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Power Transmission & Distribution Systems

Lessons learned from international projects on TSO-DSO interaction

Discussion paper

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ISGAN Annex 6 Power Transmission and Distribution Systems

December 2020

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 the different regions of the world. Their aim is not to communicate a final outcome or to advise decision-makers, but rather to lay the ground work for further research and analysis.

Disclaimer

Acknowledgments

The author wishes to thank the following for their support and contributions

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List of Acronyms

aFRR	Automated Frequency Restoration Reserve
CIM	Common information model
CS	Coordination scheme
cVPP	Commercial Virtual Power Point
DER	Distributed energy resources
DG	Distributed generator
DR	Demand response
DRES	Distributed renewable energy sources
DSO	Distribution system operator
EU	European Union
EV	Electric vehicle
FSP	Flexibility service provider
ICT	Information and communication technology
mFRR	Manual Frequency Restoration Reserve
MV	Medium voltage
OPF	optimal power flow
PF	Power flow
RSC	Regional Security Coordinators
SCADA	Supervisory control and data acquisition
SRA	Scalability and replicability analysis
TLS	Traffic light system
TSO	Transmission system operator
tVPP	Technical Virtual Power Plant

Executive Summary

The electrical power system is experiencing a paradigm shift in the way electricity is generated, transmitted, and distributed. Traditional generation plants which are centralised and dispatchable have transitioned towards those which are decentralised and considered to be more volatile. Additionally, connected loads that were fixed and non-controllable are now able to be operated through their ability to be controlled and time-shifted. The network power flow has also transformed from a unidirectional power flow to one which is bidirectional. The goal to reduce CO_2 emissions has initiated the main drivers for these changes based on the advances in technical innovations, market-based interactions, and regulations. The increase of additional renewable energy sources into the network has also contributed to the increase in network congestion, both on the transmission and distribution networks. While the increase in network flexibility, through the development of smart grids, allows the consumer to become a prosumer and is complemented through the use of localized generation, storage, and electric vehicles. Furthermore, the adoption of demand side management techniques facilitated by the increase in smart home technologies has also become an increased focus of many DSOs.

Managing these changes, as well as the increased interactions throughout the networks, remain a key challenge for safe and reliable operation of the active power systems now and in the future. This, therefore, translates to an increased need and motivation for additional TSO-DSO interaction. In this context, *interactions* relate to communication, coordination, and cooperation between DSOs and TSOs, as well as the regulatory framework they operate under. By strengthening the cooperative alliances, these interactions can provide increased benefits to each stakeholder within the power system. This topic has received increased attention in local and international power system communities, where various demonstration projects have improved or incorporated new interactions into their framework, and thus an increased knowledge base of these interactions is available.

The objective of this discussion paper is to identify and consolidate the lessons learned from international projects, use cases, and best practices on TSO-DSO interaction. The outcomes were acquired from the perspectives of four EU projects (SmartNet, Coordinate, InteGrid, INTERPLAN), as well as a study conducted in Switzerland, where TSO-DSO interaction was investigated. These outcomes are considered according to four key questions, where the challenges, successes, lessons learned, and recommendations based on the experience of these projects are addressed. Furthermore, a high-level summary of this report is showcased in the form of an info-video.

Although the results of the four key questions are specific to each project, it was shown that there is an opportunity for increased development in the TSO-DSO interaction in all cases. The key challenges of TSO-DSO interaction were identified within four focus areas of power system operation, i.e. operational (functional), Information and Communication Technology (ICT), economic, and legal and regulatory. From an operational perspective, the level of integration and (lack of) engagement towards management of flexible resources were shown to have a large impact on the demonstration projects. Due to the nature of the innovations of the projects, it was further highlighted that the implementation of innovative solutions into the demonstration networks posed as one of the biggest challenges for EU projects. Furthermore, the increased risk of data handling due to the necessity for sharing of network data and information required for TSO-DSO interaction is also considered to be a challenging task for all stakeholders. From a legal and regulatory perspective, it was highlighted that there is a lack of clearly defined roles and responsibilities for the TSO and DSO, especially those pertaining to their interaction. This is further enhanced by the limited availability of operational procedures required during the implementation of TSO-DSO interaction.

The key successes of the projects showed that through improved TSO-DSO interaction improved network operation and planning can be achieved and that there is significant potential for increased interaction in future power systems. TSO-DSO interaction has increased the reliability of network operation by incorporating successful network congestion management and redispatch techniques. Furthermore, an improvement in the coordination of unplanned events is facilitated by improved communication between the control centres of the TSO and DSO. The long-term planning for robust, efficient, and sustainable networks which consider the integration of flexibility was also shown to be successful when there is adequate TSO-DSO interaction.

The lessons learned and recommendations for TSO-DSO interaction are considered from the perspectives of all the stakeholders within the power system. The coordinated congestion management of the TSO and the DSO networks requires a coordinated transformer setting at the TSO-DSO interface. Furthermore, network congestion can successfully be mitigated through the use of flexibilities alongside increased TSO-DSO interaction. The operation of the network requires adequate network visibility from the perspectives of all operators and can be achieved when there is suitable TSO-DSO interaction. In order to do so, the sharing and handling of network data are required and can be facilitated through the use of central data hubs. From an economic perspective, flexibility providers need to know whether the investment in planning, process development, and technical infrastructure is economically feasible in order to encourage their participation within the flexibility market. The coordination schemes between TSO and DSO are key to establish operating procedures and procurement of grid services. Therefore, it is necessary to ensure that the roles and responsibilities of the TSO and DSO are clearly defined.

In conclusion, this discussion paper indicates that there is an increased awareness of TSO-DSO interaction in Europe. The outcomes of the demonstration projects, as well as the investigation conducted in Switzerland, shows that TSO- DSO interaction can, despite the many challenges, be successfully improved with increased benefits for various stakeholders within the power system. Additionally, there is a high potential for the development and improvement of TSO-DSO interaction, such that these techniques can be implemented in future power systems throughout the world.

Table of Content

1. Introduction

This report is prepared within the framework of ISGAN Annex 6 (http://www.iea-isgan.org/our-work/annex-6/). The work of Annex 6, on Power Transmission & Distribution Systems, promotes solutions that enable power grids to maintain and improve the security, reliability and quality of electric power supply. This report is based on the outcome of Task 5 within the focus area *Transmission and Distribution System Interaction*. The main objective of this focus area is to conduct studies on how distribution and transmission networks could interact in the future, ensuring stable grid operation under high levels of renewables. Figure 1 positions this work in the ISGAN context.

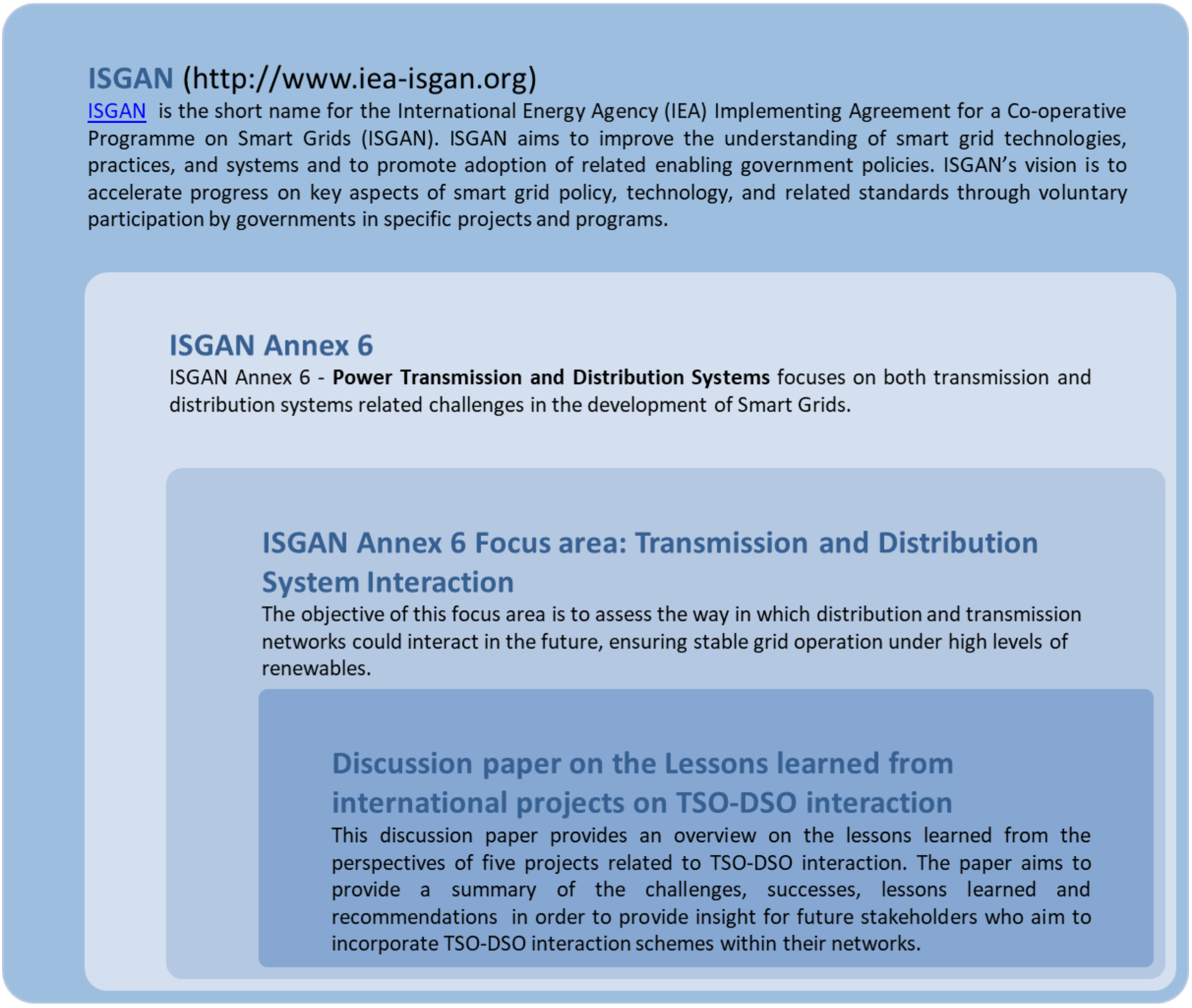

Figure 1 Position of this discussion paper in the context of ISGAN

1.1. Background and motivation: The need for DSO-TSO interaction

Since the days of its conception, the electrical power system is experiencing an evolution due to an increase in technical innovations, market-based interaction, and regulatory changes, as shown in Figure 2. The modern power system has revolutionized the goal of supplying reliable electricity based on clean and inexpensive resources and thereby, has transitioned into a bi-directional power flow system. The increase of additional renewable energy sources into the grid has contributed to the increase in network congestion, both within the transmission and distribution networks. While the increase in network flexibility, through the development of smart grids, allows for the consumer to become a prosumer complemented by using localized generation and electric vehicles. Demand side management, facilitated by the increase in smart home technologies, has also become an increased focus of many distribution system operators (DSOs) [1]. Transmission system operators (TSOs) also play a vital role in the integration and management of an active power system and therefore, it is essential the perspectives of all networks stakeholders are considered.

