrastructure. Within this paper, the main benefits were presented based on the findings of two recent European projects, TDFlex and FlexPlan from a techno-economic perspective. Based on the investigations of these projects, it was shown that by procuring DER flexibilities for transmission system ancillary services and transmission system operation a number of benefits can be provided. These benefits include optimisation of flexibility usage, grid operation support and many cost saving potentials. Additionally, it was demonstrated that by incorporating integrated grid planning approaches there are numerous benefits in terms of computational tractability, it has the potential to solve several conflicts related to the TSO-DSO coordination, without significantly impacting the planning costs optimality which, otherwise, can be achieved with the unpractical fully integrated procedure.

Barriers and challenges

The utilisation of the use of flexibility from DERs brings a wide variety of associated new challenges which can be envisioned from different perspectives, including technical, ICT, regulatory and economic. Within this discussion paper, the technical challenges associated with metering and connection requirements of DERs in the distribution system is presented. In particular, it was shown that the need for the publication of hosting capacity calculation results and allocation is vital to ensure adequate transparency to allow potential connection seekers to make informed decisions regarding possible connection points for flexibility devices. Challenges pertaining to ICT perspectives are largely centred around four main challenges topics, i.e., 1) interoperability, 2) data handling, 3) calculation, computation and fragmentation and 4) cybersecurity. In many cases, these challenges are mostly attributed to the lack of standardization and interoperability between data exchange platforms and the limitations of sharing information and learning between different projects. Additionally, the combination of new and legacy equipment and technologies still poses as an increased risk for cyber-attacks, since many of the communication protocols currently used to exchange power system data do not include many securities measures. Regulatory challenges include the fact that there is no harmonized terminology when discussing and analysing flexibility and related mechanisms and market models. This makes it difficult to assess and compare outcomes among projects and research activities. There is no “one-fit-all” approach, and thus, the system service, the product to be procured and the specific context influence the appropriateness of alternative solutions. When it comes to the integration of flexibilities, it was identified that a large variety of TSO/DSO market models exist, and that the proliferation of different flexibility markets can lead to market fragmentation.

Conclusions and Recommendations

Based on this report, it can be concluded that due to the increased integration of DER within the modern power system, there is an increased need and potential to utilise these flexibilities for the maximum benefit of all stakeholders. In order to do so, well-defined and structured coordination mechanisms are required to ensure that the interaction between all stakeholder, as well as their roles and responsibilities are clearly established. Therefore, it is essential that regulatory authorities assist in enabling the integration and utilisation of flexibilities by providing the necessary framework and support structure. By addressing the challenges identified, the benefits offered by flexibility integration and increased stakeholder interaction can be realised as soon as possible. In doing so, the transition toward developing the modern power system to ensure a safe, secure, reliable and decarbonised supply of electricity will help alleviate existing uncertainty in the sustainability of existing power systems and become an enduring reality.

Table of Content

1. Introduction

This discussion paper was prepared within the framework of ISGAN Working Group 6 (**http://www.iea-isgan.org/our-work/annex-6/**). The Working Group 6 focus area, Power Transmission & Distribution Systems, promotes solutions that enable power grids to maintain and improve the security, reliability and quality of electric power supply. The main objective of this focus area is to conduct studies on how distribution and transmission networks could interact in the future and ensure stable grid operation under high levels of renewables. Figure 1 positions this work in the ISGAN context.

ISGAN (http://www.iea-isgan.org)

ISGAN is the short name for the International Energy Agency (IEA) Implementing Agreement for a Co-operative Programme on Smart Grids (ISGAN). ISGAN aims to improve the understanding of smart grid technologies, practices, and systems and to promote adoption of related enabling government policies. ISGAN's vision is to accelerate progress on key aspects of smart grid policy, technology, and related standards through voluntary participation by governments in specific projects and programs.

ISGAN Working Group 6

ISGAN Working Group 6 - **Power Transmission and Distribution Systems** focuses on both transmission and distribution systems related challenges in the development of Smart Grids.

ISGAN Working Group 6 Focus area: Transmission and Distribution System Interaction

The objective of this focus area is to assess the way in which distribution and transmission networks could interact in the future, ensuring stable grid operation under high levels of renewables.

Flexibility harvesting and its impact on stakeholder interaction

This discussion paper provides insights to flexibility harvesting and its impact on stakeholder interaction. Within the report, the various aspects based on technical, ICT, regulatory and economics perspectives pertaining to the integration of flexibilities are presented. By doing so, contributions from various international projects are highlighted and the various benefits and challenges associated with the topic are presented.

Figure 1 Position of the discussion paper in the context of ISGAN

1.1. Background

Globally, the energy sector is continuously striving towards the most reliable, cost- effective environmentally friendly production, transmission and distribution of energy. Recent regulatory frameworks have prompted the urgent strive to become carbon neutral and with an increase in the transition to sustainable energy resources.

Traditionally, power systems were designed based on the generation-follows-demand concept, where power flows were uncontrollable and unidirectional. Within the ever-changing modern power system, this concept is no longer applicable where power flows are increasingly transitioning towards becoming controllable and bi-directional. The modern power systems are faced with increased challenges pertaining to the integration of new technologies and devices. On the one hand, the need to integrate highly volatile and decentralised renewable energy sources (such as photovoltaic and wind), while on the other hand, power systems are seeing an increase in loads and capacity due to electrification of the transport, storage and heating/cooling sector (e.g., electric vehicles and heat pumps). Additionally, a change in consumer behaviour and evolving markets are also influencing this transition. Customers are becoming increasing aware of their role as active participants as stakeholders in the power system. In this regard, consumers are becoming prosumers, and are becoming increasingly more conscience of their consumption (due to increased access to smart meters and smart appliances). Such activities create increasing complexities and challenges due to the unpredictability in power flows within the power system.

In order to overcome these challenges, system operators are relying on the use of flexibility which offer a wide range of opportunities and sought-after solution by providing a wide range of important services, which can enable system operators in operating their networks in a more efficient and cost-effective manner. In doing so, system operators are able to ensure the safe, reliable and secure supply of electricity (operation), while utilising flexibility as an alternative to (timely and costly) network reinforcement (planning). This new paradigm is aligned with the principles promoted by the European Commission package Clean Energy for all Europeans[1], which emphasizes the potential usage of flexibility sources in the phases of grid planning and operation to compete with grid expansion

Both the transmission and distribution system operators (TSOs/DSOs) can utilize these flexible resources. TSOs can benefit by using flexibility resources for frequency control, voltage control or congestion management, while DSOs could acquire flexible resources for local congestion management and voltage control. However, utilisation of these resources to their full potential requires increased coordination between all relevant stakeholders in the power system. This increased interaction will not only allow for system operators to support each other in the optimal use of their respective grids, but also ensure that operating strategies in one network do not have any negative impact on the other. Furthermore, increased interactions with large and small system end users will allow for increased participation and therefore increased opportunities available from flexible resources.

[1] The European Commission, “A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy,” Nov. 2018

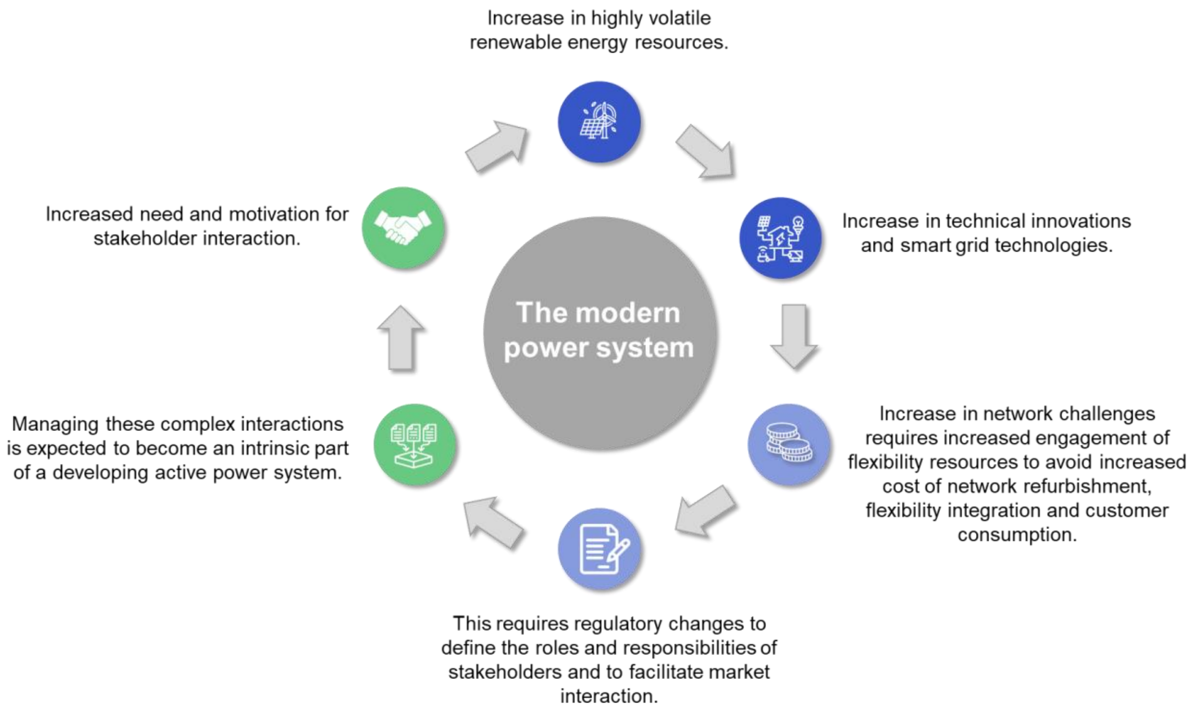


Figure 2 Overview of the modern power system and the need to stakeholder interaction[2]

Previous work conducted by Working Group 6 (previously Annex 6) on Flexibility and TSO-DSO interactions includes[3]:

- Flexibility harvesting and its impact on stakeholder interaction: key messages, 2022
- Flexibility harvesting and its impact on stakeholder interaction: Survey results, 2022
- Lessons learned from international projects on TSO-DSO interaction, 2020
- Ancillary services from distributed energy sources, 2019
- Flexibility needs in the future power system, 2019
- ICT aspects of TSO-DSO interaction, 2019
- System efficiency, 2018
- Single marketplace for flexibility, 2017
- Storage and balancing as key elements for future network planning and electricity markets design, 2016
- The role and interaction of microgrids and centralized grids in developing modern power systems – A case review, 2016.
- Why the TSO-DSO Relationship Needs to Evolve, 2015
- TSO-DSO interaction: An Overview of current interaction between transmission and distribution system operators and an assessment of their cooperation in Smart Grids, 2014
- TSO-DSO interaction, 2014

[2] Icons obtained from:

- Renewable energy icons created by monkik - Flaticon
- Solar panel icons created by wanicon - Flaticon

[3] These publications are available and can be downloaded from: https://www.iea-isgan.org/publications/

1.2. Purpose of the discussion paper

The purpose of this discussion paper is to provide an overview and insights pertaining to the integration of flexibility and its impact on stakeholder interaction. In doing so, the context of this topic is presented based on the outcomes and experiences obtained from various projects/ initiatives and expert knowledge from various stakeholders within the power sector. In this regard, the lessons learned, and key messages highlight the major benefits and challenges of flexibility integration and its impact on stakeholder interaction based on the technical, Information and Communication Technology (ICT), economic and regulatory perspectives.

This discussion paper is presented alongside the previously conducted survey[4], which presented the results based on the responses from 40 participants from 22 countries representing 9 different sectors. The survey was conducted, in order to get an overview of the topic based on three perspectives: 1) Flexibility definitions, characteristics, and applications, 2) Stakeholder interaction and 3) Projects and initiatives

Within this discussion paper, a holistic overview of power system flexibility and its importance for the development of a modern power system is presented in section 2. Thereafter, in section 3, an overview of the various stakeholders, their roles and existing coordination schemes is provided. Section 4 provides insights on the need for increased stakeholder interaction from the perspective of planning and procurement of flexibilities. Section 5 provides examples attained from recent projects which demonstrate the benefits that flexibility and stakeholder interaction can provide within the power system during operation and planning. Section 6 highlights the key barriers and challenges based and offers possible solutions to address them. Lastly, section 7 presents the conclusions with the consideration of the key findings and recommendations.

[4] https://www.iea-isgan.org/wp-content/uploads/2022/06/Flexibility-harvesting-and-its-impact-on-stakeholder-interaction-report_Survey-results_reviewed.pdf

2. Overview of Power System Flexibility

2.1. Definition of flexibility

The definitions of power system flexibility can be considered to be highly challenging and complex. The definition and understanding of flexibility can be inferred to mean different things to different people, depending on background, experiences, expertise, etc. Thus, there is no unified universal of common definition for power system flexibility. Additionally, these definitions have changed over time in an effort to adapt and facilitate the significant changes of the transition in the power grid and integration of new technologies.

Based on the literature, various authors have tried to consolidate, review and propose a common definition, however, there still remains a degree of ambiguity and limited range of scope since these definitions may vary and/or be dependent on the perspective a particular stakeholder group and/or geographical location. In general, the literature considers the term flexibility based on two processes, i.e., long term planning and short term operational.

The authors in [1] and [2] have provided an overview of various definitions obtained from various sources that have been used in context of power systems. Figure 3 shows a representative word cloud which was generated based on the collection of theses definitions. This word cloud, thus, allows for the relevance and frequency of terminology used to be represented based on a weighting (i.e., larger text can be seen as frequent and relevant). Additionally, a word count was performed to identify the number of occurrences and the top five most frequent words are also shown.

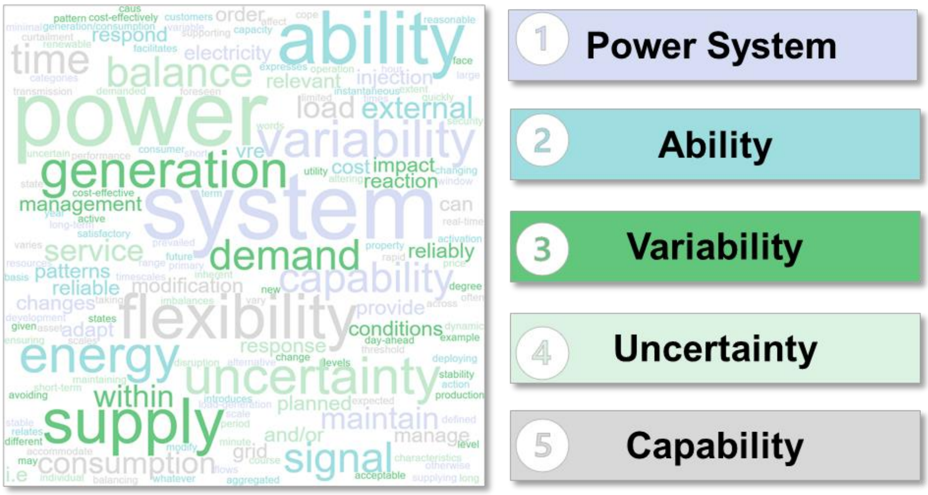


Figure 3 Word cloud generated based on a collection of definitions to identify relevence and frequency of commonly used terms

Furthermore, as part of this activity, a survey [3] was conducted in which participants (40 participants from 22 countries) were requested to select their preference between two definitions[5] of power system flexibility and were invited to provide additional input to further refine the definition. For definitions, the respondents expressed that reliability considerations

[5] Definition 1: [Flexibility is]: "the ability of power system operation, power system assets, loads, energy storage assets and generators, to change or modify their routine operation for a limited duration, and responding to external service request signals, without inducing unplanned disruptions." [5]

Definition 2: "Flexibility is the ability of a power system to cope with variability and uncertainty in both generation and demand, while maintaining a satisfactory level of reliability at a reasonable cost, over different time horizons." [6]

should be better reflected and that their respective temporal (duration/time horizon) aspects could be detailed to a higher degree. Under Definition 1, other considerations were to include implicit signals, e.g., market price signals, and add specifics elsewhere. Under Definition 2, it was recommended to broaden the scope to include cross-sector flexibility (energy) and other potential actors, e.g., aggregators.

In particular, [2] provides an evaluation of the definitions according to a set of three criteria based on the type, duration, and incentive for flexibility. In doing so, the authors were able to assess whether the definition is "general" and to what degree the criteria are met. Based on their assessment, the following definition for power system flexibility was defined [2] and since this paper focuses on flexibility from the TSO-DSO interaction perspective, this definition will be used in the context of this report:

> ***Flexibility*** *is the ability of power system operation, power system assets, loads, energy storage assets and generators, to change or modify their routine operation for a limited duration, and responding to external service request signals, without inducing unplanned disruptions.*

In a recent report [4], flexibility was defined according to the power system point of view. It emphasises that flexibility enables connected entities to exchange energy by utilising the grid as needed based on its ability to carry time-varying loads. From a technical perspective, the power system shall have the ability to allow for the connection of new users while ensuring a safe, reliable and continuous supply [4]. On the other hand, the user behaviour perspective addresses users' ability to increase/decrease their consumption/generation in such a way that they can provide services which can be used to support system operation [4]. Therefore, flexibility was distinguished according to three basic types, 1) Grid (technical/operational) flexibility, 2) Market flexibility (flexibility services), and 3) Investment and planning flexibility, as shown in Figure 4.

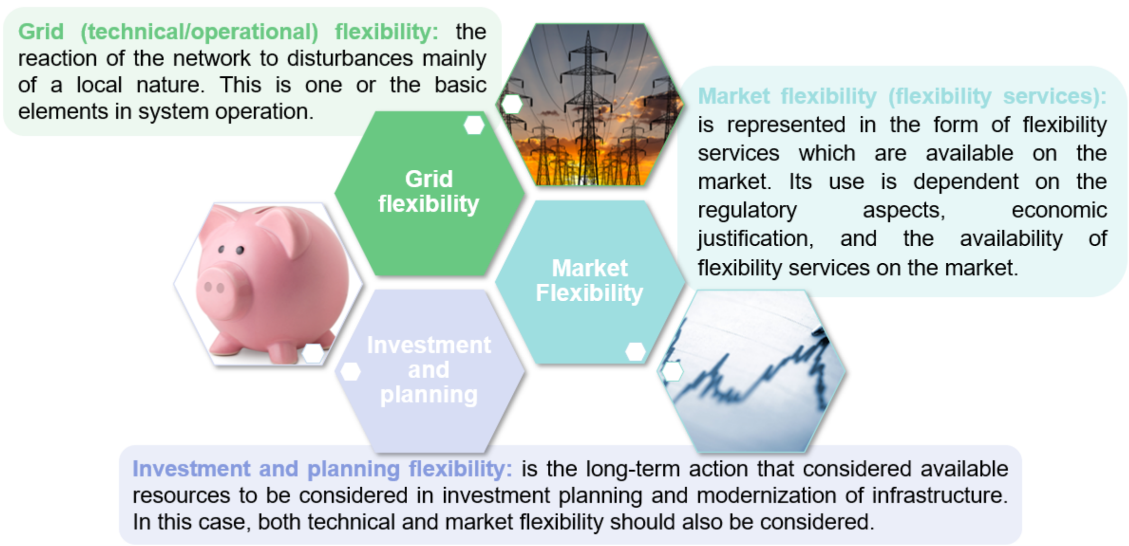


Figure 4 Basic types of flexibility, own creation adapted from [4]

2.2. Sources, characteristics, and eligibility of flexibility

Due to the advancements of new technologies, there is an increased opportunity for various power system components to be connected, offering a wide range of technical capabilities and economic attributes to provide flexibility services [4]. In order to ensure optimal utilisation of these flexibilities, it is necessary to consider the type of flexibility, its characteristics and eligibility according to regulations, delivery methods, location, and communication. This section provides an overview of the various sources of flexibility and their corresponding characteristics. Additionally, an example of eligibility requirements are provided from the Canadian and the Europe Union (EU) perspectives.

