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INTERNATIONAL SMART GRID ACTION NETWORK

Power Transmission & Distribution Systems

Exploring the interaction between power system stakeholders: Insights from Pilot Projects

Discussion paper

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About ISGAN Discussion Papers

ISGAN discussion papers are meant as input documents to the global discussion about smart grids. Each is a statement by the author(s) regarding a topic of international interest. They reflect works in progress in the development of smart grids in 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

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List of Acronyms

AMQP	Advanced Message Queuing Protocol
ATP	Automated Trading Platforms
B2B	Business-to-Business
BaU	Business as Usual
BESS	Battery Energy Storage Systems
BRP	Balancing Responsible Providers
BSP	Balancing Service Providers
BUC	Business Use Case
CECs	Citizen Energy Community
CEMS	Charging Energy Management System
CHP	Combined Heat and Power
CIM	Common Information Model
CLS	Customer Load System
DER	Distributed Energy Resource
DG	Distributed Generation
DLFM	Distribution-Level Flexibility Market
DOMS	Distribution Observability and Management System
DR	Demand Response
DRES	distributed renewable energy sources
DSM	Demand Side Management
DSO	Distribution System Operated
ECCo SP	ENTSO-E Communication & Connectivity Service Platform
EEGO	European Electricity Grid Initiative
EES	Energy Storage Systems (ESSs)
EMS	Energy Management System
ESP	Energy Service Providers
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
FEMS	Factory Energy Management Systems
FSP	Flexibility Service Provider
FSSF	File System Shared Folder
GDPR	General Data Protection Regulation
GHG	Green House Gases
HEMS	Home Energy Management Systems
HP	Heat Pump
ICCP	Inter-Control Center Communications Protocol
ICCT	Information, Communication, and Control Technologies
ICT	Information and Communication Technologies
IEGSA	Interoperable pan-European Grid Services Architecture
IoT	Internet of Things
IT	Information Technologies
LFM	Local Flexibility Market
LV	Low Voltage
MO	Market Operator

MQTT	Message Queuing Telemetry Transport
MV	Medium Voltage
NDP	Network Development Plan
NPV	Net Present Value
OPF	Optimal Power Flow
P2P	Peer-to-Peer
PTDF	Power Transfer Distribution Factors
RES	Renewable Energy Resource
SCADA	Supervisory Control and Data Acquisition
SGAM	Smart Grid Architecture Model
SHH	Social sciences and humanities
SP	Service Providers
SRA	Scalability and replicability analysis
SUC	System Use Case
TSO	Transmission System Operator
UMEI	Universal Market Enabling Interface
V2G	Vehicle to grid
VoLL	Value of Lost Load
VPP	Virtual Power Plant

Executive Summary

The increasing integration of renewable energy sources (RES), digitalization, and decentralization of power generation necessitates enhanced coordination among power system stakeholders to ensure grid stability, efficiency, and flexibility. This report, developed within the framework of ISGAN Working Group 6, synthesizes insights from international pilot projects to examine the evolving interaction between Transmission System Operators (TSOs), Distribution System Operators (DSOs), and other market participants in flexibility provision, capacity management, and regulatory adaptation.

Key Findings:

1. **TSO-DSO Coordination:** Effective collaboration between TSOs and DSOs optimizes resource utilization, mitigates congestion, and enhances system reliability. Pilot projects demonstrate that market-based coordination models, real-time data exchange, and standardized flexibility procurement mechanisms improve operational efficiency and enable the integration of distributed energy resources (DERs). Projects such as CoordiNet, EU-SysFlex, and SmartNet have highlighted best practices in joint operational planning, real-time ancillary services, and congestion management.

2. **Technological Innovation:** Advanced forecasting tools, AI-driven optimization, and modular ICT architectures enhance grid resilience and operational efficiency. The integration of smart metering, predictive analytics, and decentralized flexibility management enables robust decision-making and improved system observability. Real-time platforms, such as the ones developed in OneNet and GOFLEX initiatives, demonstrate the role of digitalization in optimizing flexibility market operations.

3. **Market-Based Flexibility Mechanisms:** Emerging flexibility markets facilitate the procurement of ancillary services, with harmonized prequalification, procurement, and activation processes ensuring liquidity and participation. Local and cross-border flexibility markets demonstrate the potential to reduce redispatch costs and support congestion management. The implementation of market-based coordination in projects like InterFlex, CoordiNet, OneNet and FlexGrid has demonstrated the effectiveness of dynamic pricing, bid stacking, and congestion relief solutions.

4. **Regulatory and Policy Frameworks:** Regulatory alignment and standardization are critical to scaling flexibility markets. Regulatory sandboxes and experimental frameworks enable controlled implementation of novel market designs. Harmonized data-sharing standards and cybersecurity measures are necessary for secure and scalable TSO-DSO interactions. The findings from the TDX-Assist and InteGrid projects emphasize the necessity for data governance frameworks that balance transparency with privacy concerns.

5. **Stakeholder Engagement and Consumer Participation:** Consumer-centric frameworks and automation tools drive participation in flexibility markets. Economic incentives, dynamic tariffs, and transparent demand response mechanisms enhance engagement from active customers (which can own generation, storage, demand response, etc.), aggregators, and industrial participants, contributing to overall market efficiency. The EUniversal and InteFlex projects illustrate the importance of consumer awareness campaigns, simplified market participation models, and automation in demand-side flexibility contributions.

6. **Insights from Surveys, Workshops and Expert Interviews**: Stakeholder engagement through a survey, international workshop and expert interviews provided additional depth to the analysis. Discussions highlighted real-world implementation challenges, including regulatory constraints, data exchange complexities, and interoperability concerns. Experts emphasized the necessity of adaptive regulatory frameworks and collaborative innovation to drive market evolution. The workshop findings reinforced the importance of coordinated operational strategies, real-time data sharing, and robust cybersecurity measures in ensuring successful TSO-DSO interaction.

This report highlights the importance of leveraging lessons from global pilot projects to develop scalable, interoperable, and market-based flexibility solutions. By synthesizing insights from technical, market, and regulatory perspectives, the findings provide actionable recommendations for policymakers, system operators, and market participants. A concerted effort towards standardization, market harmonization, and stakeholder collaboration is pivotal in advancing power system coordination toward a more resilient, decentralized, and sustainable energy future.

Contents

1. Introduction

This discussion paper was prepared within the framework of ISGAN Working Group 6 (https://www.iea-isgan.org/our-work3/wg_6/). The main objective of Working Group 6 is to establish long-term visions for the development of the future sustainable power systems. To create and project such visions, the working group clarifies system-related challenges, with emphasis on the technologies, market solutions, and policies which contribute to the development of system solutions. Within the focus area, Power Transmission & Distribution Systems, the aim is to promote solutions that enable power grids to maintain and improve the security, reliability, and quality of electric power supply. The main objective of this focus area is to conduct studies on how distribution and transmission networks could interact in the future and ensure stable grid operation under high levels of renewables. Figure 1 positions this work in the ISGAN context.

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

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

ISGAN Working Group 6 Focus Area: Transmission and Distribution System Interaction
The objective of this focus area is to assess the way in which distribution and transmission networks could interact in the future, ensuring stable grid operation under high levels of renewables.

Discussion Paper: Exploring the interaction between power system stakeholders Insights from Pilot Projects
This discussion paper explores the interaction between power system stakeholders, particularly focusing on TSOs and DSOs. It highlights insights from international pilot projects that address challenges in flexibility management, grid coordination, and stakeholder engagement. Key areas covered include technological innovations, market mechanisms, regulatory frameworks, and the role of advanced ICT tools in optimizing grid operations.

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

1.1. Background

The electricity system is undergoing a significant transformation driven by the increasing integration of renewable energy sources, widespread adoption of decentralized generation technologies, and advancements in digitalization and automation. Traditionally characterized by a unidirectional flow of electricity from centralized power plants to consumers, the grid is evolving into a dynamic, bidirectional system. Distributed energy resources (DERs), such as rooftop solar panels, wind turbines, electric vehicles, and battery storage, are playing an increasingly prominent role, generating electricity closer to consumption points and contributing to grid operations. Simultaneously, decarbonization goals and the electrification of sectors like transportation and heating are reshaping energy demand patterns and introducing new peaks and variability. This shift requires enhanced coordination among stakeholders to ensure that the system remains reliable, flexible, and efficient, while also accommodating the complex interactions of local and large-scale energy resources.

TSO-DSO Coordination in Evolving Power Systems
Transmission System Operators (TSOs) and Distribution System Operators (DSOs) play distinct yet increasingly interconnected roles in the operation of modern electricity grids. TSO-DSO coordination, in general, refers to the collaborative processes necessary to ensure efficient, stable, and flexible grid operations. However, as the energy landscape evolves, other stakeholders, including energy producers, prosumers, technology providers, regulators, and market operators, also play crucial roles in shaping grid dynamics. The growing penetration of renewable energy sources and the decentralization of power generation has intensified the interdependence between TSOs, who manage high-voltage transmission networks, and DSOs, responsible for medium- and low-voltage distribution networks. Effective coordination among these stakeholders is critical to maintaining grid reliability, optimizing energy flows, and integrating local resources into broader system operations while ensuring that market mechanisms, regulatory frameworks, and technological advancements align with the needs of the evolving power system.

Roles and responsibilities
TSOs are responsible for managing high-voltage transmission networks, ensuring system stability through frequency control, congestion management, and the real-time balancing of electricity supply and demand on a large scale. DSOs oversee medium- and low-voltage distribution grids, delivering electricity to end-users while addressing localized grid issues, integrating DERs, and enabling efficient energy delivery at the local level. These distinct roles are now increasingly overlap (due to factors such as the rise of DERs, the electrification of sectors, decentralized grid operations, and advancements in digitalization), necessitating coordinated approaches to ensure seamless operation across all levels of the grid. Beyond TSOs and DSOs, other stakeholders contribute significantly to the efficient functioning of the electricity system. Energy producers, including large-scale renewable energy operators and small-scale prosumers, inject variable and distributed power into the grid, requiring alignment between production and grid management. Technology providers supply advanced tools for data exchange, grid monitoring, and flexibility services, enabling real-time operational coordination. Regulators and policymakers establish the frameworks that govern stakeholder interactions, while market operators facilitate transactions in emerging flexibility and ancillary services markets. The interplay of these diverse roles emphasizes the importance of a collaborative, integrated approach to managing grid operations and ensuring system-wide reliability.

Key components of coordination and benefits of enhanced coordination
Effective coordination between TSOs and DSOs is critical for optimizing grid performance. Real-time data exchange allows for better monitoring and management of grid conditions, energy flows, and balancing supply and demand across systems. Flexibility markets enable distributed resources, such as batteries and demand response, to contribute to grid stability at both transmission and distribution levels. Joint operational planning ensures seamless congestion management, voltage control, and other grid services. Collaborative infrastructure planning allows for the strategic deployment of flexibility solutions, minimizing the need for costly upgrades while boosting system resilience. TSO-DSO coordination brings multiple benefits, including improved grid stability through a reliable electricity supply, even with fluctuating renewable energy sources. Shared data and coordinated services help optimize resource use, reduce operational costs, and minimize additional infrastructure investments. This approach fosters cost-effective solutions to congestion and aligns local energy generation with consumption needs.

Importance of lessons learned from pilot projects
Insights from global pilot projects highlight the critical role of TSO-DSO coordination in addressing challenges posed by decentralized, renewable-driven energy systems. These initiatives offer valuable guidance for designing scalable strategies that foster sustainable and resilient energy systems. Serving as testbeds for innovative coordination mechanisms, they provide practical lessons for broader implementation while mitigating risks associated with large-scale adoption. The shift to decentralized energy systems introduces complex technical, operational, and market challenges. Pilot projects enable stakeholders to assess the feasibility, scalability, and real-world impact of solutions across a wide variety of conditions. By experimenting with centralized, decentralized, and hybrid coordination models, these initiatives generate data to identify effective approaches tailored to specific contexts. Furthermore, pilots uncover technical challenges, such as interoperability issues between TSO and DSO systems, and help develop solutions to overcome them. They highlight regulatory and market design gaps that could hinder coordination, thereby, facilitating early interventions to establish robust frameworks for wider implementation. Beyond technical insights, pilot projects enhance stakeholder engagement and capacity building. By promoting collaboration among TSOs, DSOs, policymakers, technology providers, and other key players, they align their objectives and encourage the adoption of innovative technologies and operational models. This collaborative approach advances confidence in new strategies, paving the way for broader acceptance. The iterative nature of these initiatives drives continuous improvement, optimizing solutions for efficiency, reliability, and cost-effectiveness. Therefore, the lessons learned from pilot projects reduce uncertainty and accelerate progress toward a flexible, sustainable, and resilient energy system while minimizing deployment risks.

ISGAN, and in particular Working Group 6, has been focusing on the topic of TSO-DSO interaction and considers it to be crucial in the focus areas of smart grids. Previous work conducted by Working Group 6 related to flexibility, TSO, DSO, and stakeholder interaction since 2014 can be seen in Figure 2.[1]

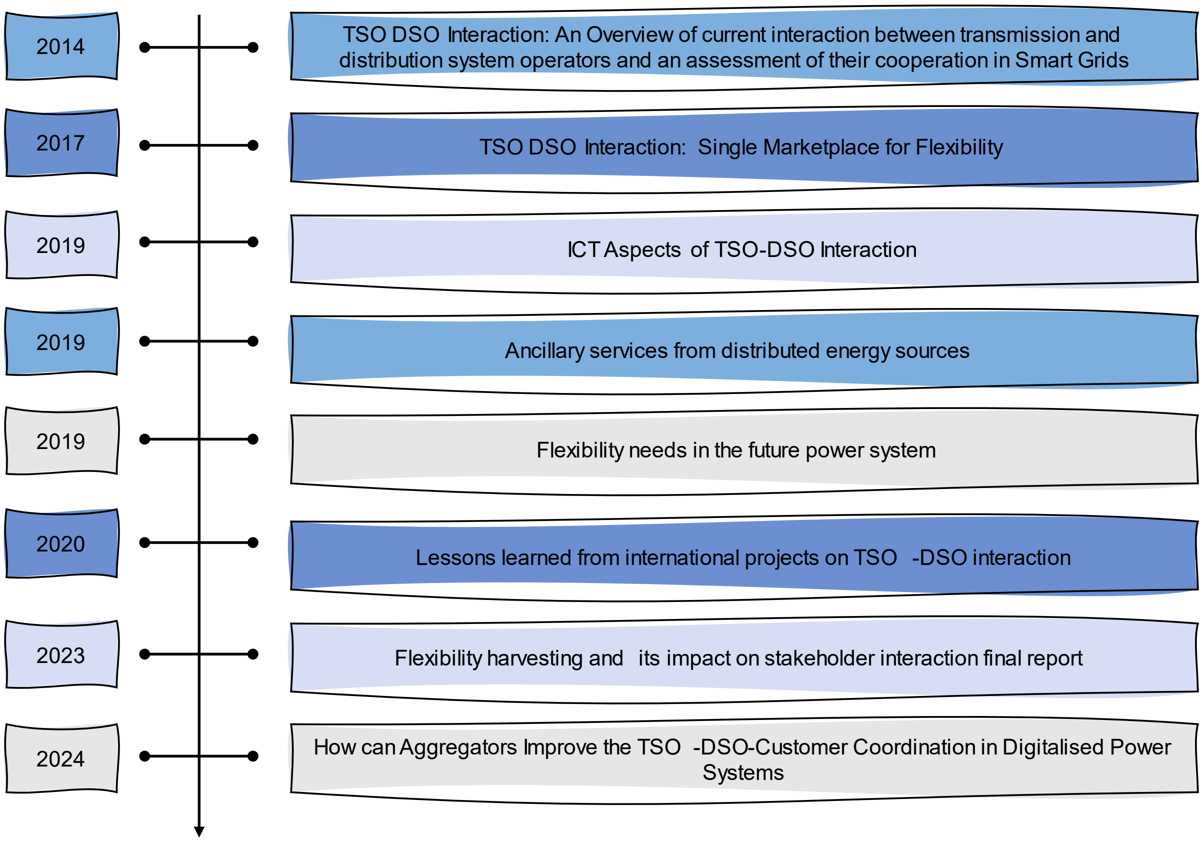


Figure 2: Overview of ISGAN Working Group 6 publications.

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

1.2. Overview of the purpose, scope, and methodology

The purpose of this discussion paper is to provide a comprehensive overview related to the experience and insights gained from global pilot projects in the field of providing flexibility for coordinated capacity management of transmission and distribution system operators. The overall goal is to provide a holistic overview of the ongoing developments in the integration of flexibility, offering valuable insights into how these projects are shaping the future of transmission and distribution network operations. The paper highlights the key lessons learned and identifies the primary challenges across several key domains, including:

- **Technical:** How flexibility solutions, such as demand-side response, energy storage, and flexible generation, have been implemented in different pilot projects to optimize grid management and capacity planning. The technical challenges of integrating these solutions into existing grid infrastructures and their potential to support a more decentralized energy system are discussed.
- **Information and Communication Technology (ICT):** The role of advanced ICT systems in enabling real-time data exchange, monitoring, and control of flexible resources. The paper explores the importance of robust communication networks, data management platforms, and cybersecurity measures in ensuring the effective and secure operation of flexibility mechanisms.
- **Economic and market-related:** The economic implications of flexibility integration, including the cost-effectiveness of various flexibility services, market design, and financial incentives required to attract investment and stakeholder engagement in the proposed solutions. Insights into the economic modelling and the role of market players in supporting the business case for flexibility are explored.
- **Regulatory:** The regulatory frameworks that have supported or hindered the deployment of flexibility solutions and stakeholder interaction, including the alignment of policy objectives with the realities of grid operation and capacity management. The paper examines how regulatory and market design elements need to evolve to facilitate better coordination between TSOs, DSOs, and other stakeholders involved in system operation.

The methodology and approach to collect the information are based on a comprehensive project and literature review, complemented by insights gathered from stakeholder engagements, including a survey, workshop, and expert interviews, as shown in Figure 3.

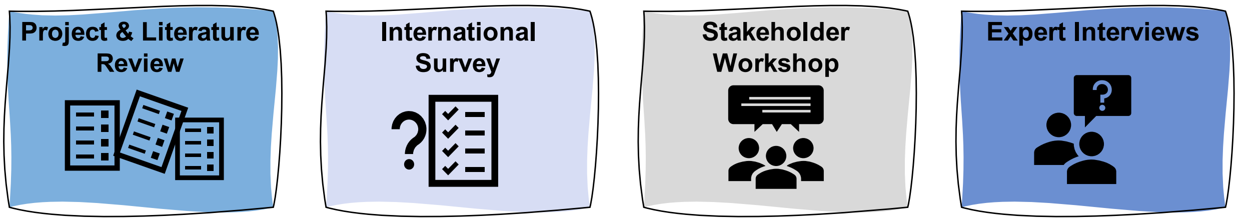


Figure 3: Overview of methodology and approach.

The project and literature review serve as the foundation, providing an overview of the publicly available material (deliverables, scientific publications, presentations, etc.) from concluded projects. Additionally, a survey was conducted and aimed to gather data from stakeholders in the energy sector based on their recent experiences from pilot projects. It focused on the effectiveness, challenges, and benefits of flexibility solutions and stakeholder interaction across technical, economic, and regulatory aspects. Furthermore, the hosted workshop facilitated in-depth discussions among stakeholders, allowing for the exchange of ideas and identification of emerging trends. It aimed to foster dialogue on critical topics, share experiences from pilot projects, and highlight best practices. Key themes included technical challenges in flexibility modelling, the role of information and communication technologies, data exchange, and cybersecurity. Economic, market, standardization, interoperability, and regulatory aspects were also discussed, particularly concerning TSO-DSO interactions. The workshop concluded with an analysis of future work and strategic outlooks, offering valuable insights for the continued integration of flexibility in power systems. In addition, expert interviews were conducted to gather in-depth perspectives from leading experts in the field. The experts shared their experiences, challenges, and strategies, combining their theoretical knowledge with practical insights.

Therefore, this paper presents and examines the key insights based on the outcomes of these pilot projects, as well as expert knowledge and contributions from a wide range of stakeholders within the energy sector. By synthesizing global experiences and expert knowledge, this paper aims to inform policymakers, industry leaders, and technical experts on the most effective strategies for enhancing flexibility in grid management and fostering improved coordination among stakeholders.

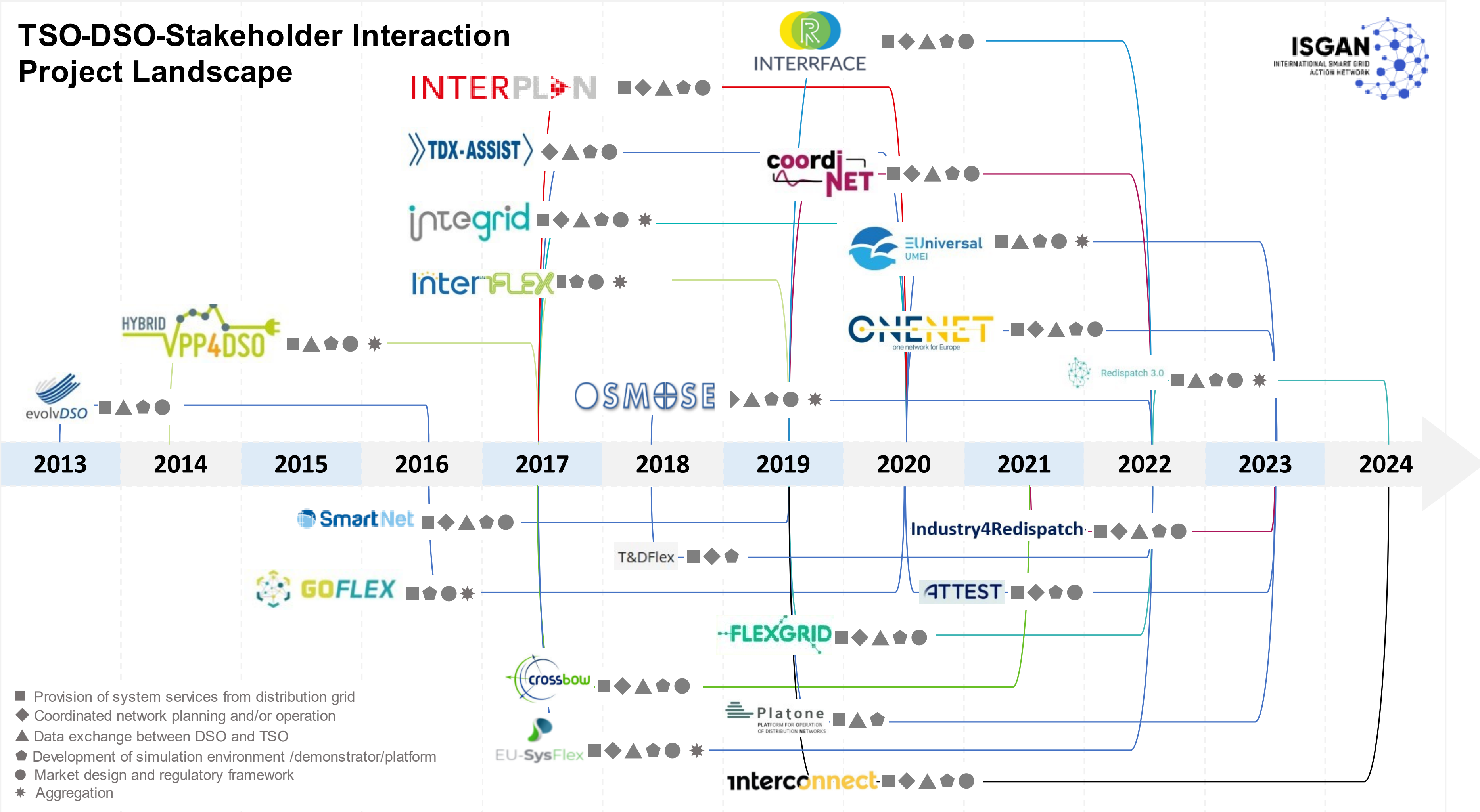
1.3. Structure of the document

This discussion paper provides an overview of international pilot projects that highlight the key lessons learned and insights from power system flexibility and stakeholder interaction, as presented in Section 2. Section 3 explores more in-depth topics, including data exchange mechanisms, market-based coordination strategies, and common prequalification procedures derived from selected pilot projects. Section 4 presents the key findings from stakeholder engagements, incorporating perspectives gathered through surveys, workshop, and expert interviews. Finally, Section 5 concludes the discussion paper by summarizing the key findings and offers an outlook on future opportunities and challenges for enhancing power system flexibility.

2. Overview of international pilot projects

The integration of power system flexibility has become a pivotal focus in addressing the dynamic challenges of modern energy systems. This section offers an overview of the key insights and highlights drawn from pilot projects across the globe. Recognizing the growing relevance of this topic, it is acknowledged that numerous projects have been conducted, and this review is not intended to provide an exhaustive list. Rather, the projects were carefully selected to represent a broad spectrum, spanning from earlier initiatives to more recent efforts, showcasing how the understanding and application of flexibility, along with stakeholder interaction, have evolved over time. Additionally, these examples offer a geographically diverse perspective within Europe, illustrating how different regions approach the shared goal of enhancing power system adaptability and resilience. Further details regarding each of the projects can be found in the appendix. The development of a TSO-DSO project landscapes highlights the multiple initiatives undertaken between 2013 and 2024, focusing on key aspects such as system services provision, coordinated network planning, data exchange, market design, simulation environments, and aggregation.

2.1. Project landscape



2.2. Project overview

2.2.1. Distribution of TSO-DSO Stakeholder interaction demonstration sites in Europe

The choropleth map, as shown in Figure 4, presents the geographical distribution of pilot and demonstration sites for the selected TSO-DSO stakeholder interaction projects across Europe. As can be seen, Germany is the most active participant in terms of hosting demonstrations or pilots, as indicated by the darkest shade. This suggests that Germany has an extensive engagement in grid modernization and TSO-DSO coordination initiatives. France, Spain, and Italy also demonstrate significant involvement. Such participation likely stems from strong policy support, well-developed energy infrastructure, and participation in EU-funded programs. In contrast, Eastern and Northern European countries, including the Baltic states, Romania, and Finland, exhibit fewer or no demonstration sites. The variation in participation levels may suggest disparities in regulatory frameworks, investment levels, funding opportunities, and technological readiness across different regions.

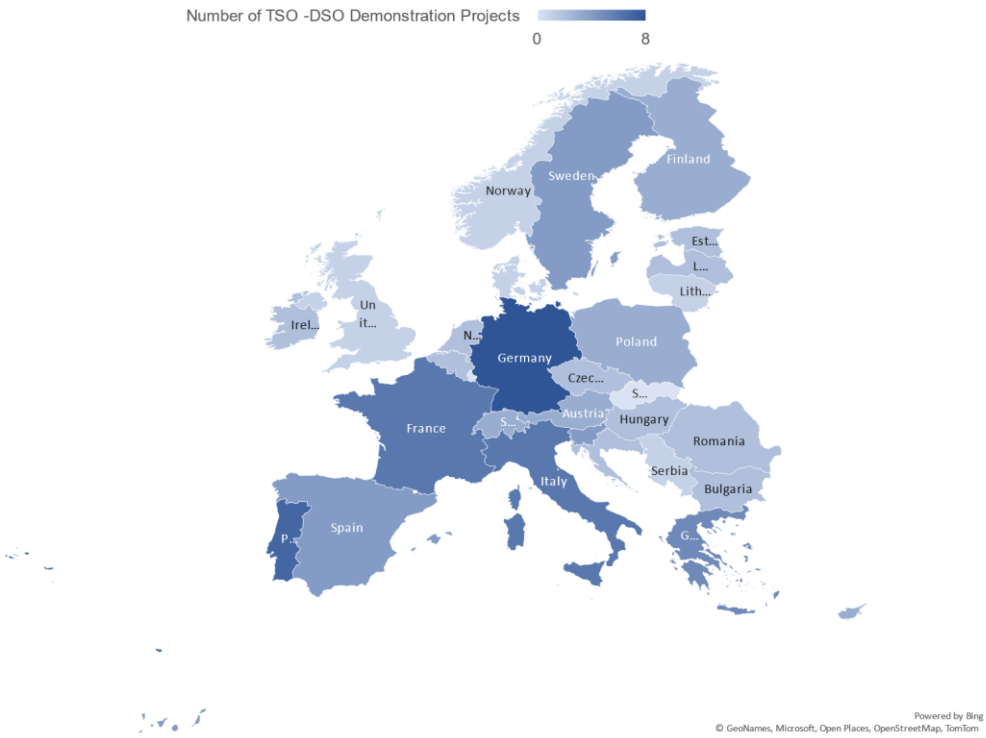


Figure 4: Distribution of TSO-DSO Stakeholder interaction demonstration sites in Europe

2.2.2. Project start year and duration

The analysis of project initiation trends from 2013 to 2022, as depicted in Figure 5, indicates a fluctuating pattern with a peak period followed by a decline. In the initial years (2013-2016), project commencements were relatively low, with only one project initiated in 2013 and 2014, followed by a slight increase to two projects in 2016. A significant surge was observed in 2017 when the number of projects reached its highest point at six. This trend was notably influenced by the priorities of the EU H2020 funding programs, which allocated significant resources to projects focused on system services, data exchange, and simulation development. These funding

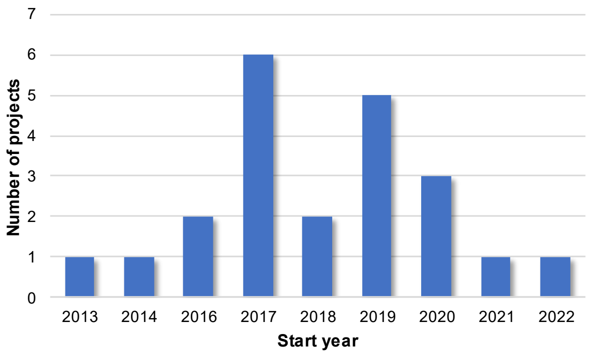


Figure 5: Overview of the number of projects start year

priorities shaped research and innovation efforts, driving advancements in these key areas This peak was followed by sustained activity in 2019, with five projects initiated. However, post-2019, a downward trend is evident, with project initiation dropping to three in 2020 and further declining to just one project in both 2021 and 2022. This decline may be attributed to external factors such as changes in technology trends, available funding programs, policy changes, economic constraints, or global disruptions (eg. Covid pandemic) affecting project initiation rates. The observed trends suggest that the most active period for project commencements was between 2017 and 2019, whereas the years following 2019 exhibited a marked reduction in new project launches.