In order to ensure the successful increase of flexibility integration within the network, it is essential for DSOs and TSOs to acquire a closer coordination in order to utilise the potential of the these flexibilities as far as possible, as defined in the regulation, in order to provide increased opportunities without hindering the safe a reliable electricity supply to consumers [2]. Flexibility from small distributed energy resources (DERs) is likely to be aggregated and to help in grid management both at the distribution and transmission levels. At the distribution grid, DER, including demand response (DR) and distributed generators (DG) are already selling energy into wholesale markets, and in some countries, are already providing services to TSOs and DSOs. At the same time, DSOs are expected to move from a “fit-and-forget” approach towards active management of the grid. As consumers become more active in the electrical network, they should be provided with a number of options to ensure that their participation is based on a wide variety of choice, affordability and reliability [1]. Network operators are, therefore, encouraged to enable consumers to be able to ensure their active participation, in order to harness the valuable and increasing amount of resources for providing services for the overall benefit of the power system [1].

Managing these complex interactions is expected to become an intrinsic part of a developing active power system and therefore, there is an increased requirement and motivation to improve the communication and cooperation among TSOs and DSOs. In order for these interactions to be successful, it is necessary for both TSOs and DSOs to form a cooperative alliance which sees both stakeholders maximizing the potential benefits of these interactions. With such partnerships, DSOs have an increased opportunity to avoid network reinforcements, to decrease the simultaneity of units providing flexibility, and the ability to acquire more information on units providing system services. Additionally, TSOs obtain higher market liquidity for balancing services, redispatch etc. along with a lower price for the use of these flexibilities. On the other hand, these interactions often endure many challenges due to the complexity of technological, economic, and regulatory barriers. Many demonstration projects have incorporated these interactions into their framework and thus an increased knowledge base of these interactions is available.

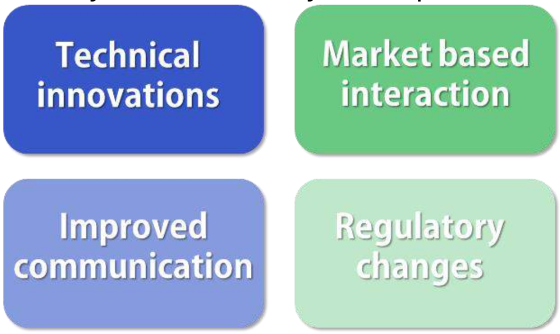

Figure 2 Main drivers for change in the electrical power system

1.2. Scope and objectives

This task aims to identify and consolidate the lessons learned from international projects, use cases, and best practices on TSO-DSO interaction. The results have been obtained from projects that are still in their early phases based on their preliminary findings as well as those that have reached their dissemination stages. Furthermore, this work aims to present a global view of developments of TSO-DSO interaction based on collaboration from stakeholders within the ISGAN community, as well as additional collaboration partners (TSOs, DSOs, project leaders, etc). The outcomes of the study aim to provide a short overview based on the key outcomes of the investigation, this will take the form of a video type deliverable. The main target audience is presented to stakeholders who are familiar with the topic and will provide them with an overview and reference towards projects such that the lessons learned can be considered within future projects. The video provides a high-level overview which encapsulates the main findings, while this report forms a supplementary consolidation of the results in order to provide additional information in more detail.

2. Methodology

2.1. Process and strategy

In order to achieve the required objectives for required the identification of international projects which incorporate TSO-DSO interaction and relevant stakeholders (ISGAN Annex 6 participants, project leaders, DSOs, TSOs, interested groups, etc.) was required. The conduction of interviews and correspondence (email, workshop, etc.) was conducted in order to collect the relevant information pertaining to four key questions. These include:

1. What have been the key **challenges** during the project
2. What have been the key **successes** during the project?
3. What have been the key **lessons learned** based on the outcomes of the project?
4. What are the **recommendations** based on the outcomes of the project?

Thereafter, the consolidation and processing of the outcomes were conducted by extracting the key concepts in order to emphasise these concepts within a video concept. The main ideas were then constructed into a video animation based on an infographic format.

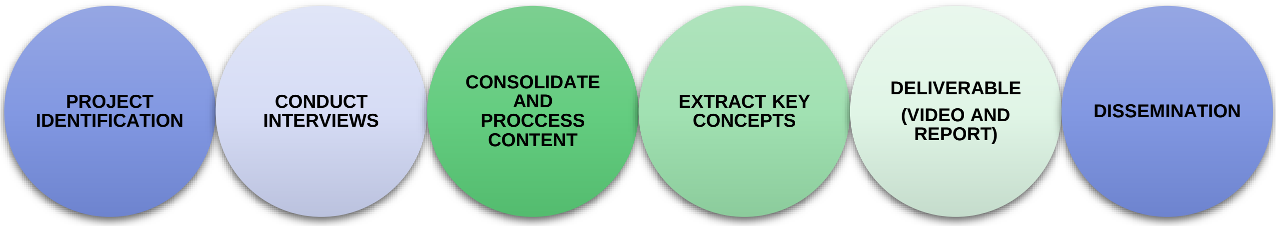

Figure 3 Methodology followed for the development of this report

3. Overview of contributing projects

This section provides an introduction to the contributing projects in order to provide the context of the project's scope with respect to TSO-DSO interaction. In this paper, four European research projects are presented, in addition, the perspectives of a study conducted in Switzerland is provided.

3.1. SmartNet

SmartNet was a European research project which aimed to compare different TSO-DSO coordination schemes and real-time market architectures for acquiring ancillary services from distributed resources. This was done by comparing each of the methods used to coordinate the action of TSOs and DSOs for acquiring ancillary services from flexibilities connected to distribution grids. In particular, balancing, congestion management and voltage regulation were analysed in detail. Within the project, a simulation platform was developed in order to implement and analyse five coordination schemes (CS) which consider three interaction layers: real-time markets, the physical network with its regulation loops and aggregation/disaggregation.

PROJECT DETAILS SmartNet

Coordinator: Ricerca sul sistema energetico - rse spa

Duration: 01/01/2016-30/06/2019

Consortium: 23 participants

Demo locations:

Website: http://smartnet-project.eu/

The investigations were conducted within three countries: Italy, Spain, and Denmark based on simulations and pilot demonstrations. The TSO-DSO coordination schemes considered by SmartNet are characterised according to the different roles and market architectures designed for ancillary services (AS). An overview of the coordination schemes includes:

1. **Centralized AS market model (CS A):** TSO contracts services directly from DER. No congestion management is carried out for distribution grids;
2. **Local AS market model (CS B):** DSO manages a local congestion market. Unused resources are transferred to the AS market managed by TSO (procuring balancing and congestion management);
3. **Shared balancing Responsibility Model (CS C):** TSO transfers to DSO balancing responsibility for the distribution grid. DSO manages local congestion and balancing market using local DER;
4. **Common TSO-DSO AS Market Model (CS D):** TSO and DSO manage together a common market (balancing and congestion management) for the whole system;
5. **Integrated flexibility Market Model (CS E):** TSOs, DSOs, and commercial market parties contract DER in a common flexibility market (raising regulatory problems: not implemented in simulation).

3.2. CoordiNet

CoordiNet is a European research project which aims to demonstrate how TSOs and DSOs should act in a coordinated manner to procure and activate grid services most reliably and efficiently. The CoordiNet project is centred around three key objectives:

1. To demonstrate to which extent coordination between the TSO and DSO will lead to a cheaper, more reliable, and more environmentally friendly electricity supply to the consumers, through the implementation of three large scale demonstrations, in cooperation with market participants.
2. To define and test a set of standardized products and the related key parameters for grid services, including the reservation and activation process for the use of the assets and, finally, the settlement process.
3. To specify and develop a TSO-DSO-Consumers cooperation platform starting with the necessary building blocks for the demonstration sites. These components will pave the way for the interoperable development of a pan-European market that will allow all market participants to provide energy services and opens up new revenue streams for consumers providing grid services.

PROJECT DETAILS

Coordinator: Edistribucion redes digitales sl

Duration: 01/01/2019 -30/06/2022

Consortium: 23 participants

Demo locations:

Website: https://coordinet-project.eu/

Three complete value chains of TSO-DSO-market participants constitute the backbone of the project, which is implemented in three demonstration macro-areas (Spain, Sweden, Greece) with ten demonstration pilots (four in Spain, four in Sweden, and two in Greece) representing various boundary grid, climatic, load, and generation conditions. Over the CoordiNet demonstration areas, the extent of demonstrations sets a high-value asset for extrapolation features on a European wide area. In each demo activity, different products are tested, in different time frames and relying on the provision of flexibility provided by different types of DER. Figure 4 presents an approach to identify (standardised) products, grid services, and coordination schemes to incorporate them into the future CoordiNet platform, for the realization of the planned demonstration activities.

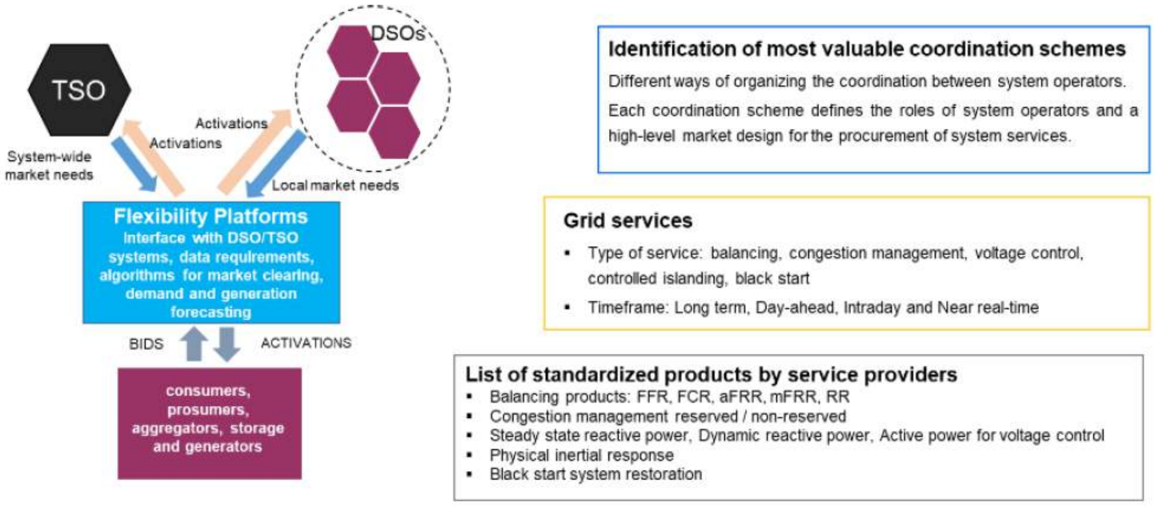

Figure 4 Overall CoordiNet approach [3]

3.3. InteGrid

The InteGrid project is a European research project which aims to bridge the gap between citizens, technology providers, and other participants within the energy system. The project aims to demonstrate the role of the DSO in enabling the active participation of all stakeholders within the energy market. This is achieved through the development of smart tools which include various data management and customer participation techniques. In this context, the projects main objectives are:

1. To demonstrate how DSOs may enable the different stakeholders to actively participate in the energy market and to develop and implement new business models, making use of new data management and consumer involvement approaches.
2. To demonstrate scalable and replicable solutions in an integrated environment that enables DSOs to plan and operate the network with a high share of distributed renewable energy resources (DRES) in a stable, secure and economic way, using flexibility inherently offered by specific technologies and by interaction with different stakeholders.