2.2.1. Sources of flexibility and their characteristics

In general, sources of flexibility can be used to respond to service requests in volume, time, availability and cost. Also, they entail the response of the sources exhibited after the service provisioning has ended, such as recovery time and rebound effect [4]. An overview of the most common sources of flexibility can be described as follows:

Generation

Flexible generation can be provided by both conventional and renewable energy resources. In such cases of conventional generation, it is important that this generation can be brought online or change their generating capability in order to balance power system flows. Their key characteristics include their fast ramp up and down rates, fast start up and shut down and their ability to operate at higher efficiency rates when operating at lower rated capacity, especially during times of highly volatile/variable Renewable Energy Resources RES (vRES) output. These units should be cost effective in order to compete as a source of flexibility. Conventional generation flexibilities include those coming from coal fired power stations, hydro, open gas turbines where the generating unit is able to ramp up or ramp down the amount of supply as and when required. Although many conventional generating units were not traditionally designed to be used as flexibility (due to a limited number of hot/cold start cycles, decrease in minimum load, decrease in start time etc.), modern technologies have allowed for feasible retrofits to enable their participation.

Demand response

Flexibility can also be provided through the alteration of the system loads based on the modification of load based on a response to demand side management (DSM) programs where the demand pattern is shifted to follow the electricity supply. This allows end users (consumers) to actively participate in the grid operation by responding (i.e., demand response) to price signals or based on long-term direct control agreements. These loads can be switched off or shifted to off-peak periods where energy prices are lower (time of use). Furthermore, industrial customers are becoming increasingly important due to their increasing potential to participate as active customers within the modern power system.

Storage

Electrical storage systems are mostly considered as components which can be used to shift the time of electricity supply which is achieved by storing surplus electricity generated until it is needed in times of low generation. This includes pump storage systems (hydro) and advancements in technologies such as battery energy storage systems (BESS), hydrogen, fuel cells, supercapacitors, and flywheels. Although many of these technologies are currently considered to be costly, these technologies are becoming more prominent, and their presence is expected to increase in the future as prices become more competitive and devices more accessible.

Sector coupling: Electric vehicle and heat pumps

Within the transportation sector, electric vehicles (EVs) are receiving increased attention due to their ability to provide both battery storage and energy demand, where they can be perceived as mobile energy storage units. EVs can support flexibility requirements with their potential to provide grid-to-vehicle (G2V) and vehicle-to-grid (V2G) capabilities. Additionally, heat pumps (HPs) can provide short-term flexibility as a means of storage and can optimise alongside peak renewable generations and low demands.

Interconnection/grid

Grid flexibility pertains to the robustness of the electricity network to be able to ensure a reliable balance of electricity supply and is closely related to the physical structure of the system [4]. This includes cross border interconnections (intra-and-inter-regional). In doing so, the electrical system is able to exchange and utilize a larger set of resources/devices across different geographical regions. For example, the increase in demand in one region may be met by a generating unit in another, or alternatively the use of other assets such as energy storage device which are able to storge surplus generation from vRES which may be located far away. Further examples may be based on the inclusion of advanced control mechanism e.g., automated control of generators, demand response or power flow (e.g., FACTS), network switching and regulation of tap changes [4].

As described in [2], the characteristics of flexibility (amongst others), can be broadly categorised based on the technical characteristic: *quantitative, qualitative, and controllability*; and economic characteristic: Capital expenditure (*CAPEX) and Operational expenditure (OPEX)*. Figure 5 provides an overview of these characteristics.

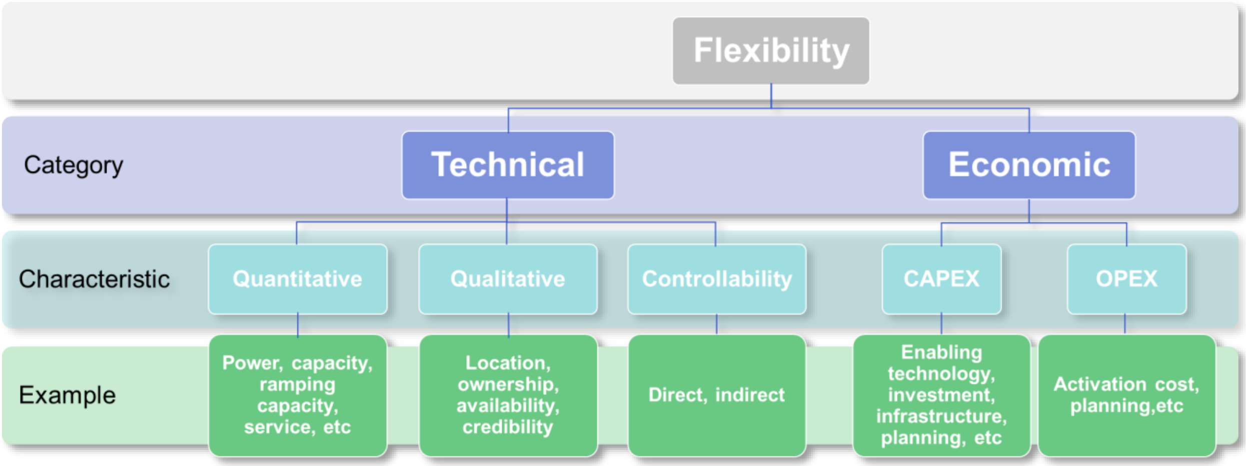


Figure 5 Categorisation of characteristics of flexibility, adapted from [2]

Furthermore, based on the survey [3], various stakeholders identified the most important characteristics of flexibilities as follows:

- Real power capacity, in either direction
- Location of the resource
- Reactive power capacity, in either direction
- Variability of resource availability
- Visibility to system operator
- Energy capacity

This list is neither static nor exhaustive. As increased control capabilities become available and more participants enter the market, it is expected that additional characteristics such as rebound effects, the granularity of control, and duty cycles will enter consideration. However, what is listed is sufficient for most of the services, applications, and use cases discussed herein. Therefore, the characteristics of flexibility resources can be broadly categorised based on their capacity (power and/or energy), time, availability, the direction of activation, ramp rate, ramp duration and cost. An overview of the most important characteristics of flexibility resources can be seen in Figure 6.

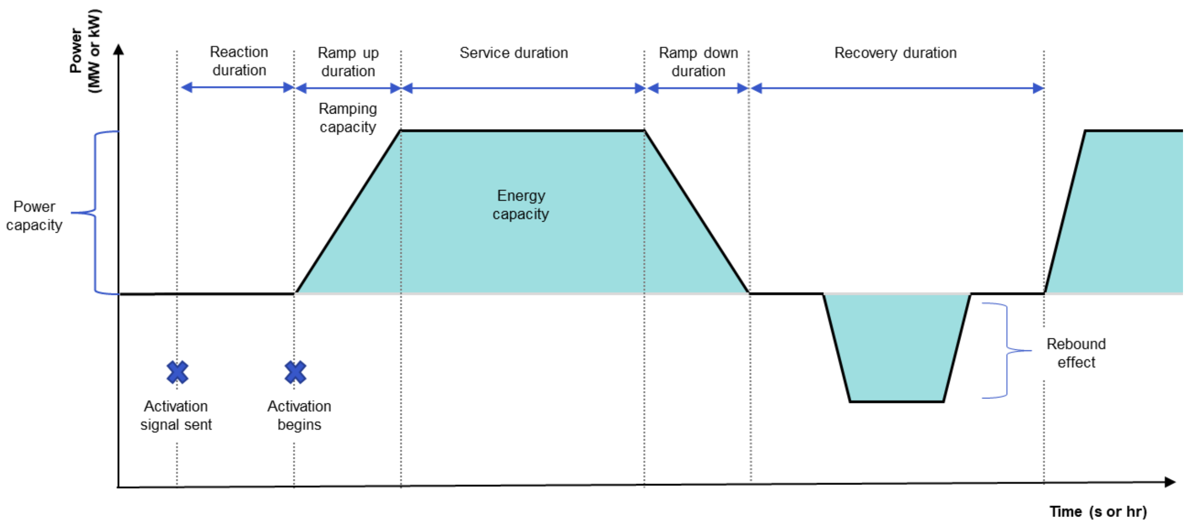


Figure 6 Characteristic of flexibility products, adapted from [2] and [5]

2.2.2. Eligibility of DER flexibility

Conventionally, flexibility has most often come from transmission-connected generators and, for peak shaving, large industrial loads. However, power systems are now evolving to capture previously untapped flexibility from Distributed Energy Resources (DER) because of both its large potential and the growing need for it. Technological, market, and regulatory barriers mean that DER eligibility is still somewhat limited though.

Flexibility resources which are connected to the distribution system vary according to size, response time, controllability and monitorability. Moreover, there are various ways in which this flexibility could be used, either in the distribution, or in the transmission or both grids. The available potential depends on the connected generation capacity size to the network. An overview of the eligibility DER to participate in Canada's province of Ontario's market, based on source, dispatchability, and connectivity as a direct or aggregated resource, is shown in Figure 7. DER participants, either individually or aggregated, must be at least 1 MW.

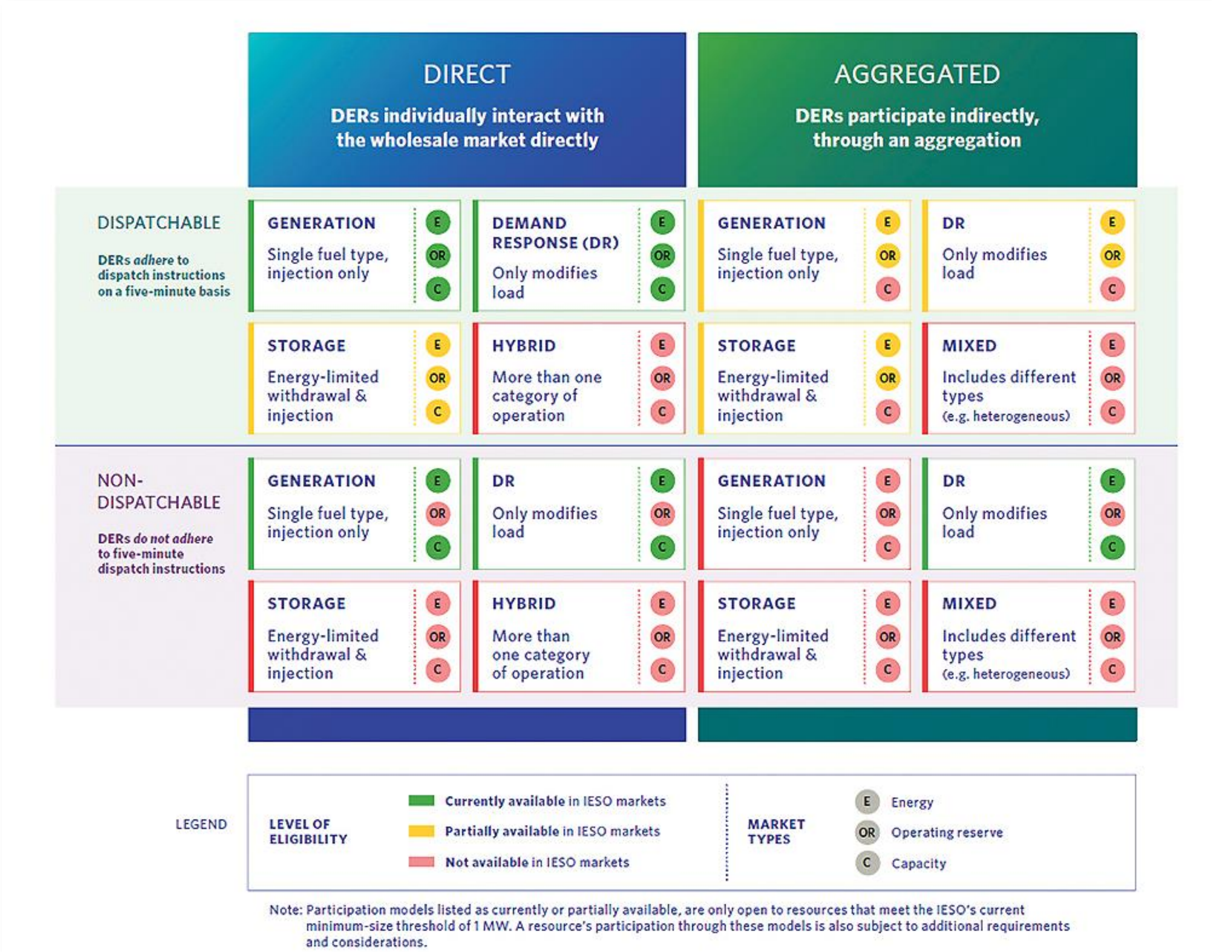


Figure 7 Eligibility of DER to participate in Ontario, Canada's IESO administered market [6]

In the EU, eligibility for DERs to participate is in the process of changing; recognizing that flexibility will play a greater role in the future electric system, EU market regulations will be, among other things, enabling consumers to become active participants in all markets, either directly or through aggregators.

The Electricity market directive adopted by the Council of the European Union explicitly states that all market participants, including those offering fluctuating renewable electricity as well as load control and storages (individually or via aggregators), must be granted non-discriminatory access to the balancing reserve market. Likewise, there must be no discrimination in the prequalification procedure for balancing reserve provision. The EU's day-ahead and intraday markets must also be organized in such a way that they are accessible to all market participants, either individually or through aggregation. Furthermore, network tariffs must neither favour nor disadvantage energy storage or aggregation [7] [8].

In Austria, the following categories of generators, and their connection requirements, are stipulated by the Technisch Organisatorische Regeln (EN: Technical Organizational Rules):

- Type A: Maximum capacity ≥ 0,8 kW and connection point below 110 kV general requirements: Fundamental requirements for frequency stability to avoid large-scale critical network conditions; limited automatic regulations
- Type B: Maximum capacity ≥ 250 kW and connection point below 110 kV general requirements: automatic control systems, robustness, remote control technology
- Type C: Maximum capacity ≥ 35 MW and connection point below 110 kV general requirements: voltage maintenance (reactive power), extended frequency maintenance, system management, and system recovery
- Type D: Maximum capacity ≥ 50 MW or connection point ≥110 kV general requirements: extensive operational management and stability requirements

Flexibility potential could range from < 100 kW aggregated on the low voltage level (connected at network level -6 transformer substation) to the free capacity available on medium voltage level if the connected assets enable this potential. It is crucial to note that this potential can only be considered in case that the when the contracted connection power limits are not exceeded, and the transformer capacity and the network operation restrictions are not violated.

In the UK, the system operator – National Grid Electricity System Operator – has a number of programs focused on capturing flexibility from DER (in addition to the DNO flexibility services that may be in place). These include the following:

- Power Responsive, a programme aiming to increase flexibility from, e.g., demand side response and storage through awareness, engagement, and working groups. [9]Demand Flexibility Service, a new service allowing eligible residential, commercial, and industrial consumers, through aggregators/supplies, to offer flexibility to the grid through demand reductions during peak periods, as dispatched [10].
  Regional development programmes, which are studies or projects examining how DERs can play an increased role through improved distribution and transmission system coordination [11].

These are also some changes in progress to have the balancing mechanism include partial MWs instead of only whole MWs.

2.3. Flexibility needs, services, and requirements

2.3.1. Flexibility needs

Since flexibility is becoming even more relevant in systems with higher share of RES, the need for flexibility and its associated services is ever increasing. Flexibility allows connected stakeholders to make use of the energy and power flows as required to help ensure a balance between supply and demand and/or solve network problems, thereby ensuring the safe and reliable operation of the network. Additionally, the flexibility market allows for further commercial incentives to be envisioned.

In [1] the categorisation of flexibility needs was differentiated according to four main category needs: 1) Flexibility for Power, 2) Flexibility for Energy, 3) Flexibility for Transfer Capacity, and 4) Flexibility for Voltage. Additionally, in [12], flexibility products for DSOs and TSOs are mainly based on system, transmission or distribution networks needs such as below:

- To optimise infrastructure investment needs and use
- To defer or avoid asset reinforcement
- To carry out more efficiently planned maintenance, asset replacement and connection works
- To deal with unplanned interruptions by mitigating the effect of network outages when they occur, and therefore minimising the impact on customers
- To improve quality of supply
- To reduce network implementation timescales
- To increase the capacity of the current grid for new renewable generation
- To increase the profitability of their assets by participating in novel local-level markets (e.g., peer-to-peer trading) as well as in existing energy market structures in the transmission level (e.g., balancing).
- To contribute to the system security maintained by the transmission system operators in daily operations and/or for infrastructure planning

2.3.2. Flexibility services

Based on the need for the use of flexibility by system operators, flexibility services can be provided by users of the power system such that network problems can be mitigated. Within the European context, the regulation (Electricity Directive (EU) 2019/944 [13]) refers to the concept of flexibility service, however, it does not provide a clear definition. Therefore, the authors in [4], after taking into considerations of various provisions, have proposed the following definition:

> ***Flexibility service*** *is a service provided by active system users to the grid operator, the purpose of which is to use the energy potential of users to manage the network or to provide an alternative to its expansion. The system user should modify its production or consumption pattern over time*[6].

Procuring flexibility services in the short-term is predominately undertaken when the network is unable to handle occurring problems, while in the long term, flexibility services can be utilised alongside strategic network development plans based on operating strategies. In both cases, it is important that the procurement of these services is economically viable [4]. Therefore, in general, owners of flexibility can offer services to the grid by reducing/increasing their withdrawal/injection from/to the grid by adjusting their demand/local generation according to the system's need.

[6] Mataczyńska E., Sikora M., Lewandowski W., Wykorzystanie usług elastyczności przez Operatora Systemu Dystrybucyjnego, cire.pl

Similarly, the Independent Electricity System Operator (IESO), as shown in Table 1, outlines the set of core physical electricity services that are required for the reliable operation of the power system [14]. As markets evolve, these services should be defined in a technology neutral manner, to permit all technology types to be recognized on a level playing field.

Table 1: Categories of core electricity services

Energy Service (Operational Time Frame)	Capacity Service (Investment Time Frame)
Active energy	Resource Capacity
Reactive energy	Network capacity
Reserve energy	

With the increasing penetration and use of Distributed Energy Resources (DERs) operators are provided with an opportunity to use these DERs as Non-Wires Alternatives (NWAs) for energy and capacity services, potentially to meet both distribution- and transmission-level needs.

Where wholesale markets exist, active energy and reserves are secured through auction mechanisms, and are typically co-optimized to provide the lowest cost set of resources for both services. Active energy and reserve energy are cleared in real-time wholesale markets and, often, are coordinated on a day-ahead basis. There are different types of energy reserve services, based on different types of response capabilities (some of which, in the EU context, are noted in Figure 8). Alternatively, reactive energy has to do with voltage management and Volt/Var control and is usually not transacted through wholesale markets. With the ongoing distribution level evolution, there is an increase in the interest to expand the reserve energy service at the distribution level.

In the investment (long-term) timeframe, capacity service refers to securing the capability to deliver real, reserve and reactive energy for the future operational timeframe, when needed to meet load requirements. These capacity service can be provided through:

- Resource capacity co-located with load with no use of network capacity,
- Resource capacity located close to load and delivered using existing network capacity, and/or
- Remote resource capacity delivered to load through new network capacity.

Network capacity is normally provided by transmission and distribution system owners/operators that are enabled to do so through the regulatory framework. Jurisdictions with capacity markets typically procure resources one to three years in advance (the “investment timeframe”) of the anticipated operational timeframe. Through capacity markets, operators may acquire new resource capacity where more cost-effective and forgo paying for new network capacity.

In the context of Europe, the Horizon 2020 project OneNet [15] [16], further classifies and identifies the services where flexibility is needed today (Figure 8), even more so in a high RES context, based on technical scarcities and system needs of both TSOs and DSOs.