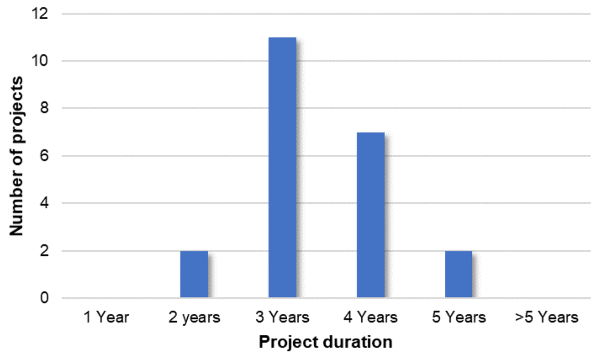


Figure 6: Overview of project duration

Figure 6 illustrates the distribution of projects based on their duration, measured in years. The graph shows that the most common project duration is 3 years, with 11 projects, followed by 4-year projects, which account for 7 projects. The lowest frequencies are observed for 1-year and 5-year projects, each with 2 occurrences, while no projects exceed the 5-year threshold. Since the majority of the selected projects fall within the EU H2020 framework, their duration is expected to be up to four years, in alignment with the typical funding and implementation timelines of the program. This timeframe allows for comprehensive research, development, and deployment activities, ensuring the achievement of project objectives.

2.2.3. Project focus area

Figure 7 presents the number of projects associated with various focus areas of power system management and market design related to the selected TSO-DSO stakeholder interaction projects. As expected, the projects are primarily focused on the "Provision of system services from the distribution grid," indicating a strong emphasis on leveraging distribution networks for system stability and flexibility. Other significant areas include "Data exchange between DSO and TSO" and "Development of simulation environment / demonstrator / platform," reflecting efforts to enhance coordination and digitalization within the power sector. The focus areas trending toward "Market design and regulatory framework" have also received increasing attention, suggesting ongoing work in refining market structures to accommodate new flexibility solutions. In contrast, "Aggregation" has the lowest number of projects, However, this is expected to change as aggregation becomes increasingly vital for optimizing distributed energy resources and enhancing grid flexibility.

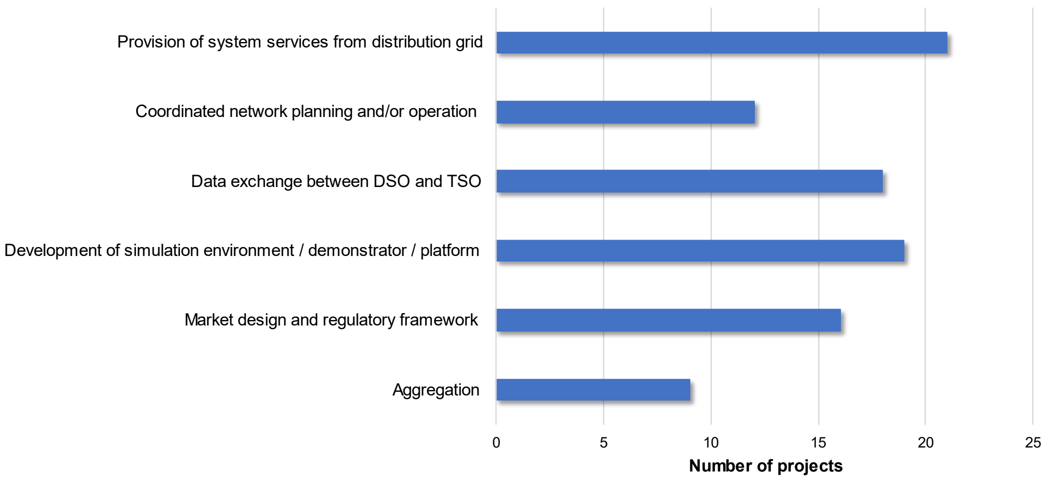


Figure 7: Focus areas of international projects on TSO-DSO-stakeholder interaction

2.3. Key Insights from pilot projects

2.3.1. Enhanced coordination between TSOs and DSOs

Insight 1: Clear stakeholder definitions and understanding of their evolving roles are essential.

- It is crucial to define clear roles and responsibilities for all stakeholders, across all system levels to ensure the effective integration and utilization of flexibility *(CoordiNet, EU-SysFlex, InteFlex, InterrFace, Platone, OneNet).*
- The role of the DSO is evolving to address the challenges posed by increased Distributed Renewable Energy Sources (DRES), growing demand, and market evolution. (*EvolvDSO, Hybrid VPP4DSO, CoordiNet)*
- The introduction of new business models highlights the evolving role of DSOs to becoming service procurers, neutral market facilitators, and enhancing consumer and prosumer engagement (*EvolvDSO, Hybrid VPP4DSO, GOFLEX, CoordiNet).*

Insight 2: Enhanced TSO-DSO coordination improves grid operations, optimizes resource utilization, and ensures system reliability.

- Improved TSO-DSO coordination is essential for managing new resources, demand growth, reduce grid reinforcement needs, and optimize planning. Flexibility procurement should be integrated into the Network Development Plan (NDP) for better long-term planning. *(CoordiNet, TDFlex, evolvDSO, TDX-ASSIST, EU-SysFlex)*.
- Real-time coordination between TSOs and DSOs is crucial for the effective provision of ancillary services, including voltage regulation, balancing, and congestion management. This marks a shift from traditional "fit-and-forget" methods to a more dynamic, Active Distribution System Management (ADSM) approach. Such a transition is essential for system operators to meet their core responsibilities while navigating the growing complexities of integrating DRES, EVs, and smart grid technologies *(SmartNet, EvolvDSO).*
- The interaction process between TSO and DSO should ensure that operational constraints at the distribution level (loading and voltage) are respected while effectively using distributed flexibilities. *(Industry4Redispatch, Interrface)*
- There are growing opportunities for industries linked to distribution networks to help mitigate transmission congestion and reduce redispatch costs through coordinated processes between the TSO and DSO. *(Industry4Redispatch)*
- Robust data exchange, coordinated maintenance, and shared resource management across multiple timeframes enhance collaboration among stakeholder (*EvolvDSO).*

Insight 3: Synergistic TSO-DSO collaboration and value stacking are central concepts in optimizing flexibility, efficiency, and reliability within the grid.

- Identifying value stacking and multi-buyer engagement as essential for scaling flexibility offerings advocates for enhanced TSO-DSO coordination to ensure optimized resource utilization *(InterFlex).*
- Synergies can be achieved by allowing DSOs to operate VPPs, utilizing existing infrastructure and expertise for grid-supportive activities. *(Hybrid VPP4DSO).*
- The hybrid TSO/DSO coordination model ensures that DSOs meet day-ahead market commitments from DERs while balancing local generation constraints and ancillary service schedules (*ATTEST).*
- Robust coordination enables value stacking and is vital to maximize resource efficiency to safeguard grid stability, and for consumer engagement through aggregators *(OneNet).*

- Leveraging synergies between flexibility needs, hybridization, and multiservice utilization enhances cost-efficiency, which in turn supports greater participation of flexibility resources, thereby contributing to improved system reliability *(OSMOSE).*

Insight 4: Effective TSO-DSO coordination helps mitigate potential conflicts and optimizes grid operations to meet flexibility needs.

- Effective collaboration between TSOs and DSOs is essential to prevent network conflicts (double service activation), particularly as TSOs increasingly procure flexibility from distribution grids *(TDX-ASSIST, EUniversal, ATTEST, CoordiNet, OneNet).*
- Aligning DSO flexibility markets with broader energy and balancing markets minimizes inefficiencies and resolves potential conflicts arising from multiple market platforms (*EUniversal, GOFLEX, CoordiNet, OneNet)*.
- Designing joint TSO-DSO flexibility market models ensures clear interaction frameworks, effective trading with Flexibility Service Providers (FSPs), and prioritization of system-wide efficiency *(GOFLEX, ATTEST).*
- Flexibility activation must avoid negative impacts on grid operations, with a prioritization framework addressing cross-border impacts, and system-level conflicts of interest. Thus, it is recommended to define a prioritisation order based on a holistic system view (*OSMOSE*).

Insight 5: Simulation and demonstration projects validate the importance of proactive strategies for TSO-DSO collaboration.

- Simulations conducted on real networks demonstrate how proactive strategies can enhance flexibility in response to increasing demand and renewable energy integration. *(EvolvDSO, OneNet)*
- Case studies in Italy, Denmark, and Spain have contributed to refining real-time coordination models, improving overall system efficiency *(SmartNet).*
- Simulated test cases validated the project developed tools in their capability to ensure grid stability and improved cost efficiency in TSO-DSO operations *(Osmose).*
- A key benefit to pilot projects allows for stakeholders to gain first-hand experience with the full suite of solutions, including the installation, setup, and operation of hardware, software, and user interfaces. This has proven to be a valuable learning experience for stakeholders, providing insights into the competencies and resources required from future market players *(GoFlex).*

2.3.2. Technological innovation and integration

Insight 1: Predictive tools and algorithms enhance grid management, flexibility and operational efficiency.

- Predictive models for asset renewal and maintenance reduce costs and extend asset lifetimes. *(EvolvDSO)*
- Data-Driven State Estimation (DdSE) reduces grid reinforcement costs and improves congestion forecasting. *(EUniversal)*
- Integrated operation planning bridges long-term and operational planning, with methodologies addressing medium- and low-voltage flexibility resources. (*InterPlan)*
- Traffic Light System (TLS) to streamline TSO-DSO interactions and ensure grid resilience and operational safety while integrating DERs was shown to be effective. By using Optimal Power Flow (OPF) algorithms, the TLS allows DSOs to evaluate grid constraints and economic factors for flexibility activation, enabling coordinated TSO-DSO operations. (*InteGrid*)
- AI-driven tools improve dynamic grid management and enable advanced forecasting and monitoring of grid states. (*GOFLEX, OneNet*)

- Scenario-driven planning and predictive algorithms enable adaptability to diverse grid conditions *(InterPlan, Inustry4Redispatch).*
- Real-time platforms integrate grid monitoring and congestion management (*Interrface*).
- The integration of blockchain, big data, and AI-enabled innovations such as Dynamic Network Usage Tariffs (DNUT) and distributed generation technologies for renewable energy optimization (*Interrface*)

Insight 2: Advanced metering, sensing, and control technologies improve grid observability and integration of flexibilities.

- The increasing complexity of energy systems calls for investments in advanced smart grid infrastructure to effectively integrate RES and ensure sustainability. *(EU-SysFlex)*
- Advanced metering, sensing, and control technologies are key enablers of system efficiency and cost-effective renewable energy integration *(EvolvDSO, OneNet, Redispatch 3.0, Platone).*
- Smart meter rollouts enable real-time power measurement and switching capabilities, benefiting DSOs through improved operational visibility and flexibility management. *(Hybrid VPP4DSO, CoordiNet)*
- In regions where smart meter rollouts are delayed, sub-metering regulations can help maintain market functionality. The use of sub-meters is advised to ensure data accuracy and support the effective operation of the market *(CoordiNet, OneNet).*
- Access to smart meter data, is a critical element for grid optimization, remains constrained by complex consent processes and strict anonymization requirements *(InteFlex).*
- The ongoing smart meter rollout in the EU further indicates the significant disparities across Member States *(InterConnect*).

Insight 3: Grid flexibility is critical for managing renewable energy sources and distributed generation.

- Advanced tools have proven effective in optimizing grid flexibility and fault management (*EvolvDSO, TDX-ASSIST*).
- Hybrid Virtual Power Plants (VPPs) mitigate voltage challenges in critical network areas, providing a robust solution for managing renewable energy feeders *(Hybrid VPP4DSO*)
- Flexibility management systems can be used to effectively integrate DERs, ensuring adaptability in grids with high renewable energy penetration. *(InteGrid, FlexGrid, CoordiNet, OneNet*)
- Advanced optimization strategies for shared energy storage systems have demonstrated significant operational and economic benefits, outperforming traditional approaches. (*ATTEST*)
- The integration of Distributed Generation (DG) constraints into market-clearing processes has enhanced real-time operational security and efficiency, significantly contributing to grid flexibility (*ATTEST, CoordiNet, OneNet*)

Insight 4: Deployment challenges highlight the need for robust solutions.

- Legacy infrastructure may pose challenges during installations and system upgrades. Deployment faced significant technical hurdles, IT security conflicts, and compatibility issues with existing/legacy infrastructure. *(GoFlex, Interconnect)*
- The integration of RES into distribution systems required new technological systems capable of real-time management and monitoring, presenting deployment challenges related to system coordination and optimization (*SmartNet*)
- Integration of cloud-based grid-market hubs for flexibility management encountered challenges related to seamless data exchange and the integration of DERs, requiring careful deployment strategies (*InteGrid*).

- The integration of advanced IT platforms and open protocols for flexibility management required overcoming challenges in scalability, security, and privacy compliance during deployment, especially in complex environments. *(InteFlex*)

Insight 5: Modular approaches are essential for implementing smart grid solutions.

- Modular architectures enable cross-platform adaptability and scalability and, thus, address regional challenges and differences in grid configurations and market requirements. *(OneNet, InterConnect, FlexGrid, Platone)*
- Modular frameworks proved to be essential for interoperability, allowing stakeholders to engage with multiple platforms while avoiding vendor lock-in *(EUniversal, InterConnect)*
- Solutions that maintain modularity allow its components to be implemented individually or as an integrated system based on the specific requirements of market actors. This is a key opportunity for the continued exploitation of the solutions beyond the project's conclusion date *(GoFlex)*.

2.3.3. Customer engagement

Insight 1: Consumer-centric frameworks enhance participation in flexibility markets.

- Empowering consumers through data-driven services enables them to access standardized data and flexible contracting options to engage in electricity markets effectively *(EvolvDSO, EU-SysFlex).*
- Consumer-centric energy systems by enabling VPPs to participate dynamically in flexibility markets. This reduces inefficiencies tied to conservative practices and promotes equitable market participation, empowering prosumers in DER-rich environments (*InteGrid*).
- Tools such as energy balance displays, and peer-to-peer (P2P) trading platforms empower users but face challenges from immature markets, low financial incentives, and complex designs. Consumer-centric solutions that enable value stacking and align with user expectations are critical for broader adoption (*InteFlex*).
- Simplified aggregator models, automated systems, and educational efforts are needed to lower participation barriers and align incentives (*OneNet*).

Insight 2: Economic, environmental, and societal incentives are drivers for consumer participation.

- Dynamic tariffs, tax incentives, and carbon footprint data effectively motivate consumers to adopt demand response behaviours (*InterConnect, EUniversal*).
- Social responsibility is closely linked to environmental impact awareness which increases user engagement and adoption of flexibility solutions (*InterConnect*).
- Enhanced liquidity and profitability mechanisms for DER investors' market architectures encourage broader participation from prosumers *(FlexGrid).*
- Not all consumers can be considered identical as there is clear variation in customer consumption and demographics. Different user demographics require distinct approaches: wealthier households, equipped with PV systems, EVs, and smart home appliances, have greater potential for offering demand-side flexibility than lower-income households facing energy poverty *(InterConnect).*
- Energy literacy of consumers should also be considered as user engagements may vary when data is presented in monetary terms (euros) in contrast to technical units (kWh) (*InterConnect)*

Insight 3: Enhanced user experience is key to building trust, driving consumer engagement, and ensuring sustained participation.

- Consumer feedback emphasized the need for simplified interfaces, clearer explanations of system benefits, trust-building efforts and improved energy monitoring tools. *(GOFLEX, OneNet, InteFlex*).
- Hybrid-VPPs were shown to enhance customer loyalty by enabling participation in balancing markets and encouraging stronger relationships with energy providers (*Hybrid VPP4DSO*).
- To ensure the sustainability of customer engagement over the long term, it is important that demand response programmes do not entail undesired and unnecessary complexities (*InteFlex, InterConnect*).
- Automation of demand response mechanisms, such as automated rescheduling of appliance operations and the introduction of push notifications to simplify consumer decision-making and improve user engagement (*InterConnect, GOFLEX, InteFlex*).

Insight 4: Awareness and education programs are key to empowering consumers.

- Many consumers expressed confusion about system purposes, highlighting the importance of trust-building, user empowerment and education programs. *(EUniversal, OneNet, CoordiNet, InteFlex, GOFLEX)*
- Consumer awareness of their role in providing flexibility services and their associated opportunities is currently low. Clear information is needed to engage prosumers and enable their participation in flexibility markets *(OneNet, CoordiNet).*
- Consumer participation was identified as a key challenge due to limited awareness of flexibility markets, insufficient incentives, and minimal direct contact with DSOs. Outreach programs and incentives (e.g., grid tariff or tax reductions) were recommended to boost engagement *(EUniversal).*

2.3.4. Advanced ICT tools as enablers of smart grid solutions and stakeholder coordination.

Insight 1: Effective coordination between TSOs and DSOs depends on advanced ICT tools for optimizing grid operations.

- Advanced ICT solutions facilitate real-time monitoring, control of distributed generation, and integration of flexibility resources, ensuring effective coordination for grid management *(EvolvDSO, ATTEST, InterPlan, EU-SysFlex, SmartNet, GOFLEX).*
- Architectures that rely on advanced ICT tools for iterative communication and decision-making, support real-time coordination between TSOs and DSOs, ensuring efficient operations in high-RES scenarios *(FlexGrid).*
- Real-time data exchange protocols and decision-support tools are critical for addressing operational challenges and optimizing system constraints in grid operations *(OneNet).*
- The integration of advanced ICT tools is essential for ensuring the feasibility and efficiency of the flexibility bidding process. These tools include algorithms that help optimize bid combinations for TSOs and DSOs *(Industry4Redispatch).*

Insight 2: ICT tools enhance operational planning, strengthen system coordination, and improve system observability.

- Enhanced operational planning frameworks demonstrate how ICT tools optimize network operations ahead of market gate closures and enable stakeholder coordination (*EvolvDSO*).

- Advanced ICT tools to enable automated trading platforms, active network management, such as grid observability tools for real-time monitoring, and dynamic line rating and flexibility forecasting tools for better congestion management *(EUniversal, GoFlex).*
- ICT solutions for addressing TSO and DSO voltage control challenges, with their capability to operate across multiple time horizons (e.g., real-time, day-ahead, and operational planning) have proven to be robust *(Osmose).*

Insight 3: Cost-effective ICT solutions enable smart grid coordination.

- The implementation of ICT systems has relatively minor costs compared operational costs for all TSO-DSO coordination schemes *(SmartNet).*
- While high initial ICT costs may deter DSOs from adopting flexibility, the integration of these tools is essential to enable real-time coordination, forecasting, and ancillary service provision and is outweighed by the long-term benefits of enhanced real-time coordination and market-based procurement of reserves. *(SmartNet, FlexGrid)*
- ICT Infrastructure capable of meeting high standards for latency, cybersecurity, and failure recovery is a necessity for the integration of smart grid solutions (*SmartNet, Hybrid VPP4DSO, Flexgrid, InterConnect).*

Insight 4: Accurate forecasting enhances flexibility management and grid optimization.

- The use of scenario-driven operation planning and reliable forecasting tools, ensures adaptability for diverse grid conditions *(IntePlan, EU-SysFlex, FlexGrid, CoordiNet).*
- Accurate load and generation forecasting and advanced simulation tools are critical for making informed decisions in flexibility bidding and network state optimization *(Industry4Redispatch, EU-SysFlex, CoordiNet).*
- Low-quality forecasts and non-unity bid power factors significantly degrade calculation accuracy, leading to misjudgements concerning the feasibility of bid combinations and ultimately to increased redispatch costs *(Industry4Redispatch).*
- Limited predictive accuracy of grid congestion and suboptimal response rates to flexibility offers lead to challenges *(GoFlex).*

Insight 5: Effective TSO-DSO Coordination relies on scalable and secure ICT solutions.

- ICT tools enable secure, scalable, and interoperable data exchange, integrating TSO-DSO coordination *(TDX-ASSIST; EUniversal, FlexGrid, EU-Sys-flex, CoordiNet)*
- The ICT infrastructure should transition toward lightweight, secure messaging protocols (such as MQTT and AMQP) to enable real-time and scalable communication between stakeholders *(TDX-ASSIST, OneNet)*
- Scalability of ICT solutions depends on reducing deployment costs and aligning stakeholder incentives. Thus, future implementations should also address these economic considerations alongside technical and user-centric improvements (*GoFlex*)
- The economic analysis proved the financial viability of flexibility trading, which further indicated scalable benefits for both prosumers and DSOs (*GoFlex*)
- By utilizing the cloud-based grid-market hub for seamless data exchange between TSOs, DSOs, and VPPs, the traffic light system ensures scalable and coordinated operations. The study highlighted the mismatch between economic drivers (pricing) and technical priorities (location of DERs) should be noted (*InteGrid*)
- The scalability of market algorithms is also critical where leveraging existing auction platforms, additional constraints can be incorporated with minimal disruption (*Interrface*).
- From a scalability perspective, processing the massive volumes of data generated daily by over six million LV grid delivery points presents substantial computational challenges (*InterConnec*t).

- Scalability and replicability depend heavily on regulatory alignment, as divergent transpositions of European Directives into national regulation contain many barriers (*InterConnect, CoordiNet*)

2.3.5. Data exchange, standardization, and interoperability

Insight 1: Standardization and interoperability are critical to addressing TSO-DSO coordination challenges.

- The importance of standardized communication protocols, data exchange and formats was emphasized for achieving interoperability, enabling cross-platform interactions, enhanced synergies and reducing complexities in TSO-DSO interaction *(EUniversal, InterConnect, FlexGrid, Osmose, CoordiNet, InteGrid, Interrface, ATTEST)*
- Effective TSO-DSO collaboration requires transparent communication, shared language, and unified efforts to address system-wide and localized issues (*CoordiNet, OneNet, Osmose*)
- The integration of a growing number of participants in the power system necessitates robust interoperability standards for secure, privacy-conscious cross-border and cross-sector data exchanges. However, these aspects can only occur with a trade-off between them *(EU-SysFlex, Industry4Redispatch, Platone).*
- Enhanced CIM standards adoption among DSOs, particularly for incremental data exchanges, is essential for aligning with TSO systems (*TDX-ASSIST, InteFlex, Platone*)
- It is recommended that standardization bodies such as IEC and ENTSO-E refine communication protocols and data exchange methodologies, thereby ensuring robust interoperability and scalability across European power grids (*TDX-ASSIST, InteFlex*)

Insight 2: Cybersecurity measures are necessary for the implementation of scalable solutions.

- The importance of cybersecurity measures, particularly for data shared over public internet links, should not be underestimated. Public internet, communication, and cloud services need to meet minimum latency requirements, ensure cybersecurity, or provide reliable failure response, to mitigate challenges required for the scalability and security of the system (*TDX-Assist, InterConnect).*
- Real-time monitoring, robust communication infrastructure, and secure protocols to mitigate cyber risks are important for distributed flexibility (*TDX-Assist*, *OneNet*).
- In contrast, local flexibility control based on time schedules or local measurements has been found to be sufficient to unlock the potential of flexibilities. By reducing the number of communications exchanges and requirements, through the scheduling of devices e.g. BESS, and simplifies the implementation of flexibility support is simplified and is considered an inherent feature of cyber security (*TDFlex*).

Insight 3: Data availability and accuracy for is critical network modelling and implementation of solutions.

- The requirement for tools that facilitate incremental updates to network models in greater accuracy poses as a challenge in TSO-DSO coordination use cases *(TDX-Assist).*
- With 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 and lack of detailed models. Intrinsic grid equivalenting methodologies and tools can be incorporated to facilitate TSO-DSO interaction *(InterPlan).*
- The resource-intensive nature of data pre-processing and network modelling for DSOs, which, while demanding, can synergize with advancements in smart metering, AI, and data quality (*OneNet*).

- Low availability and inaccuracy in LV topology data from DSOs, especially when not linked to Geographic Information Systems (GIS), pose further challenges, as accurate topology information is essential for generating precise demand response grid signals (*InterConnect*).

2.3.6. Evolving market mechanisms for flexibility: prequalification, procurement, and activation

Insight 1: Market mechanisms must evolve to support distributed flexibility resources.

- Revising market structures to remove barriers for small assets participation and resolve issues related to low-carbon generation revenues encourage investment in emerging technologies (*EU-SysFlex*).
- Local flexibility markets and dynamic flexibility areas define operational constraints while minimizing the need for extensive data sharing (*EUniversal).*
- Tailored flexibility products and cross-border ancillary services markets address varying timescales, harmonized market challenges, and operational needs (*OneNet*).
- Revision of market mechanisms is necessary to ensure that resources from both transmission and distribution networks are efficiently utilized, especially in balancing and congestion management. It is recommended that flexible market models facilitate the procurement of ancillary services, such as minimizing resource acquisition without disrupting energy market outcomes (*SmartNet*).
- A coordinated marketplace between TSOs and DSOs is essential to prevent overlapping markets and price disparities. The participation of distributed resources in these markets should ensure a level playing field, accommodating the unique characteristics of industrial loads and other distributed energy resources *(SmartNet, CoordiNet).*

Insight 2: Flexibility prequalification, procurement, and activation are key to efficient grid integration and market coordination.

- Ensuring grid compatibility with market actions strengthens flexibility procurement and DSO-market interactions *(EvolvDSO).*
- Holistic approaches to flexibility activation based on a holistic system view improve cost efficiency and avoid network constraint violations (*Osmose*, *Industry4Redispatch, InteGrid, EvolvDSO*).
- Harmonized prequalification requirements and shared market designs maximize efficiency and social welfare by allowing TSOs and DSOs to access common flexibility resources (*CoordiNet, OneNet*).
- Flexibility procurement at the local level can replace the need for costly grid infrastructure expansion, offering an alternative solution for congestion management and peak load shaving (*GoFlex*).
- Flexibility procurement should also account for time intervals, contingency cases, and network states, ensuring that the bids remain feasible across different operational scenarios (*Industry4Redispatch*).

Insight 3: Market liquidity is critical for the effective functioning of flexibility markets.

- Market-based mechanisms are critical for the utilization of flexibility resources. The design of flexibility products must address market liquidity and prevent strategic gaming to ensure fair participation and system efficiency *(EU-SysFlex)*
- The need for market standardization and liquidity to improve competition among platforms, could be addressed through regulatory intervention and harmonization *(EUniversal*).

- Local flexibility markets revealed challenges in participation rates and aggregator engagement due to low power volumes and limited business incentives *(OneNet).*
- Local flexibility markets face challenges such as low liquidity, limited aggregator engagement, and inconsistent DSO demand. Temporary incentives, complementary markets (e.g., spot, reserve), and tailored products addressing varying timescales and operational needs can improve participation *(InteFlex, OneNet).*
- Harmonizing prequalification requirements and automating processes are necessary to enhance market liquidity (*CoordiNet, OneNet*).

Insight 4: Flexibility markets enhance system reliability and cost-efficiency.

- Innovative market mechanisms, such as P2P trading and cost-effective activation of flexibility resources, to enhance market efficiency and grid stability (*InteGrid, Interrface)*
- The role of DSOs in managing congestion and grid constraints through local markets, dynamic tariffs, and certified operators, addressing challenges like low liquidity, fragile aggregator models and inconsistent demand *(InteFlex, Interrface)*
- Flexibility procurement at the local level offers alternatives to costly grid infrastructure expansion for congestion management and peak load shaving *(GoFlex).*
- Dynamic tariffs, price signals, and automated demand response effectively engage consumers, enhancing flexibility procurement and grid flexibility *(InterConnect).*

Insight 5: Business models need to be further developed to increase stakeholder participation.

- Challenges in improving the business case for flexibility service providers (FSP) have been identified. These are related to high participation costs and market uncertainty, driven by seasonal and annual variability in flexibility demand, which was shown to significantly impact FSP profitability. Increased automation could help increase market participation and support clear communication from system operators regarding flexibility needs which consequently can reduce uncertainties. Additionally, transparent, and accurate market prices reflecting the value of services based on location and availability are crucial for enhancing market predictability (*CoordiNet*).
- In some countries, national regulations hinder DSOs from recovering investments and costs for new market solutions for system services. To address this, DSO remuneration schemes need to recognize the costs associated with establishing flexibility markets and mobilizing flexibility resources (*CoordiNet*).
- From the aggregator's perspective, there is often limited business incentive due to limited customer power availability and the limited value of flexibility compared to network reinforcement costs *(OneNet*).
- Regulations market mechanisms and their integration need to be designed and further developed, especially in the case where there is an absence of existing regulations to incentivise the use of flexibility (*OneNet*).

2.3.7. Regulatory and policy frameworks

Insight 1: Policymaker and stakeholder alignment is essential to remove barriers and enable innovation.

- Market and regulatory shortcomings must be addressed to enable flexibility services, low-carbon technologies, and the integration of RES. *(EU-SysFlex, Osmose, Flexgrid).*

- Regulatory adjustments should support scalable and replicable solutions across diverse markets and ensure equitable participation for small-scale DERs *(ATTEST, CoordiNet, OneNet, InteGrid).*
- Policymakers, regulators, DSOs, TSOs, and market operators must work together to align frameworks and promote innovation *(Industry4Redispatch, OneNet, InterConnect, EU-SysFlex,GoFlex, InteGrid*).
- Clear roles and responsibilities must be defined for all stakeholders in flexibility markets, including traditional and new agents, with these definitions standardized at the EU level in network codes for demand-side flexibility at the distribution level (*CoordiNet, OneNet*).
- Flexibility solutions and optimization algorithms are prepared for large-scale implementation. However, it was noted that their successful adoption is dependent on the amendment of current national regulations and network codes (*OneNet*).

Insight 2: Overcoming regulatory barriers is essential to enable scalable solutions.

- Regulatory alignment is important to overcome barriers in TSO-DSO collaboration and scalability of innovative solutions. It is thus recommended to harmonize regulatory frameworks to support the integration of flexibility and scalability of smart grid solutions (*InteGrid, ATTEST, CoordiNet, OneNet, FlexGrid, Osmose, Industry4Redispatch, InterConnect*).
- Supportive regulations are needed for control infrastructure funding and standardization. Policies enabling grid investment deferral through flexibility remuneration and streamlined data access under GDPR are crucial for scalable implementation (*InteFlex*).
- Scalability and standardization of solutions are crucial to adapt the models across diverse regulatory environments, ensuring that multiple DSOs can be integrated without compromising market liquidity (*ATTEST*).

Insight 3: Regulatory sandboxes provide a way to test solutions in a controlled environment.