In the context of the DSO becoming a market facilitator, the TSO-DSO interaction is included through the implementation of an indirect coordination scheme. This is based on a Traffic Light System (TLS) concept which is a tool which was designed to assist the DSO in accommodating the integration of flexibilities within its network, which are used by third parties, in this case, the TSO. Within the InteGrid project, one use case investigates the manual Frequency Restoration Reserve (mFFR) using flexibilities located in the distribution grid. These flexibilities are assessed according to a prequalification process before being permitted to participate within the energy market. A flexibility operator (Virtual Power Plant-VPP)[1] is then able to bid the prequalified active power quantity within the market and offer it to the TSO once they have been evaluated through the DSO using the TLS. The TLS (which operates in the day-ahead and intraday market) evaluates the bids offered by the flexibility operator in the day ahead and

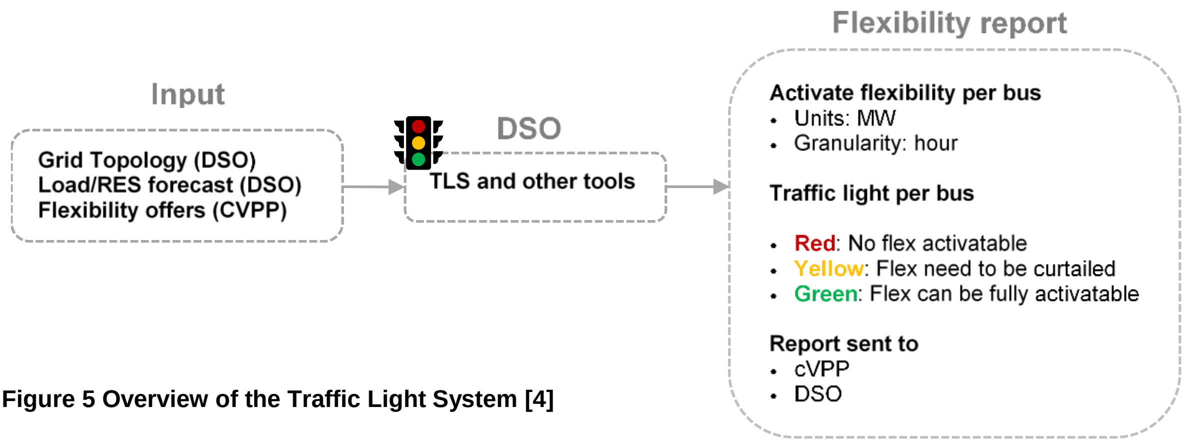

Figure 5 Overview of the Traffic Light System [4]

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[1] In InteGrid two types of virtual power plants (VPP) can be found. The technical virtual power provider (tVPP) providing flexibilities to the DSO exclusively or the commercial virtual power provider (cVPP), focusing on other third parties rather than the DSO.

intraday market to ensure that no network violations occur with the DSO network. It is designed to consider the load and generation forecast of units based on the location, volume, and price of the offered bids, as well as the current state of the network. The core operation of the TLS is based on a power flow (PF) and optimal power flow (OPF). Within the project, the TLS was implemented in two demonstration sites of Slovenia and Portugal, which also allowed for a replicability analysis of its implementation to be assessed.

3.4. INTERPLAN

The European Union (EU) energy security policy faces significant challenges due to the transition towards a pan-European network, based on the wide diversity of energy systems among EU members. In such a context, novel solutions are needed to support the future operation, resilience, and reliability of the EU electricity system in order to increase the security of supply and account for the increasing contribution of renewable energy sources (RES). The goal of the INTERPLAN project is to provide an INTEgrated opeRation PLAnning tool towards the pan-European Network, with a focus on the TSO-DSO interfaces to support the EU in reaching the expected low-carbon targets, while maintaining the network security and reliability.

INTERPLAN project focuses on the potential operation challenges which TSOs and DSOs are called to address in the 2030+ power system. The ongoing deployment of the pan–European network strongly depends on different potential scenarios related to the RES share in the generation and installed capacity, as well as penetration of emerging technologies, such as storage and demand response (DR). Although these factors represent the preferential patterns to meet the EU decarbonized energy targets for 2030 and 2050, they bring new challenges for the energy system, which outline the key operational needs of the European grid operators in the near future.

PROJECT DETAILS INTERPLAN

Coordinator: ENEA – Italian National Agency for New Technologies, Energy and Sustainable Economic Development

Duration: 01/11/2017-31/01/2021

Consortium: 6 participants

Website: https://interplan-project.eu/

In such a context, TSOs will need to evolve progressively from a "business as usual approach" to a proactive approach in order to avoid a bottleneck effect in the future European grid, and this could be addressed through suitable system operation planning. As for the distribution networks, they have been traditionally designed and operated to transport electrical energy in one direction, i.e., from the generation units connected to the transmission system to the end-users. However, with the growing share of non-dispatchable distributed generation, customers are increasingly generating electricity themselves, and, by becoming "prosumers", they are shifting from the endpoint to the centre of the power system. As a result, DSOs will need to actively manage and operate a smarter grid through appropriate system control logic, by utilizing the flexibility potential in the grid, with the aim to optimize the distribution network performance. Furthermore, an additional critical issue is the interface between transmission and distribution systems, which is expected to evolve in the near future through mutual cooperation between TSOs and DSOs, with the aim to address operational challenges such as congestion of transmission and distribution lines and at the interface between them, voltage support between TSOs and DSOs, and power balancing concerns. The increasing complexity of the grids requires that control and operation planning tools become even more advanced and homogenous among European countries.

In such a framework, the project aims to develop control system logics which suit the complexity of the integrated grid, while managing all relevant flexibility resources as “local active elements” in the most efficient manner. Moreover, by considering the 2030+ power system, the project also addresses policy and regulation aspects aiming to identify a set of possible amendments to the existing grid codes, reflecting the developments achieved in INTERPLAN through its tool, use cases and showcases. This analysis aims to mitigate the existing barriers which are associated with the integration of emerging technologies and to foster TSO-DSO cooperation in managing grid operation challenges.

More specifically, a methodology for the realistic representation of a “clustered” model of the pan-European network is provided, with the aim to generate grid equivalents as a growing library, which is able to cover a wide variety of relevant system connectivity configurations occurring in the real grid, by addressing a number of operation planning issues at all network levels (transmission, distribution and TSO-DSO interfaces). In this perspective, the chosen top-down approach leads to an “integrated” tool, both in terms of voltage levels, from high voltage level down to the low voltage level (to the end-user), as well as in terms of developing a bridge between static, long-term planning and operational issues considerations, by introducing proper control functions in the operation planning phase. Therefore, in the project, novel control strategies and operation planning approaches are investigated in order to ensure the security of supply and resilience of the interconnected EU electricity power networks, based on close cooperation between TSOs and DSOs, thereby responding to the crucial needs of the ongoing pan-European network and its operators.

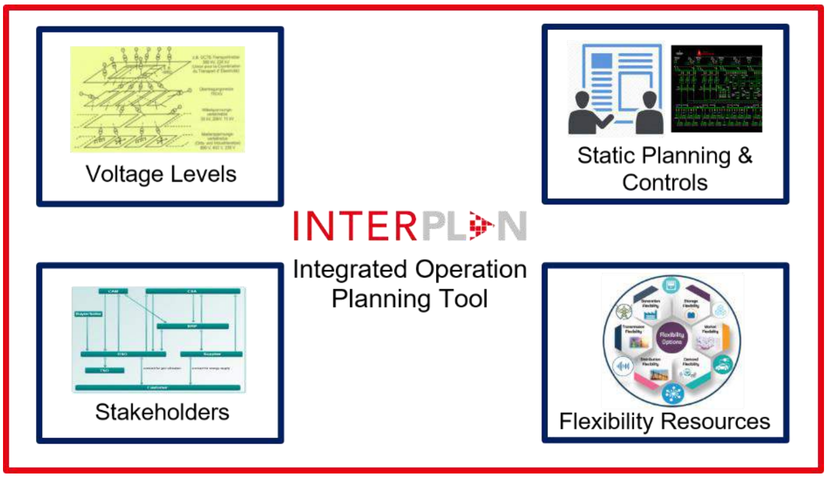

Figure 6 INTERPLAN levels of integration

3.5. Switzerland

The national and international environment of the Swiss energy supply is facing strong changes both on the supply and demand side. The development of the European energy system towards distributed renewable energy sources (DRES) is accompanied by a more active role for consumers. Consumers participate in the production and have the possibility to control their energy consumption and offer their flexibility as a part of aggregated ancillary service. The increasing use of Smart Grid technologies enables a new degree of freedom in network operation. The new role of consumers and the new degrees of freedom results in new challenges for the operation of the network: For example, higher DRES shares result in higher uncertainty of the production forecast. Furthermore, bidirectional electricity flows can now occur due to the increased production outside the transmission network. New solutions are needed to ensure the security and quality of energy supply.

As a consequence, the future tasks of the electricity suppliers are strongly influenced by new challenges and general conditions, both for the TSO and the DSO. This includes (i) increasing volatile and decentralized power production, (ii) regional temporary network bottlenecks at different network levels, and (iii) rising and fluctuating pan-European electricity flows through Switzerland as an energy transit land.

The Swiss Electricity Grid is comprised of a TSO (Swissgrid) and 800 DSOs with a meshed network on levels 1 and 3 and tree-shaped distribution grids on levels 5 and 7 as shown in Figure 7.