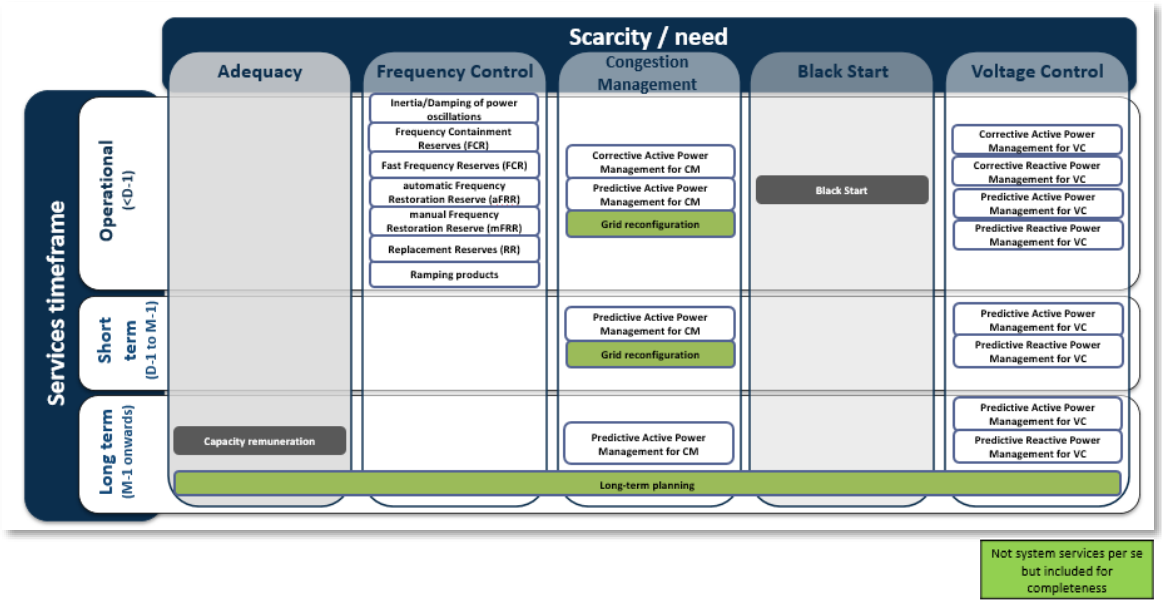


Figure 8: Classification of system needs [16]

TSO and DSO perspectives on flexibility service applications are highlighted as follows:

TSO

From a TSO perspective, needs and services include (but are not limited to) frequency control (e.g., automatic and manual frequency restoration reserve (aFRR and mFRR), voltage control (intraday and day ahead), congestion management (real-time, intraday and day ahead), and system restoration (e. black start capability). Other value-stacks for distribution flexibility services include reducing transmission demand charges, wholesale grid arbitrage, reducing grid emissions to align with environmental social governance (ESG) measures, and providing ancillary grid services such as frequency regulation, voltage regulation, and variable generation smoothing.

DSO

From the perspective of the DSO, when considering demand-side flexibility, needs includes non-frequency ancillary services (such as voltage control), local congestion management services, and grid capacity management services [12]. At the distribution level, these services have further value through various use-cases. Highest order use cases for distributors to use flexibility include improving reliability metrics by deploying flexibility on long-feeders that suffer from poor reliability due to upstream outages and deferring distribution capacity investments by reducing a community's demand for grid-supplied energy. An example, a pilot project in Ontario was IESO's York Region non-wires alternatives demonstration project that secured 10 MW of flexibility from local (distribution-level) resources in Year 1 and 15 MW in Year 2 [17]. For distributors, these services can be procured and deployed at either the distribution station level, at the distribution feeder level (behind reclosers), or at the grid-edge either in front-of-the meter or behind-the-meter.

2.3.3. Flexibility requirements

The requirements for the application/utilization of the flexibility from DERs located in distribution grids have been studied from different perspectives [18] [19]:

- Type of flexibility services (fast/slow)
- Receiver (i.e service beneficiary) of the services TSO/DSO [20] [21] [22]
- Type of markets or contracts that are necessary to enable the utilization of the distributed flexibility (e.g., participation of DER in wholesale markets, local markets, etc,) [23] [24] [25] [26]
- Regulatory requirements
- Required ICT infrastructure and the associated reliability requirements and cost of such infrastructure (installation if it does not exist, utilization if it exists)
- Technical methodologies to directly utilize or aggregate the flexibility services these resources can provide.

3. Overview of Stakeholders, Roles and Coordination Schemes

The interaction and collaboration between the various stakeholders in the modern power system play a crucial role in using flexibility-based services. In order to ensure effective flexibility utilisation and stakeholder interaction, it is essential that the roles and responsibilities of the stakeholder are clearly defined. Furthermore, the implementation of coordination schemes, which are used as the foundation for which the interaction of stakeholders is defined, provides the necessary framework.

3.1. Stakeholders

There are a number of actors and/or stakeholders in the electric power sector that may take one or more of the roles. While actors are usually considered as to real entities or parties (such as companies, market players, regulated entities and other related stakeholders) that participate in a business model [27]. Roles can be considered as the external intended behaviours of an actor [27].

The most common actors relevant to TSO-DSO interaction and flexibility harvesting are as below:

- Transmission system operator (TSO)
- Distribution system operator (DSO)
- Aggregators / flexibility service provider (FSP)
- Balance Responsible Party (BRP)
- Wholesale market operator
- Producer / Generator owner/operator
- Load serving entity
- Retail market operator
- Energy trader
- Non-participating customer
- Participating customer

In the context of this report, the following EU definition[7] for TSO and DSO [13] is used.

“Transmission system operator (TSO) system operator means a natural or legal person responsible for operating, ensuring the maintenance of and, if necessary, developing the transmission system in a given area and, where applicable, its interconnections with other systems, and for ensuring the long-term ability of the system to meet reasonable demands for the transmission of electricity.” Also known as Transmission network operator (TNO) or Regional transmission organization (RTO).

“Distribution system operator (DSO): Distribution system operator means a natural or legal person responsible for operating, ensuring the maintenance of and, if necessary, developing the distribution system in a given area and, where applicable, its interconnections with other

[7] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32009L0072&rid=1

systems and for ensuring the long-term ability of the system to meet reasonable demands for the distribution of electricity." Also known as a Distribution network operator (DNO).

3.2. Roles

Based on the Harmonised Electricity Market Role Model (HEMRM) [28], the European Commission's BRIDGE working group provides an enhanced listing of the roles and responsibilities within the electric power systems, with a focus on flexibility [29]. An abridged overview of major actors and corresponding roles relevant to this report is shown in Figure 9. Additionally, [29] identifies a number of new flexibility-related roles within the electricity market context.

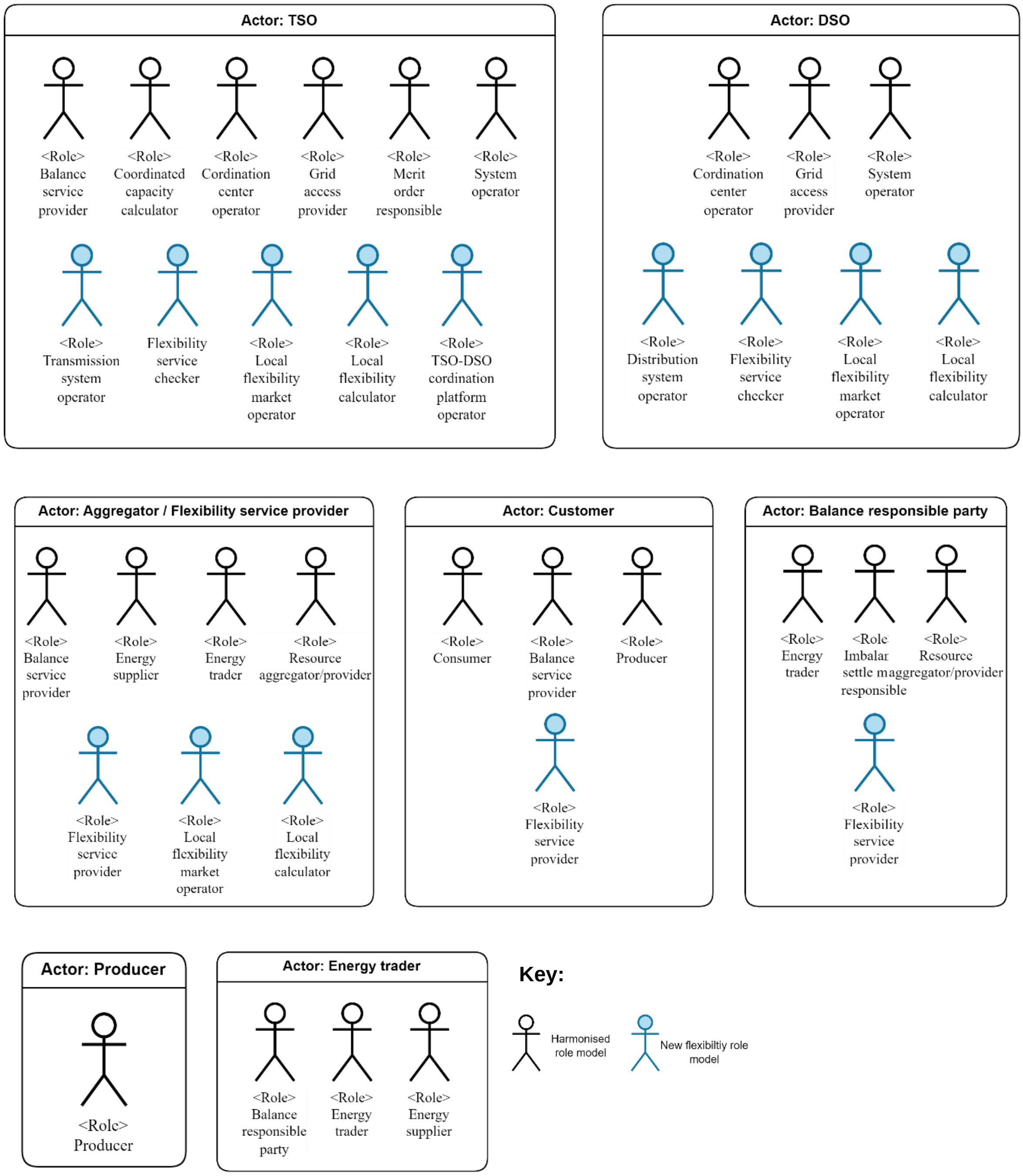


Figure 9 Example of actors and their possible roles, based on [23]

From an international perspective, these roles will not significantly differ from one region to another; however, the structure/model of the power system, that is, the arrangement of the entities themselves, can vary greatly depending on the country and governing regulations. Defining these regulations is the responsibility of the regulator, whose traditional role is to make decisions and rules that govern the protection of the energy consumer. In the EU, this role is taken by the European Commission and implemented by each member country, whereas in Canada, electricity is the responsibility of each province/territory. While traditionally rules and regulations were focused on energy reliability and affordability, the emergence of innovations in the forms of de-carbonization, digitization, and electrification alongside the associated barriers and opportunities has resulted in the need for regulators to pivot as a response.

Respondents in [3] also provided a distinction based on the roles and responsibilities of the stakeholder in the context of flexibility harvesting within the system. In Greece, the TSO and DSO identify the flexibility needs in their network and purchase flexibility based on the operational and market guidelines of the regulatory framework defined by the Regulatory Authority for Energy (RAE). In Finland, the DSO has no role in energy retail or other markets, hence they just provide the network. Aggregators, market operators, etc. have direct contracts with customers, however utilizing measurement data from DSO. In Norway, the TSO is responsible for the dispatch, transmission, electric system balancing, and dispatch of resources either directly connected to the transmission grid or connected via aggregators residing on distribution networks. The DSO is responsible for the secure operation of the distribution grids. In the UK, the Electricity Supply Operator (ESO) is responsible for real-time electricity system balancing and security; the TO/TSO is responsible for transmission asset management; the DNO/DSO is responsible for distribution asset management and operation; suppliers are responsible for meeting demand; and aggregators are responsible for providing balancing and reserve/frequency response ancillary services.

Reliability Coordination

The Reliability Coordinator has the highest level of authority to ensure safe and reliable operation of the Bulk Electricity System. This includes establishing operating tools, processes, and procedures while granted the authority to prevent or mitigate emergency operation scenarios. In North America, the accountability of Reliability Coordinators is given to the System Operators where applicable, otherwise this role is deferred to the regional transmission utility [30]. In the EU, the ENTSO-e takes on this role.

While the emphasis of distribution level resources and assets in North America were once considered out-of-scope for broader Bulk Electricity System coordination consideration, recently the Federal Energy Regulatory Commission (FERC), released order 2222 [31], that mandated that DERs participate alongside traditional resources in wholesale markets through aggregations, introducing new sources of energy and grid services. In response, regional grid operators in the United States must revise their tariffs and establish DERs as a category of market participant.

Aggregation

In order to maximise the utilisation of individual DER and ensure the coordination of these component connected to the LV and MV network, the concept of aggregation becomes relevant. In this context, “aggregation” means to ensure that flexibilities that can be offered by heterogenous types of DERs owned by various entities as well as end-users are coordinated together to provide a service to a transmission or a distribution grid operator. The coordination role can be undertaken by an "aggregator", which essentially acts like a "middle-man" between or "on behalf of" the DER owner and the flexibility need owner (i.e., transmission or distribution system operator). The aggregator resorts to a multi-period linear or nonlinear integer or mixed-integer mathematical optimization to ensure that required amount of "flexibility" is aggregated in a specific time-resolution (e.g., 15-minute, 1-hour) for a selected horizon (e.g., 1 day, 1 week). The aggregator either collects the bids of the flexibility providing DERs and performs the above-described mathematical optimization, which is essentially a "flexibility market" or makes short- (e.g., weekly) or long-term (e.g., seasonal, yearly) bilateral contracts with different DER owners to ensure that the required flexibility can be provided by aggregated DERs. Therefore, the role of the aggregator can be considered to as two-fold, flexibility expert and market expert [32]:

- **As flexibility experts:** to sum up small flexibility capacities from individual DERs, so the final amount is large enough to build marketable flexibility products.
- **As an independent market participant:** to assume, develop, and excel in the role of a market expert on behalf of its aggregated portfolio, to maximize its value through time.

Within the TDFlex project [33] , the focus was to determine the aggregated flexibility boundary over a time-horizon (e.g., 1 day in 15-minute resolution) in presence of high shares of DERs, such as solar PVs, EVs, HPs, conventional demand and BESS. An optimization-based approach was used, and the methodology introduced in [34] and [35] was expanded to obtain the potential contribution of the DERs to the provision of operational flexibility at the TSO-DSO interface. This aggregation methodology was implemented and investigated within a number of use cases. An overview of the concept is provided in Figure 10. Furthermore, the key outcomes and benefits of this project is presented in Section 5.

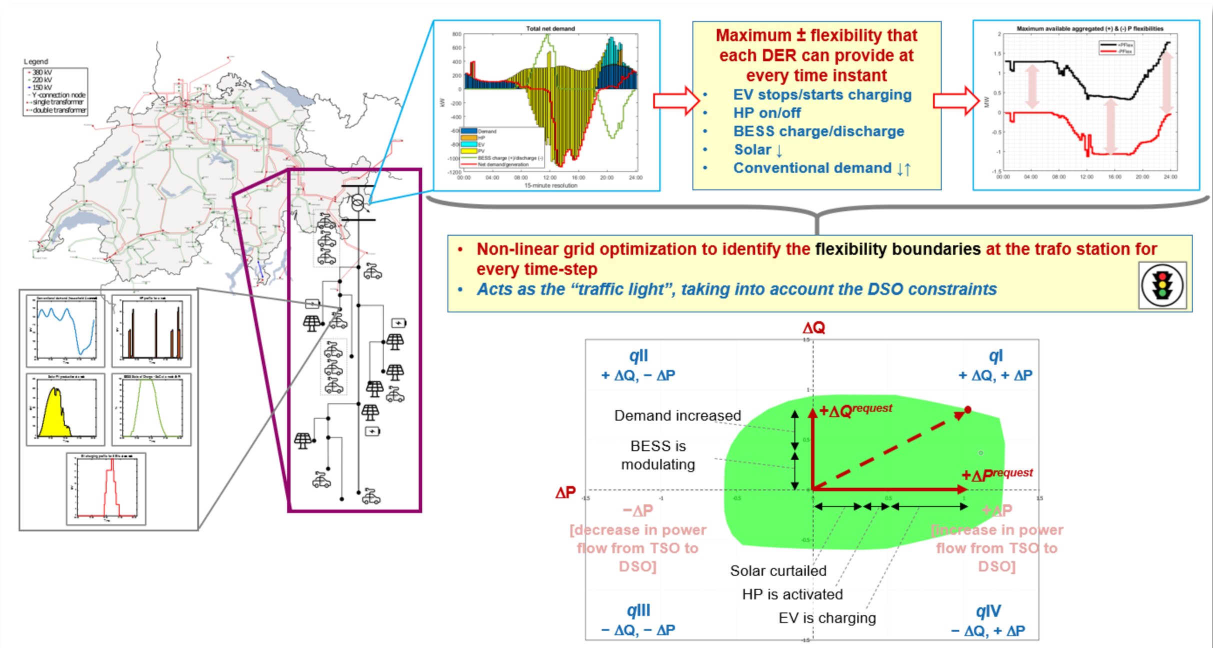


Figure 10 The concept of aggregating available DER flexibilities at the TSO-DSO interface substation [33]

3.3. Example of actors/stakeholders and their roles

In EU countries [31], unbundling regulations require separation of transmission and distribution from production/supply and retail activities. Three models are provided by the EU regarding transmission ownership and system operation: ownership unbundling, the independent system operator, and the independent transmission operator. Under ownership unbundling, ownership of production/supply and network companies are completely separated. In the independent system operator model, ownership may remain under the same company, but network operational and investment activities must be conducted by an independent company. Under the independent transmission system operator model, ownership and operations of production/supply and network may be conducted by the same parent organization, but network operational and investment activities must be conducted independently by a subsidiary. New opportunities that will allow consumers to actively participate in electricity markets, have been implemented in new EU market rules. In Canada, electricity is under provincial/territorial jurisdiction; thus, regulatory structures vary across the country. Most provinces have a majority vertically integrated utilities, within which some independent generators or distribution companies may participate. Two provinces are deregulated, having electricity markets and unbundled transmission, generation, and distribution entities. Unlike in the EU, in these deregulated systems an independent system operator exists apart from the transmission network owner. Examples of typical Canadian, United Kingdom and EU stakeholders and their roles is given in Table 2.