- To address regulatory constraints, regulatory sandboxes were identified as a way to provide controlled environments to test innovations (*EUniversal, OneNet, Platone, CoordiNet*).
- Regulatory sandboxes are proposed to explore optimal conditions for the implementation of hybrid market-based and rules-based methods as they provide mechanisms to assess and support the development concepts (*CoordiNet*).

Insight 4: Data privacy and GDPR require secure, standardized exchange while balancing transparency, confidentiality, and accuracy.

- GDPR-compliant mechanisms (*EUniversa*l) and standardized communication protocols (*CoordiNet*) ensure market data privacy.
- GDPR-compliant access to smart metering data is essential, but complex consent processes and anonymization thresholds hinder data utility. Simplifying these processes could enhance data sharing and reduce sensor requirements (*InteFlex*)
- GDPR-compliant data-sharing frameworks for effective collaboration. Its modular architecture supported the seamless integration of flexibility resources into existing systems (*Platone*).
- Transparency and confidentiality are central concerns in data exchange, with a trade-off between the two, as only two out of three key requirements, transparency, confidentiality, and accuracy, can be maximized at once (*Industry4Redispatch*).

Insight 5: Adapting regulations to support evolving roles in flexibility markets is crucial.

- Adapted regulatory frameworks are needed to consider new roles of system stakeholders (*GoFlex, CoordiNet, EvolvDSO).*
- Framework adaptations and incentives targeting DSOs, regulators, energy suppliers, and industrial customers are critical for hybrid-VPP implementation. *(Hybrid VPP4DSO)*
- DSOs need regulatory support to manage flexibility resources effectively across different voltage levels. This will support the DSOs' transition towards active distribution system management, enabling optimal grid operation and DRES integration (*EvolvDSO, EU-SysFlex*).

3. Detailed insights from selected international pilot projects

This section presents a more detailed analysis of key findings and builds on the previous overview by providing a deeper, more detailed examination of selected international pilot projects focusing on three critical areas of power system coordination. Data exchange between power system stakeholders, highlighting the importance of seamless information sharing for operational efficiency is explored. Market-based coordination, emphasizing how market mechanisms are leveraged to enhance collaboration and optimize system performance. Furthermore, coordination through common prequalification procedures is addressed, showcasing how standardized approaches can streamline stakeholder interactions and improve system integration.

3.1. Data exchange between power system stakeholders

The implementation of different TSO-DSO coordination schemes for the demonstration of system service markets in EU-funded projects has involved different types of Information and Communication Technologies (ICTs) for the data exchange between stakeholders [1].

Traditionally, the Inter-Control Center Communications Protocol (ICCP or IEC 60870-6/TASE.2) has been used for the exchange of time-series data, scheduling information, and control operations between the Supervisory Control and Data Acquisition (SCADA) systems of System Operators (SOs). ICCP is a wide area network client-server protocol whose default standard version needs the security improvements provided by Secure ICCP [2] and the data and communication security measures defined by IEC 62351-3 & 4, which include in their scope the profiles used by ICCP.

However, in the current digitalization landscape of the electricity sector, where the use of Information Technologies (IT) and IoT is increasing, the use of data exchange platforms and internet communication technologies is a common approach in innovation projects for the communications between TSOs and DSOs. In some cases, such as in the Greek and Spanish demonstrations of CoordiNet [3], the platforms developed also use ICCP for specific information, such as activation signals (Spanish demo) or general TSO-DSO coordination information (Greek demo) [1]. In other cases, such as in the Slovenian demo of TDX-Assist [4], the ICCP connection is used for the exchange of real-time data between the DSO and the market platform operated by the TSO, while meter and grid data are exchanged using the ECCo SP, which provides compatibility with AMQP, WS, and File System Shared Folder (FSSF) protocols [5]. In addition, ECCo SP was used by the “Single Flexibility Platform” demo within the INTERRFACE project as the main platform for the data exchanges between TSOs and DSOs [6]. In the case of the “Flexibility platform” demo of EU-SysFlex, the Estfeed platform, which implements its own communication protocol supporting publish-subscribe and client-server mechanisms [7], is implemented for all the interactions between stakeholders.

The use of such platforms facilitates the connection of different stakeholders, as the system to access the different types of data is the same and the different entities can connect without investing in dedicated communication links (e.g., ICCP connections). However, from the cybersecurity point of view, it must be considered that IT may require specific security measures, so information security standards such as ISO/IEC 27002 and 27019 should be adopted by SOs. In addition to this, if HTTP-based REST APIs are developed for exchange of data between systems of SOs or to connect to the platform (e.g., UMEI in EUniversal [8] or some communication links in OneNet demos [9]), these should be designed following best practices in REST API development, so that they can easily be implemented by all stakeholders, and adopting the necessary security practices depending on the data exchanged and the process involved.

Regarding data models, the Common Information Model (CIM) has gained attention in many EU-funded projects [1]. Its two-core family of standards, IEC 61970 (Energy Management System APIs) and IEC 62325 (energy market communications), and the extensions in IEC 61968 (network models and distribution network data) cover a wide range of the information that can be exchanged between SOs and other stakeholders. However, it still poses some challenges in terms of compatibility with other standards (e.g., IEC 61850, widely use in the sector) and its extensions, which are not always standardized [10]. In addition to this, it has been appreciated that it does not provide full coverage when dealing with data hubs, data aggregation and anonymization, data exchange between DERs and SOs, and when implementing other flexibility services besides balancing [11]. Table 1 summarizes the main characteristics and scope of the ICT discussed in this section.

Table 1: Summary of the characteristics and main scope of the ICT discussed.

ICT	Characteristics	Main Scope
ICCP (IEC 60870-6/TASE.2)	Wide area network client-server protocol traditionally used for communications between control centers. Considered in CoordiNet, as well as in TDX-Assist for the exchange of real-time data between the DSO and the market platform.	• Time-series data. • Scheduling information. • Control operations.
ECCo SP	ENTSO-E platform compatible with different communication protocols, including AMQP, WS, and FSSF. Used in TDX-Assist and INTERRFACE projects.	• Meter data. • Grid data. • Other TSO-DSO data exchanges.
Estfeed platform	Implemented in EU-SysFlex project, it defines its own communication protocol supporting publish-subscribe and client-server mechanisms.	• All interactions in EU-SysFlex.
HTTP-based REST APIs	Increasingly common for data exchanges between systems of stakeholders and/or to connect to platforms.	• All types of data.
Common Information Model (CIM)	Data model increasingly used in EU-funded projects. It covers a wide range of the information that can be exchanged between SOs and other stakeholders, although compatibility issues may arise during implementation.	• IEC 61970: Energy Management System APIs. • IEC 62325: Market communications. • IEC 61968: network models and distribution network data.

3.2. Market-based coordination among power system stakeholders

Among the EU-funded projects, the OneNet project focused, within other activities, on the analysis and design of coordination between power system stakeholders such as TSOs, DSOs and Service Providers (SPs). The OneNet demonstrators proposed different designs for the procurement of system services from third-party SPs. The use of third-party resources in power system operation involves at least two power system stakeholders, thus coordination between them is essential. In the context of procurement of system services, at least two-way coordination between power system actors is observed. However, more complex coordination schemes are required when more than two actors are involved in the flexibility provision process (e.g. when a TSO uses flexibility resources connected to the distribution system). Irrespective of the number of actors involved, coordination for the procurement of system services can be considered as *market-based* or *technical-based*. Market-based coordination involves a market architecture to coordinate the actors, while technical-based coordination involves direct interaction between actors through information exchange and requests for operational actions.

Within the project, the demonstrators using market-based TSO-DSO coordination adopted a scheme where the TSO and DSO are coordinated through a market architecture (Figure 8). Flexibility is allocated between the system operators via market-based processes, such as bid forwarding and prioritization in bid selection. Bid forwarding is a process where unused bids from one market can be forwarded to another, increasing the potential to be cleared. In this market-based coordination, the market architecture for procuring flexibility sits between the two system operators. For simplicity, Figure 8 does not show the necessary data exchange and activation signals between the procuring system operator and the service provider. TSO-DSO data exchange can vary depending on the adopted coordination scheme and the regulatory framework in force.

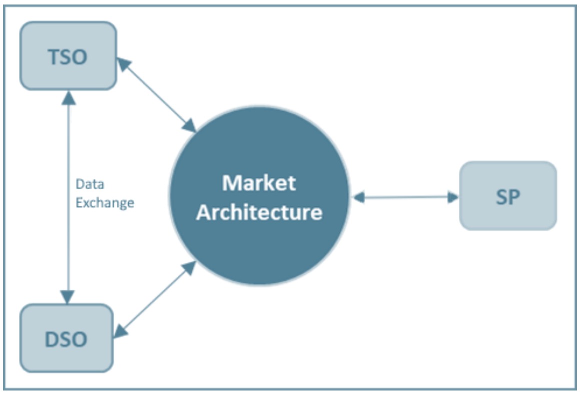


Figure 8: Conceptual scheme of the power system stakeholders coordination, source: [12], [13].

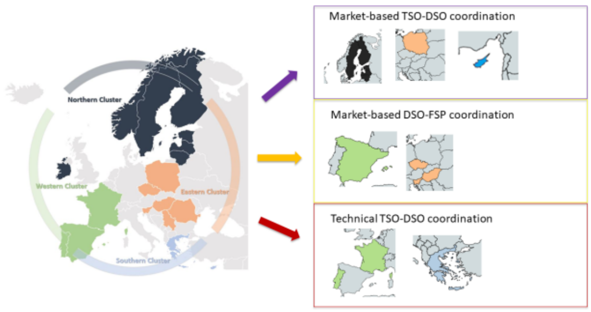


Figure 9: From geographical clustering to market design demonstrators' clustering, source: [13].

Figure 9 and Table 2 provide the result of the clustering of the OneNet demonstrators, considering the classification of the nature of the coordination as in Figure 8, based on [13], [14].

Table 2: OneNet demonstrators' classification based on the coordination type, source: [13].

Market architecture	Market-based coordination	Technical based TSO-DSO coordination
OneNet Demonstrators	Cyprus, Poland, Northern cluster, Spain, Slovenia, Hungary, Czech Republic	France, Portugal, Greece

The OneNet demonstrators dealing with market-based coordination proposed different design solutions for their market architecture and the market phases. Table 3 provides a comparison of the demonstrators depicted in Table 2 considering the stakeholders' market-based coordination aspects defined in the Theoretical Market Framework proposed in [12]:

- **Coordinated stakeholders** indicate the actors that the market-based coordination involves (Transmission System Operator – TSO, Distribution System Operator – DSO, Service Provider

– SP, Independent Market Operator - IMO). SP is considered generally as single or aggregated units, as defined in [15].

- **Mechanism for coordination:** a discrete auction market is a type of trading system where transactions occur at specified intervals, allowing multiple buyers and sellers to participate in a pooled environment. Orders are processed in batches to determine the clearing price.
- **TSO-DSO Coordination scheme**, as defined in [16], refers to the market framework in which both DSOs and TSOs can solve system needs with a large set of common resources to enhance the overall efficiency and reliability of the power grid.
- **Timeframe for coordination** defines the timing in which the service provision is procured through the market-based coordination. In this document, the procurement timeframe is classified into short-term, which includes near-to-real-time (15 minutes), intraday, and day-ahead; medium-term, which includes days or weeks ahead; and long-term, which includes months ahead, seasonally, and annually.
- **Generalized product traded**, as defined in [12], represents the electrical parameter that the parties commit to exchange to satisfy system service need, it is represented by active or reactive power availability, activation, availability and activation.
- **TSO-DSO allocation principle of flexibility**, as defined in [12], determines how the amount of flexibility at the transmission or distribution level is divided between SOs, hence defining a priority among them.
- **TSO direct access to DERs** represents the possibility for the TSO to procure from the SPs connected to the distribution network to procure system services directly.

Table 3: Comparison of the demonstrators considering the stakeholders' market-based coordination aspects.

		Spain	Poland	Czech Republic	Hungary	Northern cluster	Cyprus	Slovenia
Coordinated stakeholders		DSO, SP, IMO	TSO, DSO, SP	DSO, SP, IMO	DSO, SP	TSO, DSO, SP, IMO	TSO, DSO, SP, IMO	DSO, SP
Mechanism for coordination		Discrete auction	Discrete auction	Discrete auction	Discrete auction	Discrete auction	Discrete auction	Discrete auction
TSO-DSO Coordination scheme		Fragmented	Multi-level	Fragmented	Fragmented	Common	Multi-level	Fragmented
Timeframe for coordination		From long-term to near-real-time	From weeks ahead to near-real-time	From long-term to near-real-time	From weeks ahead to day-ahead	From long-term to near-real-time	From intraday to near-real-time	Long-term
Procured generalized product	Active power availability	X	X	X	X	X	X	X
	Active power availability activation	X	X	X	X	X	X	X
	Reactive power Availability			X	X			
	Reactive power activation			X	X			
TSO-DSO allocation principle of flexibility		Exclusivity for DSO	Priority for DSO	Exclusivity for DSO	Exclusivity for DSO	No Priority	Priority for DSO	Exclusivity for DSO
TSO direct access to DERs		Not applicable	Yes	Not applicable	Not applicable	Yes	Yes	Not applicable

The OneNet project demonstrators' market architectures can be classified according to the coordination schemes defined in the CoordiNet project [17], [18], [19]. Figure 10 illustrates the classification of OneNet demonstrators; each country block represents the corresponding market architecture. The figure also describes these market architectures in terms of the timing of TSO–DSO coordination and the corresponding level of market-based coordination. Consequently, the OneNet demonstrators fall into three different market models that define specific TSO–DSO coordination schemes: common, multi-level, and fragmented [20]. The common market model defines a single TSO–DSO market to procure system services from resources connected to both transmission and distribution grids. The multi-level market model distinguishes between TSO and DSO markets, allowing the TSO to access distributed energy resources (DERs). In the fragmented market model, TSO and DSO operate dedicated, non-linked markets, with the TSO not having access to DERs.

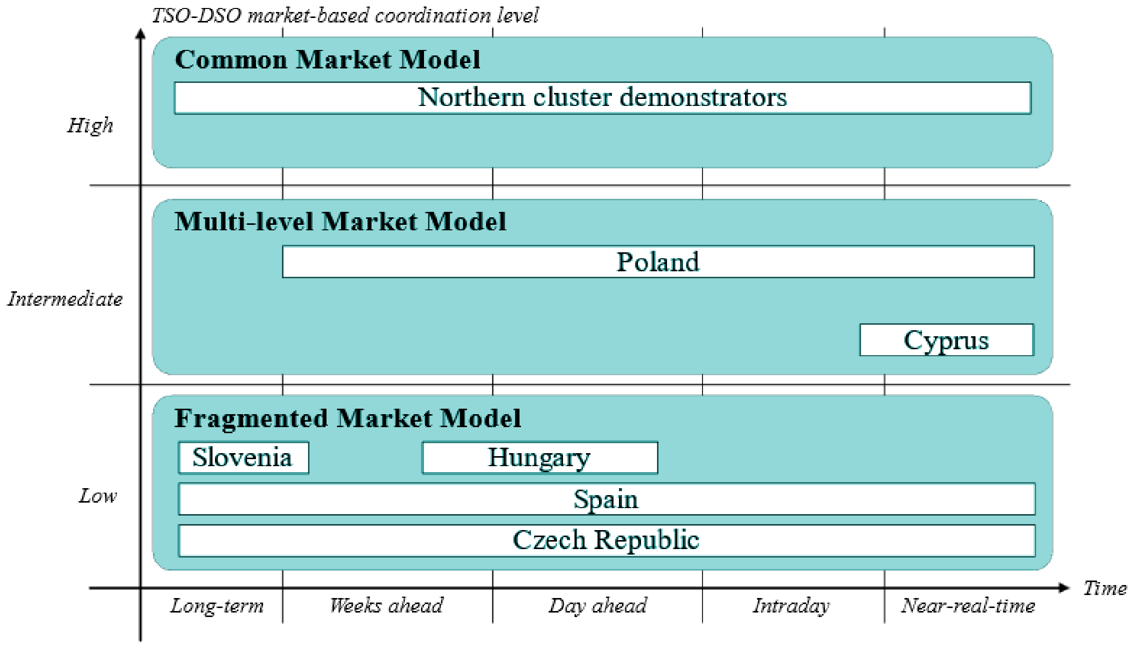


Figure 10: Market architectures of OneNet demonstrators in terms of TSO–DSO coordination schemes. Source: [12].

Furthermore, Figure 10 shows that the Northern demonstrator implements the common market model. The Polish and Cypriot market architectures implement a multi-level market model. The Hungarian, Slovenian, Spanish, and Czech demonstrators proposed a fragmented market architecture. In the following, a description of the demonstration activities related to the stakeholders' market-based coordination is provided for the demonstrators in Figure 10, based on [13], [14].

The Spanish demonstration uses market-based coordination between DSOs and SPs to ensure that the flexibility provided by DERs meets specific local congestion management needs while minimizing any impact on other areas [21], [22]. The demonstrators utilize a local market where the DSO has exclusive access to DERs. The local markets include long-term and day-ahead availability and activation markets, as well as an intraday real-time activation market. In availability markets, specifying the expected number of activations is necessary to assess the total procurement cost. SPs selected in the availability market, if activation has not been contracted in advance, must compete with other SPs in the relevant activation market to ensure that the lowest bids are selected. A digital platform that implements the local markets, allowing DSOs to acquire the necessary system services from SPs, has been designed, developed, and demonstrated in the Spanish OneNet pilots [21], [22].

The activities of the Polish demonstrator focus on facilitating the provision of system services to both TSO and DSO through distributed resources, encompassing balancing, congestion management, and voltage regulation [23], [24], [25], [26]. The primary objective was to empower resources connected to the distribution level in supporting the operational needs of both the DSO and TSO. Aligned with market-based coordination, a digital platform has been developed and tested to implement market-based coordination for system service procurement. The Polish market architecture is characterized by decentralized optimization with a sequential strategy, forwarding bids from local to national markets with priority given to DSO for flexibility allocation [23], [24], [25], [26]. Bid forwarding involves aggregation based on network topology and grid constraint checks, considering the representation of DSO grid; hence, forwarded bids undergo aggregation while considering DSO grid constraints. This aggregation process occurs through the developed digital platform in the day-ahead. The aggregated bid forwarded depends on forecasted requirements from both the DSO and TSO, representing an equivalent balancing offer at the TSO-DSO coupling point that adheres to DSO network restrictions.

The Czech demonstrator has developed market mechanisms and fostered TSO-DSO cooperation to analyse and devise solutions for addressing grid issues through the procurement of non-frequency grid services, alongside testing active customer involvement through aggregators (Small DER, DSR, BESS, EV) [24], [25], [26]. Currently, there is no established marketplace for non-frequency flexibility services, with relevant services typically contracted bilaterally or provided as mandatory support [24], [25], [26]. Efforts are underway to update the Czech grid codes, with selected updates being tested through the Trading module of the Non-frequency Ancillary Services platform within the Czech demo [24], [25], [26]. The market platform developed by the Czech Republic demonstrator exclusively focuses on non-frequency services for the DSO, with the TSO not participating in the market processes. Within the local market, the DSO can procure non-frequency grid services from SPs connected at the distribution level [23], [24], [25], [26]. These non-frequency grid services encompass both active and reactive power availability, with the procurement process comprising both long-term and short-term products exchanged on the market platform.

The Hungarian market architecture features local long-term and short-term submarkets for exchanging both active and reactive power products, primarily aimed at addressing DSO service needs [23], [24], [25], [26]. In the long-term submarket, DSO procures flexibility from SPs on a weekly basis, while in the short-term market, active and reactive power for day-ahead activation is procured daily [23], [24], [25], [26].In the Hungarian demonstrator, the long- and short-term submarkets interact explicitly concerning participation commitment in the activation submarket. However, SPs cleared in the long-term market are not obliged to participate in the short-term market, which remains open to new SPs. The coordinated auction model employs a complex merit order list, utilizing optimization models for auction-typed markets. All technically eligible SPs, standalone or aggregated, can participate as market players in this DSO-specific market. Location-specific prices are implemented, operating on a framework of single-week auctions alongside week-ahead procurement. DSO defines congestion zones influenced by factors like scheduled line outages confirmed by TSO around the week-ahead gate opening, integrated into network calculations to delineate bidders capable of resolving specific congestions.

The Northern demonstrator adopts a common TSO–DSO market architecture, with both entities acting as buyers across all sub-markets [27], [28], [29], [30], [31]. Sub-markets within this architecture cover procurement from long-term to near-real-time, enabling all resources connected to the transmission and distribution grid to participate. In the long-term submarket, resources submit bids for active power availability (capacity) alongside corresponding activation prices (energy). The day-ahead sub-market focuses on the active power availability product, while the intraday and near-real-time submarkets handle active power activation products. Availability product sub-markets determine the forwarding of cleared bids to related activation product sub-markets, with bid forwarding occurring between the intraday energy market and the near-real-time sub-markets as well. Flexibility allocation is conducted through centralized market optimization without prioritizing TSO or DSO. Bids from intraday energy markets may be forwarded to other markets, contingent upon locational information inclusion and adherence to grid constraints. Bid sharing between the intraday energy market and other sub-markets is permitted under unique conditions, with bids undergoing compliance checks for grid constraints and ensuring bid uniqueness among sub-markets to prevent double clearing. The optimization method developed for bid selection in the Northern cluster considers both congestion and balancing. In long-term submarkets, bids include both availability and energy price, with selection based on the expected activation duration if announced in the call for tender. SPs are selected in advance for availability, but SO (usually DSO) can request activation on a day-ahead basis. SPs receive the activation fee according to the real activation time and the price announced in the long-term submarket. SPs awarded in long-term or short-term capacity markets are required to bid in related energy markets (e.g., short-term energy market, near-real-time energy market), though free bids are always allowed in energy markets.

In Northern demonstrators, a form of bid sharing across submarkets is formalized. Nord Pool Intraday market cooperates with the Northern Demonstrator platform, using available intraday bids (with locational tags) as input for congestion in both transmission and distribution systems. There is no gate closure time in the intraday market, but according to pre-agreements, such as 1 or 2 hours before the delivery time, the intraday market sends all available bids to the OneNet platform (virtual gate closure).

Mitigation measures are being discussed to prevent bids from being simultaneously cleared in both markets.

Grid data concerns extend up to the level of resource aggregation, with resources aggregated at the lowest node level reported by the SO as part of grid data (SO calculates and shares the sensitivity matrix used in the bid optimization process). Bid selection relies on optimization (auction) in the developed and demonstrated TSO & DSO Coordination Platform (T&D CP), with results transferred to the Market Operator (MO) responsible for informing all related parties, including SOs and SPs. SP activation is addressed through the MO, with TSO having access to DERs if they can buy and activate flexibility from them, while the T&D coordination platform acts as the intermediary on behalf of both TSO and DSO.

The Cypriot demonstrator focuses on a market architecture featuring two new submarkets for active power, aiming to establish effective collaboration among TSOs, DSOs, Consumers, and Energy Markets. The goal is to develop an active balancing and congestion management platform, enabling coordination of distribution grids and facilitating aggregators and prosumers to provide flexibility services. Market-based TSO-DSO coordination is addressed through the OneNet platform, with TSO and DSO participating in procuring products for congestion management, frequency, and voltage control. The Cypriot market architecture includes an intraday market for TSO and an intraday local market for DSO. Products procured in the intraday submarket are pre-evaluated by DSO based on grid constraints and forwarded to TSO submarkets, considering participants' location. Frequency support products are mainly considered, procured based on availability from SPs connected at the distribution level. Cleared availability bids oblige SPs to participate in the near-real-time submarket for product activation.

The Slovenian demonstrator focuses on harmonizing EU-wide system services for DSOs, establishing an interoperable marketplace for FSPs to sell services to both DSOs and TSOs transparently and standardised. It optimizes the size of procured system services, ensuring non-contradicting service activation by DSOs and TSOs (DSO-TSO coordination). It harmonizes new DSO products with existing TSO products and designs a TSO-DSO data exchange model. The demonstrator develops and tests an interoperable marketplace for DSO services, independent of the TSO marketplace platform. This DSO platform focuses on local flexibility procurement, aiming to become the national flexibility marketplace for all SP providers and buyers (DSO and TSO), integrated into existing TSO and DSO platforms. The Slovenian demonstrator includes a locational flexibility market platform and low-voltage areas where network issues are addressed using flexibility sources from various FSPs (e.g., heat pumps, EVs). The long-term submarket allows DSOs to procure flexibility from local FSPs in terms of active power availability and activation. Availability is negotiated between DSOs and SPs within a time window for potential activation, with remuneration based on wholesale electricity prices and agreed capacity.

3.3. Coordination through common prequalification procedures

The prequalification phase, a crucial market phase within the acquisition mechanisms for system services, is essential for enabling Service Providers (SPs) to participate in service provision. Defined within the ACER's framework guidelines for demand response [15], it ensures that SPs meet the necessary technical requirements and standards, fostering their inclusion in providing essential services to the system. Hence, by definition, the prequalification phase deals with power system stakeholders' coordination.

Whenever possible, the adoption of common prequalification phases is considered beneficial as it aligns with harmonizing technical requirements, fostering knowledge sharing, and promoting best practices across the SOs community. This approach also enhances market efficiency by facilitating positive market access impact, enabling cross-SO investments for SPs and economies of scale. Hence, the OneNet demonstrators' solutions regarding the adoption of common grid and product prequalification procedures have been analyzed to identify the potential for widespread adoption or barriers to harmonization. Three coordination dimensions have been considered: the harmonization of prequalification procedures for multiple products, System Operators (SOs), or considering Service Provider (SP) units and groups, as defined in [14].

Table 4 offers an overview of the solutions implemented by the OneNet demonstrators regarding harmonized grid prequalification procedures, whereas outlines the solutions adopted for harmonized product prequalification procedures.

Table 4: Summary of the solutions implemented by the OneNet demonstrators for harmonizing grid prequalification procedures. Source: [14].

	Common grid prequalification across products	Common grid prequalification across SOs	Common grid prequalification for SP aggregation
NOC	Balancing and Congestion Management	A common TSO and DSO procedure (centralised through the Optimisation Operator)	Service Providing unit and group
CZE	Congestion Management and Voltage Control	Dedicated for the DSO	Service Providing unit and group
POL	Balancing, Congestion Management, and Voltage Control	Dedicated for TSO and for DSO	Service Providing unit
GRC	Balancing, Congestion Management, and Voltage Control	A common TSO and DSO procedure	Service Providing unit
PRT	Congestion Management and Voltage Control	Dedicated for TSO and for DSO	Service Providing unit and group
ESP	Dedicated for Congestion Management	Dedicated for the DSO	Service Providing unit and group

Table 4 illustrates the formalization of harmonized grid prequalification procedures for balancing, congestion management, and voltage control services. Across OneNet demonstrators, a trend towards defining dedicated procedures is evident, as these entail technical verifications on grid segments managed by respective SOs. Nonetheless, demonstrators recognize the possibility of coordinating grid prequalification for different segments through dedicated procedures, such as centralized optimization operators, traffic light schemes, tunnels of warranties, and flexibility registers. Most OneNet demonstrators have established common grid prequalification for SP units and groups, indicating the potential for streamlining procedures in this dimension.

Table 5 shows OneNet demonstrators' solutions for establishing a common prequalification procedure for products in Balancing, Congestion Management, and Voltage Control services. They also define common product prequalification procedures across System Operators (SOs), as this process is typically shared among different operators, unlike grid prequalification. This streamlining aligns with prequalification process design principles, ensuring validity across all involved SOs. Most of demonstrators implement a common product prequalification procedure for SP aggregation.

Table 5 Summary of solutions implemented by OneNet demonstrators for harmonizing product prequalification procedures. Source: [14].

	Common product prequalification across products	Common product prequalification across SOs	Common product prequalification for SP aggregation
NOC	Balancing and Congestion Management	TSO, DSO (centralised through Flexibility Register Operator)	Service Providing unit and group
POL	Balancing, Congestion Management, and Voltage Control	TSO and DSOs	Service Providing unit and group
PRT	Congestion Management and Voltage Control	TSO and DSO	Service Providing unit and group
ESP	Dedicated for Congestion Management	DSOs	Service Providing unit and group

4. Insights from stakeholder engagements

Understanding the diverse perspectives of stakeholders is critical to developing well-rounded and impactful solutions. This section provides insights collected from various stakeholder engagements, comprising of surveys, workshops, and expert interviews. Each method provided unique contributions: the survey captured overall trends and preferences, the stakeholder workshop fostered collaborative dialogue and collective problem-solving, and the expert interviews offered detailed knowledge. Together, these engagements provide key priorities, challenges, and opportunities, forming a robust foundation for informed decision-making and strategic planning.

4.1. International Survey

As part of the ISGAN Working Group 6 activity "Exploring the interaction between power system stakeholders: Insights from Pilot Projects", a survey was conducted to collect inputs based on the experience and outcomes from various pilot projects from around the world. The following section summarizes the key findings based on the feedback from various respondents.

Respondents and projects overview

The respondents represent a diverse array of stakeholders in the power system landscape (as shown in Figure 11), with a significant portion coming from research academia (50%), reflecting a strong emphasis on theoretical and empirical insights. System operators constitute 40% of the respondents, highlighting their critical role in the practical implementation and management of various pilot projects. The remaining 10% of respondents fall into the "Other" category, which may include industry experts, regulators, or technology providers. The insights gathered are informed by a variety of innovative projects such as SmartNet [32], DA/RE - Datenaustausch/Redispatch [33], NA-Schutz for distributed generation systems [34], Industry4Redispatch [35], CoordiNet [36] and BeFlexible [37], Redispatch 3.0 [38], Equiqy and OneNet [39]s. These initiatives span across several European countries, including Italy, Denmark, Spain, Germany, Switzerland, Sweden, and Greece, as well as extending to South Korea, showcasing a rich tapestry of international collaboration and knowledge exchange in the evolving power system sector.

The stakeholder analysis, based on the survey responses, reveals varying levels of involvement among different industry sectors in the interaction process. TSOs and DSOs both have a significant presence, underscoring their pivotal roles in managing and operating electricity transmission and distribution systems. Conversely, residential customers show relatively passive participation. In contrast, commercial, industrial, and agricultural customers exhibit substantial energy demands, reflecting their significant involvement. Generation operators are crucial for energy supply to the grid, while storage operators indicate moderate involvement, highlighting the growing interest in energy storage solutions for balancing supply and demand. Balancing responsible parties show limited engagement, which might be due to their specialized role in maintaining grid stability. Aggregators are notably active, playing a critical role in coordinating multiple energy resources and facilitating interactions among various stakeholders. The "other" category includes stakeholders from unspecified sectors, demonstrating a broad range of interests and expertise contributing to the projects.