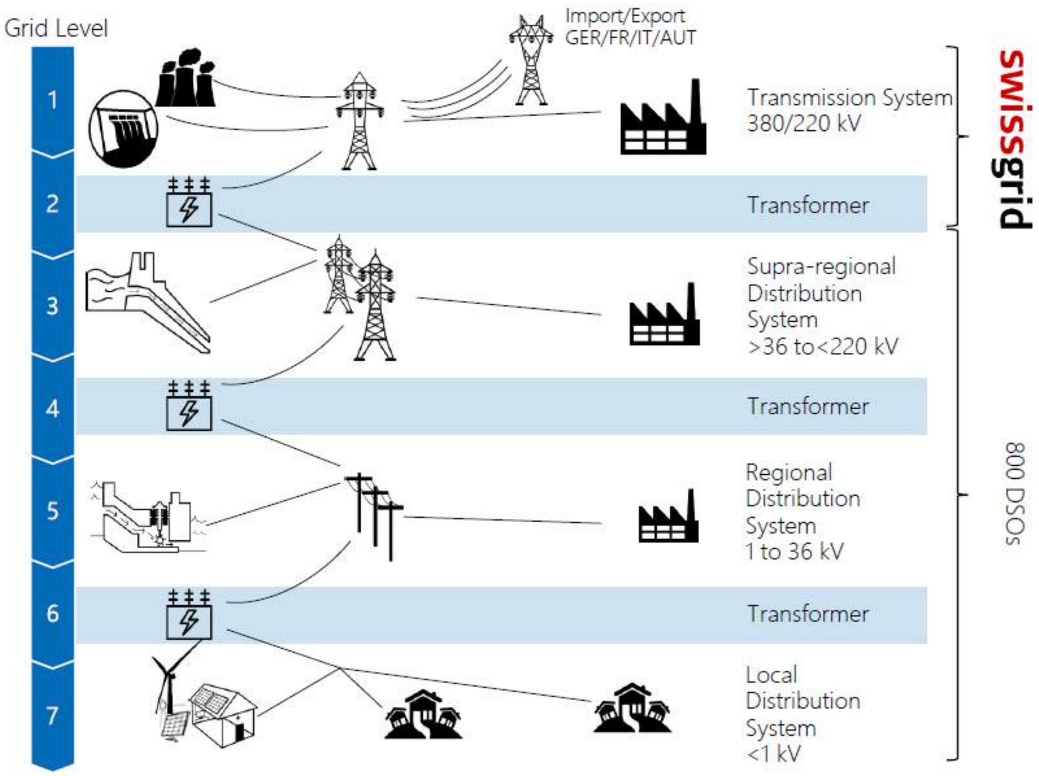

Figure 7 Overview of Swiss Electricity Grid [4]

The roles and responsibilities of the various stakeholders in Switzerland are shown in Figure 8.

Figure 8 Roles and responsibilities of stakeholders within the electrical network in Switzerland [3]

In 2019, an analysis of the current and future interaction between TSO and DSOs in Switzerland was conducted by ETH Zurich. The main objectives and topics of interest in the study were as follows:

- Provide an overview of the Swiss Electricity System
- Direct collaboration with the TSO, DSOs and other participants
- Review of current coordination procedures and future roles
- Identification of potential congestions between participants and network levels
- Demonstrate the coordination schemes with characteristic case studies
- Provide conclusion and recommendations to improve the interaction

The study provided a summary of the existing TSO-DSO coordination schemes based on a study conducted in 2014 [5], in order to provide an overview of TSO-DSO interactions within other countries. Thereafter, to gain a more local perspective, interviews along with a survey, was conducted with various network stakeholders: ABB Schweiz AG, Alpiq Holding AG, Swiss Federal Office of Energy, Elektrizitätswerke des Kantons Zürich, École polytechnique fédérale de Lausanne, Elektrizitätswerk der Stadt Zürich (EWZ, 3), Swisscom AG, Swissgrid AG (3) and Verband Schweizerischer Elektrizitätsunternehmen. Based on the answers to the survey, it was concluded that there is a perception in Switzerland, that the current TSO-DSO interaction is sufficient. However, it was also noted that there is a high potential for increased interaction in the future. In this regard, two cases studies were performed (Swissgrid and EWZ), which aimed to assess the following:

- Use of aggregated reserve power from the distribution grid.
- TSO-DSO coordination for congestion management.

Both studies showed a high potential for economic and security-related benefits of a closer TSO-DSO interaction as will be discussed in the section on key lessons learned in Switzerland.

4. Results and main findings

This section highlights the main outcomes of the investigation based on the various interviews conducted and correspondence received. The findings here within are formulated according to the perspectives of the four key questions proposed and are addressed individually.

4.1. Key challenges of TSO-DSO interaction

Based on the information received, it is generally agreed that there are (still) many challenges and unresolved aspects when it comes to TSO-DSO interaction. Within each of the projects, the challenges were addressed as far as possible such that the negative impact on the outcomes of the project was mitigated. In this section, the main challenges for each of the projects, along with proposed solutions, are discussed.

4.1.1. The SmartNet perspective

From the perspective of the SmartNet project, various challenges were experienced throughout the project. These challenges were observed both for the set-up of the simulation platform and for the creation of the demonstrations.

In the case of the simulation platform, the development and implementation of the comprehensive scenarios for 2030 posed as a big challenge due to the magnitude and complexity of the task. This includes the simultaneous representation of the full nodal network of both the TSO and DSO, the representation of the flexibility providers due to their high numbers and complex characteristics, and lastly, the representation of these stakeholders based on their interaction with each other. When modelling these interactions, it is necessary to consider the entire system simultaneously. On the one side, there is the consideration of the tertiary market layer, while on the other hand, there is the physical layer which represents the actual network with respect to each component and its low-level control system (including the Manual Frequency Restoration Reserve (mFRR), voltage regulation and other controls). To connect the two layers, there is a layer of aggregation that is implemented by taking to account the characteristic of different bidders, in particular DERs, within the market. Therefore, the biggest challenge was the dimensionality course represented by the number of equations that are needed to model these components and their interactions. Additionally, a large number of constraints to be represented by the tertiary markets also needed to be accounted for.

In one of the control schemes (CS D), the line transit limitation constraints of the TSO and DSO system were represented as part of an integrated market environment and therefore the model includes a large number of additional constraints. This posed an additional challenge due to the number of connections to be considered and the consequent significant increase of the number of constraints to consider. These additional constraints were necessary in order to accurately represent a system at nodal level so as to give an adequate locational price to congestion. Based on the outcome of this model, it was verified that a complete coordination scheme that includes both transmission and distribution network constraints up to a certain level of voltage can still be manageable from the numeric point of view. In this way, a nodal market is created which is able to provide the correct price signals to the participants in the markets.

Within the demonstration sites, the main challenge that was observed was the complexity of implementation of the coordination schemes with the local networks. In the Italian pilot, it was necessary to consider the full chain from the hydropower plants providing ancillary services, which were located in a remote alpine region in South Tyrol, through the DSO SCADA in Bozen up to the SCADA of the TSO in Rome which aggregates the control signals and then back again to the power plants for the implementation.

Furthermore, it was observed that only the responses from some power stations were compatible with the requirements of the services to be provided (aFRR) however, in other cases the response times were too long. Unfortunately, the study was not long enough to provide a full analysis of the reasons for this shortcoming. The unresolved shortcomings could be only due to the characteristics of the generation machines or also partially the consequence of the ICT chain. Nonetheless, there is the confidence that the power plants could be activated in this way for tertiary control, provided that their control systems are correctly tuned.

4.1.2. The CoordiNet perspective

Due to the complexity of the type of innovation solutions presented within the project, some of the key challenges experienced within the project have been identified as follows.

In the initial phase of the project, one of the key challenges was to define products and services which can be compatible with the current regulations including the Clean Energy Package or Network Codes that are currently under development. Due to the historical nature of such regulations with a primary focus based on legacy networks, the scope for the integration of innovative solutions is limited and can hinder the process for the adoption of these solutions.

Furthermore, the scalability and replicability of the proposed solutions were identified as another key challenge for the project. This analysis is necessary to demonstrate that the developed platforms and solutions of the country's specified products can be scaled up to the European level. Therefore, one of the main objectives is to evaluate and scale up these proposed solutions from large scale demonstration by implementing the solutions at a localised level and thereafter extracting the conclusions such that these solutions can be applied within the European level.

For a project to be successful, it requires the active participation of all relevant stakeholders within the electricity supply chain. Another key challenge identified was the difficulty to attract and engage the participation of a wider variety of network resource owners including generation, demand, and storage. Many of these stakeholders do not have a deep knowledge of the services they can provide nor the functionality of the electricity system. Therefore, the full potential of the applications of the developed solutions cannot be realised.

Another key challenge is the development of market and operational platforms which are to be compatible with existing platforms but simultaneously interoperable among the different actors.

4.1.3. The InteGrid perspective

The key challenges faced within the project with regard to the TSO-DSO interaction were manifold, as is expected with an innovative research project. The main key challenges are summarised as follows.

Most commonly with novel concept designs, one of the main challenges resides in the implementation, and this was also the case for the TLS. The challenges were more specifically pertained to the consideration of the internal complexity of DSO systems due to their level of high security. Furthermore, the interdependence of the TLS with other tools developed within InteGrid (such as the forecasting tool) and their respective interactions required numerous iterations in design before implementation. These interactions include not only those which were developed in InteGrid but also the tools belonging to the DSO.

Once the implementation of the TLS was achieved, additional challenges from the perspective of the operation and performance of the TLS were also observed. One of the main key challenges faced was due to the current state of overdesign of the networks. Currently, network constraints are almost non-existent based on the current grid status and flexibility pool size. In such cases, the results for all the medium voltage (MV) nodes receive a 'green' indication by the TLS. Therefore, to demonstrate the correct functionality of the TLS and cVPP with situations where 'yellow' and 'red' traffic light (see Figure 5) in both directions (upward or downward) are observed, it was necessary for synthetic network constraints to be created. This was achieved through the modelling of large simulated DER flexibilities which were added to the cVPP in order to drive the MV network to its technical limits.

Additionally, the operation of the TLS showed that the location of flexibility plays an important role in their activation. Due to the design of the cost function implemented within the TLS, the activation of flexibilities is dominated according to the price scheme instead of the location. This, in turn, may result in higher network constraints. On the other hand, flexibilities located closer to the primary substation are favoured when there is an increased price model applied. This poses a challenge to DSOs as the factor of 'fairness' of flexibilities needs to be exercised as well as the strive to maintain a balance based on both technical and economic perspectives. Additionally, based on the fundamental application of the TLS, the curtailment of flexibilities by DSOs could result in the unfair treatment of flexibility operators.

Another challenge with this activation process is that the activations of flexibilities by the TSO may lead to network congestion and violations within the DSO network. Additionally, there is often a miss-match between the number of flexibilities that are passed through the prequalification process and the number of flexibilities activated in reality. This is due to the fact that the activation of flexibilities is dependent on a variety of factors such as generation forecasts, maintenance schedules, etc. In order to solve these problems, the TLS aims to provide an optimised solution by considering the objectives of both network operators.