Table 2: Examples of various stakeholder and their respective roles and responsibilities

Country / stakeholder	AB, Canada	ON, Canada	QC, Canada	UK	Spain	Germany	Italy
Regulator	Alberta Utilities Commission (AUC)	Ontario Energy Board (OEB)	Régie de l'énergie	Office of Gas and Electricity Markets (ofgem)	Comisión Nacional de Mercado y Compentencia (CNMC)	Bundesnetzagentur	ARERA (National regulatory authority)
Conventional generator ownership	Various	Ontario Power Generation (OPG), Independent power producers (IPPs)	Hydro-Québec (HQ) Production	Independent power producers (IPPs)	Various	5 largest power plant operators (by generation): RWE, EnBW, LEAG, Vattenfall, Uniper	Several private owners
Variable renewable generator ownership	Various	IPPs	Independent power producers	Independent power producers (IPPs)	Various	Ownership is quite divers as many RES plants still receive feed-in tariffs (owned by private owners). Larger plants are owned by companies	Several private owners
Transmission facility ownership	Various (e.g., AltaLink, Atco Electric, Enmax, EPCOR)	Hydro One, others	HQ TransÉnergie et Équipement	National Grid Electricity Transmission Scottish Power Transmission Scottish Hydro Electric Transmission Limited Northern Ireland Electricity	Red Eléctrica de España	4 Transmission System Operators: 50Hertz, Amprion, Transnet BW, Tennet (TSOs also legally own the infrastructure)	In Italy, TERNA (TSO) both owns and manages the transmission system
Transmission system operations (TSO)	Alberta Electric System Operator (AESO)	Independent Electricity System Operator (IESO)	HQ TransÉnergie et Équipement	National Grid Electricity System Operator (ESO)	Red Eléctrica de España	4 Transmission System Operators: 50Hertz, Amprion, Transnet BW, Tennet	TERNA

Market operations	AESO	IESO	Not applicable	National Grid ESO	OMIE	Competitive environment largest energy exchanges used: EEX, EPEX Spot	GME (Gestore dei Mercati Energetici: https://www.mercatoelettrico.org/it/)
Continental reliability coordination	North American Electric Reliability Corporation (NERC)	North American Electric Reliability Corporation (NERC)	North American Electric Reliability Corporation (NERC)	European Network of Transmission System Operators for Electricity (ENTSO-E) UK Government National Grid ESO	European Network of Transmission System Operators for Electricity (ENTSO-E)	There are multiple TSO regional security coordination initiatives such as TSC or Coreso where German TSO are participating.	ENTSO-E
Regional reliability coordination	Western Electricity Coordinating Council (WECC)	Northeast Power Coordinating Council (NPCC)	Northeast Power Coordinating Council (NPCC)	UK Government National Grid ESO	European Network of Transmission System Operators for Electricity (ENTSO-E)	4 TSOs are doing Grid Expansion planning of the Transmission Grid. This process is monitored and accompanied by the regulator which also handles consultation of the public. Resource adequacy is monitored by the regulator.	-
Planning	AESO	IESO	HQ Distribution	National Grid ESO National Grid Electricity Transmission Scottish Power Transmission Scottish Hydro Electric Transmission Limited For Ireland and Northern Ireland: EirGrid Northern Ireland Electricity	Red Eléctrica de España	4 TSOs are doing Grid Expansion planning of the Transmission Grid. This process is monitored and accompanied by the regulator which also handles consultation of the public. Resource adequacy is monitored by the regulator.	TERNA
Distribution facility ownership	Various distribution companies	Local distribution companies (LDCs)	HQ Distribution	Various distribution network operators	Various distribution companies	There are 865 DSOs in Germany	In general, DSOs have the concession of operating

				(DNOs) - transitioning to distribution system operators (DSOs)		that also own the infrastructure (in 2022).	distribution systems, which can be owned by municipalities, private parties. In some circumstances, also DSOs can own some networks.
Distribution system operations (DSO)	Various distribution companies	LDCs	HQ Distribution	DSOs	Various distribution companies	There are 865 DSOs in Germany that also own the infrastructure (in 2022).	The various DSOs (>100 in Italy)
Retail operations	Various competitive retailers or regulated rate companies	Not applicable	Not applicable	Various competitive retailers	Various competitive retailers or regulated rate companies	End consumer market is liberalised, various competitive companies exist (apparently around 1423 in 2021.	Typically, the retailers are companies that were initially part of the vertically integrated utilities that, after the unbundling, have break up all network management functions and retained generation and retail.
Aggregation	Not applicable	Various aggregators	Not applicable	Various aggregators	Still to be defined	Various aggregators exist which usually market larger flexible units	Aggregators are existing, yet still a not very common figure in the Italian market. Aggregation functions were recently targeted in some sandboxes promoted by ARERA.

3.4. Boundaries between stakeholders

To gain insight as to where the boundaries between various stakeholders lie within different countries, respondents from [3] provided the following insights.

In most cases, especially within European Union (EU) countries, where the boundaries are defined according to EU legislation, the distinction is made according to the network topology based on the technical boundaries and respective system voltage levels. The TSO is responsible for the High Voltage (HV) transmission system, while the DSO for the Medium Voltage and Low voltage (LV) system. The interface between the TSO and DSO is identified to be at the HV/MV substation, while the boundary between the DSO and customer is the metering point at customer premises. Interestingly, in one case (India), the distinction is made based on political structure i.e., TSO at national vs DSO at state level. In Japan, the TSO and DSO are the same entity, and flexibility procurement is considered at TSO level. In England and Wales, the DSO is responsible networks operating at voltages up to and including 132 kV, with the Electricity System Operator (ESO) being responsible for the 400 kV and 275 kV systems as well as the transformers linking the transmission system to the distribution system. In Scotland, 132 kV is a transmission voltage, so the DSO is responsible for networks up to and including 33 kV, with the ESO being responsible for 132 kV and above. In Northern Ireland, transmission and distribution are in common ownership.

3.5. TSO-DSO coordination schemes

Within the traditional power system, the roles and responsibilities of the TSO and DSO were well defined and established, however due to the energy transition and as the electrical power system becomes more complex, the need for closer and well-defined roles and responsibilities to manage these stakeholder interactions is becoming increasing important. To facilitate these interactions, a coordination scheme can be developed to provide a structured approach towards identifying the relationship and interaction between the stakeholders. This includes the definition of the roles, responsibilities and the data exchanges between stakeholders who are involved in the activation and procurement of flexibility services [5]. According to [24], a coordination scheme can be defined as:

> ***A coordination scheme*** *is the relation between TSO and DSO, defining the roles and responsibilities of each system operator, when procuring and using system services provided by the distribution grid.*

These roles and responsibilities are often presented within area Network Codes and Guidelines, which discuss the specific roles and responsibilities of TSOs and DSOs [23]. Although it should be further emphasized that, in the case where there is shared responsibility, a well-defined coordination scheme (framework) becomes even more important and should be implemented and that a clear understanding of the impact/influence of the actions taken by one actor has on the other. Therefore, to accomplish a well manged system, the coordination and information exchange between the DSO and TSO is vital, such that flexibility activation is done as efficiently as possible and avoiding of counteracting implications. The opportunity for value stacking of assets to provide services to both the TSO and DSO should also be considered when developing coordination schemes. Additionally, not only the interaction between TSOs and DSOs need to be considered, but also that of other stakeholders and market participants and thus it is essential that the procedures to procure and utilise their services are done in a transparent and non-discriminatory way [23].

Over the years, and in particular within research projects, various coordination schemes have been developed based on the need for flexibility, the stakeholders involved and the available access to the flexible asset [4]. The following section provides insights into some examples of coordination schemes that have been considered.

3.5.1. North American Model

In North America, there are three dominant TSO-DSO coordination models that are driving sector evolution. These potential Transmission-Distribution (T-D) models differ in their allocation of roles and responsibilities among the TSO and DSO. These are the *Total TSO* and *Total DSO* models, which are the bookend models and where the TSO or the DSO assume full responsibility for distribution system operations and DER operations, and the *Hybrid* model sits in between these two bookends. Figure 11 depicts the TSO-DSO and DER interactions among these three coordination models [37].

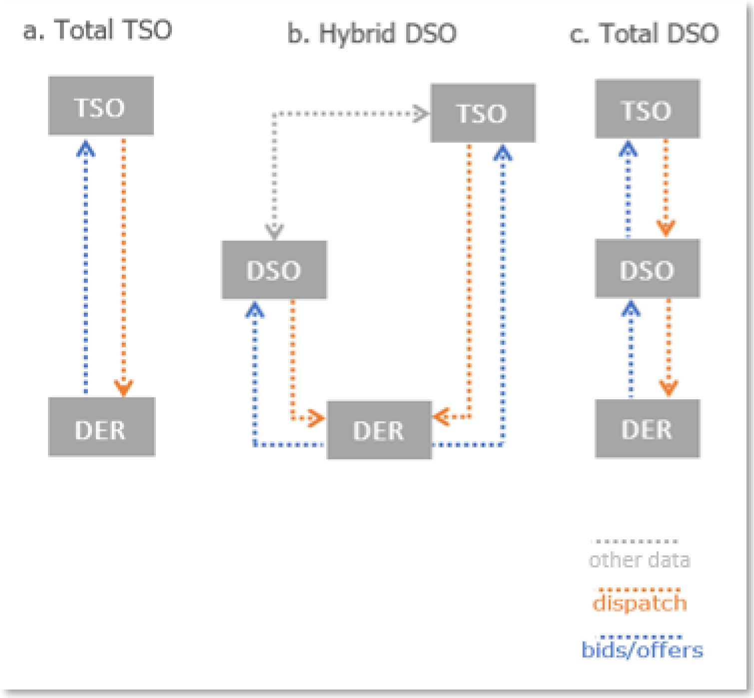


Figure 11: TSO-DSO Topologies in North America [37]

Total TSO model

The Total TSO includes the ISO/RTO, also known as the TSO, operating the transmission and extending its operations into the distribution system, thus operating in a fully centralized manner. The TSO performs all DER operational coordination for market participation and extends and has visibility and control of DERs at the distribution level (such as beyond the T-D interface). In this way, the TSO assumes responsibility for the reliable real-time operation of the distribution system with respect to DERs participating in wholesale-level markets. In the Total TSO model, the distributor, or DSO, does not expand on its traditional role of maintaining the reliable and safe operation of the distribution system's operation (for example, operating distribution assets and conducting distribution planning and maintenance activities). The key challenge with implementing the Total TSO model is in the scalability of this model, with the key question beings whether the TSO is able to scale its systems and operations to such a detailed distribution level. The risk with this Total TSO model includes what is commonly termed as "tier bypassing", whereby in the TSO's dispatch of distribution-connected DERs, the physical operations conditions of the distribution system and its various constraints are not accounted for, and due to the limited role of the traditional distributor within this model, presents safety and reliability risks to both systems, for example, the risk that DERs being relied upon for wholesale market participation are unable to meet their supply obligations due to distribution system conditions that render their supply undeliverable.

Total DSO model

At the other bookend is the Total DSO model where the DSO coordinates DER operation and DER market participation in wholesale-level markets. All services provided by DERs are funnelled through the DSO, which acts as a mega-aggregator to distribution-level resources and submits the aggregated bids/offers into the wholesale markets on DERs' behalf. The TSO views DERs' energy at each individual T-D interface as if it were a single aggregated resource located at the T-D interface. In this Total DSO model, the DSO coordinates with the TSO for market dispatch of DERs. The DSO aggregates and submits the DER bids/offers into the TSO's wholesale level markets, the TSO then runs its optimization and issues dispatch instructions to the DSO, which the DSO then passes onto DERs beneath the T-D interface. A key consideration within this model is that it requires significant enhancements to capabilities at the distribution level. In addition, there would be regulatory changes required in order to govern the responsibilities of the DSO in managing the distribution system and for the coordination relationship between the DSO and TSO.

Hybrid model

The Hybrid model resides between the two bookend Total TSO and Total DSO models described above. In particular, it is worth noting that there are several variations of the Hybrid model, however for the purposes of this paper, the most commonly known Hybrid model will be described. In the Hybrid model, DERs are able to choose which entity they interact with. For example, if DER are providing services at the distribution level, then they would interact and coordinate directly with the DSO. If the DERs are providing wholesale level market services, then they participate directly in the TSO's wholesale level markets through the TSO. The key requirement with the Hybrid model is for the TSO and DSO to coordinate with each other, through the development of coordination protocols and processes. The requirement for close TSO-DSO coordination in the Hybrid model lends the model to be the most complex of the three, requiring the implementation and adoption of formal roles and responsibilities and coordination protocols.

3.5.2. European Model

The EU Clean Energy Package (CEP) provides a regulatory framework for the use of flexibility which proposes TSOs and DSOs to procure system services in accordance with transparent, non-discriminatory and market-based procedures unless this is not economically efficient or could create distortions or additional constraints, found in Directive (EU) 2019/944 (Article 31 and Article 40) [7]. Within Europe, many projects and initiatives can therefore be found which focus on market-based procurement of system services by DSOs and TSOs, in which they both want to harvest flexibility from sources connected to the distribution grid. Enhanced coordination between TSO and DSOs is needed in this case to ensure the flexibility is used efficiently. This need has led to various discussions and developments of different coordination schemes which aim to ensure safe and system operation while accommodating the increase in DER. In [38] and [39], research was conducted, and an overview of various coordination schemes is provided. Based on these assessments, it was observed that although there appears to be a wide range of existing coordination schemes, it is often the case that different nomenclature is used for the same or similar coordination schemes.

Within the scope of the SmartNet project [24], five coordination schemes were developed and from the foundations upon which the basic reference for the identification and characterization of the recently developed TSO-DSO coordination schemes are based. In [27], based on [40], an extensive review of various European initiatives and pilot projects were studied; a simplification of the main market-based coordination mechanisms was developed. The synergies between these mechanisms and other EU projects are shown in Table 3.

Table 3 Main coordination mechanisms addressed in the EU projects [22]

TSO-DSO Coordination schemes	EU project
Centralized TSO flexibility market	CoordiNet, FlexHub, Eu-Sysflex, SmartNet, TDX-ASSIST
Local (DSO) and global (TSO) flexibility markets with resources sharing	CoordiNet, De-Flex-Market, EcoGrid 2.0, EMPOWER H2020, FLECH-iPower, Flex-DLM, FlexHub Eu-Sysflex. FLEXICIENCY, FlexMart, GOPACS-IDCONS, InteGrid, Interflex, IREMEL, NODES, Piclo Flex (and Piclo), SENSIBLE, SmartNet, USEF
Local (DSO) and global (TSO) flexibility markets with shared responsibility	CoordiNet, FlexHub Eu-Sysflex, SmartNet
Common TSO-DSO flexibility market	Coordinet, INTERRFACE, SmartNet

As a recent example, within the CoordiNet project [41], a categorization structure has been introduced to allow to group and specify these different initiatives by introducing classification layers or dimensions that highlight the differences between the coordination schemes. An overview of the coordination schemes considered within the CoordiNet project is depicted in Figure 12. The proposed coordination schemes are service-agnostic so that they can be applied to different services or even a combination of services The different proposed dimensions are based on [39]:

1) where the flexibility need is located in the system,
2) who is the primary buyer of the flexibility
3) how many markets are set up to purchase flexibility, and
4) whether or not the TSO has access to flexible resources connected to the distribution grids

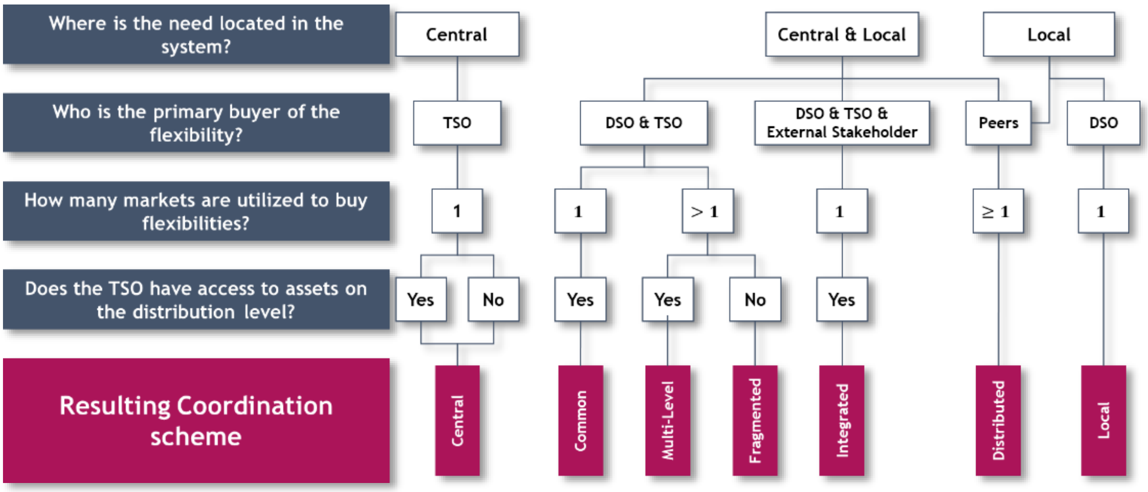


Figure 12 Classification structure of TSO/DSO coordination schemes [39]

Based on further observations, additional variations to these coordination schemes were proposed. One additional dimension is the way FSPs are allowed to bid in different markets. FSPs could for instance be allowed to modify their bids between market stages or alternatively bids could be forwarded automatically. Another potential differentiating dimension is whether or not certain agreements are made on the interface flows over the T-D interconnection. Finally, the option to share network information between system operators (namely, between the DSO and TSO, or with a third-party market actor), or the absence thereof, was proposed as an additional dimension which impacts the degree of TSO-DSO coordination [42].

4. The Need for Stakeholder Interaction

Within the modern power system, the need for increased stakeholder interaction to manage the increased complexities as a consequences of power system transitions are becoming increasingly apparent. Although there is a wide variety of reasons motivating for increased need for stakeholder interaction, this section focuses on the different phases where the distinction is made between the grid planning phase, and those related to the procurement of flexibility, i.e., prequalification, procurement and activation and monitoring and settlement phase. For each of these phases the need for TSO-DSO interaction is explained, alongside the current TSO-DSO interactions, while future options for further synergies and some best practice examples are provided.

4.1. Planning

The CEP introduces a systematic and wider application of Distribution network development plans (D-NDP) for all DSOs, subject to public consultation and to regulatory oversight by the national regulatory authority (NRA). In addition, according to Article 32 of Directive 2019/944 [39], the NDP shall, amongst others, provide transparency on the medium and long-term flexibility services needed, and shall also consider the use of flexibility (demand response, energy efficiency, energy storage facilities or other resources) as an alternative to system expansion. Network planning and the use of flexibility by DSOs will thus be more aligned in the future. In addition, high level principles for the D-NDPs are being proposed (not yet finalized) at EU level [40], including principles on the methodology, guidance on how to consider flexibility and congestion management as an alternative to grid reinforcement.

The Electricity Directive also emphasizes the cooperation of the TSO and DSOs on the network development planning. As a minimum there should be an alignment on scenario inputs, i.e., D-NDPs should be consistent with the TYNDP (Ten-Year Network Development Plan) of the national TSO(s). There are, however, further cooperation possibilities between TSOs and DSOs related to planning. The frequency and timing to establish transmission and distribution network development plans could be further harmonised, including the time horizon they cover, in order to provide a more integrated and consistent approach. Further cooperation between the DSOs and TSO with a certain country as part of overall improved TSO/DSO cooperation in grid planning and operation or even common planning should be targeted, including exchange of needed information. This will become particularly important to achieve coordinated access to flexibility that may support the needs of both the DSO and the TSO.

4.2. Prequalification

Pre-qualification is the process of verifying whether the compliance of a resource to provide a service with the requirements set by the requesting party. A prequalification process typically consists of a product prequalification and a grid prequalification. Notably, different standards, prequalification methods and requirements can be found across Europe, but also on country level for different services.

Some best practices can however already be perceived. The four German TSOs, for instance, procure all control reserves (balancing capacity and balancing energy) commonly across their control areas and partly in cooperation with neighboring countries. The prequalification process is still needed for each service separately, but the process is aligned as much as possible between the different services, so that it is easier to understand the process and prequalify for multiple services. Some requirements apply to all services, while also service-specific requirements apply. Moreover, the process is the same for the four TSOs. This can be seen as first step towards more uniform prequalification processes. In the future, the still to be developed flexibility services of the DSOs, could also align with the existing process.

It is advisable to organize a similar procedure for different services, whenever and to the extent that this is possible (e.g. a combined market prequalification for different services or simplified process once you are prequalified for one market), even if the services are to the benefit of multiple requesting parties (such as the TSO and DSOs) [45]. The CoordiNet project highlighted that, prequalifying for a service with more strict requirements could entail automatic qualification for services with less strict requirements to avoid duplicating processes [46]. As a minimum, the processes should be aligned for all flexibility services on country level to avoid unnecessary long pre-qualification procedures, leading to inefficiencies. As a next step European harmonization should be considered.

In addition, it should be noted that in the future, there may be the option that the 'grid prequalification' step becomes obsolete for (some) products and services in case grid constraints are properly integrated and managed during the procurement and activation phase of flexibility (see also below). In the latter case, a notification to the DSO might be sufficient.

4.3. Procurement and activation

The coordination between TSOs and DSOs for the procurement of flexibility is important to avoid both TSOs and DSOs compete for the same flexibility, resulting in higher costs of flexibility procurement. Moreover, similar to network planning, combining the procurement needs might lower the total volume to be procured. In addition, the coordination between TSOs and DSOs for the activation of flexibility is necessary to ensure that no congestion or imbalance issues are created in the grid of another system operator.

An important precondition to maximize the potential synergies for joint procurement by system operators is the harmonisation of different flexibility products. In addition, the procurement process should be aligned or combined (in case of joint procurement).

4.3.1. Product harmonization

The OneNet project extensively analysed all flexibility products for system services, including the needed products. Based on previous academic work [47], a detailed product framework for flexibility products (including product attributes) has been proposed and is shown in Figure 13.

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

Figure 13 Product framework for system services [15]

The overall idea was to use a common terminology and based on a common understanding of different products, determine for which products/product attributes harmonisation is possible. The OneNet project analysed where harmonisation was possible and put forward the following set of harmonised flexibility products for system operators (SOs) that should be able to cover all system needs. A distinction is made between non-locational and locational products. For the non-locational products, the activation time has been the main difference between products. For the non-locational products, a distinction has been made between products based on active power and products based on reactive power. In addition, the procurement window has been a main differentiator with some products procured to support anticipated or structural grid problems and some products to be procured in case of day-ahead deviations or close-to real time emergencies.