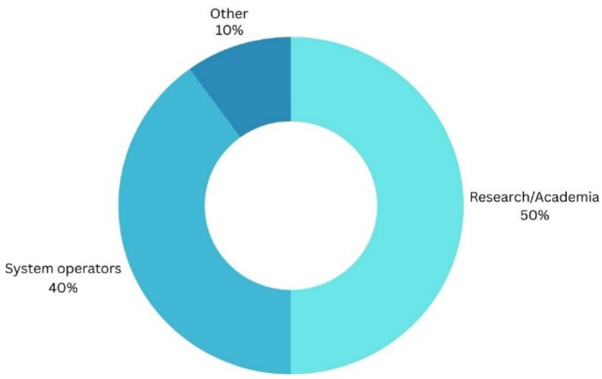


Figure 11: Survey respondents' sector of activity.

The pilot projects engaged relevant stakeholders which serves as the foundation of the experience and knowledge for the survey. According to the survey results, key strategies taken within the projects to facilitate increased stakeholder interaction include:

1. **Pilot Projects**: Three pilot initiatives focused on services provided by storage subjects in distribution grids to the TSO, specifically hydro generation in Italy, radio base stations in Spain, and swimming pools in Denmark. This practical approach helped engage stakeholders in real-world applications.
2. **Proactive Communication**: Various forms of proactive communication were employed, including events, workshops, and organized sessions to foster dialogue among stakeholders. Additionally, structured opportunities for collaboration, such as workshops throughout the project timespan, appear in 10% of responses, reflecting the importance of continuous knowledge exchange.
3. **Technical Working Groups**: A technical working group comprising experts from DSOs, solar PV, inspection, and research was established across Switzerland, Austria, and Germany.This technical working group facilitated in-depth discussions on contested topics, such as the need for external protection devices in low-voltage grids.
4. **Surveys and Data Collection**: A broad survey of stakeholders in Switzerland was conducted in one of the projects who replied to the survey; data from FSPs was collected through surveys aimed at customers connected at the distribution level. Public data was also utilized for FSPs from the transmission network.
5. **Workshops and Training**: Workshops were organized to discuss project results and introduce piloted schemes, while training sessions were held to assist FSPs with connecting to the platform.
6. **Ongoing Reviews and Testing**: Daily protection tests and regular reviews of procedures and incidents were implemented to build mutual trust regarding solution security.
7. **Joint Ventures and Collaborations**: Initiatives like Equigy, a joint venture of EU TSOs, created an ecosystem for interaction among TSO stakeholders, while Swissgrid's project on TSO-DSO coordination further promoted discussions on accessing distributed flexibility resources.
8. **National Platforms**: In the Czech Republic, project results were communicated through a national platform for smart grids, ensuring that all relevant stakeholders, including aggregators, were involved in discussions.

Based on the stakeholder interaction investigated in the project, in which timeframe does the interaction take place?

The analysis of stakeholder interaction timeframes across the various projects that answered the survey reveals a multifaceted approach to engagement within the energy sector. The most prevalent interactions occur in the intraday category, accounting for approximately 60% of responses, which highlights the strong need for agility and responsiveness. Close-to-real-time interactions are also significant, representing about 30% of responses, underscoring the importance of timely decision-making. Day-ahead interactions comprise around 50% of the responses, emphasizing their crucial role in operational planning. In contrast, monthly to annual interactions are less frequent at 10%, indicating a focus on longer-term strategic discussions. Long-term interactions, also referenced in 10% of responses, suggest a forward-looking approach that considers sustainability and broader implications of current decisions. This variety in timeframes underscores the complexity of stakeholder interactions and the necessity for flexible engagement strategies to effectively address both immediate and long-term challenges in the energy landscape.

Which type of flexibility sources are coordinated within the pilot project?

The analysis of results from the projects regarding flexibility sources (see Figure 12) reveals a complete reliance on generation resources, with 100% of projects utilizing both bulk and distributed generation, underscoring their critical role in enhancing flexibility for energy transition and grid stability. Additionally, 70% of projects incorporate storage solutions and customer-related flexibilities, such as heat pumps and electric vehicles, indicating a growing recognition of the importance of demand-side management. However, only 50% of projects involve large-scale customer-related flexibilities, reflecting the complexities associated with integrating industrial demands. Notably, there is no engagement with cross-vector sector coupling, which suggests a significant gap (based on the projects participating within the survey) in integrating different energy vectors. Furthemroe, it was observed that only 10% of projects employ network-related flexibilities, indicating limited use of traditional network management techniques. Overall, the findings highlight a strong emphasis on generation and customer-related flexibility, with opportunities for further exploration and integration of storage solutions and more collaborative approaches that enhance cross-sector connections, ultimately contributing to a more resilient and flexible energy system.

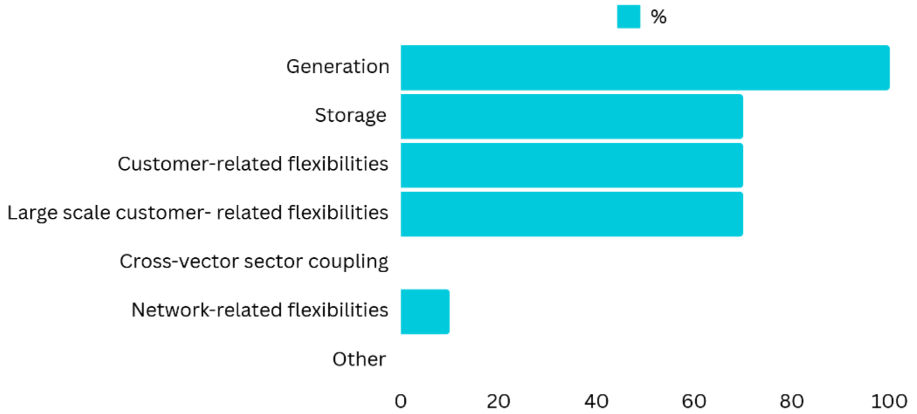


Figure 12 Type of flexibility sources are coordinated within the projects (% of all projects)

Which market related coordination schemes were investigated in the project?

The analysis of responses regarding market-related coordination schemes investigated in various projects reveals a diverse landscape. Projects such as SmartNet and BeFlexible emphasize traditional TSO-DSO interactions and the integration of decentralized energy systems, while others like Equigy and Industry4Redispatch focus on innovative algorithms and operational efficiencies for resource allocation. CoordiNet and OneNet indicate a structured approach to defining and implementing various market coordination schemes, showcasing a trend towards more integrated and flexible market solutions in the energy sector. Overall, the responses illustrate a mix of both traditional and innovative approaches, highlighting the evolving nature of energy markets and the importance of flexibility and collaboration among stakeholders.

Which type of flexibility sources are coordinated within the project?

The analysis of responses regarding the types of flexibility sources coordinated within the various projects reveals a comprehensive approach to flexibility management. Generation sources, both bulk and distributed, are pivotal in most projects, emphasizing their essential role in balancing supply and demand within the energy system. Storage solutions are also recognized for their critical function in energy flexibility, with both large-scale storage systems and distributed solutions like batteries being considered. Additionally, customer-related flexibilities, which include technologies such as heat pumps, cooling systems, and electric vehicles, underscore the importance of consumer involvement in energy flexibility, particularly in projects like SmartNet and BeFlexible. The flexibility potential from large industrial customers is highlighted in several projects, showcasing their significance as contributors to the overall flexibility landscape. While less frequently mentioned, network-related flexibilities (e.g., topology modifications, tap changers, switchable capacitor banks) point to crucial technical aspects of flexibility management, as seen in Redispatch 3.0 [38]. Overall, these projects reflect an integrated strategy to enhance the resilience and efficiency of energy systems through diverse flexibility sources.

TSOs usually have no detailed visibility of distributed energy resources and distribution network constraints. Consequently, using distributed flexibilities for transmission system operation requires a mechanism that filters flexibility combinations that provoke distribution system constraint violations. Is such a filter mechanism developed/used in your project?

The respondents said that flexibility combinations filter mechanisms are essential for effectively managing distributed systems, particularly in preventing constraint violations that may arise from integrating various flexible resources such as demand response, energy storage, and distributed generation. Approximately 70% of projects answering the survey utilize these mechanisms, with the primary responsibility for their implementation resting on DSOs, although TSOs may also play a role, and external platforms can assist in the filtering process. DSOs typically develop the necessary distribution system models to understand the network's constraints and operational limits, which inform the filtering mechanisms. However, a significant concern is the lack of transparency associated with these filters, largely due to the complex and often proprietary nature of DSO network models, which can hinder collaboration and understanding among stakeholders. To address these transparency issues, DSOs could invest in better modelling tools and share relevant non-sensitive data, while TSOs and external platforms can work together to enhance communication. Regulators may also need to consider policies that promote data sharing among all stakeholders to improve the effectiveness of flexibility combination filters and ensure better integration of flexible resources, ultimately leading to enhanced system reliability.

How is the distribution system modelled and where does the data come from?

Most of the respondents mentioned that the distribution system is modelled by each DSO using various methods and data sources. DSOs create dynamic distribution grid models based on reference networks (such as the ones provided by CIGRE) or real networks, with capabilities calculated for geographically limited perimeters using a traffic-light approach that indicates resource availability. Data is primarily sourced from the DSOs themselves, including network topology data and state estimation, as well as internal systems such as SCADA and GIS. For instance, in Portugal, the distribution system is modelled as a load connected to the TSO/DSO interface, utilizing data from DSO internal systems. In the Czech Republic, internal DSO SCADA is used, while Northern-Europe regions apply Power Transfer Distribution Factors (PTDF) for efficient modelling. In Spain, tools like PSS®E[2] are employed, and in Greece, the equivalent network is modelled directly by the DSO. For Cyprus, the distribution grid was modelled using power balance equations and a digital twin of a sub-part of the grid was created for real-time simulations, with data provided by the Cypriot DSO. Ultimately, the responsibility for modelling and ensuring compliance with distribution grid constraints lies with the respective DSOs, who utilize their existing models and data for these purposes.

Using detailed distribution system models for this mechanism increases flexibility utilization but also implementation complexity. Where is the appropriate trade-off in your opinion?

The implementation of detailed distribution system models for flexibility mechanisms can enhance flexibility utilization but also introduces complexities. Participants express that markets with clearly defined responsibilities for DSOs and TSOs may simplify implementation, though this could reduce performance in flexibility utilization. Emphasizing legal compliance while minimizing complexity is a priority, allowing systems to meet regulations without becoming overly intricate. Utilizing detailed off-line simulations for rule-based planning can effectively manage operations without constant complexity. Calculating the capability of each distribution perimeter is viewed as a reasonable trade-off, as demonstrated by Italian DSOs' acceptance of this approach for experimentation, which builds confidence in managing flexibility. However, concerns exist regarding existing models potentially overlooking all flexibility potentials, with future uncertainties addressed through scenario analysis. A positive cost-benefit analysis is vital in determining the appropriate modelling detail. The level of detail also depends on how actively a DSO is willing to manage congestion and voltage issues, with less congested areas possibly being aggregated to simplified models. Scalability concerns arise from involving multiple DSOs, suggesting that market-based coordination using simplified models could be more effective. The focus should be on achieving sufficient detail to protect DSO systems while remaining simple enough for efficient data processing. In regions like the North, linear approximations using Power Transfer Distribution Factors (PTDF) enable accurate representations while allowing rapid simulations for near-real-time market product procurement. In Cyprus, the decision to model and pre-qualify services at each substation exemplifies a practical approach to balancing detail and simplicity, ultimately highlighting the importance of context and operational goals in finding the right trade-off.

[2] https://www.siemens.com/global/en/products/energy/grid-software/planning/pss-software/pss-e.html

How does the project address aspects to effectively decrease the complexity in stakeholder interaction (plant operators <->balancing responsible party BRP <-> Market <-> DSO) in a system with an increasing number of active participants (due to increasing DER)?

The respondents mentioned that projects address the complexity in stakeholder interactions among plant operators, BRPs, markets, and DSOs in a system with increasing DER through several key strategies. For example, an aggregation layer has been implemented to streamline interactions, along with the development of an automated data exchange platform that facilitates efficient sharing of information among stakeholders. Collaborative engagement is encouraged by bringing all parties together to review concerns, enhancing mutual understanding and coordination. Several projects defined a limited number of perimeters encompassing multiple flexibility resources subject to the same limitations and established a common prequalification procedure with standardized market products. Enhanced coordination between TSOs and DSOs further reduces the effort required from Balancing Service Providers (BSPs) to participate in markets. Emphasis is placed on the interaction between the DSO and the Customer Load System (CLS) iMSys to clarify roles and streamline processes. Aggregators serve as intermediaries, managing complexity and simplifying interactions for individual resource operators. Different coordination schemes are compared to promote aggregator participation, while communication with BRPs is assumed to be effective in informing them about scheduled activations of flexibility resources. In Portugal, interactions between TSOs and DSOs are clearly defined through an API-based data exchange platform, and in the Czech Republic, a common interface facilitates participation from a larger number of stakeholders. In the OneNet project, the pilot from France emphasizes sharing only relevant information to minimize mismatches or disputes, while a flexibility register in the Northern region manages information about flexible resources across multiple networks. Additionally, local market platforms in Spain allow trading of congestion management products, and user-friendly software in Greece enhances stakeholder interactions. In Cyprus, the OneNet system centralizes data exchange among actors, providing a comprehensive platform for information sharing. Collectively, these strategies aim to simplify and enhance stakeholder interactions, accommodating the growing number of active participants in the DER landscape while ensuring efficient communication and coordination.

How did the project realise effective (real-time) communication between the relevant stakeholders?

The projects realized effective (real-time) communication between relevant stakeholders through various innovative methods and platforms. In an Italian pilot, a communication layer was established to transmit control orders from the TSO to peripheral hydro stations located in a remote valley near the Austrian border, facilitating immediate operational coordination. The project enabled the immediate exchange of planning data upon activation and updates of forecasts, ensuring that stakeholders are informed in real-time. In a pilot from Portugal, API-based communication between data exchange platforms for the DSO and TSO involved automated processes, while in the Czech Republic pilot, the IT environment was designed to provide near-real-time information on grid availability. In the case of the French pilot, real-time flexibility activation orders were communicated by TSO local automata to FSPs, with a focus on storing data related to these orders in a shared platform. The Northern region pilot emphasized the creation of standardized interfaces and data models for effective information exchange. In the Spanish pilot, the Market Operator developed local market platforms for trading congestion management products, which receive DSO needs and bids from FSPs and communicate market results to various stakeholders. In Greece, common software platforms were utilized to meet all communication needs, and in Cyprus, the OneNet system facilitated centralized data exchange among actors. Additionally, the Equigy - Crowd Balancing Platform, a blockchain-based system operational in Italy and the Netherlands, supported communication among stakeholders, although most interactions were not in real-time. Collectively, these strategies fostered a robust framework for real-time communication and coordination among stakeholders in the energy ecosystem.

To what extend are standardisation and unified data exchange critical for interoperability?

The responses to the question regarding the importance of standardization and unified data exchange for interoperability highlight a strong consensus among the projects surveyed, with all participants recognizing varying degrees of significance attached to these elements. Most respondents classify standardization and data exchange as either "very important," "critical," or "fundamental," indicating a shared understanding of their essential roles in facilitating interoperability across different systems and stakeholders. Specific references to existing standards, such as those from the ENTSO-E and the guidelines by the German Association of Energy and Water Industries (BDEW), illustrate a commitment to adhering to established frameworks to enhance coordination and data sharing. Some responses emphasize that effective standardization is crucial for enabling the integration of DERs and local flexibility markets, which are vital for advancing energy transition efforts. Overall, the feedback reflects a collective recognition that robust standardization and unified data exchange are foundational for achieving interoperability, enhancing collaboration among diverse stakeholders, and supporting the broader goals of energy system integration across Europe.

Based on the outcome of the project, what would you consider to be the best practice to establish trust between stakeholders to facilitate data exchange?

The responses to the question regarding best practices for establishing trust between stakeholders to facilitate data exchange reflect a diverse range of strategies, emphasizing the importance of collaboration, transparency, and standardization. A significant theme is the necessity for active stakeholder management and open discussions to understand each party's priorities and viewpoints, which can help in reaching mutually acceptable compromises. The suggestion for interoperable data exchange based on standard protocols highlights the technical foundation needed for effective collaboration. Additionally, several responses point to the need for pre-agreed data models and schema validation to ensure consistency and security in data handling. Governance frameworks and advanced technologies, such as blockchain, are also mentioned as means to enhance transparency and protect sensitive information. Overall, the responses suggest that fostering trust hinges on a combination of clear communication, established protocols, and robust security measures, all of which are essential for successful data exchange among diverse stakeholders.

Is it necessary/mandatory for a regulatory/legislative framework to establish the roles and responsibilities of stakeholders' interactions or can bottom-up arrangements among stakeholders be satisfactory?

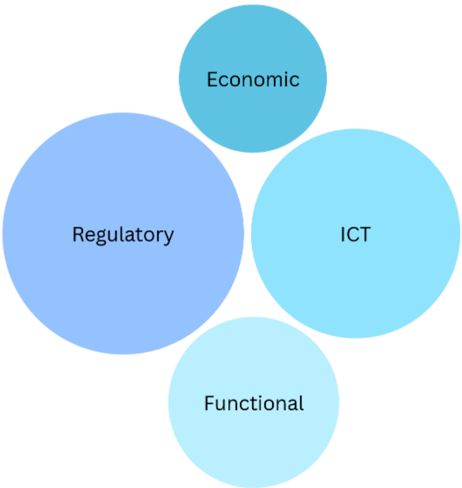
The responses regarding the necessity of a regulatory or legislative framework to define stakeholder roles and responsibilities reveal a consensus on the importance of formal structures in ensuring effective interactions. Many participants highlighted that a standardized definition of roles is crucial for fostering clarity and promoting standardized interactions and data exchange, emphasizing that a regulatory framework should be established to provide this clarity. While some acknowledge that certain interactions may be managed satisfactorily through bottom-up arrangements, the general sentiment leans towards the need for a regulatory framework, particularly to enhance transparency, trust, and inclusion of all stakeholders. Several respondents pointed out that regulatory requirements are essential, with the framework needing to be informed by tested bottom-up arrangements to ensure it reflects the interests of all parties involved. Overall, the majority agree that a comprehensive regulatory framework is necessary to clearly outline roles and responsibilities, ultimately facilitating better coordination and interaction among stakeholders in the energy ecosystem.

Flexibility potentials from the distribution grid level are limited by regulatory requirements within the transmission grid. How did your project address this? What regulatory changes/recommendations should be taken into account?

The responses to the question regarding how projects address the limitations of flexibility potentials from the distribution grid level due to regulatory requirements within the transmission grid reveal a mixed approach among the projects. Some respondents emphasize the need for regulatory reforms that grant DSOs greater responsibilities and options, thereby enabling them to fully exploit the flexibility potential of the distribution network. For instance, one project (Redispatch 3.0) specifically aims to include smaller flexibility units (under 100 kW) in its framework, addressing regulatory gaps that currently favour larger units. However, several responses indicate that the projects either do not address regulatory issues directly or focus solely on scientific methodologies without engaging with the regulatory landscape. Notably, the Greek pilot of OneNet project highlights significant barriers, such as restrictions on connecting users to the distribution network if it leads to congestion or voltage issues, emphasizing the need for a collaborative regulatory framework. In the Equigy project, a pooling concept is presented as a successful model that allows small-scale flexibility resources to participate in transmission-related services. Overall, the responses suggest a recognition of the need for regulatory changes to enhance flexibility from the distribution grid, but there is also a notable divide between projects actively engaging with these challenges and those that remain focused on technical or theoretical aspects without addressing regulatory implications.

Which focus area is likely to be the strongest barrierfor the large-scale implementation of the stakeholder interaction process investigated within the pilot country (ies)?

The responses regarding the strongest barriers to the large-scale implementation of the stakeholder interaction process coming from the projects with pilots reveal that regulatory issues are perceived as the most significant obstacle, with 80% highlighting this concern. This indicates that existing regulatory frameworks may not adequately support the innovative stakeholder interactions necessary for integrating DER and achieving effective coordination among various parties, such as TSOs, DSOs, and FSPs. Additionally, ICT challenges were cited by 60%, suggesting that while technology can facilitate interactions, issues related to interoperability, data security, and the integration of diverse systems can impede progress. Functional barriers, mentioned by 40%, likely pertain to operational aspects such as the alignment of different organizational cultures and processes among stakeholders, which can lead to inefficiencies and miscommunication. Economic barriers, noted by 30%, reflect concerns about the costs of implementing new technologies and the economic feasibility of participating in flexibility markets. Notably, no projects identified any other barriers outside of these specified categories, indicating that the primary challenges are well-captured by regulatory (80%), ICT (60%), functional (40%), and economic (30%) factors. Overall, these findings underscore the need for policymakers to revisit and potentially reform regulatory frameworks to create a more conducive environment for collaboration and innovation in the integration of distributed energy resources, while also addressing ICT and functional barriers to facilitate smoother stakeholder interactions.



4.2. Stakeholder Workshop

This section consolidates the findings from a stakeholder workshop aimed at evaluating key aspects of modern power system integration and management. The workshop served as a platform for collaboration and exchange, focusing on several key objectives: fostering dialogue to address critical topics related to flexibility and power system resilience, sharing experiences and lessons learned from pilot projects, and highlighting best practices in stakeholder interaction and flexibility for resilience. The workshop gathered insights into critical themes, including general experiences from pilot projects, stakeholder interaction and engagement, and technical challenges related to power system flexibility modelling and utilisation. It further considered aspects related to information and communication technologies, particularly focusing on data exchange and cybersecurity. Economic and market aspects were also assessed alongside discussions on standardisation, interoperability, and regulation, especially in the context of TSO-DSO and other stakeholder interactions. The strategies for effective knowledge transfer and dissemination are also presented, concluding with an analysis of potential future work and strategic outlooks. An overview of the focus areas is shown in Figure 13.

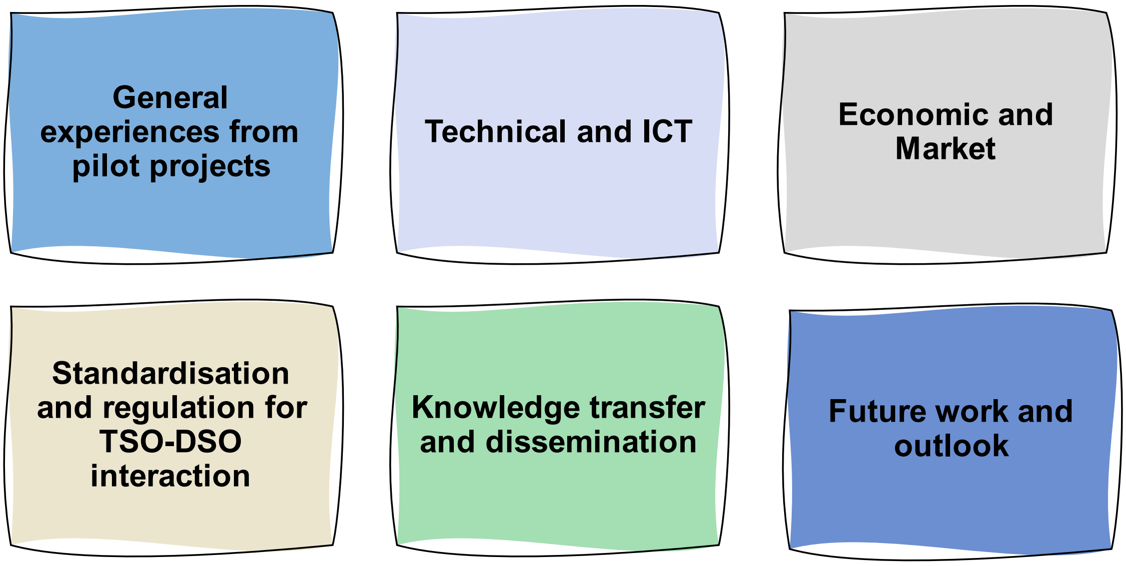


Figure 13: Overview of workshop focus areas.

4.2.1. General experiences from pilot projects

4.2.1.1. Main goals and focus areas of the pilot projects based on country experiences.

Key questions

- What are the similarities between pilots / country experience?
- What are the differences between pilots/country experience?

The implementation of flexibility in energy systems is a common theme across several countries, addressing grid challenges through innovative approaches. Both the Netherlands and Germany are currently investigating flexibility through electric vehicle (EV) charging, with Germany focusing on real-time coordination of LV networks (behind the meter) to manage grid congestion. Their pilot programs address congestion management and outages in the distribution network by introducing smart charging and protection schemes. Austria is currently investigating methods for enhancing grid hosting capacity to accommodate renewables and new loads such as heat pumps and e-mobility, offering different flexibility options. Additionally, Austria is investigating processes which can be used to strengthen DSO-TSO interactions, in particular when considering flexibility from industry. Australia shares common challenges of large-scale renewable integration but faces unique issues with limited system visibility of distributed solar, demanding improved coordination for network utilization and system service contribution. In Norway, increased focus is based on forecasting and aggregation of flexibility aims to develop and strengthen the supply chain for flexibility. In North America, the Energy Resilience Model enhances power system planning and is also exploring the idea of place-based generation and energy storage through the Energyshed concept and various pilot programs implemented by the United state

Department of Energy (USDOE). These efforts, in conjunction with demand flexibility education, legislative reforms, and system service coordination from DSO to TSO, highlight global strategies to enhance grid flexibility.

In Ireland, France and Israel, it was noted that there are currently regulations which have implemented export limitations for renewable energy providers and thus indicate that there is a need for building infrastructure in order to allow for further renewable energy resource integration than already committed by local DSOs. However, in Israel and Ireland, there are established programmes that allow the connection of these sources only for specific times. In France, the DSO, Enedis, provides smart, faster, and cheaper connections for medium voltage (MV) renewable energy producers, demonstrating industrialized solutions.

Lastly, aggregators have emerged as key stakeholders in countries like Germany, France, Ireland, and the US, who are able to manage demand control for load reduction to optimize grid performance.

4.2.1.2. The identification of the gaps was based on the outcomes of the pilot projects.

The deployment of flexibility in energy systems faces numerous challenges across technical, regulatory, and market domains. It was highlighted that a unified regulatory framework is absent in many countries, with regulatory processes noted as often being too slow to adapt, in combination with limited experiences with the regulatory learning process. Furthermore, it was mentioned that regulatory barriers often prevent the implementation of project recommendations, and the absence of real business cases for flexibility at the local/DSO level, combined with a small number of market participants and market volume, further hinders progress in the adoption of project solutions.

Key questions

- What are the gaps (technical, regulatory, economic etc)?
- Were they addressed? If so, how? Who should address these? (R&D, policy makers, end users etc)

The lack of distribution-level grid monitoring and visibility, especially in countries like Australia, where state estimation faces operational data limitations, complicates system coordination. Standardized flexibility services are still emerging, and market conditions are currently underdeveloped in many countries, particularly in vehicle-to-grid (V2G) readiness, where most vehicles only support smart charging. In some cases, it was noted that high engineering efforts are required to implement complex solutions developed within the pilot projects, where these solutions also face scalability issues. Flexibility deployment in Norway highlighted gaps in forecasting tools, supply chain readiness, and regulatory frameworks, emphasizing the need for replicable processes to be incorporated within pilot projects. Thus, lessons from these pilots suggest that projects need to focus on specific technical solutions, ensuring scalability and replicability by location. The USA's BIL and IRA projects are currently in the early stages, with significant scaling of investments and knowledge management challenges expected. Furthermore, there is often a challenge in bringing actors together from diverse fields such as ICT, electrical engineering, and market expertise to create a unified language for addressing flexibility and its related concepts. It was highlighted that many pilot projects address only technical and economic aspects, neglecting social sciences and humanities (SSH) research competencies, which are critical for holistic project development.

When considering business use cases for flexibility at the DSO level, it was noted that they currently remain limited, and in many cases, legal restrictions further impede the development of viable solutions. The value of flexibility—whether through grid reinforcement, social benefits, or addressing grid needs—is often overlooked or difficult to quantify, particularly with respect to market growth. Related to flexibility harvesting, in many of the pilots, it was highlighted that real business cases are missing (market volume and number of market participants too few), where sometimes legal restrictions are a barrier for implementing solutions. However, it was noted that France has seen some responses from the market when tendering flexibility services, which may indicate that there is potential interest within this sector.

4.2.2. Stakeholder interaction and engagement

Key questions

- How / what mechanisms were used to define the roles and responsibilities of stakeholders?
- Is there a need for a single stakeholder/common process which provides a holistic view? Why/why not? How can this be achieved?
- Which stakeholders were the most significant actors in the project?
- Which stakeholders were missing?
- What strategies should be implemented/used to engage more stakeholders?
- What strategies should be implemented/used to keep them engaged?

Based on the discussions, a common consensus highlighted that a clear definition of roles and responsibilities for TSOs and DSOs is necessary from the perspective of current challenges. Traditionally, DSOs are responsible for managing local distribution networks, facilitating DER connections, and ensuring a reliable supply of electricity. TSOs, on the other hand, oversee high-voltage transmission infrastructure, maintaining grid stability and managing the flow of electricity across regions. Collaborative efforts between DSOs and TSOs are, thus, vital for integrating renewable energy, balancing loads, and effectively managing transmission network constraints. Additionally, the effective implementation of flexibility in energy systems is founded on robust consent-building for stakeholder interaction.

These roles and responsibilities among stakeholders are typically shaped by regulatory arrangements, necessitating that social license, through community engagement, is conducted in the early phases of the project and that the process is transparent. For example, in Norway, the stakeholder's roles and responsibilities are typically defined by the project consortium. Additionally, it was highlighted that defining the end user's role in funded research projects is essential for stakeholder engagement and it was recommended that establishing this clear role from the onset ensures alignment and addresses the specific needs of the involved parties. In vehicle-to-grid (V2G) initiatives, it was noted that ambiguity often arises regarding "who steers whom dynamics": it remains unclear whether the steering is driven by the smart charging system in the vehicle, the car provider, or the grid operator. This further emphasises the need for the complete chain of organizations involved in pilot projects to have their roles defined from the beginning, ensuring clarity in responsibilities. Initiatives like Justice40 in the USA mandate that at least 40% of benefits from federal investments go to disadvantaged communities, emphasizing the importance of equitable distribution of advantages. The Department of Energy (DOE) often utilizes Requests for Information to gather feedback on emerging concepts or priorities, such as the Energyshed concept, highlighting the necessity of having a highly engaged initiator alongside a visionary who can propel projects to the next stage.