Considering the mFRR market, the TSOs and DSOs have different objectives, where the DSO aims to guarantee the safe operation of their networks, while the TSOs prefers a large volume of cost-effective flexibilities. In order to satisfy DSOs, TSOs, and flexibility operators, the interests of all participants need to be taken into account in the regulatory framework. The TLS, therefore, can be operated by simultaneously considering the objectives of both system operators. Another key challenge to note prior to flexibility activation, it is also necessary to consider the capacity of the primary transformer such that overloading of the transformer does not occur.

In this project, the TLS was demonstrated and designed to work for the mFRR market. After activation of a mFRR bid, the flexibility operator is required to increase/decrease his flexibility within a 15-minute time frame. This time frame allows for the pre-activation evaluation per request (activation). However, when using a TLS within other markets such as the automatic Frequency Restoration Reserve (aFRR), which requires faster reaction times, such an approach would take too long. To overcome this shortcoming, periodical evaluations can be done which take the current network status and the available flexibilities into account. Then, after receiving an activation, the results of the last evaluation can be used for the activation. This ensures that the current status of the network is considered and that an evaluation of the activation within the given time frame is guaranteed.

The sharing of information and data available between the cVPP and the flexibilities also proved to be an additional challenge within the project, and in particular, for the operation of the TLS. Furthermore, in the case of the forecasting model, which is used to predict the amount of load and generation for the next day, is a key component for the successful operation of the TLS. In the case of forecasting error, the resulting activation of flexibility would result in the incorrect activation scheme for the required power (over or under estimation) and therefore, it is imperative that coordination between the DSO and cVPP is well established.

From an Information and Communication Technology (ICT) perspective, the challenges associated with the interoperability of devices showed that interoperability is essential to ensure the successful integration of the cVPP. This key concept is also significant in the case of determining the complexity of the architecture, in order to include new devices, such that they adhere to the internal cybersecurity standards and that they operate in an automated way. By using the common information model (CIM) standards, the flow of communication can be easily facilitated.

The regulatory framework poses another challenge when implementing new solutions (such as the TLS) within the network. Although many regulatory frameworks exist and consider the participation of independent aggregators to participate within the energy market, there is a lack of definition in terms of the responsibilities, interaction, prequalification and communication requirements. An analysis of the level of maturity with respect to regulatory topics within the project showed that some EU countries have not yet reached an adequate maturity level. In particular to TSO-DSO coordination, the current regulation does not allow for DERs to adequately provide balancing services. In this regard the solutions are to be developed in such a way that they can be successfully integrated from a regulatory perspective and or creates the opportunity for regulations to be revised in order to adapt and facilitate these proposed solutions. These regulations are expected to allow for the safe and reliable supply of electricity whilst allowing for the integration of new market players such as aggregators and VPPs to take part in the provision of electricity in a non-discriminatory manner.

4.1.4. The INTERPLAN perspective

As indicated in the project introduction, the increasing complexity of the network requires that control and operation planning tools become even more advanced and homogenous among European countries and that they are utilised by both TSO and DSO in a cooperative manner, thereby supporting their interaction. The INTERPLAN tool is defined as a methodology consisting of a set of tools (grid equivalents, control functions) for the operation planning of the Pan-European network by addressing a significant number of system operation planning challenges of the current and the future 2030+ EU power grid, from the perspective of the transmission system, the distribution system, and with a particular focus on the transmission-distribution interface.

In this sense, the main goal of the tool is to achieve the operation planning of an integrated grid from the perspective of a TSO or a DSO through the efficient and effective management of intermittent RES as well as emerging technologies such as storage, demand response and electric vehicles. The tool supports the utilisation of potential flexibility from RES, demand side management, storage and electric mobility for system services in all network control levels.

The flowchart in Figure 9 presents an overview of the INTERPLAN tool and includes the three stages that the user (TSO or DSO) can execute for the operation planning of the network.
The three stages are described as follows:

- **Stage 1:** The user selects the planning criteria and KPIs, as well as the simulation functionality and the operating scenario
- **Stage 2:** The user selects and prepares the grid model(s)
- **Stage 3:** The user performs the simulation and evaluates the suggested use cases/showcases and related control functions

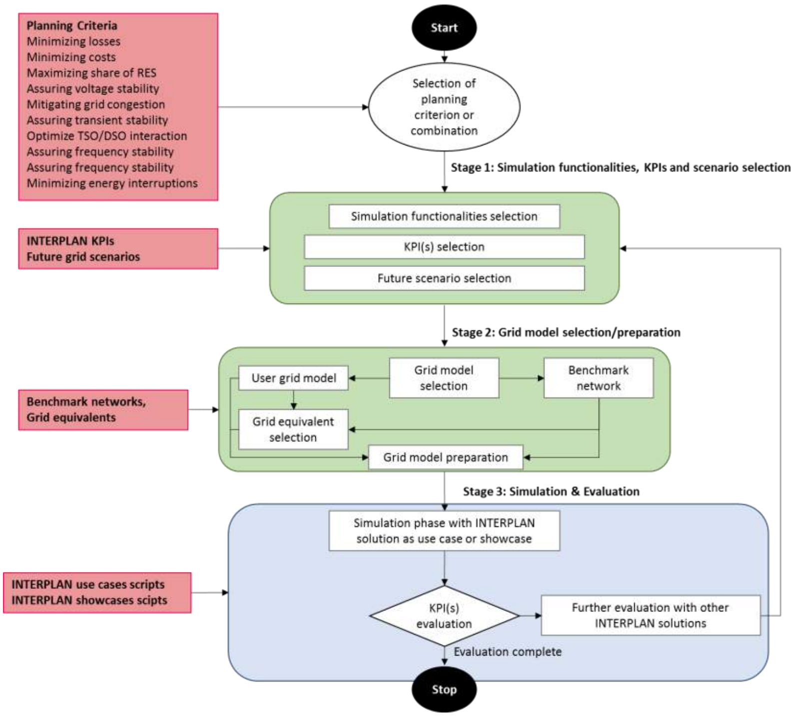

Figure 9 Flowchart INTERPLAN Tool [6]

Figure 10 presents an overview of the individual use cases and planning criteria defined within INTERPLAN, which can be combined to create individual showcases.

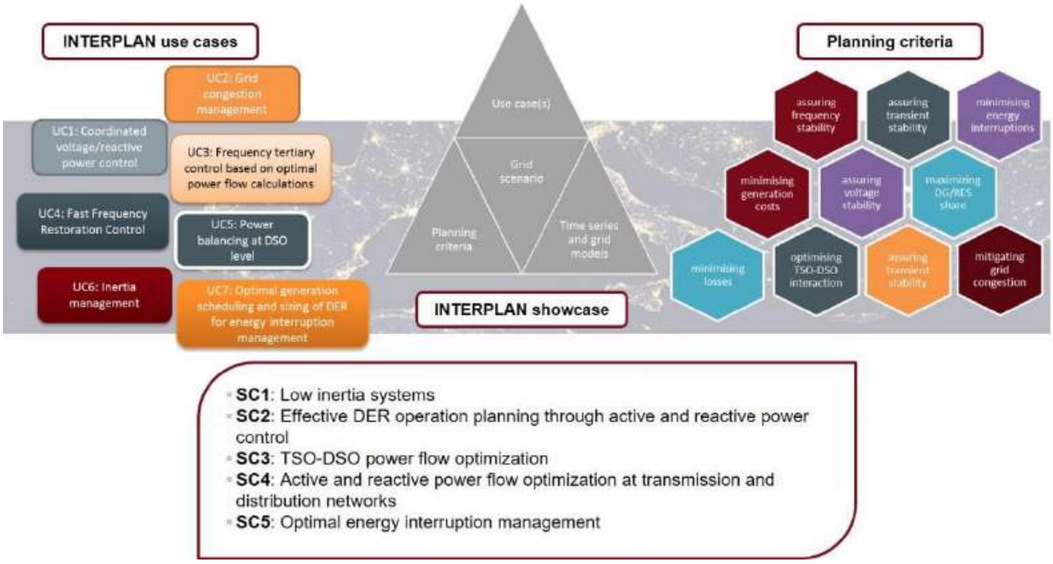

Figure 10 INTERPLAN use cases and planning criteria [7]

As an additional result of the related work, the methodology to implement control functions related to the five INTERPLAN showcases has been established and the simulation results are reported through KPI calculation.

The main challenges experienced when preparing the toolset and performing related simulations were:

- To agree on future scenarios to be investigated
- The joint definition of use cases and planning criteria taking into consideration different approaches currently used among stakeholders
- The availability of real grid data and the related development of a grid equivalenting approach in case no data is available. In addition, it was a challenge to provide dynamic models for use cases which require them. Without having suitable grid data available the tool does not provide suitable results.
- To provide control functions for problems which are not considered to be urgent and where no solutions and related models are currently available and established.
- To set up a flexible Python-based toolbox interfacing with a commercial power system simulation environment representing the integrated, operational planning tool.
- Definition of showcases in order to demonstrate the value and feasibility of the tool.

4.1.5. The Swiss perspective

In general, the willingness to increase TSO-DSO interaction is still low as the perception of network ownership and, therefore, accountability is to be confined within the respective networks. Historically, the TSO network belonged to the DSOs and the reduced willingness for additional exchange of information hinders the progression of grid control autonomy (from the side of the DSO) between the network operators. From the perspective of day-to-day operations, there is a reduced willingness to exchange information pertaining to the status of the network with other network operators.

There is a continuous endeavour for all network operators to ensure grid security. Some grid operation techniques which help the TSO, can create problems for the DSOs and vice versa. The potential benefits of increased information sharing, and coordination procedure is shown in the following examples:

- The aggregation of reserve power (required by the TSO) from flexible units connected to the distribution networks can lead to an increase in network congestion in the DSO's grid, thereby requiring new forms of communication between TSO and DSOs.
- Load flow changes within the TSO network also have an impact on the load flow with the underlying meshed DSO network and therefore results in an increased risk in network operation, stability and security. This in turn affects the overall network reliability and security of supply to consumers. In some cases, the TSO asks the DSO to adjust the transformer settings to alleviate congestions, a procedure that could be automated through systematic communication of some network parameters and settings.
- When considering the prospects of network planning, it has been observed by all network stakeholders that the long approval times required for new installations or upgrading of network components poses as a great uncertainty for network operators. Any coordination of the planning efforts (strategies, requirements, legal aspects) potentially helps the overall network security.

4.1.6. Summary

The challenges outlined within each of the projects indicate the complexity of innovation projects and that there are many aspects which need to be considered prior and during the implementation of TSO-DSO interaction strategies. Although each of the projects experienced unique challenges in line with their project specific goals, many similarities were seen to extend across all the projects. These challenges can be collected within four main areas, i.e. Functional (operational), ICT, economic and regulatory. Figure 11 provides a summary of the common key challenges of TSO-DSO interaction.