In addition, further synergies between SOs could be achieved when using some of the locational products to also cover the needs for which today, mFRR and Restoration Reserve (RR) are used. To illustrate the approach, we consider one of the products in the Northern demo of the H2020 OneNet project: "Near Real Time Active Energy" [44]. The product is built on the specification of the mFRR product but it is also used for congestion management. To achieve this, FSPs would need to provide the required information for mFRR in addition to location information. It is possible that the technical requirements of the grid, the market structure of the country or the approach to grid management of the respective SOs, justify why harmonisation is not always cost-efficient.

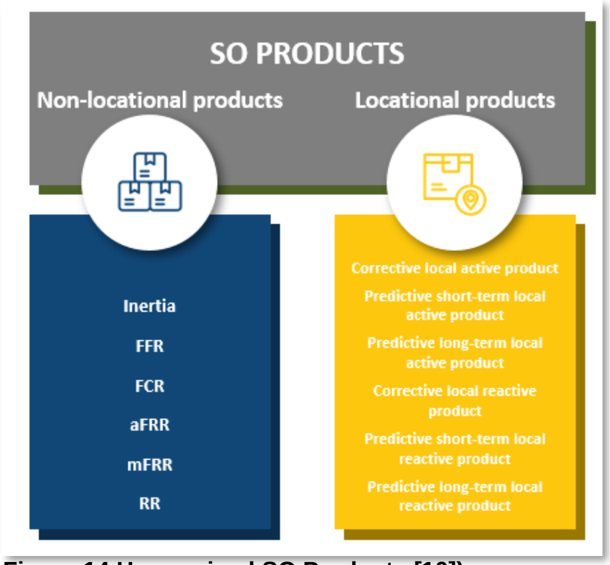


Figure 14 Harmonised SO Products [10])

4.3.2. Aligned TSO/DSO procurement

Different flexibility markets are at different maturity levels: wholesale markets and frequency ancillary services markets are already very mature, while markets for congestion and voltage control (both for the DSO and TSO) are currently emerging and under development. The importance of TSO–DSO coordination when procuring flexibility to ensure the security of supply, is, however, widely accepted. Numerous discussions on how such coordination should take place have led to the development of different propositions of coordination schemes. Despite the proposal of different coordination schemes, one of the main distinguishing factors is whether separate markets or common or joint markets to procure different services for both the TSO and the DSO are considered. There seems to be a general consensus that there does not exist a one-size-fits-all coordination scheme. This can be attributed to local circumstances, market maturities, regulatory condition etc. which differ between TSO and DSO networks and between countries [46]. Therefore, market integration can be realised in two distinct ways:

- separate markets (e.g., for congestion) can be organised, but these markets can be integrated in a smart way in the timing sequence of existing markets (wholesale markets, markets for other system services, dispatch mechanisms);
- integrated, common or joint markets can be set-up which are completely integrated into the operations of existing energy markets (e.g., day-ahead, intraday, balancing markets).

In case of separated markets (e.g., for congestion), TSOs and DSOs should implement the needed coordination between different markets to avoid discrepancies such as double activation of the same bid, or counter-effects that could endanger the system. To avoid these issues, different alternatives are possible either to have strong coordination with the TSO to account for these effects or to counter-activate a bid to keep the balance unaltered.

4.4. Monitoring and settlement

Monitoring and financial settlement have to be performed to compensate for the flexibility delivered or penalize the lack of response. To perform this process, measurement data is needed. The financial settlement requires comparing the measurements with the commitments to deliver the service if cleared in the flexibility market.

Harmonized measurement, validation and settlement procedures should be developed for different services and for different beneficiaries, such as the TSO and DSO, to the extent possible, to decrease costs and market entry barriers. Certain flexibility services might however still need specific procedures due to their specific technical nature.

5. Benefits of flexibility and stakeholder interaction

As the identification (of existing assets) and penetration (due to new assets) of flexibility within the power system increases, the opportunity to utilise these resources to provide system services also increases. In doing so, there are many benefits that flexibility harvesting may provide respective stakeholders. In order to maximise the benefits of these flexibilities, it is essential that stakeholder interaction is well defined and implemented. In general, the benefits of the increased interaction between TSOs and DSOs include [49], *1*) Increased utilisation of DER resources 2) increase system flexibility and 3) Optimised investments in grid infrastructure.

Furthermore, these aspects can be further confirmed based on the outcomes of the survey [3], where respondents provided insight pertaining to a question which assessed the way in which flexibility harvesting can be beneficial to network planning and operation in the context of stakeholder interaction. Based on the responses, several benefits could be identified, as shown in Figure 15.

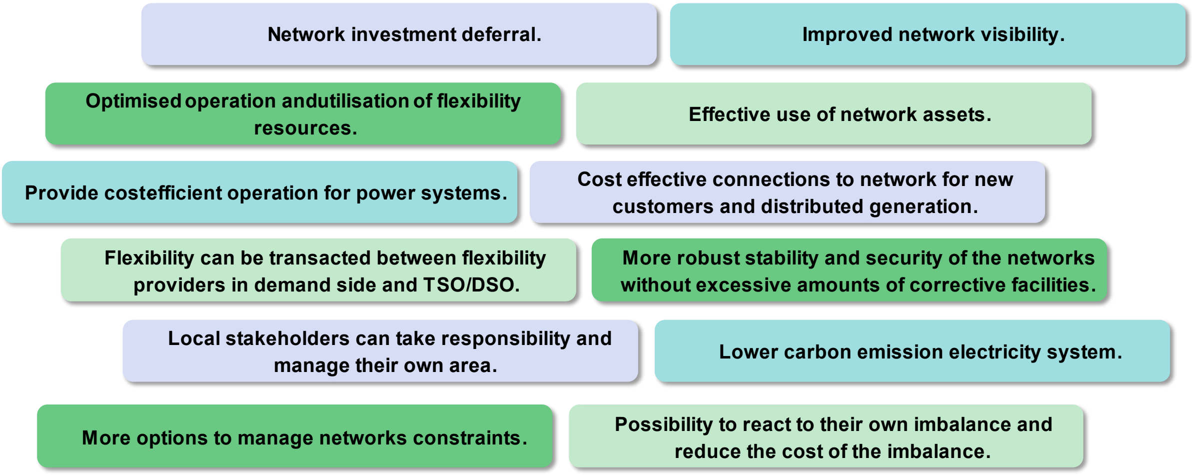


Figure 15 Overview of benefits of flexibility and stakeholder interaction [3]

5.1. Techno-economic perspectives

More recently, the benefits of utilizing the aggregated flexibility are investigated and demonstrated within the context of two projects: TDFlex [33] and Flex Plan (H2020) [50] [51].

TDFlex

Within the TDFlex project, the benefits of utilizing the aggregated flexibility were investigated and demonstrated in the context of Switzerland for ancillary services and transmission system operation. By combining realistic operational data with real grid data, the outcome of this project contributes to the efforts by the TSO and the DSO to achieve a more integrated operational framework. To assess the benefits of utilizing flexibilities that can be potentially offered by distributed energy resources such as small-scale solar PVs, residential BESSs, residential electric heat pumps and personal EVs in medium- or low-voltage distribution grids, a framework is developed from two approaches: bottom-up and top-down. The economic attractiveness and the utilization impact of aggregated flexibilities to provide services to the electricity market through offering their flexible active power capability (positive and negative) as a "capacity reserve" and as a "generator" in Switzerland are demonstrated with a number of scenarios covering different local constraints (e.g., proliferation levels, remuneration amounts, etc.) conditions and different international system conditions. Conclusions present the boundary conditions, and the parameters that influence the potential benefits of utilizing the aggregated flexibilities.

FlexPlan

The FlexPlan project has the ambition of developing a planning tool capable of optimizing both transmission and distribution networks. Such tool is tested on six large regional cases covering nearly the entire European territory. Thanks to this analysis, the FlexPlan project tries to answer the question of which role flexibility could play and how its usage can contribute to reducing planning costs yet maintaining (at least) the current system security levels. With this objective, flexibility exploitation poses unexplored challenges for the planning of both transmission and distribution networks. In fact, having considered the non-uniform concentration of flexibility sources at the different voltage levels, complexity within the coordination between transmission and distribution system operators (TSO and DSO respectively) are expected. aimed at defining a novel network planning methodology capable of considering the opportunity to introduce new storage and flexibility resources in electricity grids as an alternative to building/reinforcing grid elements (lines and transformers). This new paradigm is aligned with the principles promoted by the European Commission's package Clean Energy for all Europeans, which emphasizes the potential usage of flexibility sources in the phases of grid planning and operation to compete with grid expansion.

The following section highlight the key outcomes of the project based on various perspectives. In particular, section aims to demonstrate the services offered by small DER to the TSO only, and therefore the flexibility aggregation is assumed to be performed at the TSO-DSO substation. It is assumed that there is an established framework to aggregate the flexibility, which can be performed by the distribution utility or an aggregator. The benefits of utilizing the aggregated flexibility are investigated and demonstrated according to the following key questions:

- **Transmission system ancillary services (TDFlex):** Can aggregated DER flexibility be competitive in ancillary markets day-ahead or intra-day by relying on the flexibility provided by the distributed energy resources so that it is to the benefit of the overall system?
- **Transmission system operation (TDFlex):** Is it technically and economically feasible for aggregated der flexibility at the TSO-DSO substation to help line loading and voltage profiles throughout the transmission grid so that it brings benefit to the overall system operation?
- **Grid infrastructure planning (FlexPlan):** Is it technically and economically feasible to use new storage and flexibility resources in electricity grids as an alternative to building/reinforcing grid elements (lines and transformers)?

5.1.1. Flexibility for transmission system ancillary services (TDFlex)

The aggregated flexibilities of the components that make up the represented DFlex unit (conventional load, HPs, EVs, PV, and BESS) have the potential to provide services to the electricity market by offering their flexible active power capability (positive and negative) as a capacity reserve in Switzerland. Based on the investigation, the following was observed:

- DFlex is procured as a reserve during any hour when its offer price is below the reserve clearing price and the impact of procuring DFlex for reserves is consistent across all simulated scenarios. The use of DFlex for upward reserves relieves hydro capacities, which in turn produce more energy in place of other more expensive generators, leading to lower total dispatch costs. Alternatively, the use of DFlex for downward reserves generally does not have a direct impact on the dispatch costs, except during hours when Swiss generators are curtailed in favour of cheaper imports. At these times, a small number of Swiss hydro-units are online solely to provide the required downward reserves and the procurement of downward DFlex capacity at such an hour allows for less "must-run" use of these hydro units and leads to lower total dispatch costs.
- The downward reserves provided by BESS, conventional demand, HPs, and EVs have the greatest potential for reserve procurements because these DERs together have significant available power during hours when their offer price is below the reserve price.
- The impact of procuring aggregated DER flexibilities for reserves is consistent across all simulated scenarios. The use of DERs for upward reserves relieves hydro capacities, which in turn produce more energy in place of other more expensive generators, leading to lower total dispatch costs.
- The remuneration scheme is a critical assumption in this assessment since it has the most direct influence on when DFlex capacities are cost competitive. In this work, the bulk of all procurements from DFlex occur during hours when the offer price is zero. This is also the reason so little upward DFlex capacity is procured since during most of the zero price hours DFlex has little or no available upward power capability. While this work applies specific remuneration schemes for the four DFlex components, the general message is that most offer prices (both high and low) are in close range of the reserve prices and different remuneration schemes would likely fall into this same range, where DFlex capacities are shown to be competitive and provide useful system benefits.
- Most offer prices by aggregated DER flexibilities (both high and low) are in close range of the reserve prices and different remuneration schemes would likely fall into this same range, where the capacities of DER flexibilities are shown to be competitive and provide useful system benefits.
- Beyond the local composition and remuneration of DFlex, system-wide aspects could also influence the competitiveness and benefits of DFlex. While the Swiss and wider European system dispatch is clearly sensitive to restrictions on the market NTCs, the price of natural gas, and the level of RES integration achieved, all three system aspects have little effect on the use and benefits of aggregated DER flexibilities for reserves.
- Overall, the influence of the remuneration scheme is more significant than the changes in the system-wide conditions.
- Scaling up the quantity of communities participating and therefore the associated available power flexibility of DFlex leads to proportional increases in the system dispatch cost savings. When scaled up enough, DFlex was found at times to provide the entire downward reserve requirement as well as around two-thirds of the upward reserve requirement. At this level, the utilization of DFlex for reserves yielded a cost savings of over 2.8 million Euro for the two simulated weeks combined.
- Utilization of DER flexibilities leads to proportional decreases in the system dispatch cost. This means that there is potential for additional remuneration of the aggregated flexibility resulting from system cost savings, in addition to the remuneration the DER owners already receive to compensate for their loss of opportunity.

- The sensitivity of the benefits to the amount of BESS within the DFlex community clearly shows that a reduction in the size of BESS directly reduces the amount of available power as well as resulting procured power from DFlex. However, both sensitivities assessed involving the offer prices (i.e., ∆Tariff and Feed-In) reveal only minor changes to the procurements and benefits of DFlex since they do not noticeably alter the economic attractiveness of the "DFlex Down Group" consisting conventional load, HP, EV, and BESS.

5.1.2. Flexibility for transmission system operation (TDFlex)

The aggregated flexibilities of DERs (conventional load, HPs, EVs, PV, and BESS) at the TSO-DSO substations have the potential to provide services to the system operation by offering their flexible active and reactive power capabilities (in both directions) as ”generators” in Switzerland. Based on the investigation, the following was observed:

- Utilization of DER flexibility can potentially help reducing required hydro dam generation requirements in Switzerland (relevant for “winter hydro requirements reserves”), acting as a generator by providing energy to the wholesale energy market.
- The aggregated DER flexibility at all load buses throughout the Swiss transmission grid can potentially alleviate internal CH transmission grid loading and support the voltage profile, resulting in more efficient network utilization. This benefit reduces if the DER flexibility is concentrated on selected load buses.
- The benefits of DER flexibility in reducing the required hydro dam generation requirements increase especially following the phase-out of nuclear units.
- It is important to note that the economic attractiveness of the DFlex units is dependent on (i) wholesale energy prices and (ii) remuneration schemes for DER flexibilities, which constitutes the cost of DFlex units (i.e., the minimum price to be paid to the DER owner). Inspecting the unit costs of providing active and reactive power flexibility, a boundary on economic competitiveness can be identified.
- The benefits of the power flexibility provided by the DFlex units to the system are easily measurable and observable by observing the reduction in the power generation of the hydro dams as well as loading relief along Swiss transmission lines. The resulting benefits are due to the combined effect of the simultaneous provision of active and reactive power flexibility supplied by the DFlex units to the system. It is observed that almost all DFlex units act like generators (providing "-" flexibility, by decreasing demand or discharging BESS) and inject active power into the system, while there are few instances that they provide "+" active and reactive power flexibility by acting like a demand (+ flexibility, by increasing demand, charging BESS, curtailing solar).
- The contribution of BESSs is the main driving factor, and the availability of aggregated BESS is essential to ensure that a meaningful amount of power flexibility is offered. The total available reactive power flexibility is, however, restricted due to the limitations of BESS in injecting reactive power to the system. It is noted that the resulting benefit by DFlex units can be reduced significantly due to low proliferation of BESS by solar PV owners. In that case, the aggregator shall resort to higher number of communities, with other DERs such as conventional demand, HPs, and EVs available to provide flexibility.
- Reactive power provision by solar PV and residential BESSs are at the expense of reducing the active power utilization. Therefore, the remuneration of reactive power provision is high and not competitive with the current reactive power pricing structure of the transmission system operator of Switzerland, Swissgrid. However, if the overall system benefit is taken into account (increase of cheap import of active power with the

help of adjustments of the reactive power thanks to the flexibilities), these services can be subsidized, thus enabling them to provide services.

- Since the voltage support is a location-dependent need, the utilization of location-relevant DER flexibilities exclusively for voltage support will increase the system benefit. Therefore, the aggregators can resort to methods to utilize active power flexibility only in selected load buses and reactive power flexibility in other buses, to maximize the flexibility extracted from the DFlex units. The selection process can be based on the needs of the transmission system operator and provision of such dedicated services may be remunerated differently.
- The benefit of flexibilities is greatest during times of high loading of the transmission system (through transit flows or high demand). If the flexibilities, spread throughout the network assembled by the aggregators, cannot be provided at the same level in a continuous manner, further investigations are required to identify the critical times for flexibility requirements by the transmission system operators. For example, the availability of different flexibility types varies over time (e.g., demand cannot be decreasing its demand at every hour, while a residential BESS can only discharge until it is empty), that may not coincide with the time of greatest benefit to system operation.
- It can be concluded that BESS-based DFlex units are competitive when the wholesale energy prices are higher than 150 CHF/MWh and other technologies such as conventional demand, HPs and EVs are competitive when the wholesale energy prices are higher than 50 CHF/MWh under the assumptions made in this study.
- Given the time-, availability- and forecast-dependent nature of the flexibilities, it is important to note: (i) simultaneously aggregating the DER flexibilities offered by multiple communities is assumed to be performed by an aggregator by employing intelligent ways of procuring the flexibility so that same DERs are not relied upon all the time, (ii) it is assumed that BESS is discharged during the night and does not start charging until there is excess solar. Since the probability of excess solar occurrence is very low especially in winter times, BESS will be idle under this assumption. However, the BESS owner may be motivated via a remuneration scheme during these idle times, so that BESS units can still be utilized for operational flexibility.

These conclusions are highly dependent on the selected remuneration system, and the evolution of the retail electricity tariffs. Enabling lower generation requirements of hydro dam plants is a benefit to the overall system and can have the potential to unlock other mechanisms to further compensate the utilization of the DFlex units. It is important to emphasize that the remuneration method does not take into account the impact of providing flexibility services on the technology lifetime, which can further increase the cost of the flexibility by DERs for the system services. It is noted that the lifetime impact will be significantly higher if services are offered in operation, compared to services in reserves, which has low deployment probability.

Flexibilities and aggregation process

- To accurately capture the behaviour and the potential of the available flexibility that can be provided by small DERs so that they can be aggregated to provide services, it is essential that DER consumption/generation/charging are measured in sub-hourly time resolution (e.g., 5- or 15- minute). This is true for the ”availability signal” concept proposed as well, which helps the DER owners to communicate the availability status of their assets in high time resolution.

Impact of remuneration on competitiveness

Aggregated DER flexibilities are competitive for reserve and operation services under the following conditions:

- During low-tariff hours, especially if the electricity tariff is in the range of or lower than the wholesale energy prices or reserve prices in Switzerland because the main contributors to the flexibility provision are BESSs and the remuneration of BESS owners, based on the loss of opportunity, is driven by the consumer's low tariff.
- When the wholesale price is high (impacting the service offered to reserve up and daily operation) [large difference between 2020 vs. 2050].
- When the difference between the consumer's high-tariff and low-tariff is small.
- When solar remuneration is low, especially lower than the wholesale energy prices or reserve price in Switzerland.

5.1.3. Flexibility for integrated grid planning (FlexPlan)

Power system is constantly evolving, and the generation mix is changing in favour of renewable energy resources. Conventional generators, which in addition to supply energy demand also provide services, are gradually decreasing their contribution to flexibility reserve and new technologies are becoming ready to compete in ancillary services markets. In fact, the research community is currently investigating the potential of innovative demand response and energy storage technology for the provision of power flexibility that can support network operation and planning.

5.1.3.1. Non-uniform availability of power flexibility

In addition to the conventional reserves (mainly aimed to the operation of transmission networks), flexible resources can provide services to the distribution grid in which they are located, and regulation is currently promoting initiatives aimed at demonstrating the cost-effectiveness of local flexibility for the planning of distribution networks [52] [13]. Focusing on the exploitation of flexibility for the solution of local problems, the scientific community proposes many distribution network planning strategies aimed at determining the best trade-off between local flexibility and new lines/transformers [53]. All of them are clearly showing how the current practices (based on pure infrastructure reinforcement/expansion) do not guarantee the same cost-effectiveness of planning options in which flexibility is considered. Nevertheless, having considered that flexible resources can be part of regulation reserve for transmission services too (even if connected at distribution level), DSOs might be required to operate/plan their network in order to efficiently delivery flexibility services to transmission even from resources connected to the lowest voltage levels. Therefore, it can be reasonably expected that flexibility reserve will not be located exactly where the service is needed, but it will spread according to the geography of the flexible resources which often is based on external factors (availability of energy sources, climate conditions, customers engagement potential, etc.) rather than the characteristics of the electrical network.