The grid operator was identified as a key stakeholder, but it is equally important to ensure that those stakeholders not directly engaged in the project are also considered. It was noted that the regulator is very often missing in projects. Noting that the non-inclusion of external parties or stakeholders who are not directly engaged in the project poses the risk of creating "one-off" solutions, preventing valuable lessons learned from being applied in other environments. On the other hand, it was also noted that the involvement of more stakeholders should be done only when there is a genuine need since the different stakeholders require different strategies and solutions typically arise in response to specific stakeholder-identified problems. For instance, engaging multiple stakeholders is valuable when shaping regulatory frameworks, defining market mechanisms, or addressing cross-sector concerns. However, in highly technical or operational discussions, such as refining algorithms for grid optimization or defining internal operational limits, too many stakeholders can hinder progress without adding significant value. In such cases, focused expert discussions may be more effective.

Stakeholder workshops were identified to serve to find a common language among project participants, highlighting the need for the involvement of diverse stakeholders, including those who may not initially seem relevant, as strategies may vary significantly based on their engagement levels. Approaching customers and users through trusted entities, such as Users TCP [40] fosters engagement. To enhance engagement, incorporating Users TCP in projects can allow for the utilisation of their expertise in effectively involving end-users particularly given the wealth of knowledge available within the initiative. Consent-building between stakeholders is also deemed necessary, as is considering remuneration for end-users to encourage participation. It was suggested that customer integration in smart grid concepts should be fully automated to streamline processes and improve responsiveness. Lastly, the mapping of stakeholders was noted as critical to identify those likely to be affected by implementation, those who influence it, and those who possess necessary information or data.

4.2.3. Technical aspects: Power system /flexibility modelling and utilisation

4.2.3.1. Power system and flexibility modelling

The power system and flexibility modelling landscape face significant challenges, with data access being a fundamental issue since DSOs often lack visibility of their networks, particularly in medium-voltage (MV) and low-voltage (LV) grids. In many cases, basic grid data and detailed system configurations are either unavailable or incomplete. This data scarcity is even more pronounced at the local and residential levels, where data exchange issues and the absence of monitoring infrastructure are notable. It was further highlighted that accurate modelling of underlying MV and LV grids is critical for understanding grid behaviour and optimizing operations, yet the lack of real data minimizes these efforts. It was noted that one of the key aspects of flexibility modelling is capturing end-user behaviour, which is highly variable and stochastic, especially at the residential level. While realistic modelling of consumer behaviour is vital, it often relies on data that is difficult to access due to privacy concerns and regulatory restrictions such as GDPR[3]. Balancing the need for detailed consumer data with privacy safeguards may pose a conflict of interest which stakeholders need to carefully navigate. Efforts like the InterFlex project [41] have highlighted innovative solutions to these challenges. For example, in France and the Netherlands demonstration, the respective DSOs helped develop dedicated IT platforms to share actual and potential flexibility demands with commercial service providers and aggregators. These platforms enabled DSOs to source flexibilities on localized markets, improving operational efficiency and grid performance. However, such demonstrations also revealed the limitations in scalability and the need for an integrated system approach to tools and models. To advance flexibility modelling, it was mentioned that increased access to real-world data is essential. This requires not only addressing technical and regulatory barriers but also fostering collaboration among stakeholders. Furthermore, scalable tools and models that integrate system-wide perspectives and are built on real data can provide more accurate insights into grid dynamics.

Key questions
• What are the challenges when it comes to power system/ flexibility modelling? • How are these challenges overcome?

4.2.3.2. Power system and flexibility utilization

The integration of flexibility within energy systems requires dynamic interactions with demand-side management and energy storage systems (ESS), which can be executed directly or facilitated through Automated Trading Platforms (ATPs). TSOs require detailed information regarding the system frequency and thus need to monitor the system's response and other operational parameters of DERs to assess their contributions and impact on system-level services effectively. This information is critical for maintaining grid stability and ensuring that the energy supply meets fluctuating demand.

Furthermore, it was suggested that customer integration into smart grid concepts be fully automated to optimize system responsiveness and enhance user engagement. Automated systems can streamline communication and operational processes, reducing delays and improving decision-making. However, conducting cost-benefit analyses (CBA) shows that the introduction and maintenance of flexibility utilization platforms can incur substantial costs. Particularly at lower voltage levels, the economic feasibility often favours grid extension over the implementation of flexibility schemes, as the latter may not yield sufficient return on investment under current market conditions.

Regulatory frameworks also play a crucial role in shaping the landscape for flexibility services. For instance, the introduction of regulatory compulsion to implement technically and ecologically viable concepts, such as Redispatch 2.0 [42], emphasizes the need for flexibility within distribution networks to enhance operational capacity. It was acknowledged that centralized solutions alone cannot effectively address the complexities and demands of modern power systems, which makes distributed flexibility essential for improving grid performance. To encourage the participation of aggregators in local flexibility

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[3] General Data Protection Regulation

markets, there is a need for greater market signals and incentives. This includes creating transparent pricing mechanisms that reflect real-time supply and demand dynamics, enabling aggregators to make informed decisions about when and how to provide flexibility. Real-time communication infrastructure is vital to facilitate this interaction, allowing stakeholders to rapidly respond to system changes and optimize their operational strategies accordingly.

Currently, in the Netherlands and Germany, the application of EV charging technologies is predominantly confined to the distribution grid, limiting the potential for larger-scale integration at the TSO level. As one step towards more integrated operations, initiatives in the Netherlands have begun exploring TSO actions for flexibility offers of 1 MW, representing a significant step towards more integrated operations. In Germany, several TSOs are actively involved in funded projects that aim to enhance stakeholder interaction, emphasizing the importance of collaboration among various entities, including grid operators, energy providers, and end-users.

Based on the facilitated discussions, it was agreed that the effective integration of flexibility within energy systems relies heavily on the establishment of a common data exchange platform and the adoption of unified data models. This foundational framework allows for the coordinated development of realistic grid models by TSOs and DSOs, enabling the modeling and development of innovative concepts through collaboration with academic institutions, for example, those utilizing the Simbench[4] framework. A key to successful and practical modeling lies in the use of a standardized data model that is compatible across both TSO and DSO operations, which facilitates consistency and clarity in data interpretation.

4.2.4. ICT aspects: Data exchange and cybersecurity

4.2.4.1. Data exchange between power system stakeholders

Key questions

- What are the best practices to establish trust between stakeholders to facilitate data exchange to provide flexibility services?

Data access remains a critical challenge in the exchange of information between power system stakeholders. . Stakeholders must navigate the complexities of data governance, privacy, and security to gain access to the necessary datasets that can inform decision-making and operational strategies. A collaborative approach to data access, underpinned by clear agreements and standards, will be essential for leveraging the full potential of flexibility services in energy systems. By addressing these challenges, the sector can move towards a more integrated and resilient energy future, supported by reliable data-driven insights and innovations. The strive for European-wide common standards is vital to ensure scalability and interoperability among diverse stakeholders. Such standards facilitate collaboration and data sharing, allowing different entities—such as independent system operators (ISOs), RTOs, and utilities—to access and utilize each other's data seamlessly. However, it is currently unclear whether these organizations possess interoperable data systems, particularly at the operational scales necessary for flexibility and resilience. Currently, these stakeholders appear to be skeptical about federal interventions which highlights a significant barrier to effective data sharing. Furthermore, it was mentioned that stakeholders who participate in funded projects often emerge as front runners when it comes to solutions, as they gain valuable experience based on valuable insights and practical applications that can drive further innovation. Although, for the outcomes of these funded projects to gain acceptance and trust among all stakeholders, they must be convincing, practical, and useful. Initiatives such as the Users TCP are also instrumental in building confidence among stakeholders.

[4] https://simbench.de/en/

4.2.4.2. Cyber security

Key questions

- How should cyber security threats be addressed by TSOs and DSOs to ensure grid resilience?

Addressing cybersecurity within the energy sector is of paramount importance, particularly in the context of increasing digitalization systems. This is particularly important when combining new “digitised” components with legacy components and subsystems. The integration of new digital components with legacy systems in the energy sector introduces cybersecurity risks due to the outdated security capabilities of legacy infrastructure. These systems often lack advanced security features, creating vulnerabilities when interfaced with modern, digitally-enabled technologies. Furthermore, the differing protocols and security standards between legacy and contemporary systems can lead to interoperability gaps, which may expose the network to potential exploitation.Therefore, data communications should incorporate security-by-design principles, meaning that cybersecurity measures must be considered during the initial stages of product and service development. However, it was also mentioned that cyber security safeguards should be integrated at all stages. This proactive approach ensures that vulnerabilities are addressed before they can be exploited.

Furthermore, anomaly detection systems should be implemented within the infrastructures of TSOs and DSOs to monitor and identify unusual patterns that may indicate cyber threats, enhancing overall system security. Software support is as crucial as cutting-edge technology, as reliable software can significantly mitigate risks associated with cyberattacks. Identifying and reinforcing the weakest points within systems—such as potential backdoors that could be exploited—must be a priority for organizations.

Adopting a modular data-sharing approach was determined to be an essential aspect of enhancing security, allowing for flexibility in data management while maintaining robust security protocols. Additionally, open-source approaches were identified as a means to foster collaboration among developers, enabling more individuals to contribute to identifying weaknesses and improving security measures. Integration of cybersecurity measures should occur at all stages of system development and operation, emphasizing the need for standards in protocol design to ensure interoperability and security across different utilities.

The diversity of technologies utilized across different utilities presents inherent risks, making it essential for organizations to adopt a unified approach to cybersecurity that addresses these challenges comprehensively. Failsafe backup approaches that do not rely on consumer communication systems are also deemed to be critical, as they provide a safety net in the event of a cyber incident. Regular penetration testing and cybersecurity audits are also mentioned to be critical in practices since they help identify vulnerabilities in systems and ensure that security measures are effective and up to date.

Regulatory bodies like the North American Energy Reliability Corporation (NERC) play a pivotal role in providing oversight and establishing cybersecurity standards within the energy sector. While it was also noted that a comprehensive cybersecurity regulatory framework is necessary for interactions between Smart Meter Gateways (SMGWs) and Home Energy Management Systems (HEMS), which promotes consistency in security practices across all connected devices.

Finally, a concerted effort to strengthen cyber-threat awareness and competence is essential. Enhancing a well-developed cybersecurity culture and awareness among TSOs and DSOs facilitates capacity building as personnel must be equipped with the knowledge and skills to recognize and respond to cybersecurity threats effectively.

4.2.5. Economic and Market related aspects

4.2.5.1. Role of business models

The design of business models are crucial in accelerating the transition toward a more adaptable and resilient power system. Their development in the energy sector is closely tied to the advancement and adoption of flexibility solutions. However, a significant risk arises when insufficient business models hinder implementation. To address this, numerous pilot projects are now dedicated to exploring the opportunities for utilizing flexibility, aiming to create compelling business models and integrate them into these initiatives.

Key questions

- How do evolving business models in the energy sector and among third-party providers impact flexibility solutions, and how can innovation drive a more flexible, resilient grid?
- What challenges do TSOs and DSOs face in adapting their models to flexibility services, and how can they ensure reliability, affordability, and new revenue streams?
- What partnerships or collaborative models can TSOs, and DSOs explore to enhance synergy, resilience, and address challenges like distributed energy and climate change?

From the perspective of system operators, several challenges are evident, including increased uncertainties in long-term system planning and the integration of flexibilities. To address these challenges, DSOs must prioritize greater involvement of FSPs, particularly during the tendering phase, to enhance grid reliability, boost operational efficiency, and support the seamless integration of renewable energy sources. By establishing a robust TSO/DSO interaction process, FSPs can participate in both mechanisms (flexibility for TSO and/or flexibility for DSO), paving the way for additional business model opportunities.

Key challenges for system operators also include balancing technical feasibility with regulatory considerations. In some cases, legislation is perceived as a barrier to creating viable business cases. For instance, in many countries, system operators are prohibited from owning storage systems, or regulatory frameworks adhere to a "one asset, one service" model.

Although a wide array of technical solutions exists, meaningful stakeholder involvement must encompass both technical and non-technical perspectives. This requires establishing mechanisms such as incentives for end-user participation and risk mitigation strategies. One approach is to develop business models that serve the customer’s interests alongside those of the energy system.

Regulatory sandboxes, such as those in Austria, are playing an increasingly pivotal role in enabling the exploration of new business models within specific frameworks approved by regulatory authorities. These sandboxes allow for testing and evaluating business models in controlled environments, facilitating an understanding of how innovations perform under real-world conditions before broader implementation. Through this process, essential data can be gathered, risks identified, and regulatory compliance ensured. This knowledge equips regulators to make informed decisions, ultimately supporting the successful implementation of innovative business models.

4.2.5.2. Putting a price on a modern grid

The integration of flexibility solutions within energy systems requires a rigorous comparative analysis against reference solutions to determine their economic viability and societal value. Flexibility must be quantified and valued appropriately to enable cost-effective deployment. Thus, a reference price needs to be determined. Quantifying the willingness to pay for flexibility requires robust modelling frameworks that account for heterogeneity across customer groups and system configurations.

Key questions

- How can we effectively determine the monetary value of a sustainable grid that accounts for not only the economic benefits but also the environmental and societal advantages.
- What strategies can be employed to ensure fair and transparent pricing models for both consumers and grid operators?

It was further highlighted that nodal and dynamic pricing mechanisms offer potential pathways to signal locational and temporal value, addressing inefficiencies and incentivizing optimal system behaviour. However, these mechanisms also introduce complexities such as the potential for cross-subsidies, necessitating detailed assessments to ensure equitable outcomes.

Policies directing investment toward disadvantaged communities must incorporate considerations of "system value," balancing economic efficiency, environmental sustainability, and social equity. The adoption of carbon pricing frameworks, such as carbon taxes, further highlights the need for integrated approaches that align market incentives with decarbonization objectives.

4.2.6. Standardisation, interoperability and regulation for TSO-DSO interaction

Key questions

- How can standardization efforts and regulatory frameworks be optimized to facilitate seamless TSO-DSO coordination and ensure interoperability among various flexibility providers, ultimately promoting grid resilience and efficient flexibility utilization across different regions and markets?
- Are these strategies aligned from technical, social, economic, environmental, and regulatory perspective?
- How can potential misalignments be addressed to ensure holistic success in grid resilience and flexibility utilization?

To effectively address potential misalignments and enhance overall grid resilience and flexibility utilization, challenge/gap-focused collaboration projects between TSOs and DSOs can serve as a pragmatic approach, where adopting a "less is more" philosophy, is proposed in Norway.

In the Netherlands, ongoing research aimed at the standardization of smart energy systems is currently ongoing and aims to facilitate more cohesive operations across grid management. Complementing this effort are significant projects centred around a referential architecture based on the Smart Grid Architecture Model (SGAM), which will aid in resolving fundamental questions related to grid integration and interoperability. These projects are taking a holistic approach by considering the entire PESTEL (Political, Economic, Social, Technological, Environmental, Legal) framework, ensuring that all relevant factors are incorporated into the development of flexibility solutions.

A crucial aspect of enhancing flexibility in energy markets involves the standardization and unification of network models and data exchange protocols between grid operators. It was highlighted that establishing greater common European Union (EU) standards will enable quicker innovation and facilitate seamless integration among diverse systems. However, the process of developing standards presents inherent challenges: while standards are essential, they do not guarantee interoperability; and the establishment of standards process is often considered to be too slow. Furthermore, the relationship between the EU policy framework, national law, and national standards must be supported for harmonization efforts. This process requires time, and the incorporation of lessons learned from previous initiatives. The rapid evolution of technology often outpaces the development of standards, leading to a disconnect that can impede progress. Increasing human capacity and strategically allocating budgets to support standardization efforts could significantly enhance the alignment between emerging technologies and established standards.

A more standardized flexibility lexicon is vital for fostering a shared understanding of flexibility among stakeholders, thereby enhancing communication and collaboration. An improved understanding of how TSO and DSO control centres interact is essential for optimizing operational efficiency and ensuring seamless data exchange. Standardizing and clearly defining flexibility products is also a necessary step in this process, alongside the broader effort of network grid code standardization. These initiatives collectively contribute to the establishment of a resilient and flexible energy system that is responsive to the evolving demands of the energy landscape.

4.2.7. Knowledge transfer and dissemination

> **Key questions**
>
> - What can be done to improve the knowledge transfer to create increased awareness and impact based on the lessons learned from pilot projects?
> - Based on your experience, how far would you consider the 'reach' and impact of the outcomes/lessons learned of the pilot project? Is this on a regional or international level?
> - Are these key messages reaching the relevant stakeholders?

Effective impact and evaluation mechanisms are vital for advancing energy system innovation by ensuring that outcomes are shared, understood, and actionable. In the Netherlands, internal subsidiary programs and external initiatives such as the Smart Energy Systems Community and the annual Smart Energy Day facilitate knowledge dissemination. These platforms provide opportunities to share project outcomes and enhance collaboration among stakeholders. However, it was recognized that, in some cases, such events tend to focus on showcasing commercial products or academic research, leaving a gap where research projects can directly engage with policymakers and other stakeholders. International platforms such as ISGAN address this need but require further integration. Furthermore, demonstrating clear, actionable use cases is critical to bridging this gap and promoting practical adoption. Platforms like Technology Platform Smart Grids Austria (TPSGA) [43] exemplify how results from research projects can be effectively communicated across the value chain, ensuring direct engagement with relevant stakeholders. When considering mechanisms in order to improve knowledge exchange, it was highlighted that a balanced approach utilizing face-to-face interactions, virtual meetings, and curated online resources enhances accessibility and relevance are highly beneficial. However, common communication tools that are used to deliver knowledge transfer must strike a balance between detail and simplicity, thereby providing meaningful insights without overburdening experts. This combination facilitates collaboration, builds consensus, and maximizes the impact of research and innovation efforts.

4.2.8. Future work and outlook

The future work and outlook for the integration of flexibility resources and the evolving interaction between TSOs and DSOs require the concerted efforts of various key stakeholders. These include governmental bodies, regulatory authorities, TSOs, DSOs, market participants, and technology providers. Each stakeholder is encouraged to take proactive measures to ensure a resilient and sustainable energy grid. Thus, it is crucial for stakeholders to collaborate on developing and implementing specific strategies, such as the establishment of standardized procedures, methodologies, and roadmaps, to guide the transition of pilot projects into real-world applications. These actions should be initiated as soon as possible, with clear timelines and milestones, so that they are able to address emerging challenges and facilitate the smooth integration of flexibility resources into the grid. Regulators and policy makers were identified as key stakeholders, in collaboration with other stakeholders, and are responsible for ensuring that adequate frameworks are in place. Effective policy is essential for setting the strategic trajectory, defining priorities, roles and responsibilities and establishing operational parameters for energy systems. Regulatory frameworks complement this by structuring the "rules of the game," should encourages an environment which is conducive to experimentation and adaptation. This requires legislative action and strong political commitment. Implementation strategies for energy system innovation require an integrated framework that involves regulatory clarity, policy coherence, and community engagement. It is recommended that regulators establish clear guidelines, which also define the roles and responsibilities of all stakeholders, including policymakers, regulatory authorities, and decision-makers at both DSO and TSO levels. This

> **Key questions**
>
> - Who are the key stakeholders that need to act, what specific measures should they implement, when should these actions be initiated, and how can they collaboratively address the evolving challenges of TSO-DSO interaction and the integration of flexibility resources to ensure a resilient and sustainable energy grid?
> - What are the minimum requirements (e.g. procedures/ methodologies/ roadmaps) to be implemented to transition the developed concepts from pilot project to implementation in practice?
> - What strategies and mechanisms can TSOs, and DSOs implement to transparently communicate the value proposition of flexibility solutions to consumers and other stakeholders, ensuring that their participation in grid services is mutually beneficial and aligns with broader energy sustainability goals?

clarity will help remove systemic barriers and ensure that mission-driven solutions are implemented effectively. In this way, the alignment across the entire value chain for collaboration among all actors can be established. Additionally, engaging TSOs and DSOs more actively in research pilot projects remains a significant challenge but is crucial for developing scalable, practical solutions. Real-life experimentation can incentivize increased participation and accommodate innovative approaches, which further advance solutions from modelling and analysis to large-scale demonstration and deployment. Expanding community flexibility demonstrations strengthens the bridge between theory and implementation, ensuring that communities directly benefit from energy system advancements and solutions. In order to achieve this, adequate funding through dedicated R&D budgets was identified to be an essential aspect of supporting technical innovation. Furthermore, confidence-building measures are also vital, while systems may seem unique, shared challenges and archetypes of distribution systems can serve as valuable references, which enables stakeholders to learn from other jurisdictions.

To improve the idea of value creation for stakeholders, it was highlighted that the development of business cases for flexibility providers that are predictable and provide clear assurances of return on investment (ROI) should also be encouraged. Building a collaborative ecosystem around these innovations requires the establishment of clear business cases and a predictable, transparent approach to value generation. Furthermore, it was emphasized that the communication of key facts to all stakeholders should include broader system-level benefits, such as reducing the need for grid expansion and minimizing curtailment of RES while addressing macroeconomic and environmental considerations. To build trust and foster broad stakeholder participation, value propositions must emphasize system-wide benefits over individual gains. Clarity and transparency are essential for aligning interests and encouraging engagement from all actors, including aggregators, who require consistent and actionable price signals to unlock greater business value. Demonstrating the tangible benefits of these approaches in an intuitive, low-effort manner is critical to overcoming cognitive barriers and ensuring stakeholder buy-in. These strategies not only support efficient grid operations but also create an ecosystem of trust, collaboration, and shared value for all stakeholders within the energy sector.

4.3. Expert interviews

To gain a deeper understanding of the subject, expert interviews were conducted with leading experts in the field. These conversations provided valuable perspectives, uncovering nuanced insights that might not be apparent through secondary research alone. The experts shared their experiences, challenges, and strategies, offering a blend of theoretical knowledge and practical application. This section synthesizes their key observations, highlighting recurring themes, innovative approaches, and actionable recommendations that can inform future decisions and practices.

Project	Industry for Redispatch
Overview of the project	
The Industry4Redispatch (I4RD) project is a key initiative within the NEFI – New Energy for Industry model region. It aims to develop innovative grid support solutions to (i) provide flexibility from both the demand and supply sides at the distribution network level for redispatch and (ii) demonstrate a predictive, holistic control concept for industrial energy systems that optimizes market participation while ensuring energy security. This approach allows the industry to engage in redispatch and drives technological progress within the NEFI community, particularly in digitalization and industry flexibilization. The primary goal of I4RD is to enable industrial plants to provide flexibility for redispatch. The project explores the technical, regulatory, economic, and organizational prerequisites for implementing redispatch, along with the required coordination and optimization between transmission system operators (TSOs) and distribution system operators (DSOs).	
How is your project related to TSO/DSO interaction?	
The I4RD project designs, analyses, and demonstrates an interaction process between industrial customers, distribution system operators and transmission system operators that allows utilizing the flexibilities of industrial customers for redispatch at the transmission level while respecting distribution network constraints.	
Please describe the main process steps of the DSO/TSO interaction designed in the project.	
The DSO calculates the simplified distribution system model based on the schedules of the industrial customers and sends it to an aggregation platform. The platform receives the bids from the industrial customers and solves an optimization problem to identify a set of pareto optimal bid combinations. It provides these aggregation results to the TSO who can select the most suitable one for redispatch at the transmission level.	
Which major hurdles for the coordination and aggregation of distributed flexibilities have been identified?	

• Using distributed flexibilities for transmission system operation leads to large coincidence factors at the distribution level. As distribution networks have historically been dimensioned for low coincidence factors, the activation of distributed flexibilities on request of the TSO may lead to constraint (current and voltage) violations at the distribution level. Consequently, the distributed flexibilities must be aggregated by considering the distribution network constraints, i.e., the aggregator needs a distribution network model.
• There exists a trilemma between confidentiality, transparency, and resource utilization. Only two of these requirements can be maximized at the expense of the remaining one.
  ○ Transparency and confidentiality are maximized by using and disclosing low-fidelity network models as the basis of coordination. Such models can be derived from the detailed ones by applying (fidelity-impairing) simplifications or obfuscation techniques.
  ○ Transparency and resource utilization are maximized by using disclosed high-fidelity network models as the basis of coordination. The disclosure of detailed network models impairs confidentiality and thus security and economic competitiveness.
  ○ Confidentiality and resource utilization are maximized by using nondisclosed high-fidelity network models as the basis of coordination. Using nondisclosed models impairs transparency, thus facilitating market manipulation and abuse and worsening competition.	

Industrial flexibility providers are usually not able to calculate the reactive power change associated with the bidden active power change. However, these reactive power changes are crucial to check compliance with the distribution networks voltage limits after flexibility activation.
How have you addressed these hurdles?
We have maximized confidentiality and transparency at the expense of resource utilization by using a simplified (linearized) distribution system model that contains less confidential data. This simplified model is used by a third-party platform to aggregate the flexibility bids of the industrial customers.
What are the major difficulties associated with your approach?
• The DSO must calculate and send a huge amount of data, as the simplified distribution system model must be calculated for all relevant time intervals, contingency cases, and switch states. • The calculation of the simplified distribution system model requires comprehensive observability of the distribution system, which is currently given only at the high but not at the medium and low voltage levels. • Distribution systems behave non-linear, especially in terms of reactive power. The simplified distribution system model cannot capture this nonlinearity, and consequently, safety margins are necessary to compensate for the calculation errors. These safety margins impair resource utilization as they may lead to an erroneous rejection of cost-efficient bid combinations.

Project	Redispatch 3.0
Overview of the project	
The Redispatch 3.0 aims to enhance the existing Redispatch 2.0 process by expanding its activities and outreach. A goal is to foster increased cooperation and information exchange between Distribution System Operators (DSOs) and Transmission System Operators (TSOs).	
How is your project related to TSO/DSO interaction?	
The Redispatch 3.0 project aims to strengthen the exchange of information between DSOs and TSOs, while further advancing the congestion management frameworks introduced under Germany's Redispatch 2.0 framework. A key focus of the project is addressing the integration of distributed energy resources (DERs) with a nominal power below 100 kW, which remain excluded under the current Redispatch 2.0 regulations. The primary objective is to develop standardized and interoperable approach for data exchange between DSOs and TSOs to facilitate effective congestion management for these smaller and controllable energy resources.	
Please describe the main process steps of the DSO/TSO interaction designed in the project.	
The Redispatch 3.0 project addresses key technical challenges in congestion management processes, particularly the interaction between DSOs and TSOs. Focusing on DERs below 100 kW at the low-voltage (LV) level, intelligent metering systems (iMSys) with smart meter gateways (SMGWs) are pivotal for leveraging DERs in congestion management. Real-time coordination and interoperability between DSOs and TSOs in combination with the integration of low-voltage flexibility can optimize congestion management. The project progresses through five phases, beginning with a requirements analysis to identify and classify use cases for defining the system architecture. It incorporates existing regulatory frameworks, including the Federal Network Agency (BNetzA) regulations, the German Association of Energy and Water Industries (BDEW) Redispatch 2.0 guidelines, and standards by the VDE and IEC to address TSO-DSO coordination. Subsequent phases develop the technical foundations for implementation, such as incentive models for marketing flexibility, technical connections for small DERs via iMSys/CLS interfaces, communication protocols for operator cascades, and algorithmic solutions for operational planning and management. The increasing deployment of flexible resources in LV grids raises concerns about communication cascades. Addressing congestion at TSO levels relies on leveraging flexibility from DSO. Effective solutions require access to grid element measurements, controllable resources, and state estimation. Before field deployment, the developed technologies are validated in realistic laboratory settings using real-time simulations of network topologies. These tests evaluate the impact of information communication technology (ICT) conditions and include the entire chain, from communication cascades to SMGWs and CLS interfaces. Following laboratory validation, field tests are conducted at two DSO sites to implement and assess the developed solutions. In the final project phase, the marketing potential of unused flexibilities in small-scale plants is evaluated through qualitative and quantitative analysis of field test results, exploring different application scenarios.	
Which major hurdles for the coordination and aggregation of distributed flexibilities have been identified?	
According to the VDE FNN 2030 scenario, a significant increase in distributed energy resources (DERs) is projected, including photovoltaic systems, 10 million electric vehicles, and household heat pumps, with a combined total capacity of 14 GW at the low-voltage (LV) system level. The coordination and aggregation of these DERs present significant challenges. The Redispatch 3.0 project uses an aggregation-object approach as a potential solution, facilitating efficient information exchange between grid operators. This approach enables the provision of data on grid limitations and available flexibilities to upstream grid operators. By aggregating DERs resources, the approach ensures that upstream grid operators can access comparable information to that available for other controllable resources integrated under the Redispatch 2.0 framework.	
How have you addressed these hurdles?	

The Redispatch 3.0 project aims to build a resilient and effective coordination framework for grid operators and establishes the requirements for a communication cascade. By leveraging the concept of aggregation objects, upstream grid operators gain access to information on flexibilities within the low-voltage grid. Consequently, coordination among different DSOs and TSOs is structured into a cascading hierarchy of interactions, following the principles of VDE 4140. The defined requirements from Redispatch 3.0 and the aggregation object concept are integrated and validated within this framework, where preparation and execution times are critical for effective curative congestion management.
What are the major difficulties associated with your approach?
The integration of low-voltage flexibilities into TSO-DSO coordination processes is complex. Unlike large power plants, e.g. wind parks, low-voltage systems are neither schedule nor forecast-driven. For example, the flexibility potential of a customer with an electric vehicle, photovoltaic and battery system is difficult to predict as the flexibilities interact with each other based on the customer preferences. Thus, for coordinating the flexibility of many different resources at the low-voltage level, it is required to determine their potential on an automated process. Moreover, accessing the flexibility leads to interoperability issues, which are currently addressed by standardisation committees to roll out the access to those flexibilities. Besides, it has to be considered that not only grid operators foresee the integration of low-voltage flexibility into their demands, but also the market participants try to unlock that flexibility (e.g. through dynamic tariffs).