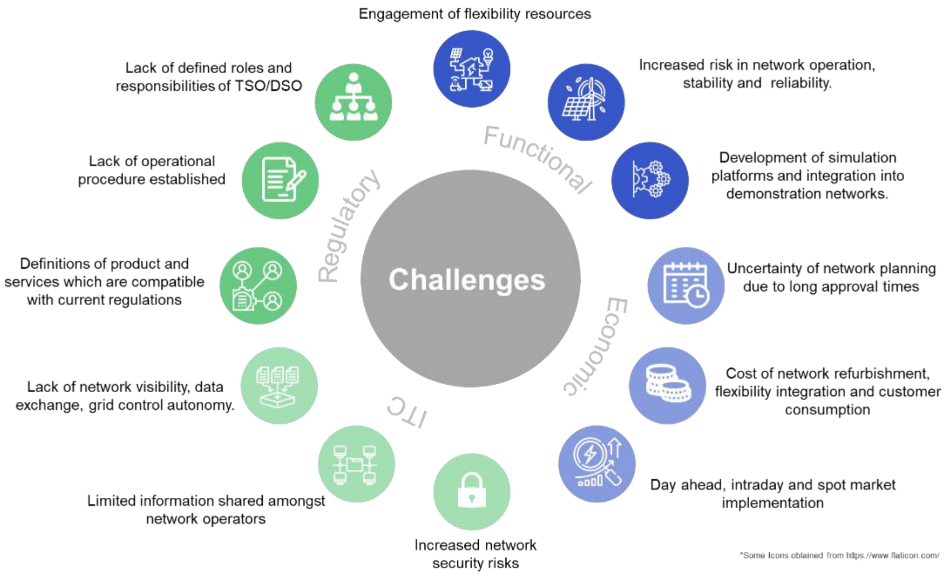

Figure 11 Overview of the common key challenges of TSO-DSO interaction

4.2. Key success of TSO- DSO interaction

The opportunity for these projects, as well as their implementation, has allowed for the number of key successes to be identified which provides the foundation and motivation for potential future development in various aspects of TSO-DSO interaction. In many cases, the advantages of increased interaction between the system operators showed that there are increased benefits for all stakeholders within the power system. The key successes based on the perspectives of each project are highlighted in the following section.

4.2.1. The SmartNet perspective

The simulation results allowed for the clarification of the respective advantages and disadvantages of different TSO-DSO interaction modalities, which allowed to elaborate some regulatory guidelines. These regulatory guidelines (see 4.3.1) can be used to ensure seamless integration and transition of these coordination schemes into the respective networks.

With regards to the pilot implementations, one of the key successes was to test the real-life implementation and performance of the coordination schemes defined within the project. In particular, the testing of the market as well as the deployment of ICT infrastructure was achieved.

4.2.2. The CoordiNet perspective

The project will develop market mechanisms and platforms for the implementation and test of services using real life trials in Greece, Spain and Sweden. The value of such projects is that TSOs and DSOs from such countries are directly involved in the demonstrations. This allows the project to deliver accurate results and contributes to bringing the flexible scenarios to reality. The presence of several pilots allows for the opportunity to test different coordination schemes according to the local needs and market issues. Moreover, EU regulations allows for the opportunity to use cascading funds which can be used to get support from external stakeholders on the provision of novel services that can add additional value to the pilot implementation.

Although the project is at its early stages, the project can contribute to the enabling of user grids services by exploiting the experience of the project partners who were previously engaged in EU funded projects. This allows the consortium to concentrate most of the efforts on the pilot implementation and benefit from the work done previously, especially when considering the definition, set up framework and consumer engagement strategies. It should be mentioned that the consortium envisioned also represents the local municipalities which can act as the end user for the complete demonstration of the services.

From the perspectives of work package one (WP1), which sets the foundation for the preparation of the demonstration campaigns, the gaps, barriers and drivers for TSO-DSO-Consumer coordination and the potential of various types of DERs to provide system services, typically through flexibility service providers (FSPs) was identified. This allowed for the following objectives to be fulfilled as part of the key successes of the project:

- To define the coordination schemes and products for each demonstration site.
- To assess the most valuable ones in their context.
- To analyse the type of system services that will be negotiated among stakeholders in the different schemes.
- To define the user engagement plan.
- To define the KPIs and the process of measuring the impact of the new solutions in the demonstration site.

These achievements set the basis for the development of the market and operational platforms as well as the demonstrators.

4.2.3. The InteGrid perspective

The results of the project indicated that the TLS can successfully be implemented within operational networks and that it can successfully enable indirect coordination between TSO and DSOs via the VPP which bids on the balancing market and is only limited by the DSO in constraint grids. In constrained network areas and in areas with a high share of flexibilities, the TLS deployment eases the pre-qualification process for the flexibilities and enables an increased volume of flexibility for the TSO. Through the utilisation of the TLS, the amount of flexibilities allowed to participate in energy markets can be determined dynamically, by considering the current network conditions.

Based on the scalability and replicability analysis (SRA) which was conducted in the project, the results indicated that the implementation of the TLS is successful when considering both current and futuristic scenarios. This indicates that the TLS will be able to play a vital role in facilitating improved interaction between the DSO and TSO. This is further enhanced in the case when there is sufficient flexibility located throughout the entire feeder (which is expected in future scenarios), the activation of these flexibilities selected by the TLS allows for a more ‘fair’ consideration of activated flexibilities. This success allows for DSO to promote customers to become active participants within the network. In turn, this allows for the opportunity for the cVPP to create a portfolio in order to exploit the flexibility of customers without jeopardising the safe and secure operation of the distribution network. Furthermore, in the case when there is an increase in RES by a significant amount, the use of the TLS becomes essential. The results are based on the integration of the connection of a wind park which has a strong influence on the maximum volume of upward reserve. During high levels of production, the upward reserve margins can be significantly reduced. Thus, the TLS provides an adequate mechanism to assist network stakeholders in the integration of RES into the network. Considering the implementation of the TLS within two different demonstration sites, namely Portugal and Slovenia, the results showed that the TLS can be successfully implemented within different boundary conditions. Such replicability of smart tools plays an essential role when considering large scale deployments both nationally and internationally.

4.2.4. The INTERPLAN perspective

The project successfully demonstrated the technical feasibility of a toolset for integrated operational planning of the power system addressing different planning issues at all network levels (transmission, distribution and TSO-DSO interfaces). Different control strategies have been developed and implemented in the tool. Operation planning approaches have been investigated in order to ensure the security of supply and resilience of the interconnected EU electricity power networks. It is clear that the future network challenges require close cooperation between TSOs and DSOs. Some of the INTERPLAN use cases primarily focused on the TSO–DSO interaction such as grid congestion management and coordinated voltage/reactive power control in a short term. Furthermore, some of the use cases are expected to require more interaction in the future. For example, inertia management in case of inertia provision by components located at the distribution system level.

The prototypical toolset has been developed and successfully utilized along different use cases and control logics have been developed and integrated in order to meet several planning criteria in parallel. To harvest the full potential of integrated operational planning tools which extend across different voltage levels and different grid stakeholders (mainly DSOs, TSOs and Regional Security Coordinators -RSCs) the following is requested:

- Increased awareness of TSOs and DSOs on the value added by strong cooperation and interaction
- Commercial availability of related tools and standardized interfaces between them in order to enable joint investigations
- Willingness and technical possibilities (interfaces and data formats) in order to share information as well as the definition of standardized processes to do so
- Availability of grid data and related model as well as possibilities to share them

The INTERPLAN project showed the feasibility of an integrated, operational planning tool. The proposed solution received very positive feedback from grid stakeholders. This serves as a foundation for continuous interaction with various network stakeholders and software vendors in order to discuss possible commercialization (increasing the TRL level).

4.2.5. The Swiss perspective

One of the many successful results of TSO-DSO interaction in Switzerland is the robust, efficient, and sustainable long-term planning of the network. The networks in Switzerland have sufficient stability reserves, despite long approval times for the construction of new lines and other network elements, high transit flows through Switzerland and increased uncertainty from volatile load and production units. Furthermore, the advantage of TSO-DSO interaction, in the case of repeated issues in the network, is that it allows for the adequate coordination during planned maintenance events such as services, refurbishment and construction. In contrast to the key challenges, if the TSO-DSO interaction is well established, short, mid, and long-term planning of grid expansions can be well executed. This can be achieved through regular interactions such as participation within working groups, meetings, and workshops.

In the case of network congestion, the associated benefits of TSO-DSO interaction can assist in managing these events. The TSO and DSO can manage the interface between the two network levels, i.e. the transformer. In the case of unexpected congestion, due to unplanned events, the impact can be managed directly through the interaction between grid control centres. The impact of network congestion can therefore be mitigated through the change of transformer settings or redispatch. Although this strategy has been implemented and has been successful, there is no well-established technical framework.

Additionally, since the partial exchange of information between TSO and DSO already exists, due to aggregated load schedules at nodes located within the TSO network, this process can be further leveraged for future increased interaction. Further enhancements can be made to improve this data exchange for scenarios such as identifying future congestion and by securing aggregation of balancing power from the distribution network.

4.2.6. Summary

The key success of TSO-DSO interaction relies on the degree of willingness and commitment of every stakeholder within the power system to achieve a common goal towards the safe and reliable operation of the power system. In many cases, the successful implementation of TSO-DSO interaction can ensure that all stakeholders are able to attain increased benefits through the establishment of these cooperative alliances. Figure 12 provides the main benefits of improved TSO-DSO interaction.