5.1.3.2. Integrated planning of transmission and distribution grid

The planning of electricity system is traditionally based on grid expansion/reinforcement measures, which lead the system operator in affording capital investments only (CAPEX). This planning strategy is currently adopted in the vast majority of electrified countries, mainly because of regulatory restrictions. In practice, it consists of an optimization problem aimed at minimizing the costs of investments for the solution of congestion/adequacy/security issues. Having considered that the electricity system is managed by two distinct categories of operators (TSOs and DSOs), separated planning routines are conventionally adopted which, in mathematical terms, can be summarized as follows:

Conventional planning algorithm for transmission systems

$$\begin{cases} \min \mathrm{CAPEX}_{trans} \\ such\ that \\ \quad \text{transmission grid constraints are respected} \end{cases}$$

Conventional planning algorithm for distribution systems

$$\begin{cases} \min \mathrm{CAPEX}_{distr} \\ such\ that \\ \quad \text{distribution grid constraints are respected} \end{cases}$$

In most of the cases, the transmission planning problem can be solved by using new transmission assets. The same can be stated for distribution system, which is normally expanded by using reinforced distribution lines and transformers. In general, this means that the separation of the planning problem among voltage levels is TSO/DSO level does not impact on the optimality of the calculation:

$$\begin{cases} \min \mathrm{CAPEX}_{trans} \\ such\ that \\ \quad \text{transmission grid constraints are respected} \end{cases} \quad \begin{cases} \min \mathrm{CAPEX}_{distr} \\ such\ that \\ \quad \text{distribution grid constraints are respected} \end{cases}$$

coincide with

$$\begin{cases} \min \mathrm{CAPEX}_{trans} + \mathrm{CAPEX}_{distr} \\ such\ that \\ \quad \text{transmission grid constraints are respected} \\ \quad \text{distribution grid constraints are respected} \end{cases}$$

The research community [53] [54] [51] is currently demonstrating the potential of power flexibility for the provision of services aimed at reducing and/or deferring the reinforcement of the infrastructure. This means capital expenditure can be mitigated, but another cost dimension needs to be added to the calculation: the operational costs (OPEX) related to the flexibility exploitation. Accordingly, regulation is currently considering the introduction of power flexibility as a possible planning candidate, such that the two separated planning process can be done independently by:

Modern planning algorithm for transmission systems

$$\begin{cases} \min \mathrm{CAPEX}_{trans} + \mathrm{OPEX}_{trans} \\ such\ that \\ \quad \text{transmission grid constraints are respected} \end{cases}$$

Modern planning algorithm for distribution systems

$$\begin{cases} \min \mathrm{CAPEX}_{distr} + \mathrm{OPEX}_{distr} \\ such\ that \\ \quad \text{distribution grid constraints are respected} \end{cases}$$

In this case, the solution of these two calculations leads to a situation in which distribution flexibility ($OPEX_{distr}$) is used for distribution planning and transmission flexibility ($OPEX_{trans}$) for transmission planning. However, having considered that distribution flexibility can provide services also to the transmission system, the separation of the planning problems does not generally return an optimal solution. For this reason, research is currently trending towards investigating the adoption of integrated planning approaches [56] [55] [57], which guarantee the exploitation of the full potential of flexibility, independently of the voltage level to which it is connected, while ensuring that the grid constraints are still respected.

Integrated planning algorithm for transmission and distribution systems

$$\begin{cases} \min \mathrm{CAPEX}_{trans} + \mathrm{CAPEX}_{distr} + \mathrm{OPEX}_{trans} + \mathrm{OPEX}_{distr} \\ such\ that \\ \quad \text{transmission grid constraints are respected} \\ \quad \text{distribution grid constraints are respected} \end{cases}$$

Considering this planning approach however, it can be noticed that the possibility of distributed flexible resources (represented by $OPEX_{distr}$) for the provision of services to the transmission system is considered, but it requires the integration of information related to both transmission and distribution systems. This means that the current TSO-DSO data management needs in terms of planning and access to flexibility [54] should be reconsidered in order to include additional network information and to deal with the potential confidentiality issues. In particular, this last aspect represents one of the major barriers for the adoption of an integrated planning approach, and solutions that guarantee an effective (but still confidentiality-preserving) information management are vital for the full exploitation of flexibility for planning purposes.

5.1.3.3. System planning considering distribution flexibility for transmission services

As stated above, flexibility sources are expected to be mostly located at distribution level and it has a great potential to compete with grid reinforcement/expansion measures within the planning routines. For this reason, the European directive [13] promotes the exploitation of local resources as alternative to new asset investments which, in terms of distribution planning routine, can be translated as:

Modern planning algorithm
for distribution systems
(DSO has priority on flexibility located at distribution level)

$$\begin{cases} \min \mathrm{CAPEX}_{distr} + \mathrm{OPEX}_{distr} \\ such\ that \\ \quad \text{distribution grid constraints are respected} \end{cases}$$

The previous section mentions the reasons for which the solution of this procedure is not optimal in general, since it neglects the potential necessity of flexibility reserve for transmission services and planning. Nevertheless, this planning strategy is still meaningful when the adopted TSO-DSO coordination scheme assigns to the DSO the priority on local flexibility exploitation. In this case:

- The DSO runs its own planning algorithm, regardless of the local flexibility potential to provide services to the transmission system.
- Once the best planning candidates are selected (the ones that minimize local $CAPEX_{distr} + OPEX_{distr}$), the remaining flexibility (represented by $OPEX_{distr\_for\_trans}$) can be used for transmission services. In this case, the transmission network planning problem can be formalized as follows:

Figure 16 shows the illustrative results of a distribution planning problem for different portions of local flexibility reserved for transmission services. It can be noticed that the minimum costs are obtained for a combination of capital investments and exploitation of distribution flexibility such that only 30% of it can be reserved for other functions.

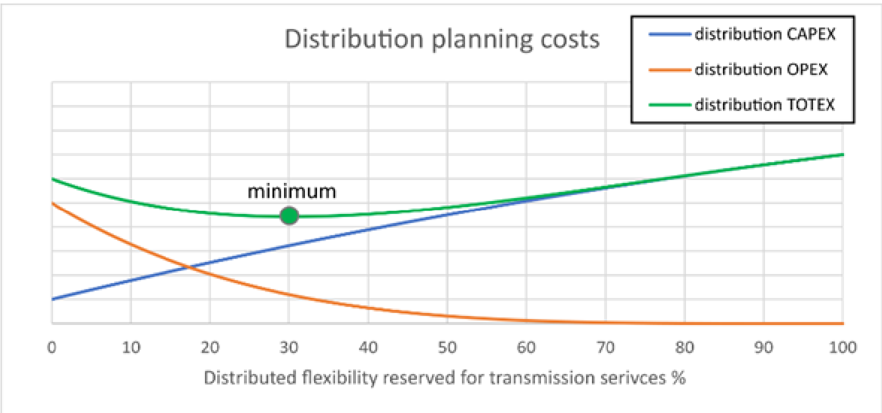


Figure 16 Distribution planning costs for different values of local flexibility reserved for transmission services

Of course, this portion could be non-optimal for the containment of transmission planning costs, however this topology of TSO-DSO coordination has one main advantage: it guarantees a separation of the TSO-DSO planning procedures and the data exchange among network operators is limited on the monitoring and exploitation of the available local flexibility (for which the necessity of a dedicated standard has been agreed in the past already [58]). On the other hand, as anticipated in the previous section, the minimization of global planning costs (transmission + distribution) can be achieved by adopting an integrated procedure, which requires a more cooperative exploitation of distribution flexibility. A further step in the direction of a TSO-DSO collaborative planning consists of the reservation of a distribution flexibility portion for transmission services, aspect that can be formulated by means of the following optimization problem:

Modern planning algorithm
for distribution systems
(including pre-allocated flexibility
reserve for transmission services)

$$\begin{cases} \min \mathrm{CAPEX}_{distr} + \mathrm{OPEX}_{distr} \\ \textit{such that} \\ \quad \text{distribution grid constraints are respected} \\ \quad \text{a portion of local flexibility is reserved for} \\ \quad \qquad \text{transmission services} \end{cases}$$

The proposed planning approach leads to a coordination scheme in which the TSO has the priority in exploiting a pre-agreed volume of flexibility located at distribution level. A possible procedure foresees that:

- The TSO runs its own planning algorithm, which identifies the flexibility needs. The portion of flexibility reserve located at distribution level (for which the full potential is requested) is communicated to the DSO.
- The DSO runs its own planning algorithm, which is primarily oriented to the solution of local constraints and to guarantee the exploitation of the requested flexibility reserve by the TSO. The remaining flexibility can be used for the local network planning, insofar it does not interfere with the TSO services.

This TSO-DSO coordination scheme features the same data management characteristics described for the previous architecture, which can be deduced from the exemplifying curves reported in Figure 17. In this case, distribution flexibility is in favour of cost reduction for the transmission system and the optimal planning solution leads to different reserve values (62%).

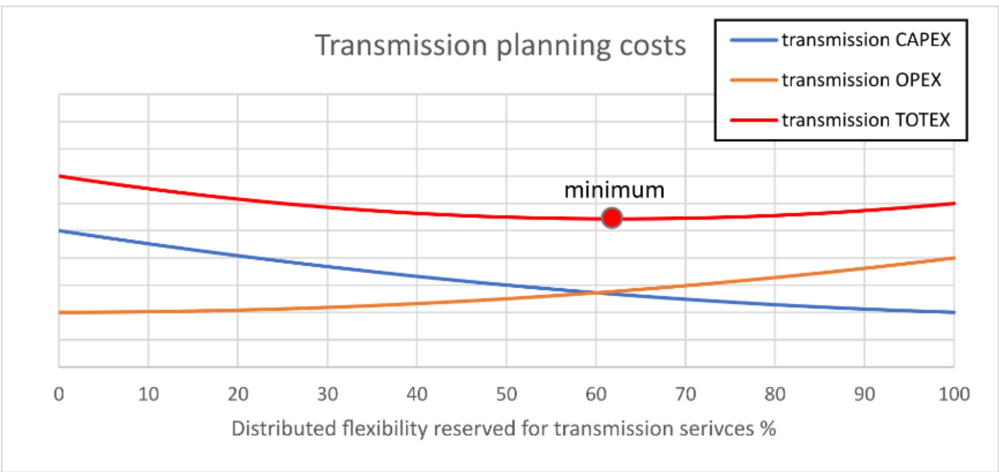


Figure 17 Transmission planning costs for different values of distribution flexibility reserved for transmission services

5.1.3.4. Collaborative transmission and distribution planning procedure

The previous section identifies two possible options for the planning of both transmission and distribution systems. The first one guarantees the minimization of the costs ($\mathrm{CAPEX}_{distr} + \mathrm{OPEX}_{distr}$) related to distribution planning, at the expense of remaining flexibility for the transmission system. The second one, instead, supports the minimization of the transmission planning costs ($\mathrm{CAPEX}_{distr} + \mathrm{OPEX}_{trans} + \mathrm{OPEX}_{distr\_for\_trans}$) with the support of distributed resources, but it decreases the flexibility exploitable for distribution services.

Depending on the evolution of the electricity scenario, the profitability of one TSO-DSO coordination scheme varies significantly. As stated above, the optimal solution in terms of global costs reduction (transmission and distribution) requires the processing of a fully integrated planning procedure. In fact, having assumed the same cost figures reported in the previous section, Figure 18 demonstrates that prioritizing flexibility for distribution or transmission is not leading to the optimal solution for the entire system (which in this case corresponds to the 40% of flexibility share).

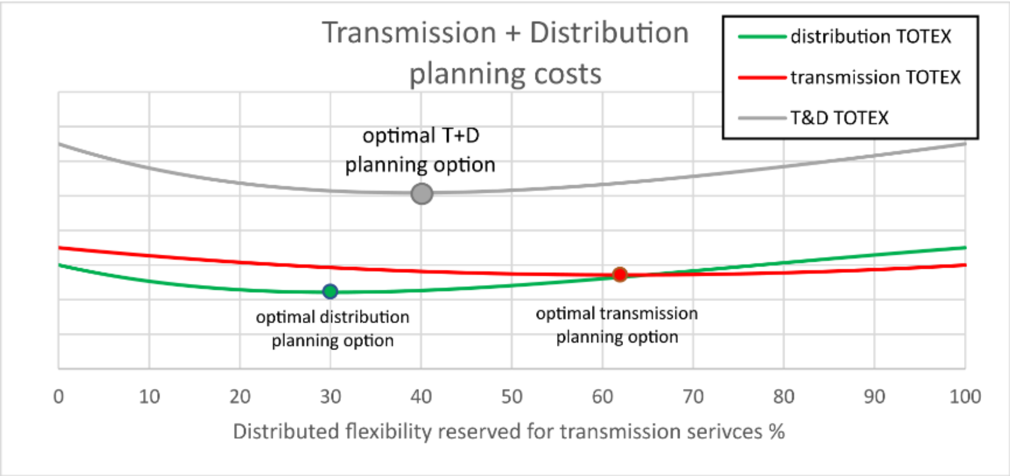


Figure 18 Electricity system planning costs for different values of distribution flexibility reserved for transmission services

An integrated planning procedure, instead, would directly return the optimal set of investments and flexibility elements for both transmission and distribution systems, such that the total planning costs are optimized. However, in addition to the technical challenge of managing and processing a large set of data, TSO-DSO coordination barriers are limiting the full exploitability of an integrated planning. To solve these limitations, an alternative collaborative approach can be defined on the basis of a TSO-DSO consultation and negotiation on the amount of distribution flexibility that can be reserved for transmission services. FlexPlan explores a method based on a multi-step procedure, which can be found in [56].

Based on the investigation and the outcomes of the implemented methodology where the collaborative planning strategy for transmission and distribution networks, capable of considering the potential of resources located at the lowest voltage level to provide flexibility services to the entire system was implemented. Although the procedure is characterized by a non-negligible complexity, its adoption introduces significant advantages for an integrated optimization of distribution and transmission systems:

- Automatic and independent distribution planning routine, which explores different options in terms of required regulation reserve for transmission services.
- Cooperation between system operators is expected to be simple and efficient, since the identified distribution planning options can be negotiated with a limited exchange of standard and non-sensitive information.

This approach, which is in its early development phases, has the main goal of supporting the decoupling of planning routines for transmission and distribution networks. In addition to the benefits in terms of computational tractability, it has the potential to solve several conflicts related to the TSO-DSO coordination, without significantly impacting on the planning costs optimality which, otherwise, can be achieved with the unpractical fully integrated procedure.

5.2. ICT perspectives

The ICT requirements differ depending on the type of the flexibility service (e.g., for reserves, for intra-day operation, infrastructure planning) and whether the flexibility service is aggregated by an aggregator or provided individually by the flexibility resource owner. If the flexibility is required in intra-day operation for relieving congestion or supporting voltage, very high reliability of communication network is required along with an “flexibility management system” at the site of the flexibility provider, such that when the signal for the flexibility requirement” is received it can reliably “dispatch” the flexibility. Such framework can also be referred to as “direct/full controllability” and treats the distributed flexibility owners as conventional “dispatchable” generators, resulting in very stringent requirements for availability and reliability of an ICT infrastructure.

Another option can be based on “time-ahead” flexibility signals that are sent automatically by the “flexibility management systems” at the site of the flexibility resource (i.e., edge), which provides a binary signal identifying when the resource will be available to provide flexibility. For example, such a framework can be established *x-hour*-ahead intraday, and every “*x*” hours each flexibility resource sends a signal to the Energy Management System (EMS) of the utility or the transmission systems or to the aggregator, providing the amount of flexibility that can be provided and when it can be provided. In this case, the ICT requirements may not be as stringent as it is for the “full controllability”.

In both examples, the time-resolution of the signals or measurements does not need to be sub-minute unless the flexibility service is utilized for inertia services.

5.3. Regulatory perspectives

Participation of small-scale (<100 kW) distributed energy resources in markets at transmission system level directly or indirectly (via aggregators) require regulatory actions. The required steps will be different in various regions (e.g., EU, North America, etc.). The regulation has to take into account the fact that the flexibility services offered by the distributed energy resources connected to the MV- and LV-networks through different mechanisms (e.g., markets, remuneration schemes, etc.) shall ensure “equal opportunity” for all DER owners. That means, the remuneration shall be irrespective of where the flexibility service is located. This requirement may not be an easy objective to achieve due to the distribution grid constraints and due to “flexibility” needs are usually “location-dependent”. Finding a compromise is dependent on the political culture and the structure of the region and the country. In addition, if the remuneration mechanism of flexibility services is based on forward markets (e.g., day-ahead coupled with intra-day dispatch), the "liquidity” of such flexibility markets shall be ensured by the regulation. Finally, the end-customers who do not own distributed energy resources shall be protected and the regulation have to ensure a “fair” electricity pricing.

6. Barriers and challenges of flexibility and stakeholder interaction

To use the flexibility from DERs new challenges from different perspectives need to be overcome, including technical, ICT, regulatory and economic perspectives. Figure 19 provides a high-level overview of possible barriers in the context of TSO- DSO interaction and flexibility integration.

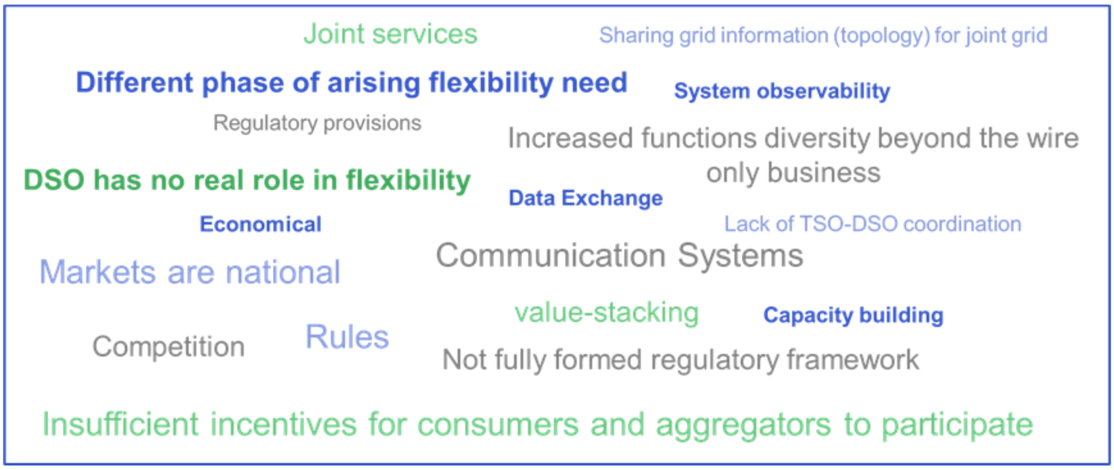


Figure 19 Overview of barriers to TSO-DSO coordination with respect to flexibility [3]

Although, the topic of flexibility and stakeholder interaction has received increased attention over the last few years, many solutions have been proposed to mitigate the various challenges and barriers which may exist. The following sections provide an overview of selected barriers and challenges based on the outcomes of various projects and experiences.

6.1. Technical perspective

While there has been a wide range of research and investigations, many of these technical challenges can be overcome including the visibility and controllability of aggregators and receiving signals from DSOs or TSOs. However, there are a few challenges which remain related to metering and technical requirements at the connection point which are highlighted below.