Project	CoordiNet
Overview of the project	
The CoordiNet project, which concluded in June 2022, aimed to enhance coordination between Distribution System Operators (DSOs) and Transmission System Operators (TSOs) to efficiently procure grid services and integrate distributed energy resources (DERs).	
How is your project related to TSO/DSO interaction?	
CoordiNet demonstrated how DSOs and TSOs could collaborate to procure and activate grid services reliably and efficiently. Through large-scale demonstrations, the project explored various coordination schemes to optimize the use of flexibility resources across transmission and distribution networks. The project has specified and developed TSO-DSO-consumer cooperation platforms, starting with the necessary building blocks for the demonstrations. The platforms facilitate the procurement of flexibility services from various market participants, ensuring efficient data exchange and coordination among stakeholders. Those platforms are currently used or form the basis for flexibility service provision.	
Please describe the main process steps of the DSO/TSO interaction designed in the project.	
The project outlined several key steps for DSO/TSO interaction: • **Identification of Grid Needs:** Both DSOs and TSOs assessed their networks to determine flexibility requirements for congestion management, voltage control, and balancing. • **Standardization of Products:** Development of standardized products and key parameters for grid services, including reservation, activation, and settlement processes. • **Market Platform Development:** Creation of a TSO-DSO-consumer cooperation platform to facilitate the procurement of flexibility services from various market participants. • **Procurement and Activation:** Coordinated procurement of flexibility services through transparent market-based procedures, followed by activation as needed. • **Monitoring and Settlement:** Continuous monitoring of service delivery and execution of settlement processes to compensate providers.	
Which major hurdles for the coordination and aggregation of distributed flexibilities have been identified?	
The project identified several challenges: • **Regulatory Barriers:** Existing regulations may not support market-based procurement of flexibility services, limiting DSO and TSO capabilities. • **Market Design Complexity:** Developing standardized products and processes that accommodate diverse local conditions and regulatory frameworks is complex. • **Data Exchange and Communication:** Ensuring efficient and secure data exchange between DSOs, TSOs, and market participants is critical. • **Consumer Engagement:** Encouraging active participation from consumers and small market players in flexibility markets poses challenges.	
How have you addressed these hurdles?	
The project proposed frameworks that support flexibility markets and the roles of DSOs and TSOs. It has also defined and tested standardized products and key parameters for grid services to harmonize market participation. Additionally, CoordiNet developed a cooperation platform to facilitate efficient data exchange and coordination among stakeholders. CoordiNet implemented several measures: • **Regulatory Engagement:** Collaborated with regulators to propose frameworks that support flexibility markets and the roles of DSOs and TSOs. • **Standardization Efforts:** Defined and tested standardized products and key parameters for grid services to harmonize market participation. • **Platform Development:** Developed a cooperation platform to facilitate efficient data exchange and coordination among stakeholders. • **Demonstration Projects:** Conducted large-scale demonstrations in Spain, Sweden, and Greece to test and validate coordination schemes and engage consumers.	
What are the major difficulties associated with your approach?	
Despite progress, challenges remained:	

- **Regulatory Alignment:** Achieving harmonized regulations across different regions to support flexibility markets was complex.
- **Scalability and Replicability:** Ensuring that solutions were scalable and replicable across diverse European energy systems required careful consideration.
- **Market Acceptance:** Gaining widespread acceptance of new market designs and operational procedures among all stakeholders was challenging.
- **Technological Integration:** Integrating new platforms and processes with existing systems demanded significant effort and resources.

Project	OneNet
Overview of the project	
The OneNet project, concluded in March 2024, aimed to enhance the coordination between Transmission System Operators (TSOs), Distribution System Operators (DSOs), and network customers to effectively manage distributed energy resources (DERs) and ensure a reliable, efficient, and flexible power system.	
How is your project related to TSO/DSO interaction?	
OneNet established a seamless integration of all actors in the European electricity network, emphasizing the synergistic operation between TSOs and DSOs. By developing standardized products, key parameters for grid services, market models, and a platform for markets and the technical coordination of the involved actors, the project facilitated coordinated actions among grid operators and consumers, optimizing the overall energy system. One of OneNet pillars is to create a standardized, interoperable framework that facilitates seamless collaboration and data exchange between these entities. This interaction is critical for managing (DERs), ensuring grid stability, and enabling a unified approach to grid management across Europe. Second OneNet pillar is the formalization of harmonised market designs for integrating flexibility markets into the existing market architectures and allow the efficient allocation of flexibility to cover the TSOs and DSOs need ensuring value staking for flexibility service providers. By integrating market schemes and IT platforms, the project addresses the complexity of coordinating operations between DSOs and TSOs.	
Please describe the main process steps of the DSO/TSO interaction designed in the project.	
The OneNet project outlines a structured approach to DSO/TSO interaction with the following key steps: 1. **Data Collection and Sharing:** o DSOs and TSOs collect data from various sources, including DERs, market participants, and grid sensors. o The OneNet Decentralized Middleware ensures secure and standardized data exchange using common protocols. 2. **Flexibility Needs Identification:** o TSOs assess system-wide needs, while DSOs evaluate local grid requirements, identifying areas where flexibility services are needed. 3. **Coordination of Market Activities:** o The project integrates flexibility markets where DSOs and TSOs can procure services collaboratively. o Market activities are coordinated through a decentralized platform to avoid conflicts and ensure efficiency. 4. **Validation and Activation:** o Flexibility offers are validated by DSOs and TSOs to ensure feasibility. o Services are activated based on agreed-upon conditions, ensuring no negative impacts on the local or transmission grid. 5. **Performance Monitoring:** o Both DSOs and TSOs monitor the delivery of flexibility services in real time. Post-delivery evaluations ensure transparency and accountability.	
Which major hurdles for the coordination and aggregation of distributed flexibilities have been identified?	
The project identified several challenges: • **Data Exchange Complexity:** Efficient coordination required seamless data exchange between TSOs, DSOs, and market participants, which was complex due to differing data models and communication protocols. • **Data Silos:** Limited interoperability and lack of standardized data models create inefficiencies. • **Regulatory Misalignment:** Variations in regulatory frameworks across EU member states hinder cross-border standardization. The lack of standardized products and key parameters for grid services across Europe hindered effective coordination.	

- **Market Fragmentation:** The existence of isolated markets for flexibility services complicates the aggregation and coordination processes. Developing market designs that accommodated both local and system-wide services without conflicts was complex.
- **Technical Barriers:** Smaller stakeholders face challenges in integrating advanced IT systems due to resource constraints.
- **Conflicting Interests:** DSOs and TSOs sometimes have competing priorities, leading to coordination difficulties.

How have you addressed these hurdles?

To tackle these challenges, OneNet:

- **Developed a Common Market Design:** By defining standardized products and key parameters for grid services, the project facilitated coordinated actions among all actors. The project developed a Theoretical Market Framework to describe different market designs alternatives.
- **Market Integration:** The project integrates flexibility markets at both local and system-wide levels, reducing fragmentation.
- **Established a Common IT Architecture:** This open architecture enabled interactions among various platforms, allowing any participant to join any market across Europe, thus simplifying data exchange. The introduction of the OneNet Decentralized Middleware allows for secure, scalable, and standardized interactions.
- **Conducted Large-Scale Demonstrations:** Implementing and showcasing scalable solutions across different European regions validated the effectiveness of the proposed models.
- **Stakeholder Engagement:** Active collaboration with regulators, market participants, and grid operators ensures alignment of priorities and solutions.

What are the major difficulties associated with your approach?

Despite these efforts, challenges remained:

- **Complexity of Implementation ensuring interoperability:** Integrating decentralized platforms and ensuring compliance with diverse standards requires significant effort and resources. Achieving seamless interoperability between diverse IT systems and platforms across different countries was complex.
- **Regulatory Alignment:** Aligning regulations across various jurisdictions to support the new coordination schemes required significant effort and collaboration.
- **Scalability Issues:** Adapting solutions to varying sizes and capabilities of grid operators, especially in regions with less advanced infrastructure, can be challenging.
- **Regulatory Delays:** Achieving regulatory alignment across multiple countries is a slow process.
- **Cybersecurity Concerns:** Ensuring the security of data exchanges in a decentralized system adds complexity.
- **Market Adoption:** Encouraging all stakeholders to adopt new processes and systems can be a lengthy and resource-intensive task.

Project	InteGrid

Overview of the project

InteGrid bridges citizens, technology, and energy stakeholders by empowering DSOs to optimize the energy system and facilitate market participation. The project demonstrates scalable solutions for integrating renewable energy and flexible resources into stable, efficient grids. Key focuses include proactive DER planning, innovative business models, and enhanced collaboration among stakeholders. With a diverse consortium and real-world demonstrations, InteGrid aims to deliver replicable solutions and unlock new opportunities in the energy market.

How is your project related to TSO/DSO interaction?

Demonstration of predictive grid management tools for flexibility management in MV and LV grids, considering a grid and market hub platform to support information exchange between different stakeholders (TSO, DSO, aggregators) about flexibility. Demonstration of a predictive traffic light concept for TSO-DSO coordination.

Please describe the main process steps of the DSO/TSO interaction designed in the project.

Within the InteGrid project, a traffic light system (TLS) has been developed (algorithm), which is involved in the flexibility bid offering and activation process. Thereby, it can curtail flexibility offers if network constraints are foreseen or suggest alternative flexibilities to be activated if an activation would cause problems in the network. The TLS has two operation modes:

- Day-ahead: In the day-ahead mode, the flexibility operator (FO) periodically sends its flexibility bid offers to the TLS before the gate closure of the market. The TLS analyses these offers and flexibilities, which could lead to network constraints. With this information, the FO can adapt its bids to not interfere with the safe operation of the DSO's network. Before gate closure, the FO sends its final bids to the TSO, which the TLS has validated. If the TSO accepts the offers, the bids can be activated on the next day for the mFRR market.
- Intraday: In intraday, the TSO can activate the bids accepted on the day before. Thereby, the TSO forwards a bid activation to the TLS. It evaluates the bids to be activated and suggests an alternative bid activation to the FO if the activation would lead to network constraints.

Which major hurdles for the coordination and aggregation of distributed flexibilities have been identified?

- Minimize bid size of 1MW per delivery point. This significantly limits the aggregation of flexible resources.
- Lack of standardized flexibility products at the DSO level.
- Short-term vs long-term flexibility markets: the pros and cons of both time horizons are unclear and if both can co-exist and how.

How have you addressed these hurdles?

In the project, we provided the following recommendations:

- DSOs should be explicitly allowed to procure flexibility services from grid users or aggregators managing a portfolio of flexible DER.
- In the early stages, DSOs and third parties should be allowed to test different flexibility market configurations, under regulatory sandboxes if necessary. Over time, flexibility markets and products may be standardized if deemed required.
- Long-term procurement, years-ahead and with a contract duration of several years, should be encouraged to enable incorporating it in the DSO investment plans. In other words, this recommendation is oriented to include flexibility as an integrated part of the DSO investment plan (e.g., considering a mix between traditional network reinforcements and flexibility resources), which currently is for 3 years in Portugal.
- The activation price of flexibility sources that are contracted under a long-term framework should be determined in the short-term under a market-based mechanism competing against

all available sources of flexibility (including those without a long-term contract and flexible connection agreements). • Long-term contracts may include a cap on the activation price to protect DSOs against opportunistic behaviours from flexibility providers. • DSOs should submit investment plans as part of the price review process. These plans should reflect fairly the use of flexibility as an alternative to grid reinforcements and make it clear how the different expenditures are related to the outputs that want to be attained. • Enhanced TSO-DSO coordination (operational planning and real-time operation timeframes) is necessary to ensure seamless participation of aggregators in both local and centralized markets.
What are the major difficulties associated with your approach?
The main difficulties with our approach include the lack of harmonization in regulations and market structures across countries, which limits replicability, and the absence of standardized flexibility products. The traffic light system is recognized by several stakeholders as important, but not translated to current network codes, as far as we know.

Project	Insights from Japan
Overview of the project	
The project aims to enhance the integration of renewable energy sources like solar and wind, which are weather-dependent, by improving existing systems rather than relying on costly and time-consuming upgrades. NEDO will focus on enabling non-firm connections, where new power sources can be added with output control during periods of grid congestion. This includes developing prediction and control systems, as well as optimal control technologies to manage voltage and power flow variations in the distribution system. Additionally, the project will work on establishing a decentralized network system.	
How is your project related to TSO/DSO interaction?	
In Japan, TSO and DSO are the same company. For example, the functions between TSOs and DSOs are shared in supply and demand control and congestion management for transmission grids. The system that makes this possible is called the Connect & Manage System, which is described in the following material: https://www.nedo.go.jp/english/activities/activities_ZZJP_100150.html	
Please describe the main process steps of the DSO/TSO interaction designed in the project.	
The Connect & Manage System enables power supply, demand, and congestion management of the power transmission grids by taking into account the power supply of the power distribution grids through the following steps. 1) TSOs receive power generation plans from power generators including distribution grids. 2) Formulate power flow plans by incorporating the demand and power source plans for each sub-transmission and distribution (48 slices /30 minutes per 24 hours), through the connect & manage system. 3) TSOs develop power flow plans for the lines and send commands for individual curtailment control of each generator 4) Power generators automatically or manually control generators based on these commands.	
Which major hurdles for the coordination and aggregation of distributed flexibilities have been identified?	
System construction and the cost to realize connect & manage and rewriting the output power when redispatch is conducted. However, there are other challenges if we aim to build a local flexibility market for power distribution systems in the future, for example, is it possible to ensure DER flexibilities, what kind of incentives should be given to aggregators to use DER flexibilities, how to operate the distribution grids in consideration of daily grid switching, etc.	
How have you addressed these hurdles?	
The use of DER flexibility is currently being considered in NEDO projects etc.	
What are the major difficulties associated with your approach?	
Clarifying cost-effectiveness (comparison with grid reinforcement), system construction, and coordination with TSO operations, etc.	

4.3.1. Summary of expert interviews

	Industry4Redispatch	Redispatch 3.0	coordiNET
How is your project related to DSO/TSO interaction?	The I4RD project enables industrial flexibility for transmission redispatch while respecting distribution network constraints	The Redispatch 3.0 project enhances DSO-TSO information exchange and advances congestion management frameworks from Germany's Redispatch 2.0.	CoordiNet demonstrated TSO-DSO collaboration for grid services, developing platforms for efficient flexibility procurement & coordination, now in use or forming the basis for service provision.
Please describe the main process steps of the DSO/TSO interaction designed in the project.	The DSO creates a simplified distribution model from industrial schedules, the platform optimizes bid combinations, and the TSO selects the best for transmission-level redispatch.	The project addresses congestion management by improving DSO-TSO coordination and using sub-100 kW DERs with intelligent metering for real-time, low-voltage flexibility	DSOs & TSOs assessed grid needs, standardized products, built a TSO-DSO-consumer platform, coordinated flexibility procurement & activation, and ensured monitoring & settlement
Which major hurdles for the coordination and aggregation of distributed flexibilities have been identified?	There is a trilemma between confidentiality, transparency, and resource utilization. Only two of these requirements can be maximized at the expense of the remaining one.	The VDE FNN 2030 scenario forecasts 14 GW of DERs at LV level, including PV, EVs, and heat pumps. The project streamlines data exchange on grid limits & flexibilities, aligning with Redispatch 2.0.	Regulatory barriers, market design complexity, data exchange challenges, and consumer engagement difficulties hinder effective flexibility service procurement & coordination between DSOs, TSOs, & market participants.
How have you addressed these hurdles?	Maximized confidentiality and transparency at the expense of resource utilization by using a simplified (linearized) distribution system model that contains less confidential data.	Redispatch 3.0 develops a coordination framework for grid operators, using aggregation objects and a cascading DSO-TSO hierarchy for efficient congestion management.	The project designed flexibility market frameworks, tested standardized grid services, and developed a platform to improve data exchange and coordination among DSOs, TSOs, and stakeholders
What are the major difficulties associated with your approach?	The DSO must calculate extensive data for the distribution system model, but limited observability and nonlinearity require safety margins that reduce resource utilization and may reject cost-efficient bids.	Integrating low-voltage flexibilities into TSO-DSO coordination is complex due to unpredictable interactions and interoperability issues, with efforts from both grid operators and market participants to unlock flexibility.	Challenges included regulatory alignment, scalability, market acceptance, and technological integration, requiring effort to harmonize regulations and integrate new platforms.

	ONENET one network for Europe	integrid	
How is your project related to DSO/TSO interaction?	OneNet unifies Europe's electricity network by standardizing products, market models, and coordination platforms for TSOs, DSOs, & consumers, optimizing DER management and flexibility allocation	The project showcases predictive grid management tools for flexibility in MV & LV grids, using a grid& market hub platform for TSO-DSO-aggregator information exchange & a predictive traffic light concept (TLS).	In Japan, TSOs and DSOs are the same company, sharing functions like supply and demand control and congestion management for transmission grids through the Connect & Manage System.
Please describe the main process steps of the DSO/TSO interaction designed in the project.	The project defines a structured DSO-TSO interaction, covering data sharing, flexibility needs, market coordination, service validation, and real-time performance monitoring.	The InteGrid project's TLS manages flexibility bids by curtailing or suggesting alternatives to prevent network constraints, operating in day-ahead for bid adjustments and intraday for activation.	The Connect & Manage System in Japan manages power by having TSOs receive generation plans, formulate power flow plans, send curtailment commands, & have generators adjust output accordingly.
Which major hurdles for the coordination and aggregation of distributed flexibilities have been identified?	The project identified challenges such as data exchange complexity, data silos, regulatory misalignment, market fragmentation, technical barriers, and conflicting DSO-TSO interests, hindering coordination and integration.	Challenges include minimizing bid size to 1MW, limiting resource aggregation, lack of standardized flexibility products at the DSO level, and uncertainties around short- and long-term market coexistence.	System construction and the cost to realize connect & manage and rewriting the output power when redispatch is conducted.
How have you addressed these hurdles?	To address challenges, OneNet developed a common market design, integrated flexibility markets, created a unified IT architecture, conducted large-scale demos, and engaged stakeholders to align priorities.	The project recommended that DSOs procure flexibility services, test market setups, include flexibility in investment plans, and ensure TSO-DSO coordination.	The use of DER flexibility is currently being considered in NEDO projects etc..
What are the major difficulties associated with your approach?	Despite efforts, challenges remained in ensuring interoperability, regulatory alignment, scalability, addressing delays, managing cybersecurity, and achieving market adoption across stakeholders.	Main difficulties include lack of regulatory harmonization, limiting replicability, and absence of standardized flexibility products. While recognized, the TLS has not been integrated into network codes.	Clarifying cost-effectiveness (comparison with grid reinforcement), system construction, and coordination with TSO operations, etc.

5. Conclusions, recommendations and outlook

This discussion paper presents the critical importance of system flexibility in modern power networks and the imperative for enhanced coordination between TSOs, DSOs, market operators, and other key stakeholders. The transition towards a decentralized, renewable-based energy paradigm necessitates the establishment of robust market architectures, adaptive regulatory frameworks, and state-of-the-art technological advancements to maintain grid stability, optimize operational efficiency, and minimize system costs. Insights from international pilot projects reinforce the need for well-defined roles, market-driven flexibility procurement mechanisms, the deployment of advanced ICT solutions. Regulatory convergence is also essential in ensuring the seamless integration of DERs and the scalability of flexibility markets.

The analysis shows that advanced TSO-DSO coordination not only optimizes resource allocation but also mitigates grid congestion, enhances resilience, and refines operational planning. The digitalization and implementation of predictive analytics, and real-time automation is instrumental in streamlining market operations and grid management. Nevertheless, persistent challenges such as regulatory misalignment, limited market liquidity, cybersecurity vulnerabilities, and interoperability constraints across digital platforms must be systematically addressed. Overcoming these barriers requires an integrated approach combining regulatory evolution, multi-stakeholder collaboration, and continued investment in technological innovation.

Based on the findings from international pilot projects and stakeholder feedback, the following recommendations aim to enhance TSO-DSO coordination, deploy advanced ICT tools and market mechanisms, and refine regulatory frameworks.

1. **Strengthen TSO-DSO Coordination:**
   - Enhance collaboration between stakeholders to improve grid efficiency, optimize flexibility resources, and ensure a more resilient energy system.

2. **Invest in Technological Innovation and Integration:**
   - Prioritize investments in enabling technologies and their seamless integration to enhance grid flexibility, support digitalization, and improve overall system efficiency. This includes the integration of advanced data analytics, real-time data exchange, and predictive modelling.
   - Ensure that all ICT solutions adhere to robust cybersecurity standards (e.g., ISO/IEC 27002/27019) and comply with data privacy regulations (e.g., GDPR) while facilitating interoperability.

3. **Evolve Market Mechanisms for Flexibility**:
   - Develop and refine market structures to better accommodate flexibility services, ensuring fair compensation, increased participation, and efficient resource allocation.
   - Establish flexibility markets that support dynamic pricing, bid stacking, and bid forwarding. These models should enable both DSOs and TSOs to procure ancillary services efficiently while balancing local and system-wide needs.
   - Develop incentives and standardized prequalification procedures to increase participation from distributed energy resource (DER) providers, aggregators, and service providers.

4. **Strengthen Regulatory and Policy Frameworks**:
   - Establish clear, forward-looking regulatory and policy frameworks that promote innovation, market stability, and the effective integration of new flexibility solutions.
   - Align and update network codes and regulatory frameworks to reflect the evolving roles of TSOs, DSOs, and emerging market players, ensuring that innovative coordination models can be scaled up.
   - Create controlled environments to test and refine new market designs, ICT solutions, and coordination strategies before broader implementation. This can be achieved through the implementation of regulatory sandboxes.

5. **Promote Stakeholder and Consumer Engagement:**

- Actively involve all relevant stakeholders, including consumers, in the energy transition by increasing awareness, providing incentives, and enabling participation in flexibility markets.
- Simplify market participation through user-friendly interfaces, dynamic tariffs, and transparent communication about system benefits.
- Increase consumer awareness and energy literacy so that prosumers and aggregators can effectively contribute to and benefit from flexibility markets.

6. **Facilitate Continuous Learning and Knowledge Transfer:**
   - Encourage ongoing learning initiatives, knowledge-sharing platforms, and collaboration among industry stakeholders to stay informed about emerging trends, best practices, and technological advancements.
   - Regularly review lessons learned from international pilot projects to adapt operational strategies, refine technologies, and update market models.
   - Encourage workshops, surveys, and expert interviews to continuously share experiences and drive collaborative innovation across the energy sector.

Looking forward, the transformation of the energy sector demands the further evolution of flexibility markets to accommodate increasing levels of renewable energy penetration and the widespread electrification of industrial, commercial, and residential sectors. Future research and industry efforts should prioritize refining procurement methodologies, enhancing real-time bidirectional coordination between grid operators, and advancing sector-coupling mechanisms to foster multi-energy system interoperability. The integration of advanced digital technologies such as artificial intelligence-driven optimization, blockchain-enabled smart contracts, and real-time analytics will be critical for maximizing the efficiency of flexibility trading and ensuring optimal system balancing.

Regulatory bodies are encouraged to persist in adapting and harmonizing frameworks to foster innovation while upholding system reliability, security, and market transparency. Policymakers should strive for regional and international policy synchronization to establish a unified approach to flexibility integration, ensuring market coherence and minimizing cross-border inefficiencies. Further pilot projects and large-scale demonstration initiatives will be essential in validating, refining, and scaling emerging solutions to ensure their practical applicability across diverse energy markets. Incorporating social sciences and humanities (SSH) research competencies will be crucial in understanding stakeholder behaviors, regulatory impacts, and societal acceptance.

In conclusion, the successful deployment of flexibility services will depend on an integrated effort from all relevant stakeholders, including policymakers, regulators, TSOs, DSOs, aggregators, market participants, and consumers. By leveraging solutions, optimizing market structures, and achieving regulatory harmonization, the power sector can transition towards a more resilient, sustainable, and economically optimized future. The continued engagement and cooperation among all actors will be crucial in addressing the evolving complexities of modern power systems and achieving a fully integrated, decarbonized, and intelligent electricity grid.

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7. Appendix

7.1. evolvDSO

The EvolvDSO project [44] addressed the challenges faced by DSOs associated with the complexities of integrating RES, decentralized production, and new electricity demands such as electric vehicles (EVs). The project aimed to enable a proactive distribution management approach by offering tools and strategies to improve network planning, operations, and data-driven services, while defining new DSO roles based on future electricity system scenarios [44]. Central to the project was the development of future scenarios considering varying levels of RES penetration, demand evolution, and technological flexibility across short (1-4 years), mid (8-10 years), and long-term (20 years) horizons. Using these scenarios, the project created 10 innovative tools, as shown in Figure 14 [45]. The project focused on developing these advanced tools and methods across various DSO functions, including planning, operational scheduling, real-time operations, and maintenance and were validated through simulations and real-world environments across six European countries (Belgium, France, Germany, Ireland, Italy and Portugal) to ensure scalability, replicability, and effective deployment [44]. By facilitating distributed generation and flexible grid capacity, EvolvDSO supports the European Electricity Grid Initiative (EEGI), renewable energy targets, and smart city objectives.

evolvDSO	Development of methodologies and tools for new and evolving DSO roles for efficient DRES integration in distribution networks
Coordinator	E-distribuzione SPA
Duration	2013-2016
Demo locations	
Funding	Seventh Framework Programme
Website	https://cordis.europa.eu/project/id/608732

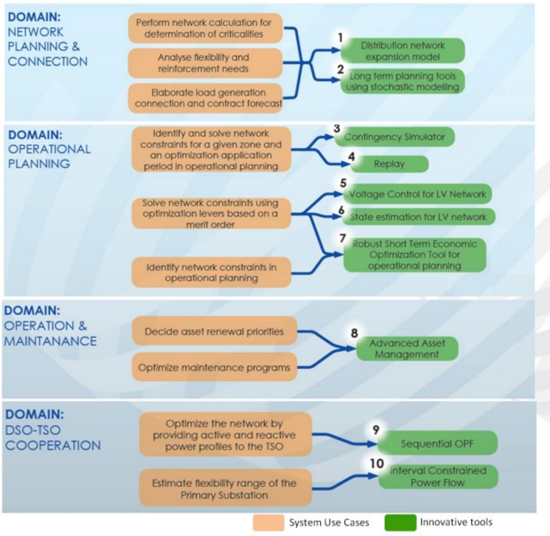


Figure 14: Overview of tools developed in EvolvDSO

In [46] the evolving roles of DSOs in addressing challenges posed by increased distributed renewable energy sources (DRES), demand growth, and market evolution is presented. It highlights the ten key services derived from the EvolvDSO project to support DSOs' transition towards active distribution system management, enabling optimal grid operation and DRES integration. These services span five domains:

1. **Network Planning and Connection:** Focused on optimizing network development using data-driven tools, creating masterplans incorporating flexibility, and offering non-firm grid access contracts to minimize costs and reinforce network use.
2. **Operational Planning:** Includes improving work coordination among stakeholders and optimizing network operations ahead of market gate closure to manage constraints effectively.
3. **Operation and Maintenance:** Prioritizes asset renewal and maintenance using predictive models to reduce costs and extend asset life.
4. **Market Interaction:** Certifies flexibility operators, ensures grid compatibility for market actions, and establishes a distribution constraints market for cost-effective flexibility activation.
5. **TSO-DSO Cooperation:** Enhances collaboration with TSOs through robust data exchange, coordinated maintenance, and shared resource management across multiple timeframes.

The key insights from the project showed that by adopting these services, DSOs can act as neutral market facilitators, improve grid reliability, and support regulatory compliance while addressing emerging challenges in the power system. The analysis also emphasised the importance of strengthened TSO-DSO collaboration and advanced information management for effective service delivery. As shown in [47] the critical need for DSOs to transition from a passive "fit and forget" model to an Active Distribution System Management (ADSM) approach to ensure the fulfilment of DSO's core responsibilities and address the growing complexities of integrating DRES, EVs, and smart grid technologies is becoming increasingly prominent. This evolution entails optimizing network planning, contracting flexibility resources, and enhancing cooperation with TSOs, while facilitating electricity markets and providing data-driven services to empower consumers. The project introduces new and evolving roles for DSOs, such as Distribution System Optimiser and Neutral Market Facilitator, to ensure efficient and secure grid operation. Furthermore, it was shown that challenges such as bi-directional power flows, increased unpredictability, and regulatory barriers enhance the need for sound policy frameworks and financial incentives. It was shown that by adopting advanced metering, sensing, and control technologies, DSOs can improve system efficiency, integrate renewables cost-effectively, and enhance service quality, ultimately delivering systemic benefits to all stakeholders.

Furthermore, [48] highlights the key lessons learned from the EvolvDSO project and describes the contributions towards the development and testing of innovative grid management tools to improve coordination between TSOs and DSOs. In particular, the Interval Constrained Power Flow (ICPF) tool aggregates network flexibility to estimate feasible active and reactive power range at TSO-DSO boundaries and was shown to facilitate improved planning and coordination. Additionally, the Sequential Optimal Power Flow (SOPF) tool optimizes flexibility activations to minimize operational costs and maintain power flows within pre-agreed limits. Both tools demonstrated notable efficiency and scalability, with ICPF providing rapid and cost-effective flexibility estimation compared to Monte Carlo simulations and SOPF achieving significant reductions in power losses and operational costs. Simulation results based on test cases, conducted on French networks, showed the influence of network configurations, renewable energy penetration, and flexibility resources have a substantial impact on the power loss reductions. While, on the other hand, simulations conducted on Portuguese networks indicated results which emphasise the role of reactive power compensators. Flexibility improvements were linked to demand growth and renewable energy expansion, particularly in long-term scenarios, while short- and mid-term scenarios highlighted the need for dynamic management strategies. It was, thus, concluded that both these tools offer a viable solution and contribute toward TSO-DSO cooperation studies.

7.2. TDX-ASSIST

TDX-ASSIST	Coordination of Transmission and Distribution data eXchanges for renewables integration in the European marketplace through Advanced, Scalable and Secure ICT Systems and Tools
Coordinator	Brunel University London
Duration	2017-2020
Demo locations	
Funding	Horizon 2020
Website	http://www.tdx-assist.eu/

The TDX-ASSIST project [49] addressed the critical challenge of improving the coordination and information exchange between TSOs and DSOs. In particular, the project focused on the design and development of innovative ICT tools and techniques to enable scalable, secure, and interoperable information systems and data exchange between TSOs and DSOs. Key outcomes of the project include scalability to accommodate growing user bases and data volumes, robust security measures to protect against external threats, and interoperability to ensure seamless communication and information exchange in adherence to existing and emerging international smart grid ICT standards [50]. The TDX-ASSIST project primarily focused on enhancing TSO-DSO interoperability, which complimented the already established TSO-TSO collaboration via ENTSO-E's Common Grid Model Exchange System and the motivation that strengthening TSO-DSO interaction will also support future TSO-TSO interoperability. Additionally, it addressed the interactions between DSOs and other market participants, such as aggregators, distributed energy resource operators, and micro-grid operators, while enabling streamlined business processes through accessible data portals. The project's Deliverable D4.7 [51] consolidates the key insights and future needs derived from three national demonstrators, Slovenia, France, and Portugal, each focusing on distinct yet interrelated use cases of TSO-DSO interaction. The main findings are summarised as follows.