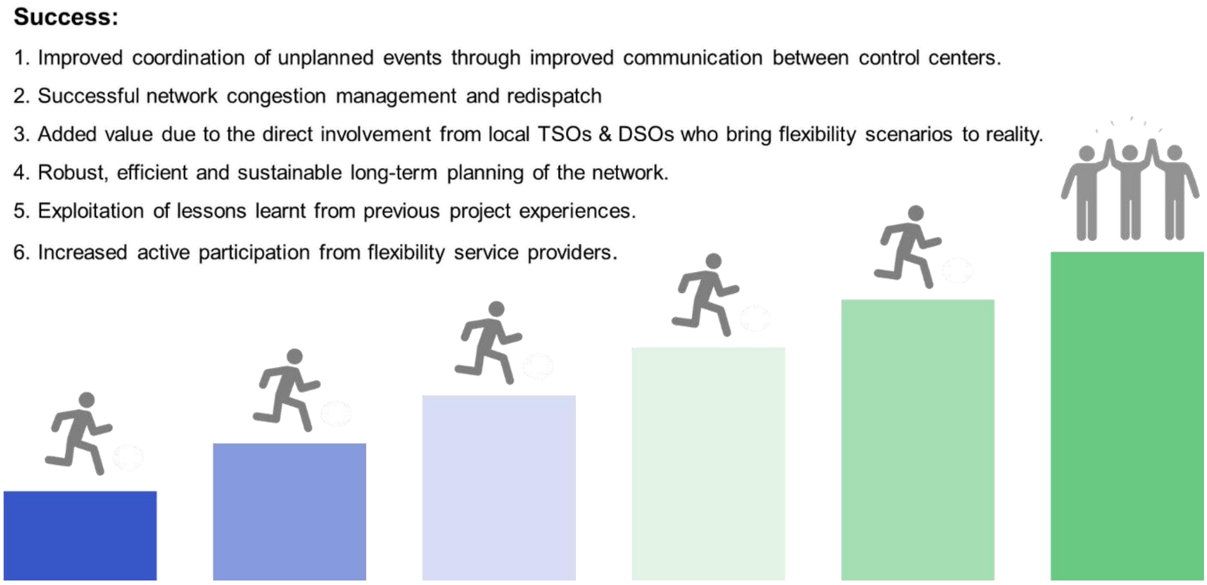

Figure 12 Overview of the key success of TSO-DSO interaction

4.3. Key lessons learned from TSO-DSO interaction

Based on the key challenges and successes exposed during the projects, numerous lessons learned can be identified. These lessons learned are key to identify to which extent successful TSO- DSO interaction can be achieved and serves as a foundation for which future stakeholders, who wish to enhance TSO-DSO interaction, can use in order to achieve high success. Furthermore, future development of the strategies developed within the projects can be accelerated when the lessons learned are shared amongst the electrical system community.

4.3.1. The SmartNet perspective

Traditional TSO-centric schemes could stay optimal if distribution networks do not show significant congestion. This, however, will be possible only if distribution grid planning will abandon the fit-and-forget policy, which is presently applied and foresees an oversizing of the distribution grid based on worst-case scenarios. In future scenarios, in order to ensure efficient participation of resources and to make it possible for distribution to provide flexibilities services, it will be necessary to implement monitoring systems so that the networks can provide real-time status of their network. The trade-off, however, is that the cost of implementation of these devices is considered to be a deterrent for DSOs who could prefer to consider remunerating investments in grid elements (CAPEX) rather than in intelligence (OPEX). Incentives should therefore be implemented in order to allow DSOs to transition their efforts toward intelligent monitoring schemes in the future.

More advanced centralized schemes incorporating distribution constraints show higher economic performances, but their performance could be undermined by big forecasting errors therefore, it is important that the gate closure is shifted as much as possible toward real-time, market clearing frequency is increased and forecasting techniques are improved.

Decentralized schemes are usually less efficient than centralized ones because of the two-step optimization process and as a consequence this leads to undue rigidities (e.g. imposing flow at the TSO-DSO interface in CS C).

Scarcity of liquidity and potential impact of local market power (not investigated in SmartNet), along with extra constraints introduced to avoid counteracting actions between local congestion market and balancing market (e.g. increasing system imbalance while solving local congestion) furthermore negatively affects the economic efficiency of decentralized schemes.

Local congestion markets should have a “reasonable” size and guarantee a sufficient number of actors are in competition in order to prevent scarcity of liquidity and exercise of local market power. Small DSOs could need to pool-up by making a consortium within themselves.

Ensuring a level playing field in the participation of distributed resources (especially industrial loads) to the tertiary market by incorporating new products and taking into account some peculiarities of such resources.

4.3.2. The CoordiNet perspective

As previously mentioned, the project has not yet reached its final stages of completion, however, the preliminary key lessons learned have been identified.

The results have shown that the use of flexibilities can successfully alleviate network congestions. This was indicated through the decrease in the number of violations present between TSO and DSO when the flexibility market was available and operating. The flexibility platform developed by the Swedish consortium members, received positive feedback from both flexibility providers and DSO operators, praising the user-friendly applications fulfilling all basic needs to participate as well as informative and even enjoyable visualization

The coordination schemes between TSO and DSO are key to establish operating procedures and procurement of grid services. Even if coordination schemes have been defined in previous projects, new alternatives are being considered within the project based on 4 different layers, the system needs, the buyer, the number of markets and the resources considered. In this regard, the additional benefit during the project showed that the dialogue between DSO and TSO created new values in understanding how better coordination can lead to a more efficient grid use. This is further emphasised by the requirements for DSOs to know which flexibilities are available when they are most required. However, in order to facilitate these coordination schemes, it is essential that adequate network visibility from the perspectives of all operators is implemented. The flexibility platform developed within the project allowed for this visibility to be achieved and thus, ensured that control room operators could foresee the upcoming grid situation. Network operators were then able to take corrective actions as required. Furthermore, developing and operating the platform as an integral part of the DSO grid planning and operations provides understanding for needs, changes and possibilities when acting as a DSO with a higher level of visibility. Additionally, the request for automisation of interfaces between network operators was significant. Although the sharing and handling of network data, from a management and security perspective, is often considered to be difficult and time-demanding, the project incorporated a central data hub which proved to be highly valuable in such applications.

From the market design perspective, the coordination schemes with cascading market closing times, was seen to be the most effective. However, in order to maximise the full potential of the flexibility, it was shown that the day-ahead market should be complemented with an intra-day market to continuously update the energy forecasts and manage the system needs.

Furthermore, it was also identified that flexibility services in the day-ahead market are dependent on the accuracy of grid state forecasting and therefore requires the production and load forecasts. From the perspectives of flexibility providers, it was observed that preparation based on the amount of time and effort required to provide flexibility is often underestimated. In some cases, certain flexibility providers can only operate on a day-ahead basis (e.g. industries and district heating), while other flexibility providers, prefer to provide flexibility closer to the delivery hour (such as aggregators or energy storage).

Business use cases are essential to organise and define the general framework of the demonstrators, the key activities amongst the market parties and the responsibilities and also their interrelations. From the perspective of the demonstration in Sweden, it was identified that the volume of flexibility required varies significantly from year to year which was attributed to the variations in the weather significantly impacting the flexibility needs of the system operators. Flexibility providers need to know whether the investment in planning, process development and technical infrastructure will result in a return of investment. In this regard, it was seen that business cases with free bids are insufficient for customers to invest adequate time and money when considering becoming flexibility providers. The compatibility of the business use case alongside the regulations is essential for the success of such coordination schemes. Therefore, it is essential to review the current regulation both on national and European levels to understand what is currently allowed and what is needed to be modified in current regulations to enable efficient procurement of grid services.

4.3.3. The InteGrid perspective

Based on the outcome of the project, there is a wide variety of key lessons learned observed through the implementation of the TLS.

With regards to the operational perspective, the project indicated that the TLS provides an adequate solution in order to provide adequate congestion management within MV networks, provided that these congestions do occur. Furthermore, it was shown that the TLS is able to support the network based on numerous futuristic scenarios, as shown by the SRA. Therefore, the necessity of the TLS is increasing alongside the increasing growth of electrical networks and market participants.

In the case of implementation, however, it is important to consider the current and future state of the network. In this regard, the number and location of the flexibilities play a key role in order to optimise the proposed activation schedule based on cost and volume optimisation. Furthermore, a linear pricing model[2], results in the TLS to favour flexibilities located closer to the substation. In the case when there is significant penetration of RES, the TLS plays an essential role in ensuring that the network congestions are avoided. On the contrary, however, the scenario for the significant increase in electric vehicle (EV) penetration showed that the downward reserve cannot be fully activated. This indicates that large-scale integration of EV could pose as a significant challenge to DSOs in the future. When considering the use of The TLS in different network topologies (i.e. rural vs urban), a key outcome was that the TLS does not show any significant impact on the business model. Moreover, the accuracy of the forecasting tools used in combination with the TLS also plays a significant in order to adequately active the required flexibilities. In order to facilitate the aforementioned concepts, it is clear that communication and information sharing is key in order to enable the facilitation of the TSO-DSO interaction.

To enable successful communication, it is extremely important that the ICT infrastructure is reliable, scalable and interoperable. With respect to the implementation of ICT devices, as seen from the perspective of the VPP, it is clear that moving towards interoperable solutions will increase their chances of higher penetration in distributed networks and offer a higher

[2] In the context of InteGrid, two types of linear pricing were considered, 1. Flexibilities close to the primary substation are the cheapest and get linearly more expensive when the feeders are traversed, 2. Vice versa

flexibility pool to the DSO. In addition, a modular system, as it is presented in InteGrid by the VPP, based on microservices, is key for proper scaling performance.

From an economic perspective, both the number of DER aggregated and the average available flexibility per DER may play an important role in the economic results of the cVPP. It was shown that in Slovenia, pools with a small size are not economically feasible, regardless of the DER capacity aggregated; while in the case of Portugal, pools with limited flexibility, regardless of their size, are not economically interesting. In the latter, it only becomes feasible, for a given pool size, when aggregating clients with a significant amount of flexibility as their number and, consequently, the costs associated to DER are lower.

The impact of regulatory conditions plays a significant role in the implementation of TSO-DSO interaction schemes. The design of markets and products, will not only allow the participation of all stakeholders but also change the possibility of economic benefit. In the case where markets pay for capacity and energy, the economic potential of such coordination schemes proved to be more favourable.

4.3.4. The INTERPLAN perspective

The INTERPLAN toolset is a prototypical implementation which allows for the ‘proof of concept’ to be realised. Currently, the tool is at a rather low technology readiness level (TRL5). There is still a lot of interaction between stakeholders, representing both network operators and software vendors which are required to further develop the tool to become commercially available. It is crucial to draw a clear path on how to integrate and deploy such a tool in the daily business of the stakeholders. Several advantages of applying such a developed tool within future networks have been identified and are described as follows:

It allows for the operation planning of the Pan-European network to be conducted through an integrated approach. In fact, by offering the possibility to simultaneously investigate all network voltage levels for operational planning purposes, the tool facilitates the integration of the actions made by different stakeholders such as RSCs, TSOs, DSOs, which are considered as the primary users for the tool. Additionally, this integrated approach bridges the gap between static, long-term planning and considering operational issues by introducing sufficient control functions in the day-ahead operation planning phase.

With the current network operation planning approaches, it is not possible to consider all existing networks (including full models) in an integrated planning tool due to computational limitations, lack of detailed models, etc. Therefore, through the use of intrinsic grid equivalenting methodology, the tool integrates functionalities by simplifying certain parts of a grid while keeping the relevant characteristics. This grid equivalenting methodology, which is applicable to both transmission and distribution levels, plays a vital role for TSO-DSO interactions, especially in the presence of flexibility resources which are mainly connected at medium voltage (MV) and low voltage (LV) levels and can be used to address possible operational challenges occurring at all network levels.

Through the control functions embedded within INTERPLAN use cases and showcases, it is possible to address several operational challenges occurring in current and future 2030+ power networks from the perspective of both TSOs and DSOs. In detail, INTERPLAN use cases address very specific operational challenges that grid operators may be faced with, in the presence of high penetration of RES, storage, demand response and electric vehicles. On the other hand, the showcases address a combination of operation challenges, thereby representing typical situations that the grid operators may experience, for grid operation planning purposes.