6.1.1. Metering requirements for DER (in combination with non-flexible loads or a single source equipped with its meter)

DERs can be classified according to their location and the characteristic of being metered with inflexible loads and the type of resource [6]:

- **Location:** connected to the distribution system equipped with its meter, or indirectly connected to the distribution system behind the interconnection point with the grid and metered together with customer's inflexible loads; and
- **Type of resource:** generator, storage, or flexible load

When DERs are located inside customer premises and measured together with inflexible loads, the quantification of the provision of flexibility becomes challenging. To overcome this challenge, baselining methodologies, which use sub-meters which measure individual assets or a combination of both can provide beneficial alternatives. In such cases, both baseline and data measurement are used for verifying the delivery of the services and the financial settlement. However, one disadvantage of poor measurement or misleading baseline methodology, is that it may result in gaming strategies as it becomes difficult to verify the delivery of procured flexibility from resources that are measured with inflexible loads. Although technical solutions exist, the regulatory decisions and definitions of baselines methodologies, roles and responsibilities still need to be defined.

Furthermore, an additional challenge, lies in the fact that there is limited information about where flexible resources are located (on the distribution grid level) and DSOs do not have real-time information about the actual load in the grid. Most of the information is obtained from smart meters, where hourly data for 24 hours is collected during the night [6]. This limits the ability of DSOs to determine their flexibility needs.

6.1.2. Connection requirements to distributed systems

In various countries, the ambitious governmental RES expansion targets require the rapid integration of new renewable generation capacity into electricity networks. A simple and transparent procedure to access the network is crucial for incentivising private investment in RES generation capacity [43]. For assessing an investment opportunity, investors need to be able to anticipate their chances of connecting to the electricity grid, as well as estimated costs inquired. Furthermore, knowing the hosting capacity[8] of the network and how to define it is a critical aspect for the assessment.

Available distribution network hosting capacity is difficult to assess because it might be case-specific. As DSOs need to guarantee system stability, the potential connection of new generation or demand units might require a detailed, dynamic system analysis. By using power-flow models, DSOs can evaluate different operational scenarios, providing robustness to the evaluation of a new connection. Estimation of available hosting capacity can be published for informative purposes. Several system operators in Europe already provide this information for third parties interested in connecting to their grid [59]. In some areas in North America (e.g., Ontario, Canada and California, US), utilities are required to provide it for their systems (though there is no standard methodology or presentation). By doing so, system operators enable connection seekers to assess available hosting capacity at their selected connection point prior to initialising the permitting process.

Depending on national law, this available hosting capacity is then allocated to parties requesting electricity grid access according to different procedures [60] [61] [62] [63] [64] [65]:

- **First-come-first-served (FCFS):** available capacity is assigned in the temporal order of requests.
- **Batch**: a group of applicants that requested permission in a regulated time frame is evaluated in a common process.

[8] Hosting capacity is the ability of the distribution electrical system (DES) to accommodate DERs without adversely impacting reliability, protection schemes, thermal limits, power quality (e.g., voltage deviations, flickers, harmonics), or any other criteria the utility considers important or relevant. Alternatively, hosting capacity is the ability to connect a DER or DERs without the need to upgrade or add to existing DES infrastructure.

- **Auctions**: capacity is assigned on a market-based approach according to bids of participants (mainly capacity or energy-based).

All of these hosting capacity allocation mechanisms might include a priority for renewable generators in case of competition with other technologies to support the rapid grid integration of non-emitting generation technologies. RES priority is granted in Germany and in the Flemish region of Belgium, for instance [59].

The most common approach for allocating hosting capacity in Europe is FCFS [59]. This might prevent connection seekers from estimating the possibility of obtaining network access, as the existing queue of projects being evaluated is commonly unknown. However, transparency can be created by including data on capacity in the queue for obtaining access in the publication of hosting capacity as performed, for example, by Spanish DSOs [66] [67]. By publishing the capacity in the queue, a higher degree of predictability of the chance of obtaining access permission is provided. Connection seekers can manage their projects accordingly based on where obtaining access is the most promising. The abovementioned transparency allows sending locational signals, so connection seekers maximise the use of the existing network. However, in the course of the decarbonisation of the energy sector [68], new generation capacity will sooner or later exceed available hosting capacity. Depending on the country's regulation of the power sector, the charges for reinforcing the electricity grid might be assigned entirely to the connection-seeking party [59]. While greater projects usually dispose of funds to allow for grid connection charges, smaller distributed generator connections might be considered economically unfeasible due to high network upgrade requirements [69]. The reinforcement of the wider network, if necessary, is usually carried out by the grid owner, resulting in potentially long connection times [70].

Possible Solutions

As previously mentioned, the employment of flexibility can represent an alternative to costly reinforcement of network assets. While flexibility markets represent a useful tool to increase renewable grid integration at minimum reinforcement costs, the creation of flexibility markets requires liquidity. The allocation of flexible access rights instead of traditional firm access is an alternative to guarantee the efficient use of existing hosting capacity and deferring network reinforcement. This option allows the system operator to "relax" the available capacity calculation criteria in exchange for converting firm connections into interruptible connections [67]. Commonly, flexible connections are considered rather for distribution grids. The non-firm access is agreed on by the connection-seeking grid user and the system operator before signing the access and connection agreements.

The use of interruptible connections is already partly implemented in European distribution networks. The German regulator allows DSOs to account for up to 3% of RES curtailment in their grid reinforcement planning [68]. In Belgium and the Netherlands, DSOs are allowed to grant temporary non-firm grid access to RES generation for the duration of reinforcement works [55]. This allows for the reduction of the connection time and generators can already make use of existing hosting capacity while waiting for their firm access once the network upgrade works have been carried out. In the UK, the regulator (Ofgem) offers this option of preliminary non-firm grid access to transmission connecting generation and demand units under the "Connect and Manage" scheme. Additionally, Ofgem is considering non-firm RES connection options via the Significant Code Review [66]. Furthermore, in Germany, DSOs are obliged to offer flexible connections to controllable LV loads in exchange for a reduced grid tariff [73].

Apart from the reduction of grid tariffs as in the case of German controllable LV loads, users might be compensated differently for the interruption of their grid connection. In any case, users experience a reduction in the connection time as they do not have to wait for reinforcement of the network to be carried out. For permanent flexible connections, users might experience a reduction of connection costs in regulatory systems that employ deep or shallow connection charges. Compensation payments are another approach to encourage users to opt into a flexible network connection. In that case, it is economically beneficial for the system operator to allow new capacity into the grid until the compensation payment sum reaches the threshold of avoided reinforcement costs [74].

Previous research on the topic of non-firm generator access and the first regulatory adaptations of the mechanism has shown that network reinforcement avoided with flexible connections is beneficial for both, DSOs and connection seekers. Aspects that should be considered for the regulatory implementation of flexible connections include:

- The cost-optimal solution might be a mixed approach of network reinforcement and curtailment [75].
- Grid users of different sizes might prefer different connection agreements. Small generators might prefer to pay for network reinforcement to increase certainty [76].
- However, if non-firm access is applied to large grid users only, these will experience increased amounts of curtailment for the large ones without participating in the mechanism [77].
- The application of curtailment to already connected users can help significantly reduce reinforcement requirements for the connection of future capacity [78].

Table 4 Barriers and possible solutions on connection and network access requirements

Network access procedure	Common methodology	Barrier	Possible Solution
Calculation of available hosting capacity	Individual power-flow analysis	Missing transparency for connection seekers	Informative publication of an estimation of available capacity
Hosting capacity allocation	First-come-first-served	Lack of transparency for connection seekers to estimate their chance of grid access permission even though hosting capacity estimation is published by system operator	Include capacity in queue in the publication of hosting capacity estimation
Connection of the user	Firm connection	• Limited available hosting capacity vs targets of integrating high-RES shares. • High connection charges. • Long connection time.	Non-firm, interruptible connections to reduce both connection costs and time and allow for additional connections in network nodes where reinforcement is unfeasible

As per many distribution system connection agreements with net injecting flexibility resources, a customer-owned distributed generator (DG) must cease generating and injecting to the grid when the normal feeder configuration changes. The main driver for these policies is to ensure safety for both the system and individuals working on the grid during system restoration due to fault conditions (i.e., situations that result in unplanned outages) or planned work including preventative maintenance or capital expansion programs to ensure continued system reliability. While distributors have no obligations to keep customer owned DGs online during outage conditions, with the recognition that these resources can provide valuable grid services and to align with policies such as FERC order 2222 [31], local utilities are planning for ways to keep DGs connected and generating. These include the development of Operating Strategies on customer owned DG assets. Considerations of these strategies include:

- Distributors controlling all feeders and their assets with embedded DG connections
- Distributors controlling the DG assets themselves

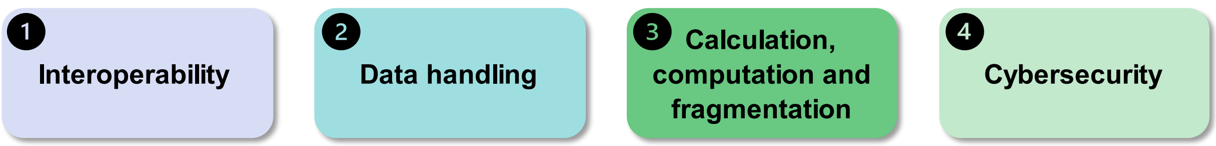
In undertaking this strategic decision, a robust decision-making criterion must be established including considerations around customer service, safety, affordability and reliability; distributor workload; and open fairness and competition in a flexibility market.

In Ontario, there are opportunities for DGs to remain connected if the system configuration changes due to a planned outage. If DGs are less than 250 kW in size, it may be transferred from their normal supply feeder to an alternate supply subject to a distributor load-transfer study that evaluates the aggregated impacts of this generation. For DGs above 250 kW in size, it must remain disconnected [79].

Long-term distributor operating strategies are pivoting more toward the allowance of controlled islanding to allow DGs to remain connected and energize portions of the feeder [80]. Undertaking controlled islanding is complex and requires significant coordination between generation and load assets to ensure there is a balance between both as well as the appropriate isolation from the wider distribution grid. Furthermore, detailed network operating instructions and procedures are also necessary along with a robust distribution-level Supervisory Control and Data Acquisition (SCADA) system to ensure assets (breakers, switches, protection schemes) within the planned island operate seamlessly to meet real-time system conditions and align to the real-time status of generation and loads.

6.2. ICT perspective

Some of the main challenges when implementing flexibility mechanisms in electricity grids are related to the information and communication technology (ICT) used to coordinate the different stakeholders involved. In Europe, the experience acquired in several EU-funded projects where the coordination between system operators and other actors was needed has allowed the identification of four main challenges related to ICT [81]:



These four challenges are described in more detail in the following sections.

6.2.1. Interoperability

Interoperability can be understood as the ability of two or more systems to exchange information and be able to use that information. For this purpose, the use of standards is essential. Within various EU projects, the implemented ICT solutions may differ from one demo/area to another [82]. In some cases, an ad hoc platform that integrates with stakeholders' systems is developed. The main problem with this approach is that it may be challenging to replicate the same platform in other areas if the ICTs used by the stakeholders' systems are different. In other cases, an already-existing data exchange platform (DEP) compatible with different standards and protocols or that implements a well-defined Application Programming Interface (API) is used instead. However, there are numerous DEPs currently available and some of them have not been specifically designed for energy data. To achieve seamless interoperability between stakeholders connected to different DEPs, DEPs should define mechanisms (e.g., APIs) to allow for the possibility of exchanging data cross-platform [83].

In addition to this, it has been observed that due to the lack of standards for some interfaces, such as the aggregator-appliance interface or the interfaces with other systems (either legacy or new), poses great challenges for these demonstration projects. Apart from using open and international standards, projects should allow for the opportunity to share more information between them and participate in cross-project interoperability tests [81].

6.2.2. Data handling

Data handling refers to the ownership, access, quality, and harmonization of the data exchanged between stakeholders. The data must be well structured, complete, following a specification or format, and exchanged at appropriate time intervals. Furthermore, the ownership of every piece of data must be clearly defined. To comply with data protection regulations, it must also be evaluated if additional actions on data are needed (e.g., aggregation or anonymization).

Due to the increasing need to optimize flexible resources across grid levels, data exchange among actors is increasingly critical, and shared measurements immensely improve the currently valid observation and control areas in the grid. However, due to various reasons such as economic conflicts of interest and grid security issues, actors lack the willingness to provide corresponding data to other actors. In general, monitoring and observability will be critical for the reliability and controllability of the grid. Therefore, the extension of the ICT infrastructure and adequate data handling will be crucial.

Among the different data models, the Common Information Model (CIM) can be considered to be the most extended and commonly used in TSO-DSO coordination projects [82]. However, despite its significant contribution to interoperability, CIM raises some practical issues when a system is being developed, mainly related to CIM extensions, harmonization with other standards, and the validation of model instances [84]. In Europe, it has been identified that CIM has does not cover, among others, all the requirements needed for TSO-DSO coordination [81], data exchange between TSOs [85], and when implementing flexibility services [86]. To improve the data exchange between DERs and SOs, the harmonization of CIM with IEC 61850 and the development of extensions are considered to be of the utmost importance [81]. To ease the process of developing CIM extensions, it is recommended that projects and CIM standardization groups should keep a close collaboration in order to facilitate knowledge exchange.

When considering data management aspects, some projects define different data roles depending on the systems and type of data involved. In general, projects should align with available role models such as the Harmonised Electricity Market Role Model (HEMRM) [83] or, if new roles are identified, propose their inclusion in such models [77].

6.2.3. Calculation, Computation and Fragmentation

When considering the simulation, calculation and the computational resources, energy management and coordination algorithms used by grid operators require a detailed grid topology as input where the results of the calculations are highly dependent on the accuracy of the topology. Therefore, if there are changes of the topology new calculations will be required, because results are often only valid under the original conditions and no longer apply to the changed conditions.

However, detailed grid topology information is often not available, or the level of details are high resulting in very large grid models. In a centralized approach, where combined grid models of multiple grid operators are used, may result in high computation efforts which require longer lead times. On the other hand, decentralized algorithms lead to higher operational costs and divide or cluster flexibilities. This results in higher fragmentation, which deteriorates the grid operation, as flexibilities cannot be optimized properly, which, as a consequence, decreases the availability of flexibility for the system. This outcome then increases the requirements and costs for communication and the ICT infrastructure.

6.2.4. Cybersecurity

The increasing digitalization of the electricity sector is expanding the cyber-attack surface, causing a rise in cybersecurity challenges when the interaction and coordination between different stakeholders are required.

The BRIDGE Cybersecurity report [88] highlights that the main cybersecurity risks faced by EU projects are related to the combination of new and legacy equipment and technologies, since many of the communication protocols currently used to exchange power system data do not include many security measures [89]. For example, some EU projects implementing flexibility schemes combine the use of legacy Inter-control Centre Communications Protocol (ICCP) for real-time data exchange, which requires several cybersecurity improvements [90], with new systems that use protocols such as MQTT+TLS or HTTPS-based REST APIs, which are usually used by the platform or system developed for the flexibility market. In addition to this, the interface of Information Technology (IT) with Operational Technology (OT) can represent a challenge from the cybersecurity perspective that should be considered [81].

The vast number of stakeholders that can be involved in a flexibility scheme (e.g., TSOs, DSOs, FSPs, etc.), and the increasing deployment of Internet of Things (IoT) devices in power systems, make it necessary to also consider the risk of the cascading effect. This means that, for example, a cybersecurity vulnerability in the system of an FSP may raise cybersecurity and operational risks for the TSO and DSO. The energy sector does not usually address the cybersecurity challenges fast enough; therefore, stakeholders should cooperate amongst each other by exchanging data about potential cyber threats and incidents as soon as they are identified so that their impact can be minimized [91].

Table 5 Summary of the main challenges and key factors from the ICT perspective

Main challenges	Key factors
Interoperability	• Lack of standards for some interfaces. • Lack of interoperability between data exchange platforms. • Lack of cooperation mechanisms between projects to carry out interoperability tests.
Data handling	• Data ownership must be clear when exchanging data. • Despite its extended use, CIM raises some practical issues during implementation, naming CIM extensions, harmonization with other standards, and validation of model instances. • CIM does not completely cover the requirements for TSO-DSO coordination, data exchange between TSOs, and when implementing flexibility services. • Data management roles must be clear and based on role models such as the HEMRM.
Calculation, Computation and Fragmentation	• Detailed and accurate grid topology is required which are only valid under certain conditions • In centralized approaches, where combined grid models of multiple grid operators are used, may result in high computation efforts requiring longer lead times. • In decentralized algorithms lead to higher operational costs and divide or cluster flexibilities. • Higher fragmentation deteriorates the grid operation, as flexibilities cannot be optimized properly.
Cybersecurity	• Combination of new and legacy equipment and technologies. • IT-OT interface. • Cascading effect. • Slowness of the energy sector in addressing cybersecurity challenges and lack of an efficient cooperation between stakeholders in these aspects.

6.3. Regulatory and market design perspectives

The decentralisation of electricity generation and the need to attract new types of flexibility, including the resources connected to the distribution grid, bring about new challenges and require enhanced coordination between system operators and flexibility providers. The CEP lays the ground for establishing a new electricity market design, in particular, the Electricity Directive [7] emphasizes that DSO should buy ancillary services following market-based procedures (articles 31 and 40). In particular, TSO-DSO coordination concerns all the cooperative efforts required to operate the power system, including the procurement of flexibility from the connected resources, in terms of ancillary services and congestion management (i.e., system services). Different approaches can be adopted for procuring system services and a single approach of general validity does not exist, and several related challenges can be identified. Outclassing these challenges would allow for effective TSO-DSO coordination for power system planning and operation. This section provides focus on the regulatory and market design-related barriers which can hamper the exploitation of flexibility by TSOs and DSOs.

Terminology harmonisation

Currently, there is no harmonized terminology when discussing and analysing flexibility and related mechanisms and market models. Terminology harmonisation can ease the comprehensiveness of the proposal and results’ comparison among projects and research activities. Fostering the development of novel and effective approaches for TSO-DSO coordination requires commonly acknowledged frameworks to describe and define high-level coordination models and market models.

Flexibility mechanisms

There is no "one-fit-all" approach in the context of flexibility mechanisms [92]. Flexibility mechanism design has to consider the system service and the product to be procured, and the characteristics of the context (e.g., voltage level, the timing of the need, volume requested, network type, the volume of flexibility potentially available, number of expected FSPs participants, resources, types of FSPs). Moreover, several principles are pointed out to guide the flexibility mechanism design and integration (e.g., economic efficiency, transparency, equity, implementation concerns, customer engagement and reliability). Even limiting the design exercise to one flexibility mechanism typology, solutions of general validity do not exist; the corresponding design choices (e.g., definition of the dynamic network tariffs or market structures) have to be evaluated case by case.

When specifically focusing on market-based procurement by DSOs, there is unclarity about its meaning, especially for DSOs. There are market liquidity concerns in the case of DSO markets, certainly for very local grid issues within lower grid levels as the number of potential providers is limited, increasing the risk for market power. Furthermore, for DSOs, non-delivery can have a very high impact (e.g., outage, failure of network components), therefore the DSO should be able to rely on flexibility delivery and would always strive to have a back-up option. As using market-based flexibility within the grid increases the responsibility of FSPs, grid operators might favor conventional methods of grid expansion instead of solely relying on the liquidity of the market and the delivery of FSPs. In order to increase the attractiveness of market-based approaches, the regulatory framework needs to ensure that high liquidity is possible and market-based measures are preferable for grid operators.

Market integration

As already stated, a variety of TSO/DSO market models/topologies exist with different implications for roles and responsibilities of TSOs and DSOs. If every buyer (the TSO, the different DSOs) of flexibility organizes its own market to cover its own needs for different services, this can lead to market fragmentation. From a societal point of view, this could lead to higher costs as possible synergies between markets are not realised. On the other hand, local grid needs, may ask for local solutions and local customization, hence local flexibility markets. Within Europe, the alignment between flexibility markets and the EU wholesale and balancing markets may be challenging as they often take place in the same timeframe and coherence between market prices, activation signals, etc. should be carefully considered. Improved TSO-DSO coordination and market integration mechanisms, therefore, require an accurate design of the timing of flexibility mechanisms to foster liquidity. The chosen TSO-DSO coordination model, the level of market integration and the timing of the different markets influence the allocation of available flexibility between TSOs and DSOs (i.e., priority or exclusivity). In addition, it influences the market's performances in terms of economic efficiency, implementation complexity, customer engagement and should thus be carefully considered. Complementing a zonal based market design (of the wholesale energy market) with a nodal flexibility or congestion management market for local flexibility provision raises the question of occurrence of increase-decrease gaming. This relates to the fact that market participants can anticipate the results of the nodal flexibility market and therefore adjust their bidding behavior within the zonal market exacerbating congestions. This gaming behavior has been observed during the transition of the Californian market from a zonal to a nodal system in the early 2000s and recently caught attention during the discussion of nodal markets for redispatch [93].