Slovenia

The Slovenian demonstrator emphasized two key Business Use Cases (BUCs): BUC 1, which considers the activation of DSO-connected resources for balancing services, and BUC 9, focused on TSO-DSO coordination for long-term network planning. The demonstration utilized the ENTSO-E Communication & Connectivity Service Platform (ECCo SP) for secure, real-time data exchange and adopted CIM[5] profiles for modelling and communication. The tools developed, such as Python applications for baseline load forecasting and protocol converters, enabled data exchange via lightweight protocols like MQTT[6]

[5] Common Information Model

[6] Message Queuing Telemetry Transport

and AMQP[7]. However, challenges identified include the need for tools that facilitate incremental updates to network models and CIM enhancements for greater detail in DSO networks. Moreover, the results highlighted the importance of Internet of Things (IoT) architecture and enhanced cybersecurity to support scalable, real-time operations.

France

The French demonstrator, implemented on EDF's[8] R&D platform (with simulated market participants such as TSO, DSO and BSP), focused on BUCs 5 & 6, which involved optimizing reactive power management for voltage control, and BUC 2, addressing distributed flexibility services in a marketplace. In BUCs 5 & 6, it was shown that the demonstrations successfully utilized an Enterprise Service Bus (OpenESB) as a data exchange platform between the TSO and DSO. This implementation was aligned with ENTSO-E responses and the European Market Style Profile (ESMP) related profiles ensuring consistency with ENTSO-E recommendations. The demonstrations were deployed on different environments: OpenESB Glassfish installed on a Windows platform and a Linux-based system for interoperability testing. To secure transactions, the HTTP Binding Component employed both Transport Layer Security (TLSec) and Message Layer Security (MLS). Despite the progress, areas for improvement were identified such as automating the generation of service descriptions (WSDL files) from data models (XSD structures), simplifying the setup of basic Java code for web services, streamlining the coordination of web services using BPEL, and building a "Storage layer" to define databases and state variables for stakeholders. In BUC 2, it was shown that the since the Flexibility Operator (FO) interacts with both the TSO and DSO, it is necessary that a coordination mechanism is validated to prevent simultaneous double activation of the same service. Thus, TSO and DSO collaboration is essential to mitigate any adverse effects of Distributed Flexibility Resource (DFR) activation on their respective networks.

Portugal

The Portuguese demonstrator investigated advanced grid management capabilities through tools like Interval Constrained Power Flow (ICPF) and Sequential Optimal Power Flow (SOPF). These tools were tested in operational planning (BUC 7) and fault location scenarios near the TSO-DSO interface (BUC 11). It was shown that the observability of the TSO over the DSO grid enhances the reliability of the TSO grid by ensuring timely and accurate data sharing. It was shown that a common model that enables seamless integration between different software frameworks would streamline information exchange, improving operational efficiency. This approach ensures that the most relevant data is consistently shared, supporting better decision-making and system performance across the TSO-DSO interface. Additionally, it was highlighted that the development of standardized protocols for interoperability is key to achieving this goal, facilitating real-time monitoring and response to grid conditions.

Across all demonstrators, several overarching lessons were identified. The ICT infrastructure should transition toward lightweight, secure messaging protocols such as MQTT and AMQP to enable real-time and scalable communication between stakeholders. Furthermore, enhanced CIM standards adoption among DSOs, particularly for incremental data exchanges, is essential for aligning with TSO systems. The importance of cybersecurity measures, particularly for data shared over public internet links, was emphasized as smart grids increasingly depend on interconnected devices. It is recommended that standardization bodies like IEC[9] and ENTSO-E should incorporate these findings to refine communication protocols and data exchange methodologies, thereby ensuring robust interoperability and scalability across European power grids.

[7] Advanced Message Queuing Protocol

[8] https://www.edf.fr/

[9] International Electrotechnical Commission Standards organization

7.3. InterPlan

INTERPLAN	INTEgrated opeRation PLAnning tool towards the Pan-European Network
Coordinator	ENEA - Italian National Energy Agency for New Technologies and Sustainable Economic Development
Duration	2017-2021
Demo locations	N/A
Funding	Horizon 2020
Website	https://www.interplan-project.eu/

The INTERPLAN project [52] provides an INTEgrated opeRation PLAnning tool for the pan-European Network, with a focus on the TSO-DSO interactions, to support the EU in reaching the expected low-carbon targets, while maintaining network security and reliability. The project aim was to generate grid equivalent tools as a growing library able to cover phenomena relevant to operation planning issues that might occur in a large, interconnected power system at all voltage levels (transmission, distribution, and TSO-DSO interfaces). Moreover, novel control strategies and operation planning architectures were investigated to ensure the security of supply and flexibility of the interconnected EU electricity grid, based on close cooperation between TSOs and DSOs.

The conceptional toolbox developed within the project addresses the network challenges occurring at all voltage levels, related to the growing share of non-dispatchable distributed generation. The toolbox focused on the exploitation of flexibility resources installed all over the network, and on their functional representation from the transmission and transmission-distribution interface perspective. The flexibility measures analyzed were based on supporting technologies such as storage, and on the active participation of end-users, which are the center of all activities through active demand response, and on aggregated services, smart use of infrastructure, and smart response to system needs.

In detail, these flexibility measures are included in the operation planning process as control parameters used to solve the operational issues identified in semi-dynamic simulations of grid equivalents through proper control system logic based on cluster controllers and/or interface controllers. As the need for more active involvement of all stakeholders and collaboration, INTERPLAN has a focus on TSO-DSO interfaces, by addressing the main issues occurring at the specific interfaces within the interconnected grid and applying adequate intervention measures.

Among these issues, there is, for instance, the congestion that may occur at transmission-distribution interfaces, mostly due to both increasing loads, and increasing distributed generation connected to the distribution grid. In such a context, the main idea of INTERPLAN is to generate grid equivalents as a growing library able to cover all relevant system connectivity possibilities occurring in the real grid, and to develop novel control logic at all network levels, triggering the involvement of all stakeholders as well as a close coordination of TSOs and DSOs. This ensures a joint new vision of the pan-European network to give more flexibility to electricity networks.

INTERPLAN applied the following steps:

- Define detailed use cases for future grid planning and operation and related requirements.
- Identify a methodology for clustering (grid equivalenting).
- Develop a set of tools for operation planning in the integrated domains of steady-state and quasi-dynamic (for flexibility assessment) and small signal stability (detection of conditions giving rise to critical modes of oscillations, finding measures in an optimal way).

The flowchart representing the INTERPLAN toolbox overview including the various stages that the user (TSO or DSO) can perform for the operation planning of the network under consideration is shown in Figure 15.

As shown, the user identified as a TSO or a DSO selects the planning criteria to be considered for the network operation planning. This selection is based on the list of planning criteria identified by INTERPLAN consortium which also includes the optimization of TSO/DSO interaction.

After the planning criteria selection, the following three stages are performed by the user:

- Stage 1: Simulation functionalities, KPIs, and scenario selection
- Stage 2: Grid model selection / preparation
- Stage 3: Simulation & Evaluation

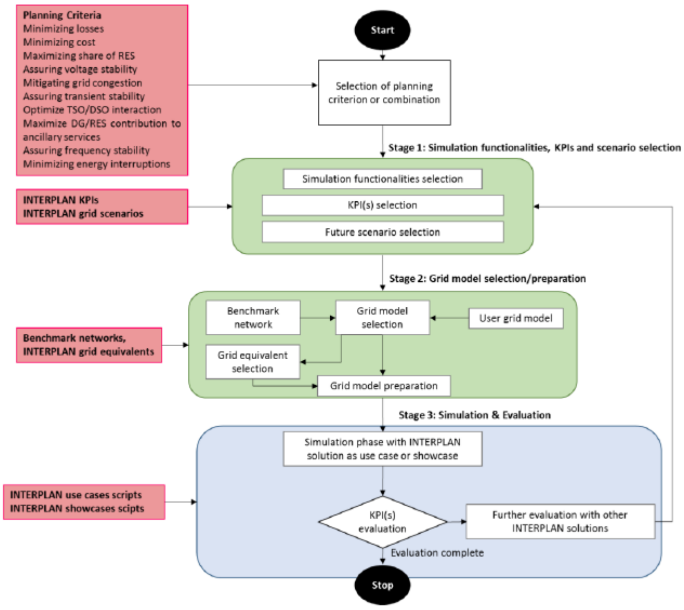


Figure 15: INTERPLAN tool overview.

Key lessons learned:

- The tool allows the operation planning of the Pan-European network through an integrated approach. By offering the possibility to investigate all network voltage levels for operational planning purposes, the tool also allows for the integration of the actions made by different stakeholders such as TSOs and DSOs, who are considered to be the primary users of the tool. In addition, this integrated approach allows for building a bridge between static, long-term planning and considering operational issues by introducing proper 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 and lack of detailed models. Through the intrinsic grid equivalenting methodology, the tool allows simplifying certain parts of a grid while keeping the relevant characteristics. This grid equivalenting methodology which applies to both transmission and distribution levels results to be needed for TSO-DSO interactions, especially in the presence of flexibility resources mainly connected at medium voltage (MV) and low voltage (LV) levels, which can be used to address operational challenges occurring at all network levels.
- Through the control functions embedded within INTERPLAN use cases and showcases, the tool allows for addressing several operational challenges of the current and future (2030+) power networks from the perspective of both TSOs and DSOs. INTERPLAN use cases address in detail, very specific operational challenges that grid operators may face with high penetration of RES, storage, DR, and EVs. On the other hand, INTERPLAN showcases address a combination of operation challenges, representing cases that the grid operators may typically face for grid operation planning purposes.
- From the practical point of view, in the future, the INTERPLAN toolset can be transformed into a Python-based toolbox interfacing with PowerFactory (under the simulation phase in stage 3), consisting of grid equivalents and control functions for use cases and showcases for addressing the related operational challenges under the selected scenario and operation planning criteria.

7.4. SmartNet

SmartNet	Smart TSO-DSO interaction schemes, market architectures and ICT Solutions for the integration of ancillary services from demand side management and distributed generation
Coordinator	RSE Ricerca Sistema Energetico
Duration	2016-2019
Demo locations	🇮🇹 🇩🇰 🇪🇸
Funding	Horizon 2020
Website	https://smartnet-project.eu/index.html

The SmartNet project [32] was initiated to address the need for solutions to the growing integration of RES into the existing electricity transmission network. The technological evolution resulting from increased RES integration has not only impacted the structure of electricity markets but also transformed the interactions between TSOs and DSOs. The project aimed to develop optimized tools and mechanisms to improve coordination between national and local grid operators (TSOs and DSOs) and to enhance the exchange of information for system monitoring and the procurement of ancillary services. These services included reserve and balancing, voltage control, and congestion management, sourced from entities in the distribution network, such as flexible loads and distributed generation. As the amount of energy produced by RES increases, alongside significant changes in distribution networks (such as the deployment of distributed generation, local storage, and flexible loads), distribution systems are experiencing the injection of larger quantities of energy into the transmission grid. Variable generation in distribution could be operated in conjunction with local storage and active demand to provide both local grid services (e.g., voltage regulation and congestion management) and services for the entire system through connections to the transmission grid. Historically, distribution networks have been managed with a "fit-and-forget" approach. However, it has become clear that future systems require real-time coordination between all actors involved in providing ancillary services. Optimizing the interface between TSOs and DSOs was identified as a crucial factor for achieving overall system efficiency. The project compared different TSO-DSO interaction models through case studies in Italy, Denmark, and Spain, where physical pilots were developed. These pilots monitored transmission-distribution interactions and explored methods for procuring ancillary services from resources within distribution networks. The main findings are compiled in [53] and are summarized as follows:

Traditional TSO-centric schemes can remain effective in distribution networks with limited congestion, though fit-and-forget reinforcement policies may lead to inefficiencies. High initial costs for monitoring and control systems might deter DSOs from adopting flexibility, highlighting the need for revised remuneration schemes that include both OPEX and CAPEX. Centralized schemes were shown to perform better from an economic perspective but are vulnerable to forecasting errors. As RES (e.g., PV, mini hydro) dominates distributed generation, improving forecasting approaches and adjusting gate closures closer to real-time is essential, where the accuracy of such approaches varies according to technology type. The argument against DSOs assuming balancing responsibility lies in high ICT costs and technical challenges; however, in some cases separating transmission and distribution markets was shown to help mitigate price disparities. Decentralized schemes face inefficiencies due to the rigidities of the two-step process, liquidity issues, local market power, and the conflict between local congestion and balancing markets, all impacting economic efficiency. In these schemes, coordination between TSO and DSO is critical to avoid the double-selection of resources in both markets, which can be achieved via a common marketplace. Local congestion markets should be sufficiently large to maintain competition, and smaller DSOs may need to pool up to reduce ICT costs and enhance market liquidity. In intraday markets, gate closures need to be closer to real-time, but overlapping intra-day markets with service markets creates uncertainty, which makes this coordination scheme unfavorable. Market objectives should focus on acquiring minimal resources for balancing and congestion management without disrupting energy market outcomes and avoiding practices like market arbitrage. The participation of distributed resources in tertiary markets should ensure a level playing field for all participants. This requires market products that accommodate unique characteristics of resources (e.g. industrial loads), which may involve complex bids or sophisticated mechanisms which make it feasible for them to participate. Finally, real-time compatibility in control loops requires thorough testing to ensure they meet reaction time requirements (ie should not be too slow), while ICT implementation costs were shown to be minor compared to operational costs across all TSO-DSO coordination schemes.

7.5. EU-SysFlex

The EU-SysFlex project [54] demonstrates the potential of decentralized flexibility resources in addressing TSO and DSO needs through coordinated efforts across multiple EU countries. The main objective was to ensure the provision of efficient system services to enable world-leading levels of RES integration while maintaining the resilience expected by European electricity consumers. To achieve this, a three-step approach was followed (1) identifying the technical needs of a pan-European system with over 50% RES and translating these into services and products within an enhanced market design, (2) augmenting electricity market design and regulations to effectively procure these services, and (3) removing barriers to competition by clarifying stakeholder roles across all system levels, including generation, TSOs, DSOs, and regulators. The EU-SysFlex initiative included demonstrators in Germany, Portugal, France, Estonia, Italy, Poland, and Finland, which explored decentralized energy flexibility for TSO and DSO needs. Germany focused on high-voltage grids, developing automated tools for voltage control and congestion management, with field tests validating real-time processes. Italy targeted medium-voltage grids, improved forecasting, and tested technologies like energy storage and STATCOMs to enable renewable integration and resilient smart grids, while Finland addressed low-voltage flexibility, piloting aggregation of e-car charging and small-scale batteries. In the Portuguese demonstration, The Flexibility Hub (FlexHub) served as a platform for DSO-TSO coordination, leveraging the flexibility of assets like renewable energy sources and storage connected to the distribution grid. It featured a reactive power market simulator to balance DSO and TSO reactive power needs, a DSO tool for bid qualification to ensure secure active power provision in an enhanced restoration reserve market, and dynamic models to represent grid response during frequency or voltage disturbances. Furthermore, the demonstrator developed a utility-scale VPP to aggregate large hydro and wind farms, optimizing RES participation in energy markets. The VPP's core and controller modules, along with its IT architecture, were fully developed. The French demonstration developed an operational Energy Management System (EMS), including both a day-ahead and intraday scheduler to optimize planning and services, alongside a short-term controller to manage the VPP for continuous operation. This ensured the optimal use of distributed resources, enabling the VPP to participate fully in system services. Additionally, an advanced offline simulation platform was created to simulate the system's behavior (EMS + VPP) under realistic conditions, ranging from days to months. Lastly, In Ireland and Northern Ireland, the project addressed the Qualification Trial Process (QTP), which includes five new trials. These trials were designed to qualify new providers of system services, such as solar PV, and test new communication protocols for control and data acquisition. Additionally, the trials demonstrated how aggregations of residential devices, including domestic batteries and electric vehicles capable of discharging to the grid, can provide system services. The project's deliverables D6.1 [55] and D10.5 [56] highlight the key messages for the future EU power system as summarised below.

EU-SysFlex	Pan-European system with an efficient coordinated use of flexibilities for the integration of a large share of RES
Coordinator	Eirgrid PLC
Duration	2017-2022
Demo locations	
Funding	Horizon 2020
Website	http://eu-sysflex.com/

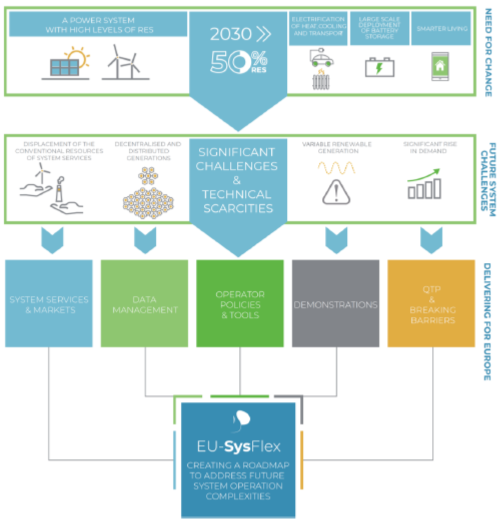


Figure 16 Overview of EU-SysFlex

The key findings from EU-SysFlex highlight the critical need for improved system observability to monitor distributed generation behaviors accurately. Without this visibility, efficient integration of RES into grid operations becomes challenging. Furthermore, the increasing complexity of energy systems necessitates investments in advanced smart grid infrastructure, supported by well-defined remuneration mechanisms to ensure sustainability. Moreover, DSOs must transition to active system operators across all voltage levels, empowered to utilize flexibility technologies for fulfilling their responsibilities. This shift requires enhanced DSO/TSO coordination for effective planning and execution of congestion management and voltage control, as the majority of flexibility resources are connected to distribution grids. Efficient coordination between TSOs and DSOs was shown to be critical, given the significant share of resources connecting to the distribution network. The increasing integration of RES at the distribution level has shifted the traditional roles of DSOs and TSOs, requiring DSOs to take a more active role in system operations, including congestion management and voltage control. Effective DSO/TSO collaboration is therefore critical, with joint planning, automated flexibility management, and adherence to principles like "local before regional" optimization ensuring efficient and stable grid operations. DSOs are evolving into active system operators, necessitating advanced tools and regulatory support to manage flexibility resources across voltage levels. Meanwhile, TSOs must adapt to the impact of distributed resources by accommodating bidirectional energy flows and enhancing data exchange with DSOs for informed decision-making.

Trials and scalability analyses validated the necessity of a dedicated coordination approach to optimize resource utilization across all system layers. It was demonstrated that aggregating decentralized resources, such as wind turbines, energy storage, electric vehicles, and heat pumps, potentially through virtual power plants could enhance system reliability, performance, and profitability through coordinated controls and optimization. When considering available resources, it was noted that flexibility activation and selection processes must be automated and guided by principles emphasizing local optimization before regional coordination to enhance system resilience and efficiency. Market-based approaches are, therefore, recommended for flexibility utilization, provided market liquidity and strategic gaming are addressed.

In terms of technical and ICT solutions, reliable forecasting, optimization tools, and communication systems were shown to be essential to enable the effective use of flexibility resources within energy markets. Efficient data management was also noted to be a critical component, with the project emphasizing the principle of “data thrift,” ensuring grid data remains within the system operator’s domain, grid impact analysis responsibility stays localized, and data exchange is aggregated to reduce complexity. These measures support decentralized frameworks that prioritize local optimization and coordination. A customer-centric approach, with standardized data access and data-driven services, is vital for ensuring interoperability between stakeholders and information systems, facilitating effective data exchanges across Europe. Additionally, interoperability proved to be a fundamental requirement for the future power system, where a growing number of participants will handle and share vast amounts of energy-related data. Data platforms based on standardization can gradually enable secure and privacy-conscious cross-border and cross-sector data exchanges.

Existing energy market structures were shown to be insufficient to guarantee the flexibility and investment needed, with projections indicating financial shortfalls for low-carbon generation due to reduced long-term energy revenues. It was concluded that new flexibility products and market evolution were required, alongside the removal of unnecessary barriers to market entry, to integrate emerging technologies. Additionally, regulatory and market barriers must be resolved through collaborative efforts involving policymakers, regulators, and stakeholders to unlock new and technically feasible solutions.

7.6. EUniversal

EUniversal UMEI	Market enabling interface to unlock flexibility solutions for cost-effective management of smarter distribution grids
Coordinator	E-redes - Distribuicao De Eletricidade Sa
Duration	2020-2023
Demo locations	Germany, Poland, Portugal (flags)
Funding	Horizon 2020
Website	https://euniversal.eu/

The EUniversal project [57] aimed to address the challenges of integrating flexibility into distribution networks. Central to this effort was the Universal Market Enabling Interface (UMEI), a modular and standardized communication framework enabling interactions between DSOs and market participants. Key innovations included tools for grid observability, Dynamic Line Rating (DLR), flexibility forecasting, and active network management [58]. Demonstrations in Portugal, Germany, and Poland validated these solutions in real-world scenarios. Each demonstration showcased tools like data-driven state estimation, congestion forecasting, and market-based flexibility procurement, tailored to address localized network constraints while ensuring scalability and replicability. Flexibility markets were designed to encourage consumer and aggregator participation, addressing barriers like entry thresholds, standardization gaps, and trust. The project developed aggregation algorithms and GDPR-compliant data-sharing mechanisms to facilitate market engagement and secure data handling [58]. The lessons learned from the EUniversal project, are highlighted in [58], which provides detailed insights into the technical, operational, and regulatory aspects of integrating flexibility into energy systems. The main findings are summarised below.

The importance of standardization in communication protocols, as exemplified by the UMEI's modular API framework proved to be essential for interoperability, allowing stakeholders to engage with multiple platforms while avoiding vendor lock-in. Its adaptability and open design emphasized the need for a European-standardized API structure to facilitate market scalability and interoperability across countries. Furthermore, consumer participation and engagement were identified to be a significant challenge due to the barriers associated with limited awareness of flexibility markets, insufficient incentives, and limited direct contact between the DSO and the end -user. To counter these barriers, EUniversal recommended combining outreach programs with incentives such as grid tariff reduction or taxation. Furthermore, aggregation algorithms were shown to be vital for enabling the pooling of smaller-scale assets into competitive market bids. This allows smaller flexibility providers to participate, addressing economic and technical limitations in their operations.

In terms of data sharing and stakeholder responsibilities, the EUniversal project highlighted that critical data-sharing arrangements are essential for enabling flexibility markets, particularly in compliance with GDPR requirements. To address regulatory constraints, a practical solution such as regulatory sandboxes was identified, which provided controlled environments to test innovations. At the low-voltage (LV) level, data sharing faces stricter regulations, thus it is proposed that such issues be proactively addressed during the project proposals phase. The UMEI framework demonstrated innovative solutions for secure data transfer, employing a distributed approach that minimizes risks. For further development, the project recommended enhancing UMEI with data exchange functions specifically designed for improved bid aggregation and voltage control. Stakeholder responsibilities in the procurement phase highlighted two approaches to bid selection: 1) within the market for transparency or 2) outside the market for detailed DSO constraints. This choice is topology-dependent, where meshed grids benefit from DSO control, while radial grids may favour a simpler market-based selection process. Additionally, dynamic flexibility areas provided a novel way to define operational constraints while reducing the need for extensive network data sharing.

On the operational side, predictive tools and planning mechanisms were highlighted to provide advanced solutions. Tools such as Dynamic Line Rating (DLR) and Data-Driven State Estimation (DdSE) were shown to enable the reduction of grid reinforcement costs while improving real-time grid observability and congestion forecasting. By leveraging historical and near-real-time data, DSOs were able to identify potential constraints in LV and MV networks, enabling smarter, cost-effective management of grid constraints without substantial infrastructure investments.

Furthermore, TSO-DSO coordination was emphasized to be an essential aspect of successful flexibility markets. With TSOs increasingly procuring flexibility from the distribution grid, potential conflicts can arise between transmission and distribution needs. Integration of DSO flexibility markets into the broader energy and balancing markets is, therefore, crucial to prevent inefficiencies, especially in areas with multiple market platforms. To optimize operations, it is recommended that local flexibility markets should follow wholesale market closures, enabling DSOs to forecast congestion needs accurately. Additionally, current challenges with market standardization and liquidity were shown to limit the viability of competition among platforms but can be addressed through regulatory intervention and harmonization. Furthermore, while counterbalancing issues are minor in small-scale implementations, their significance will grow with expanded market use, which calls for the need for focused research to further develop scalable solutions.

7.7. GOFLEX

GOFLEX	Generalized Operational FLEXibility for Integrating Renewables in the Distribution Grid
Coordinator	IBM IRELAND LIMITED
Duration	2016-2020
Demo locations	
Funding	Horizon 2020
Website	https://goflex-project.eu/

The GOFLEX project [59], [60] focused on integrating renewables into distribution grids through innovative smart-grid technologies. The project aimed to demonstrate the cost-effective use of energy flexibility to support an increasing share of renewable electricity generation. The project enhances grid adaptability, improves observability for demand response, and prevents congestion and imbalances while reducing investment needs in transmission and distribution networks. The developed GOFLEX platform facilitates the commercial management and trading of energy flexibility among consumers, generators, and prosumers, tested in demonstration sites in Cyprus, Germany, and Switzerland. Key results include the development of the FlexOffer[10] concept, a standardized format for energy flexibility, and an integrated system for automatic extraction, aggregation, and trading of flexibility. This system includes energy management systems, an AI-driven grid observability tool, a trading platform, and a conceptual model for system roles and business processes. GOFLEX project fosters market growth in energy flexibility by collaborating with various stakeholders. Therefore, GOFLEX's main objectives were to 1) accelerate the GOFLEX technology solution in Europe by developing and demonstrating mature and commercially viable, scalable, and easy-to-deploy solutions for distributed flexibilities and automated dynamic pricing enabling sustainable and flexible and 2) establish a market for distributed flexibilities and automated dynamic pricing to improve the secure energy supply at the local level and increase the economic efficiency of the overall energy system [60].

The GOFLEX system is a market-oriented ICT platform designed to facilitate active participation and flexibility trading among diverse energy market stakeholders, including prosumers (such as households, commercial buildings, industries, and EV charging stations), aggregators BRPs, and DSOs. The GOFLEX system consists of multiple interconnected building blocks (sub-systems), each with specific functions and responsibilities. These sub-systems are categorized into two primary groups: the Automated Trading Platform (ATP) and the Distribution Observability and Management System (DOMS), as shown in Figure 17 [61]. This structure allows ATP and DOMS to work in tandem to support both commercial and operational grid processes effectively.

- **Automated Trading Platform (ATP)**: A decentralized, automated trading platform that supports demand-response services by engaging all key market participants, including active flexibility providers (prosumers), intermediaries (such as aggregators and Virtual Power Plants), and flexibility users (e.g., BRPs, DSOs, and TSOs). The ATP collects and aggregates FlexOffers from diverse sources and matches them to ensure the socio-economically optimal utilization of flexibility within specific local trading areas.

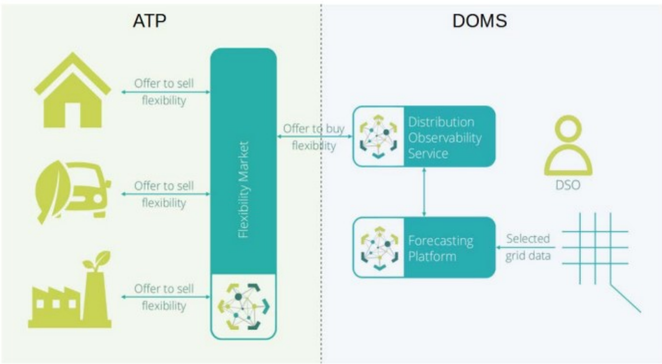


Figure 17: GOFLEX Integrated Solution Architecture

- **Distribution Observability and Management System (DOMS)**: Focused on grid operations, this system provides tools for monitoring, forecasting, and managing the distribution grid's state, enabling a more active, efficient, and dynamic grid operation. DOMS generates FlexOffers as bids to purchase flexibility and serves as the central system leveraging the traded flexibility within GOFLEX.

The GOFLEX concept successfully delivered a comprehensive end-to-end platform that integrates all relevant stakeholders, including end-users (prosumers and producers with varying flexibility capacities), microgrids, energy communities, flexibility aggregators, BRPs, system operators, and any entity requiring flexibility. The platform provided a unified solution for managing local flexibility, addressing the diverse needs of all market participants. A key benefit of the project is that it offers valuable insights to the DSO, enabling them to collaborate with the TSO and regulators on the development of regulatory frameworks for DSM congestion, and balancing management. Despite being a complete solution, the platform maintains modularity, allowing its components to be implemented individually or as an integrated system based on the specific requirements of market actors. In terms of integration of Information, Communication, and Control Technologies (ICCT) it was highlighted that these technologies are crucial for DSOs in the transition toward more intelligent energy systems. GOFLEX leveraged edge technologies and open protocols to automate the operation of a complex end-to-end flexibility platform, thereby guiding the DSO in the integration and deployment of these technologies.

[10] The FlexOffer concept was created in 2012 in the FP7 Mirabel project and further developed in the Arrowhead project and the H2020 GOFLEX project (https://www.flexoffer-community.eu/Projects.html)

Cyprus

The Cyprus demonstration implemented two complementary use cases to enhance energy management and grid efficiency. The first use case focused on microgrid energy community management, with the University of Cyprus campus acting as an aggregator to optimize its energy portfolio and trade residual flexibility with the DSO. The second use case addressed local congestion management, where the DSO purchased flexibility from 18 prosumers across two cities to balance the grid and mitigate congestion [61]. The evaluation of the demonstration results and relevant lessons learned is documented in [62] and the main insights are summarised below.