4.3.5. The Swiss perspective

According to the survey conducted in Switzerland, two promising topics for the increase in TSO-DSO interaction were identified and studied in two dedicated case studies.

First, the future scenario based on an increase in TSO-DSO interaction encompasses a wider integrated reserve system required for balancing power which requires the coordination of stakeholders including the TSO, DSO and end customers which have flexible assets. The objective is to procure reserve power while ensuring that the network operation remains secure and reliable. As a proposed solution, such as the Veto or Traffic Light System (TLS) can be implemented for the DSO. Furthermore, by introducing a finer granularity of reserve products which can be procured by the TSO (time horizon, locational preferences, smaller minimum power requirements), the overall availability of flexibility from the DSO would be increased. It has already been established that even minimal knowledge of the available network capacity can lead to a significant increase in the amount of secure flexibility available from the DSO network. However, in order to successfully improve this concept, the method used to procure reserve power would need to be adapted. In particular, the time granularity and inclusion of the DSO in the procurement process.

The second concern highlighted by the Swiss DSO, relates to the coordinated congestion management for the TSO and meshed DSO network, which focuses on the coordination of the transformer setting at the TSO-DSO interface. In Switzerland, this technique has proved to add significant value through additional available network capacity for transit flow. Although this transit flow is limited by the voltage and current limit within the TSO network, in order to provide network relief, it is possible to allow for the adjustment of the load flow to be transferred to neighbouring DSO networks (if it allows). This adjustment is conducted via transformer tap changer settings and not through load shedding techniques or curtailment of production. This was tried and tested for a number of load flow scenarios in Switzerland. It indicated that the success of such operation only requires a small increase in TSO-DSO communication with respect to individual aggregated parameters used in the network and the status of the transformer settings.

4.3.6. Summary

In summary, it can be acknowledged that there are many key findings which can be used to facilitate the future implementation of TSO-DSO interaction. It is highly established that network congestion can be mitigated through the combination of flexibilities and TSO-DSO interaction. However, the number and location of these flexibilities play a vital role when maximising the overall benefits of such interaction. Furthermore, accurate forecasting methods are essential to ensure that the activation of the required flexibilities is achieved. Additionally, the key lessons learned attained from the perspectives of the European research projects are highly beneficial in that new strategies can be integrated and tested within demonstration sites which provide added value when actualising theoretical concepts.

4.4. Recommendations for TSO-DSO interaction

Based on the outcomes of the aforementioned sections, it is clearly evident that the increased coordination between TSO and DSO needs to be conducted incrementally and that it is not an easy task. The following section offers recommendations for future implementation of DSO-TSO interaction.

4.4.1. The SmartNet perspective

The regulatory framework should assist in the transition of DSOs to abandon the fit-and-forget (oversizing) planning policy. The integrated TSO-DSO market shown in CS C can perhaps be recommended, but due to the complexities of its implementation, it is recommended that the number of nodes that are to be considered arrive to consider medium voltage level and doesn't push the detail level up to low voltage and household nodes.

4.4.2. The CoordiNet perspective

There must be a clear understanding of the network and the technical probabilities of the resources participating in the project. This should be evaluated as soon as possible in order to ensure that the implementation and execution of the developed solutions can be well established.

The identifications of KPIs is a relevant step to define the quantitative parameters among which the success of the project can be benchmarked. Therefore, it is recommended that these KPIs are developed and agreed upon in order to evaluate whether the project meets the required objectives. KPIs should be considered from the technical, economic, social and environmental perspectives in order to obtain a holistic view of the implemented solutions.

In general, from the perspective of stakeholders, there is usually a set of preferred coordination schemes and parameters for flexibility products and grid services. Therefore, some of the project parameters should be generic to all the demonstrations, as a first step toward the dissemination of such projects. It is, however, noted that there are some parameters could be still country or site specific which is necessary in order to reflect local conditions. However, in order for the developed solutions to have a wider impact, an overall architecture implementation guideline set for the intraday market platform for faster deployment and scaling up at EU level is still required. The results from these guidelines should also include documentation for all the processes, definitions of roles for the actors, technical interfaces and the definition of general requirements to be used in the context of legislation in different member countries.

Particular attention should be given to customer perception and the effectiveness of the engagement strategy in the demonstrations. The concept of 'customer is key' is clearly demonstrated within the project, and especially for the successful implementation of TSO-DSO coordination schemes. Therefore, it is essential to define the customer engagement process at the early stages of the project, taking into consideration from previous experience, the location for customer engagement including segmentation, their motivation and drivers for participation.

4.4.3. The InteGrid perspective

In order to ensure the success of the TLS implementation with respect to TSO-DSO coordination, the following recommendations are highlighted.

A hosting capacity analysis is recommended in order to identify the current status of the targeted networks. This is necessary to understand the current violations, if any, their location and potential future congestion points. Before the activation of flexibilities, it is also recommended to ensure that the capacity of the primary substation transformer is not exceeded, and DSOs should ensure that this is taken into consideration as part of the hosting capacity analysis. Therefore, it is essential that network operators are well informed and know the status and operation of their networks

Adequate network information sharing should be established between the TSO and DSO such that the current state of the network can be assessed adequately from both perspectives. This includes additional information such as the network type, (Urban vs Rural) and network characteristics (resistive vs inductive). Although the availability of data did not directly affect the operation of the TLS, it did, however, have an impact on the accuracy of the forecasting tool. This consequently has an impact on the operation of the TLS. Therefore, it is recommended that the data quality and availability is assessed such that it is readily available.

From an ICT perspective, plug and play solutions (alongside interoperability) should also be considered which incorporating communication systems in order to facilitate TSO-DSO interaction. This allows for the integration of new solutions into the respective architectures to be achieved in a fast and effortless manner. The interoperability and scalability of the TLS should be ensured while maintaining a high level of cybersecurity since it has a direct impact into the network especially when sensitive information is being shared.

Regulations should consider and make provisions for the quantification of fairness of flexibility operation. This should be clearly established based upon a merit order which takes a cost function into consideration. This is to be assessed in conjunction with the economic evaluation. Furthermore, due to the respective objects of both TSO and DSO operators, the TLS can be operated in a manner in which it simultaneously considers the objectives of both system operators over a wider range of scenarios. These procedures and guidelines should be adequately identified and defined within regulatory sandboxes. Regulations should, as far as possible, be maintained and developed in order to ensure legal security which is open and fair to all stakeholders. The regulations should be made to be appealing for all network stakeholders in order to ensure sustainability and compliance.

4.4.4. The INTERPLAN perspective

The investigation within INTERPLAN demonstrated the improved benefit of a strong collaboration between TSOs and DSOs. Coordinated use of integrated operational planning tools can be used as a solution to bridge the gap between static, long-term planning and considering operational issues by introducing proper control functions in the day-ahead operation planning phase.

It is highly recommended to continue and enhance the interaction between research, grid stakeholders and software vendors in order to provide and use integrated planning tools in the future. Furthermore, it is necessary to develop an implementation path on how to integrate and deploy such a tool in the daily business. The following recommendations are highlighted:

- Continue and facilitate further discussions regarding the future scenarios which foresee increased challenges and provide possible solutions in order to increase the awareness of TSOs and DSOs on the value added by resilient cooperation and interaction.
- Develop and enhance the cooperation between all stakeholders in order to make related tools commercially available as well as to define standardized interfaces between them in order to enable joint investigations
- Provision of possible technical solutions (interfaces and data formats) in order to share information. This includes the definition of standardized processes which facilitates the safe, secure and reliable sharing of data.
- Increase the availability of grid data and related models as well as processes to share them

Finally, results based on joint investigation of different control strategies between TSOs and DSOs can strongly support the definition and discussion of future grid codes and related regulatory measures in order to support both the massive integration of renewable energy resources as well as emerging technologies while maintaining the high level of security and quality of supply in the European power system.

4.4.5. The Swiss perspective

As was identified in the survey conducted, it is evident that the increased coordination between TSO and DSO needs to be conducted incrementally and that it is not an easy task.

Within the scope of Switzerland, the primary focus to improve TSO-DSO interaction focused towards a more coordinated congestion management and reserve procurement schemes. In order to achieve this, the first steps have been taken to identify the potential congestions coupled within the TSO-DSO network is achieved by estimating the power flows through the transformer on the day-ahead time scale. Additionally, the network parameters are also exchanged between the network operators based on the aggregated information. These network parameters are also used to conduct an impact assessment and thereafter establishes a potential redispatch methodology which considers the voltage limits of each network. Based on this assessment, in order to implement the changes required, the regulatory framework and tariff system needs to be revised and adapted. Currently, in Switzerland, this integrated market for nodal redispatch is planned while a possible future auctioning process of critical line capacities is being discussed.

Further topics from interviews discussed during the interviews with the various Swiss network partners include support for holding voltage bounds, during black-start, synchronisation and coordinated protection. These topics should be observed and could become interesting in the future but are not a current focus for either TSO or DSO.

4.4.6. Summary

Based on the outcomes of the study, there are numerous aspects of TSO-DSO interaction which require increased attention and thus recommendations for future development are provided. From the perspective of the network operators, an increase in network visibility would further enhance and facilitate the interaction between TSO and DSO. Additionally, an increase in the collaboration between network operators through the sharing of network data, via dedicated central data hubs, is recommended. From a regulatory perspective, a revision of the regulations, both locally and internationally, is required in order to identify and define the roles and responsibilities of the network operators. This recommendation also applies to the establishment of operation procedures and the procurement of grid services.

5. Final remarks

TSO-DSO interaction continues to be highly topical in the context of active management of electrical power systems around the world. This can be attributed to the global objective to reduces CO_2 emissions, in combination with the continuous strive towards the increased integration of RES, flexible devices, and increased participation of consumers, facilitated by smart grid technologies that have resulted in a paradigm shift of the power system. These aspects have increased the necessity for improved TSO-DSO interaction in order to ensure the successful operation of the network.

This report has provided some insight into the perspective of four European research projects, which implemented TSO-DSO interaction schemes based on their simulations and incorporation into actual networks through the use of demo sites. Additionally, the perspectives based on a study conducted in Switzerland were also included. The outcomes attained from each of the perspectives with regards to the main challenges, successes, lessons learned, and recommendations have been provided.

In conclusion, this discussion paper indicates that there is an increased awareness of TSO-DSO interaction in Europe. The outcomes of the demonstration projects, as well as the investigation conducted in Switzerland, show that TSO- DSO interaction can, despite the many challenges, be successfully implemented with increased benefits for various stakeholders within the power system. Although there are many aspects of TSO-DSO interaction which are already well established, there is a high potential for the development and improvement of TSO-DSO interaction, such that these techniques can be implemented in future power systems throughout the world.

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