Fairness of market access

Non-discriminatory market access is not always assured. Currently not all markets for flexibility services are open to flexible resources connected to all grid levels or to all types of flexible resources. Related to this, depending on the flexibility service, certain requirements, conditions and technical regulations may apply to the flexibility to be provided. This may mean that not every flexibility service is equally accessible to every type of flexible resource. In addition, operational processes such as prequalification can be rather complex (limited scalability and automation), constituting an important barrier for potential flexibility providers, especially for smaller consumers. Further, for these smaller consumers, there is no common agreement on how to arrange prequalification at an aggregated pool level (with a large number of assets) rather than for each delivery point individually.

Product standardisation

Cross-SO interoperability requires adopting an adequate level of product standardisation. However, TSOs and DSOs have different requirements regarding features of the products to be procured for system service. For example, local markets may require flexibility dedicated product specifications that consider the peculiarities of local resources and lower requirements from the products for central markets. Hence, a relevant TSO-DSO coordination challenge concern the identification of the compromise on product standardisation.

Limited experience of market-based procurement by DSOs

DSOs are currently still in an exploration phase toward market-based procurement of their system services. Since the novelty of procuring system services from third-party resources, coordination mechanisms design is pioneering and requires regulatory experimentation to explore alternative mechanisms, considering local conditions, and assess the related strengths and weaknesses. Regulatory experimentation may help the National Regulatory Authorities to obtain evidence that helps to elaborate the regulations needed for implementing the future TSO-DSO coordination mechanisms.

Lack of appropriate renumeration mechanism of SOs

The way in which system operators are financed is an important aspect which influences the potential use of flexibility by grid operators. Regulatory approaches to revenue setting for and financing of Electricity Transmission and Distribution System Operators diverge across Europe. In most countries, there is no framework yet to incentivize and adequately remunerate SOs to procure flexibility. A fundamental prerequisite is a need for combined incentives considering capital and operational expenditures to adequately decide between flexibility options or grid investments. In the future, incentive schemes for SOs to tackle new regulatory challenges, might need to follow a holistic approach, i.e. a ”whole system approach”.

Definitions of roles and responsibilities

Roles and responsibilities should be further clarified, and appropriate frameworks should be introduced to allow new actors. Clarity is in particular needed about which market functions should be implemented in the commercial domain and which functions in the regulated domain. Views on the preference of a Neutral market operator vs. DSO / TSO as market operator diverge. Following the CEP, member states should establish an appropriate implementation model and approach to governance for independent aggregation. A model for perimeter correction (also called Transfer of energy) is very important; The CEP further stresses that the "chosen model should contain transparent and fair rules to allow independent aggregators to fulfil their roles as intermediaries and to ensure that the final customer adequately benefits from their activities". Approaches between countries diverge and are at different stages of implementation.

Cost assignment, price regulation and opportunistic bidding are a further issue in this context. In cases of emergency situations at the market, price caps might be necessary to avoid strategic flexibility provision and bidding and the resulting extreme revenues and market distortion. Furthermore, transfer of flexibilities between regions has to be regulated accordingly to meet EU normatives.

Table 6 Summary of the main challenges and key factors from the regulatory perspective

Main challenges	Key factors
No harmonized terminology	• No commonly agreed framework for flexibility mechanisms and market models • Difficult to compare among projects and research activities.
There is no "one-fit-all" approach	• The system service, the product to be procured and the context influence the appropriateness of alternative solutions • Design choices for specific solution have to be evaluated case by case.
Integration issues	• A large variety of TSO/DSO market models exist • The proliferation of different flexibility markets can lead to market fragmentation • Flexibility markets are not always well integrated in the EU wholesale and balancing markets
Market access	• Not all markets for flexibility services are open to flexible resources connected to all grid levels or to all types of flexible resources • Certain requirements, conditions and technical regulations may apply to the flexibility to be provided • Complex and diverse prequalification processes
Product standardisation	• Adequate level of product standardization needed • TSOs and DSOs have different requirements
Lack of experience of market-based procurement by DSOs	• Unclarity about the meaning of "market-based procurement" • Market liquidity concerns • No established solution yet and no one-fits-all solution
Lack of appropriate renumeration mechanism of SOs	• No framework to incentivize and adequately remunerate DSOs to procure flexibility • Financing of grid operators currently does not support the use of flexibility
Unclear roles and responsibilities	• Market functions in the commercial domain vs. regulated domain. • Neutral market operator vs. DSO / TSO as market operator diverge. • Lack of established aggregation framework

6.4. Customer perspectives

As previously mentioned, substantial flexibility volumes from existing and new type of flexibility resources will be needed to meet the growing demand for flexibility by DSOs and TSOs. Establishing flexibility markets could open new revenue streams and benefits for consumers providing flexibility services. However, barriers still exist to access flexibility markets and for developing a convincing business case for these new types of FSPs (aggregators and the customers they represent).

Based on the experience learnt from the CoordiNet project [42], it was identified that the high costs for FSPs to manage their market participation reduces their margins of profit significantly. FSPs participating in the demonstrations suggested that support for higher degrees of automation and control capabilities could help increase participation in the markets and reduce time spent to manage their market participation. Furthermore, insecurities regarding return on investment was seen as an important barrier, due to the uncertainties of the amount of (future) flexibility needs, the differences in flexibility demand between seasons/year-to-year and the value (price) of the offered flexibility. These factors make it difficult to convince new types of customers to offer their flexibility. For small consumers, to cope with the technical requirements of markets, aggregation is needed. The concept of independent aggregation is formalized in the CEP, but full implementation is taking time. The aggregator should be able to participate in flexibility markets on the same terms as all other FSPs and the implementation of the CEP in national law should be facilitated to increase the viability of the aggregator business model, allowing for overall increased liquidity and create opportunities for all types of customers to offer their flexibility regardless of their size. Currently, there is low level of awareness and understanding of potentials for flexibility service provision. Providing clear and reliable information on how to access markets via user friendly and well-designed platforms and interfaces will be important to bridge information gaps on market opportunities. Clear and transparent provision of information regarding potential for market participation will be important to help new market participants understand their electricity consumption profile and the value of their flexibility.

Within the German Enera project [90], a flexibility market platform, enabling the usage of decentralized flexibility for transmission and distribution grid congestions, has been showcased. The demonstration showed a high divergence of the price expectation for flexibility of grid operators and FSP. One of the outcomes of the project indicated that the grid operators price expectation was dominated by the costs of the operational alternatives to the flexibility market that was mainly curtailment of RES. However, the FSP price expectation was higher than the regulated compensation for curtailment. This mismatch might increase the risk of low liquidity. Table 7 summarizes the main challenges from the customer/FSP perspective [42].

Table 7 Summary of the main challenges and key factors from the customer perspective

Main challenges	Key factors
Variation in requirements	• Different standards, procedures and requirements for flexibility delivery exist across Europe, but also on country level for different services. • This leads to single purpose offerings by technology providers (e.g. EMS), leading to increased costs.
Lack of experience	• Flexibility provision is not the core activity of organizations / small consumers. • Flexibility market participation perceived as something that increases the workload / decreases comfort, especially in relation to the small financial benefit. • Customers do not know how they can participate in flexibility markets and are not able to evaluate the benefits of their participation.
Technical requirements	• High entry costs, mainly due to the technical requirements, is considered as a main barrier.
Viable business case for (small) consumers	• No clear business case for (small) consumers to take part in flexibility services (system value of flexibility too low, lack of clear information about opportunities, unclear quantification of costs and benefits, including future revenue streams, unclear revenue stacking).

	• Impact of taxes, grid costs on bids for flexibility services can further decrease the value of flexibility.
Impact of aggregation	• Independent aggregation not yet possible in all countries. • Aggregation is a precondition/means for the participation of small consumers to flexibility markets, but the revenue sharing approach, pool composition, impact the value of LV flexibility. These aspects are difficult to assess for small consumers. • Clear information on aggregation offerings for small consumers is lacking

7. Conclusions

Within the global context, the electrical energy system is transitioning in the way that electricity is generated, transmitted and distributed. Due to these changes, system operators are faced with various challenges (technical, ICT, regulatory and economic) to accommodate new technologies and solutions due to the drive toward modern power systems. However, these changes have also allowed for the increased opportunity for system development and the inclusion of new market players. Flexibility will provide network operators (together with other stakeholders such as prosumers, aggregators, etc.) with the possibility to increase the stability of the electrical system and ensure a safe, secure and reliable supply. Stakeholder interaction is key to facilitate and enable the integration and utilization of flexibility in future power systems.

Discussion and key findings

Power system flexibility

Power system flexibility is important and necessary in a modern power system. The definitions of power system flexibility can be considered to be highly challenging and complex. Currently, there are many different definitions for flexibility depending on the perspective of the stakeholder. There should be a strive toward a universal definition to increase awareness and understanding. Based on a summary of various definitions found in the literature, the following keywords are the most frequent: *Power system, Ability, Variability, Uncertainty, Capability.*

As the power system evolves, the increase in existing and new sources of flexibility are emerging, each having its unique characteristics that can be exploited according to the needs of the power system. Needs of the power system flexibility from the perspectives of the TSO and DSO was presented and included frequency control, voltage control, congestion management etc. By utilising (based on a well-defined coordination schemes) the available flexibility resources can be activated, and various power system needs can be met by modification of their production or consumption over time.

Generally, DER and load-based flexibility eligibility for participation in networks has been constrained to smalls number of individual or aggregated resources 1 MW or larger. There is now significant recognition of the flexibility potential of smaller resources and movement to encourage participation of such resources through, e.g., DSO-based mechanisms into transmission services markets.

Stakeholders and stakeholder interaction

Within the electrical energy supply chain, there are many different stakeholders who play an active role in order to ensure the safe and reliable and secure supply of electricity. These roles can be defined according to the Harmonised Electricity Market Role Model (HEMRM), which provides a clear definition for the role and actor. In order to facilitate the interaction between these stakeholders, it is necessary to design and develop a coordination scheme/mechanism which provides a structured framework for each stakeholder. In doing so, the relation between the TSO and DSO and their respective roles and responsibilities are clearly defined. This is particularly important when procuring and utilising flexibilities for system services connected to the distribution grid. In the case where there is a shared responsibility, these coordination schemes are increasingly more important, such as the impact of the actions taken by one actor does not negatively impact that of the other. Various coordination schemes have been developed and tested within a wide range of EU projects/initiatives. While these coordination schemes may differ slightly, they are mostly based on a similar framework, with differentiating nomenclature.

Benefits of flexibility and stakeholder interaction

There are many benefits that flexibility harvesting may provide respective stakeholders within the electrical power system. In order to maximise the benefits of these flexibilities, it is essential that stakeholder interaction is well defined and implemented. In general, the benefits of the increased interaction between TSOs and DSOs include [45], *1) increased utilisation of DER* 2) increased system flexibility and *3) Optimised investments in grid infrastructure.* Within this paper, the main benefits were presented based on the findings of two recent projects, TDFlex and FlexPlan from a Techno-economic perspective. A few key findings can be summarised as follows:

Flexibility for transmission system ancillary services (TDFlex):

- The downward reserves provided by BESS, conventional demand, HPs, and EVs have the greatest potential for reserve procurements.
- The impact of procuring aggregated DER flexibilities for reserves is consistent across all simulated scenarios.
- The remuneration scheme is a critical assumption in this assessment since it has the most direct influence on when DFlex capacities are cost competitive
- Overall, the influence of the remuneration scheme is more significant than the changes in the system-wide conditions.
- Scaling up the quantity of communities participating and, therefore, the associated available power flexibility of DFlex leads to proportional increases in the system dispatch cost savings.
- Utilization of DER flexibilities lead to proportional decreases in the system dispatch cost.

Flexibility for transmission system operation (TDFlex)

- The aggregated DER flexibility at all load buses throughout the Swiss transmission grid can potentially alleviate internal CH transmission grid loading and support the voltage profile, resulting in more efficient network utilization. This benefit reduces if the DER flexibility is concentrated to selected load buses.
- The benefits of DER flexibility in reducing the required hydro dam generation requirements increase especially following the phase-out of nuclear units.
- It is important to note that the economic attractiveness of the DFlex units is dependent on (i) wholesale energy prices and (ii) remuneration schemes for DER flexibilities, which constitutes the cost of DFlex units (i.e., minimum price to be paid to the DER owner).
- The benefits of the power flexibility provided by the DFlex units to the system are easily measurable and observable, by observing the reduction in the power generation of the hydro dams as well as loading relief along Swiss transmission lines.
- The contribution of BESSs is the main driving factor and availability of aggregated BESS is essential to ensure that a meaningful amount of power flexibility is offered.

Flexibility for integrated grid planning (FlexPlan)

Although the procedure is characterized by a non-negligible complexity, its adoption introduces significant advantages for an integrated optimization of distribution and transmission systems:

- Automatic and independent distribution planning routine, which explores different options in terms of required regulation reserve for transmission services.

- Cooperation between system operators is expected to be simple and efficient, since the identified distribution planning options can be negotiated with a limited exchange of standard and non-sensitive information.
- In addition to the benefits in terms of computational tractability, it has the potential to solve several conflicts related to the TSO DSO coordination, without significantly impacting on the planning costs optimality which, otherwise, can be achieved with the unpractical fully integrated procedure.

Barriers and challenges

The utilisation of the use of flexibility from DERs brings a wide variety of associated new challenges which can envisioned from different perspectives, including technical, ICT, regulatory and economic.

Within this discussion paper, the technical challenges associated with metering and connection requirements of DERs in the distribution system were presented. With regarding to metering, when DERs are located inside customer premises and measured together with inflexible loads, the provision of flexibility becomes challenging. To overcome this challenge, baselining methodology, using sub-meters which measure individual assets or a combination of both provide possible solutions. However, when inaccurate measurements or misleading baseline methodologies occur, it opens the possibility of gaming as it becomes difficult to verify the delivery of procured flexibility from resources that are measured with inflexible loads. Despite the existence of technical solutions to mitigate these challenges, current regulatory decisions and unclear definitions of baseline methodologies and subsequent definition of roles and responsibilities, hinder the process. When considering the challenges associated with connection requirements, the assessment and calculation of the network hosting capacity become notable. This includes the lack of transparency in publication of the hosting capacity calculation/estimation results which could be used to enable connection seekers (flexibility owners) to evaluate possible connection points. Further, challenges include allocation and transparency of the available hosting capacity since this is often done on a first-come-first serve basis.

From an ICT perspective, four main challenges centered around interoperability, data handling, calculation, computation and fragmentation and cybersecurity was discussed. In most cases, the lack of standardization, interoperability between data exchange platforms and the limitations of sharing information between different projects, still poses as additional challenges. Furthermore, although it is the most used in TSO-DSO coordination projects, the CIM still contains a high degree of complexity when it comes to CIM extensions, harmonization, and validation. Regarding the simulation, calculation and the computational resources, energy management and coordination algorithms used by grid operators require a detailed grid topology as input and the results are highly dependent on the accuracy of the topology, of which is often not available. This may result in high computation times when applied to centralized approaches, or alternatively higher operation costs in the case of decentralized approaches. The increase in digitalization in the electricity sector, increases the risk of potential cyber-attacks which are related to the combination of new and legacy equipment and technologies, since many of the communication protocols currently used to exchange power system data do not include many security measures. The great number of stakeholders that can be involved in a flexibility scheme (e.g., TSOs, DSOs, FSPs, etc.), and the increasing deployment of IoT devices in power systems, further increase the challenges associated with ICT due to the risk of the cascading effect.

From a regulatory perspective, various challenges from an EU perspective were presented, based on the market design perspective. In general, it was identified that, currently, there is no harmonized terminology when discussing and analyzing flexibility and related mechanisms and market models. This makes it difficult to assess and compare outcomes among projects and research activities. There is no “one-fit-all” approach, and thus, the system service, the product to be procured and the specific context influence the appropriateness of alternative solutions. When it comes to the integration of flexibilities, a large variety of TSO/DSO market models exist. The proliferation of different flexibility markets can lead to market fragmentation. Furthermore, flexibility markets are not always well integrated in the EU wholesale and balancing markets and their alignment may be challenging as they often occur at the same timeframes. Lack of appropriate renumeration mechanism of SOs due to limited framework to incentive and adequately remunerate DSOs to procure flexibility, further translated to increased challenges in TSO-DSO interaction. Lastly, the clarity of the roles and responsibilities of existing and new actors should be addressed. Clarity is needed regarding which market functions should be implemented in the commercial domain and which functions in the regulated domain.

Challenges pertaining to customer and their ability/willingness to provide flexibility services are mostly based on the accessibility to flexibility markets and for the development of business cases for new FSP types. Based on the outcomes of the CoordiNet project, it was shown that high costs for FSP to manage their market participation has a negative impact on the amount of profit. Furthermore, insecurities regarding return on investment was seen as an important barrier, due to the uncertainties of the amount of (future) flexibility needs, the differences in flexibility demand between seasons/year-to-year and the value (price) of the offered flexibility. For small consumers, to cope with the technical requirements of markets, aggregation is needed. However, independent aggregation not yet possible in all countries and aggregation is a precondition/means for the participation of small consumers to flexibility markets, but the revenue sharing approach, pool composition, impact the value of LV flexibility. These aspects are difficult to assess for small consumers. Additionally, there is limited information on aggregation offerings for small consumers. Additionally, a demonstration project in Germany, showed that a high divergence of the price expectation for flexibility of grid operators and FSP. The grid operators price expectation was dominated by the costs of the operational alternatives to the flexibility market that was mainly curtailment of RES. However, the FSP price expectation was higher than the regulated compensation for curtailment. This mismatch might increase the risk of low liquidity.

Recommendations

Based on the outcomes of this discussion paper, the following key findings and recommendations are noted:

- Increased need for one universal definition for flexibility is required. An agreed upon all-encompassing universal definition which can be recognised on a global scale is required.
- There is a high potential for the increased integration of new flexibility resources.
- Stakeholder coordination schemes should be well developed and defined such that the use of flexibility can be optimised, while ensuring a safe, reliable and secure operation the network.
- Flexibility aggregation, especially at the TSO-DSO interface, can provide a wide range of techno-economic benefits.
- Increased stakeholder interaction and integrated system planning approaches can be optimised, thereby providing a wide range of advantages from technical and economic perspective
- The calculation of available hosting capacity should be made available to assist potential connection seekers in the decision-making process.
- Lack of transparency for connection seekers to estimate their chance of grid access permission should be mitigate by publishing the details hosting capacity allocation.
- Non-firm, interruptible connections can be used to reduce both connection costs and time and allow for additional connections in network nodes where reinforcement is unfeasible.
- Due to the limited visibility and controllability, DSOs do not have real-time information about the actual load in the grid. Therefore, there should be a prioritisation of smart meter roll-outs.
- There should be clear understanding regarding of data ownership when exchanging data.
- Despite its extended use, CIM raises some practical issues during implementation, naming CIM extensions, harmonization with other standards, and validation of model instances.
- CIM does not completely cover the requirements for TSO-DSO coordination, data exchange between TSOs, and when implementing flexibility services.
- Data management roles must be clear and based on role models such as the HEMRM.
- Lack of interoperability between data exchange platforms can be overcome by standardization and interoperability testing and knowledge sharing from pilots / demonstrations.
- Harmonised terminology is required as there is no commonly agreed framework for flexibility mechanisms and market models.
- There is no “one-fit-all” approach. The system service, the product to be procured and the context influence the appropriateness of alternative solutions. Design choices for specific solution must be evaluated case by case.
- Clear roles and responsibilities need to be defined. There are currently many challenges in market functions in the commercial domain vs. regulated domain, clarification regarding neutral market operator vs. DSO / TSO as market operator diverge and lack of established aggregation framework

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