Based on the approaches developed within the project, GOFLEX was shown to extend the European Harmonized Electricity Model by addressing the structuring of the monopolistic grid segment, particularly at the distribution level. This extension recognizes that local (distribution) level issues, such as grid congestion, are easier to manage compared to system-wide (transmission) challenges. Therefore, the extension allows for the introduction of new business models and highlights the evolving role of DSOs as service procurers, in addition to their traditional responsibilities of service provision and neutral market facilitation. GOFLEX provided additional clarification for the new DSO role, which involves locally balancing energy flows within the distribution grid and addressing grid congestion both technically and economically. A key example is based on the Cyprus demonstration site, which focused on congestion avoidance through the procurement of local flexibility facilitated by the DSO, rather than relying on inefficient grid infrastructure expansion, which is often noted to be underutilized. Furthermore, GOFLEX offered a transparent, holistic solution by supporting a diverse range of use cases across all market participants, including system operators, aggregators, suppliers, and BRPs, within various market environments. In Cyprus, where there is a single DSO, a new use case emerged: the distribution BRP. This approach involves the delegation of local balancing responsibilities from the DSO to one or more distribution BRPs (i.e. sub-BRPs), who, in turn, procure flexibility services from FSPs, such as aggregators or flexible prosumers. Energy flows occur between the DSO and FSP, with contractual and financial exchanges between the DSO and BRPs, and between BRPs and FSPs. If multiple BRPs are involved, a separate Local Flexibility Market Operator is required, though the DSO or its subsidiary may assume this role when services are limited to ancillary services. In cases with a single BRP, it was identified that it is plausible for the DSO to also act as the market operator. For Cyprus, this model combines the DSO and BRP balancing responsibilities into a unified market operator role, especially for ancillary services. At the TSO-DSO boundary, the DSO's local balancing role helps the TSO maintain the Market Balancing Area by resolving imbalances through the procurement of balancing energy from FSPs at the distribution level, rather than at the transmission level. The business case for the DSO involves a split of network tariffs with the TSO, based on avoided costs of local balancing, including reduced energy transport and balancing energy costs. By considering energy flexibilities from prosumers, it was noted that the need for dedicated peaker stations is minimized, with investments focusing on control systems and environmental adaptations instead. A key challenge identified, however, is managing the potential conflict between TSO and DSO flexibility requirements, which emphasizes the need for optimal TSO-DSO cooperation. This cooperation was shown to be crucial for designing a joint flexibility market model that aligns TSO and DSO platforms, defines their interactions, and establishes an effective trading model with FSPs.

The solutions implemented through the GOFLEX platform at the Cyprus demo site have demonstrated the importance of the involvement of multiple stakeholders, such as the Market Operator, BRP, Aggregator of delegated prosumers, and potentially Energy Services Companies that provide access to flexibility for direct-trading prosumers. Within the demonstration, the DSO has actively participated in these roles, gaining first-hand experience with the full suite of solutions, including the installation, setup, and operation of hardware, software, and user interfaces. This collaboration has proven to be a valuable learning experience for the DSO, providing insights into the competencies and resources required from future market players who will sell flexibility services to the DSO. Moreover, it has revealed several technical challenges in the integration of demand-response-ready users, such as communication issues, installation constraints due to existing home configurations and infrastructure, as well as limitations posed by conventional (non-smart) home appliances. These insights were shown to be crucial for shaping the future market environment and addressing technical hurdles.

Switzerland

This demo case focused on leveraging flexibility to optimize grid balancing, thereby reducing corrective costs, and employing demand-side management to mitigate peak loads on the distribution grid. This initiative involved Factory Energy Management Systems (FEMS), Home Energy Management Systems (HEMS), a Charging Energy Management System (CEMS) and a Charging/Discharging Energy

Management System (CDEMS) demonstrating targeted strategies for enhancing grid efficiency and reliability. The evaluation of the demonstration results is documented in [63] and provides a comprehensive analysis of its deployment, technical performance, user experiences, and economic impact in demonstrating energy flexibility integration. The main insights are summarised below.

It was observed that the deployment of the GOFLEX solutions faced significant challenges, including technical hurdles during sensor installations, IT security conflicts that hampered communication between systems, and compatibility issues with pre-existing infrastructure. These obstacles required substantial corrective actions, such as software updates and hardware replacements. This highlighted the complexity of retrofitting advanced energy systems into existing environments with legacy equipment. However, once the solutions were successfully installed, the demonstration proved to be successful in showcasing energy flexibility, with measurable KPIs indicating improvements in grid observability (e.g., an 89.66% observability KPI for grid state variables) and an increase in self-consumption rates. However, further challenges were also identified, such as limited predictive accuracy of grid congestion and suboptimal response rates to flexibility offers. Furthermore, it was shown that the performance of individual subsystems, HEMS and CEMS, varied; where HEMS showed moderate improvements in energy management, while CEMS faced issues with user adoption and functionality.

Based on insights attained from user feedback, it was highlighted that the role of consumer engagement is critical for the system's success. Surveys conducted within the project, revealed mixed levels of interaction with GOFLEX technology, with many participants valuing energy monitoring features but they expressed confusion about the system's purpose and control mechanisms. Based on this, suggestions for improvement include enhancing the usability of interfaces to provide clearer explanations of system benefits and incorporating features such as comparative energy analytics and automated optimization for greater user empowerment. The feedback also highlighted the importance of building trust and understanding to foster wider acceptance of such technologies.

In terms of economic viability, it was demonstrated that there is a high potential for cost savings in grid operations, primarily through peak shaving and congestion management. These results emphasize the feasibility of energy flexibility as a tool for operational efficiency. However, it was noted that the scalability of such systems depends on reducing deployment costs and aligning stakeholder incentives. It is therefore recommended that future implementations will need to address these economic considerations alongside technical and user-centric improvements.

Germany

The German demo site showcased innovative energy management led by the utility company, which acts as both an energy provider and DSO for Wunsiedel and neighboring municipalities. The primary goal was to meet the energy demands of residential and commercial customers entirely with renewable, regionally produced energy [61]. The results and evaluation of the demonstration can be found in [64] and are summarised below.

As part of the user feedback engagements, significant insights into system operation and interaction were identified. Participants appreciated GOFLEX's ability to provide energy monitoring and automation, yet usability issues were evident, particularly with mobile app functionality and the clarity of system control. Many users were unclear about system purposes, suggesting the need for improved communication and interface design. Concerns regarding data privacy and the perceived complexity of flexibility calculations for EV charging demonstrated the necessity of user-centric approaches in future developments. The economic analysis proved the financial viability of flexibility trading, which further indicated scalable benefits for both prosumers and DSOs. However, achieving wide-scale deployment requires addressing the limitations of legacy systems and ensuring robust network integration.

Lessons learned emphasize the importance of addressing technical and operational barriers to system deployment, such as legacy infrastructure and the need for reliable connectivity. Effective user engagement, including clearer communication of benefits and simplified interfaces, is critical to adoption. Additionally, enabling EV integration through advanced communication standards like ISO 15118 and exploring further storage solutions were identified as priorities for future enhancements. The GOFLEX project highlighted the transformative potential of integrating renewables into the grid while emphasizing the need for technical refinement, user-focused design, and adaptive business strategies to achieve sustainable and scalable energy solutions.

7.8. Hybrid VPP4DSO

	Hybrid-VPP4DSO
Coordinator	AIT Austrian Institute of Technology GmbH
Duration	2014-2017
Demo locations	
Funding	
Website	https://www.grazer-ea.at/hybridvpp4dso/front_content.html

The hybrid-VPP4DSO [65] research project focused on the development of hybrid virtual power plants (hybrid-VPPs) capable of participating in electricity markets and actively supporting distribution grid operators. The hybrid VPP concept was analyzed in the project from technical, economic, and regulatory perspectives and tested as a proof-of-concept [66]. The project involved simulating and economically evaluating the coupling of various grid, market, and customer use cases for available flexibilities, in collaboration with local stakeholders from Austria and Slovenia. An overview of the Hybrid VPP concept is shown in Figure 18.

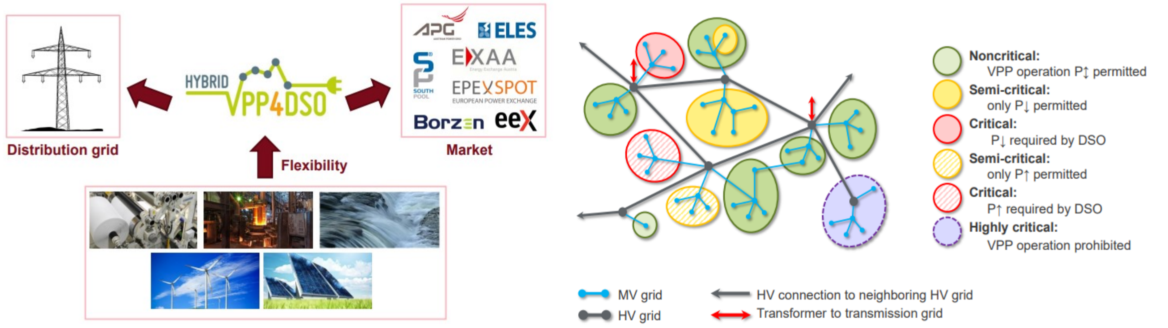


Figure 18 Overview of the Hybrid VPP concept.

From a technical standpoint, the hybrid VPP's potential to support the distribution grid was investigated in selected medium-voltage grids in Austria and two regions in Slovenia. The coordinated operation was simulated over a year at 15-minute intervals, prioritizing the distribution system operator's activation over market-driven activations. Backup capacities in unencumbered networks were used to meet market demands. Furthermore, the impact of hybrid VPP operations on distribution network health was assessed through load flow simulations, which also conducted a break-even analysis and was based on various economic considerations. Revenues from marketing flexibilities on day-ahead, intraday spot markets, and the tertiary balancing energy market were calculated for current and future scenarios, with comparisons made against installation and operation costs. Regulatory feasibility, remuneration options, and ownership models were also analyzed. The proof-of-concept demonstrated real-world feasibility, with further simulations validating the results. The project identified obstacles, opportunities, and recommendations to enable the future implementation of hybrid VPPs. The outcomes were aimed at enabling grid operators to enhance future planning and investment, energy suppliers to offer new services, and policymakers to make informed decisions on renewable energy expansion. The recommendations of the project are presented in [67] and are summarised as follows:

General framework conditions

The results of the project showed that a hybrid-VPP, with sufficient flexibility, contributed toward the mitigation of voltage problems in critical network sections, the integration of renewable feeders, the deferral of grid expansion, and the enabling of new customer connections. Furthermore, it was demonstrated that flexibility was most effective when located at the end of feeders, where voltage fluctuations were most pronounced. The increase in renewable energy, e-mobility, and heat pump penetration was shown to increase the importance of hybrid-VPPs by reducing grid expansion costs and addressing higher generation volatility and load peaks. Additionally, it was shown that the high costs of hybrid-VPPs rendered flexibility commercialization unfeasible on the day-ahead and intraday markets. Moreover, high ICT architecture standards for availability, data protection, and safety were shown to increase costs, raising the required flexibilities for profitability. Lastly, it was identified that framework adaptations and incentives targeting regulators, DSOs, energy suppliers, and industrial customers are critical for the successful implementation of hybrid-VPPs.

Regulatory framework
To provide grid-supporting flexibility as an alternative to grid expansion, the hybrid-VPP framework requires reducing cost uncertainties for VPP operations. This involves enabling "smart" investments in switching infrastructure and ensuring operational costs are comparable to annual upstream grid expenses. Furthermore, it was shown that new output parameters for grid benchmarking are necessary to address the impact of peak load reduction which would weaken the output-parameter for incentive regulation, ensuring smart grids' contributions are properly recognized. The use of synergies could be achieved by allowing DSOs to operate VPPs, thereby utilising existing infrastructure and expertise, while clarifying cost-sharing mechanisms and financial recognition for market- and grid-supportive activities. Additionally, standardizing communication and switching infrastructure was shown to be a vital aspect since this facilitates the possibility for customers to change providers, and minimize costs. Furthermore, it is recommended that DSOs evolve into neutral market facilitators, thereby offering non-discriminatory access to VPP infrastructure and supporting customers to switch between flexibility market.

Incentives for distribution system operators
The project emphasized that during the planning for future grid expansions, stakeholders should evaluate the potential for hybrid-VPPs to support grid operation and influence customer behaviour, including the flexibilities that market players offer, to enhance efficiency. A hybrid-VPP can assist distribution system operators, particularly during short-term peak periods, which may arise from volatile feeders such as PV and wind energy plants or potential temporary overloads. Furthermore, DSOs can expand their role as market facilitators by providing communications infrastructure along with measurement, aggregation, and switching services for aggregators and flexibility marketers. This approach uses smart meters and advanced data management to avoid redundant infrastructure and ensure high data availability. Furthermore, enhanced smart meters rollouts, with customer consent, could enable real-time power measurement and switching capabilities through suitable communication channels. This provides increased benefits to the DSO since they are able to obtain information pertaining to grid operation and the exact status of the flexibilities.

Incentives for energy providers and aggregators
Hybrid-VPPs offer multiple benefits for energy providers and customers, as they enhance customer loyalty and encourage market participation. By enabling operators of small to medium-sized plants (e.g., hydro plants) to participate in the balancing market, hybrid-VPPs allow energy providers to deliver additional services and foster stronger customer relationships. Hybrid-VPPs improve data availability, which supports better day-ahead predictions and real-time imbalance estimation, thereby reducing the need for balancing energy. Economic opportunities for hybrid-VPPs exist in the tertiary balancing market under current conditions; however, leveraging spot market price differences remains unprofitable. For economic viability, a hybrid-VPP should provide a minimum of 15 MW of flexibility with availability exceeding 65%. Furthermore, profitability improves as flexibility and connection point capacity increase. Contract durations of two years were found to be optimal for aggregators, as they balance predictability for operators with customer preferences. Shorter durations or frequent aggregator switching, as proposed in the "winter package,"[11] could pose challenges to the hybrid-VPP business model.

Incentives for industrial and commercial customers and generation plants
Hybrid-VPPs can reduce connection costs for new customers or grid extensions by leveraging switchable generation or consumption to simplify and accelerate grid access. Flexibility is particularly useful for loads such as electrolytic processes, electric heating, heat pumps, cooling machines, and e-mobility, provided they can switch at least 300 kW per location for a minimum duration of 4 hours, with a lead time of ≤10 minutes. Key switching times for positive balancing energy (e.g., connecting producers, cutting loads) are during early mornings and evenings, especially in winter, while negative balancing energy (e.g., cutting producers, connecting loads) is most relevant on weekends and during early morning hours on weekdays. Hybrid-VPPs also provide economic benefits by reducing power failures through predictive maintenance and environmental impact mitigation. Visualization of per minute user behaviour offers additional value by optimizing load peak reduction and performance-based grid fees. Generators like combined heat and power (CHP), hydro plants, emergency generators, and gas turbines are suited for flexibility usage, but renewable plants under green electricity funding schemes

[11] EC, 2017. Directive of the European Parliament and of the council on common rules for the internal market in electricity, COM(2016) 864 final/2,2016/0380 (COD); online: https://ec.europa.u/energy/sites/ener/files/documents/1_en_act_part1_v7_864.pdf; download June 1st 2017

and standalone wind power face regulatory limitations. Participation in the Austrian balancing market (at the time of the project) is restricted to pooled setups to ensure reliable balancing power.

Based on the project results, the Austrian findings were tested in an international context through the H2020 project InteGrid.

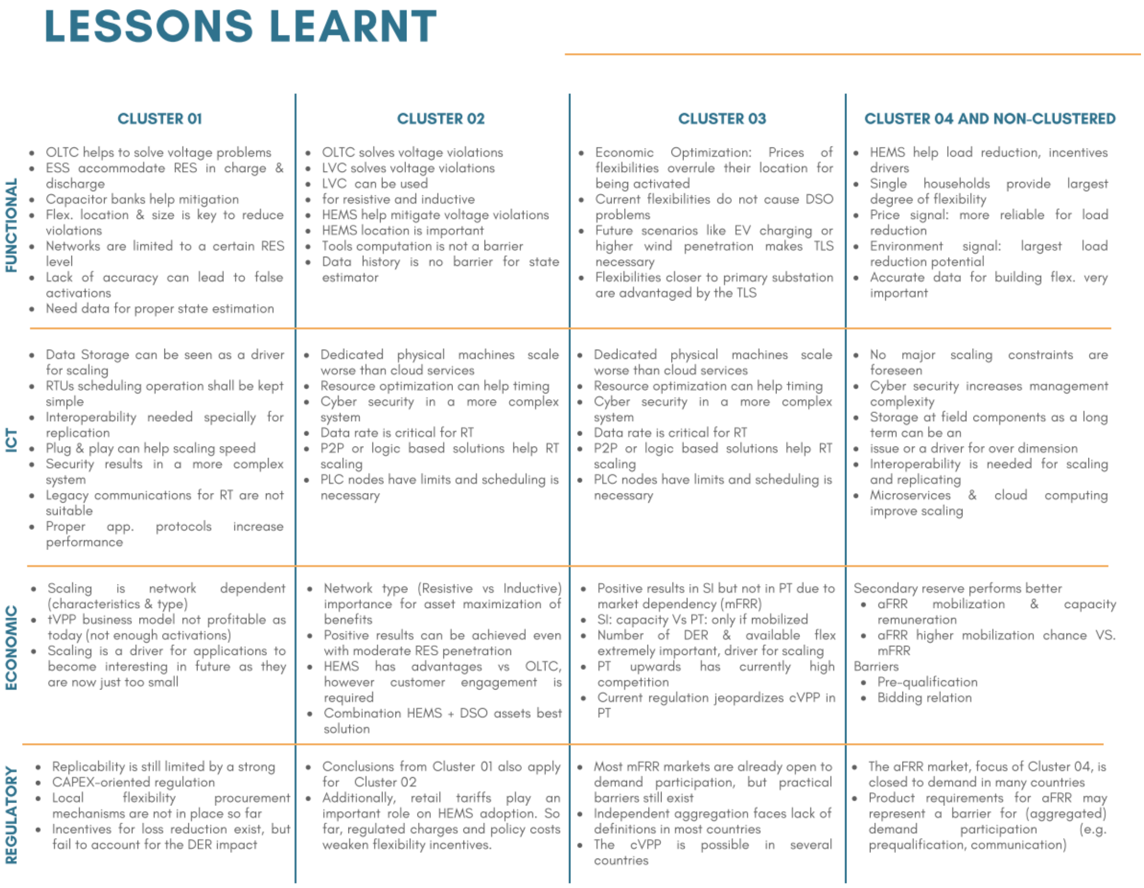
7.9. InteGrid

integrid	Demonstration of INTElligent grid technologies for renewables INTEgration and INTEractive consumer participation enabling INTEroperable market solutions and INTErconnected stakeholders
Coordinator	E-redes - distribuicao de eletricidade sa
Duration	2017-2020
Demo locations	
Funding	Horizon 2020
Website	https://integrid-h2020.eu/

The H2020 project, InteGrid, aimed to bridge the gap between citizens, technology, and key stakeholders within the energy ecosystem [68]. The project focused on empowering DSOs to engage stakeholders in energy market participation and grid management through innovative business models, data management techniques, and strategies for enhanced consumer involvement. By implementing scalable and replicable solutions, InteGrid developed solutions to enable DSOs to efficiently manage networks with high penetration of DRES while ensuring stability, security, and cost-effectiveness. The project built itself on three foundational pillars: proactive operational planning with DRES, innovative business models for flexible DER, and effective information exchange among power system stakeholders. Through the development of a Market Hub Platform, combined with smart grid technologies and advanced business models, InteGrid facilitated the deployment of emerging technologies and the creation of new services, accelerating progress in the energy sector. The project tested the InteGrid-developed solutions across different European contexts, with pilots in Portugal, Slovenia, and Sweden. The Portuguese pilot showcased the ability of DSOs to use local flexibility markets to manage low-voltage grid congestion effectively, leveraging predictive tools to anticipate and resolve issues before they escalate. The Slovenian demonstration highlighted the interoperability of smart grid solutions, enabling TSOs and DSOs to share real-time data through the Grid and Market Hub. This platform acted as a mediator, supporting coordinated decision-making by providing a common operational picture for both entities [68].

In particular, the InteGrid project explored innovative ways to enhance interactions between TSOs and DSOs to support a smarter, more resilient grid. A major focus of the project was implementing the Traffic Light System (TLS), which addresses the challenges of integrating DERs into electricity markets while preserving the operational integrity of distribution networks [69]. The TLS provided a framework for evaluating the impact of VPP flexibility bids on the grid, ensuring safe activation by categorizing grid conditions as green (safe for activation), orange (partial constraints, requiring adjustments), or red (unsafe for activation). The TLS enables DSOs to perform ex-ante (day-ahead) and pre-activation evaluations using an Optimal Power Flow (OPF) algorithm that considers grid constraints such as voltage and line loading, along with economic factors. By utilizing the cloud-based grid-market hub for seamless data exchange between TSOs, DSOs, and VPPs, the TLS ensures scalable and coordinated operations [69]. The TLS was investigated through simulations, as shown in [69], which were conducted on benchmark networks and demonstrated its ability to optimize flexibility activation by curtailing bids that would otherwise cause operational violations, and prioritizing lower-cost bids. For example, in upward flexibility scenarios, TLS avoided overvoltage by curtailing bids economically, while downward flexibility management addressed line overloading. These adjustments ensure compliance with operational limits while maximizing market participation. The TLS also allows VPPs to make intraday adjustments, enhancing flexibility and reducing inefficiencies associated with conservative prequalification practices. Initial tests demonstrated promising results, supporting scalability for diverse markets and services like aFRR, highlighting its potential for wider deployment under evolving regulatory frameworks.

Scalability and replicability analyses (SRA) conducted under varied scenarios, including changes in DER penetration and network configuration, confirmed the TLS's effectiveness in larger networks. The study highlighted the mismatch between economic drivers (pricing) and technical priorities (location of DERs). While pricing often drives flexibility activation, DERs located closer to primary substations generally deliver greater benefits, especially for manual frequency restoration reserves (mFRR) [70] Moreover, scenarios involving network congestion, urban vs. rural network configurations, and economic impacts of bid price changes demonstrated the TLS's adaptability. In high-DER scenarios, TLS mitigated network violations, facilitated TSO-DSO coordination, and supported economic optimization. These findings establish TLS as a crucial tool for ensuring future grid resilience, operational safety, and the effective integration of DERs into market structures [70]. InteGrid also identified critical regulatory and technical barriers to effective TSO-DSO collaboration. The project also emphasized the need for standardized protocols to ensure seamless data exchange and equitable market participation. Regulatory alignment was recommended to address discrepancies in market frameworks, which can hinder the scalability of such innovations. By integrating predictive management, local flexibility markets, and advanced decision-support tools, InteGrid established a scalable and replicable model for TSO-DSO interaction, ultimately paving the way for a consumer-centric energy ecosystem. In the final stages of the project, the consortium developed a roadmap which consolidated the key lessons learned from the functional, ICT, economic and regulatory perspectives for each of the clusters as shown in Figure 19, while a more detailed description can be found [71].


LESSONS LEARNT

	CLUSTER 01	CLUSTER 02	CLUSTER 03	CLUSTER 04 AND NON-CLUSTERED
FUNCTIONAL	• OLTC helps to solve voltage problems • ESS accommodate RES in charge & discharge • Capacitor banks help mitigation • Flex. location & size is key to reduce violations • Networks are limited to a certain RES level • Lack of accuracy can lead to false activations • Need data for proper state estimation	• OLTC solves voltage violations • LVC solves voltage violations • LVC can be used • for resistive and inductive • HEMS help mitigate voltage violations • HEMS location is important • Tools computation is not a barrier • Data history is no barrier for state estimator	• Economic Optimization: Prices of flexibilities overrule their location for being activated • Current flexibilities do not cause DSO problems • Future scenarios like EV charging or higher wind penetration makes TLS necessary • Flexibilities closer to primary substation are advantaged by the TLS	• HEMS help load reduction, incentives drivers • Single households provide largest degree of flexibility • Price signal: more reliable for load reduction • Environment signal: largest load reduction potential • Accurate data for building flex. very important
ICT	• Data Storage can be seen as a driver for scaling • RTUs scheduling operation shall be kept simple • Interoperability needed specially for replication • Plug & play can help scaling speed • Security results in a more complex system • Legacy communications for RT are not suitable • Proper app. protocols increase performance	• Dedicated physical machines scale worse than cloud services • Resource optimization can help timing • Cyber security in a more complex system • Data rate is critical for RT • P2P or logic based solutions help RT scaling • PLC nodes have limits and scheduling is necessary	• Dedicated physical machines scale worse than cloud services • Resource optimization can help timing • Cyber security in a more complex system • Data rate is critical for RT • P2P or logic based solutions help RT scaling • PLC nodes have limits and scheduling is necessary	• No major scaling constraints are foreseen • Cyber security increases management complexity • Storage at field components as a long term can be an • issue or a driver for over dimension • Interoperability is needed for scaling and replicating • Microservices & cloud computing improve scaling
ECONOMIC	• Scaling is network dependent (characteristics & type) • tVPP business model not profitable as today (not enough activations) • Scaling is a driver for applications to become interesting in future as they are now just too small	• Network type (Resistive vs Inductive) importance for asset maximization of benefits • Positive results can be achieved even with moderate RES penetration • HEMS has advantages vs OLTC, however customer engagement is required • Combination HEMS + DSO assets best solution	• Positive results in SI but not in PT due to market dependency (mFRR) • SI: capacity Vs PT: only if mobilized • Number of DER & available flex extremely important, driver for scaling • PT upwards has currently high competition • Current regulation jeopardizes cVPP in PT	Secondary reserve performs better • aFRR mobilization & capacity remuneration • aFRR higher mobilization chance VS. mFRR Barriers • Pre-qualification • Bidding relation
REGULATORY	• Replicability is still limited by a strong • CAPEX-oriented regulation • Local flexibility procurement mechanisms are not in place so far • Incentives for loss reduction exist, but fail to account for the DER impact	• Conclusions from Cluster 01 also apply for Cluster 02 • Additionally, retail tariffs play an important role on HEMS adoption. So far, regulated charges and policy costs weaken flexibility incentives.	• Most mFRR markets are already open to demand participation, but practical barriers still exist • Independent aggregation faces lack of definitions in most countries • The cVPP is possible in several countries	• The aFRR market, focus of Cluster 04, is closed to demand in many countries • Product requirements for aFRR may represent a barrier for (aggregated) demand participation (e.g. prequalification, communication)

Figure 19: Overview of InteGrid's Lesson Learnt

7.10. InterFlex

InterFLEX	Interactions between automated energy systems and Flexibilities brought by energy market players
Coordinator	ENEDIS
Duration	2017-2019
Demo locations	
Funding	Horizon 2020
Website	https://interflex-h2020.com/

The InterFlex project [41] [72] [73] explored how local flexibilities can reduce grid congestion and enhance resilience. The DSO benefits from this new business model by avoiding grid management costs and managing congestion through flexibility procurement in local markets. In cases of island operation, the DSO is also responsible for balancing. Although the project does not emphasize TSO-DSO coordination, aggregators can potentially submit bids to both DSO and TSO markets, with the DSO requesting flexibility based on local needs [72]. A key outcome of the project was the development of a grid tariff for flexibility, reflecting the cost savings achieved by using local flexibility. Flexibility is traded locally, focusing on long- and mid-term as well as day-ahead forecasts. Energy storage can be owned by DSOs, commercial players, or a combination, depending on system requirements. The project identified challenges related to market liquidity, emphasizing the need for economic incentives for local aggregators and the importance of clearly defined flexibility products that align with both TSO and DSO needs. Six demo sites were implemented across Sweden, Germany, the Czech Republic, the Netherlands, and France.

InterFlex explored the local trading of flexibility for distribution grid purposes. In the French and Dutch demonstrations, the respective DSOs developed specialized IT platforms to communicate real and potential flexibility needs with commercial service providers, specifically aggregators. The DSOs aimed to procure flexibility through local markets to enhance the operational efficiency of grid management. Based on the outcomes of the project, it was shown that Local flexibility markets successfully achieved key advancements by implementing flexibility mechanisms that clearly define stakeholder roles, development of IT tools such as forecasting engines, market platforms, and aggregator interfaces using open protocols such as USEF[12], EFI, CIM [73]. Despite this achievement, challenges related to flexibility market implementation were also identified. It was shown that sourcing available flexibilities is an essential component to the success of the flexibility market. This is of particular concern, during the initial phase of development when low flexibility value and sporadic DSO demand, lead to fragile aggregator models, and low liquidity [73]. Thus, reliability risks arise from the degree of local flexibility availability which may lead to the necessity of complementary markets (e.g., spot for opportunistic offers, and reserve for capacity contracts). Since the demonstration areas currently lack sustainable conditions due to limited grid constraints and low demand, the establishment of adequate business models is not considered to be feasible. However, this is expected to change in the future. Therefore, it is recommended that temporary incentives for aggregators and DSOs are implemented to encourage the use of flexibilities in order to enhance economically efficient and fail grid management [73]. Since the DSO is not the sole user of flexibility resources, it is recommended that through the engagement of multiple buyers, the growth of flexibility offerings can be accelerated, whether locally sourced or otherwise. Therefore, exploring DSO-TSO coordination in flexibility procurement and examining the potential for value stacking through sales across various markets and applications is essential. In particular, the project summary can be found in [73] and is summarised as follows.

Demand response & customer empowerment.
InterFlex tested a broad range of demand response flexibilities, utilizing various activation channels and addressing country-specific needs. In the German demonstration, the frequent need for curtailments led to a preference for direct DSO control over flexible loads. The Swedish demonstration in Simris focused on the particularities of a Citizen Energy Community(CECs). In the Czech Republic, the charging power of electric vehicles connected to the DSO’s charging stations could be curtailed when distribution grid constraints arose. The comparative analysis provided valuable insights into the respective advantages and challenges of these approaches. The InterFlex project successfully demonstrated direct DSO-control and the operation of local flexibility platforms with validated technical functionalities through ex-post service checks. In Germany, the technology was fully integrated with the national smart meter framework, offering high scalability, immediate large-scale implementation potential, and strong privacy and cybersecurity protections for customers. These results serve as a successful showcase and provide a blueprint for coupling infrastructure with IT systems, integrating grid control and smart meter rollouts. InterFlex’s demand response solutions support the growth of CECs, which attracted numerous pilot customers and enabling tools like household energy balance displays and a real-time simulated peer-to-peer (P2P) market for private energy trading. Thus, successful customer engagement is key and indicates a potential for national deployment and consumer-centric energy innovation.

The key challenges for DR solutions that were identified during the project include the need to finance control infrastructures and secure regulatory and industry commitment to new direct-control standards. The lack of a mature flexibility market, especially in the Business-to-Business (B2B) and residential segments, and insufficient financial incentives fail to meet customer expectations, in addition to the complexity of offers that do not align with essential needs, also poses a significant challenge that needs to be addressed. Thus, designing flexibility products to enable value stacking across markets and exploring benefits beyond financial remuneration could enhance the cost-effectiveness of demand response solutions. Flexibility for grid investment deferral emerged as a promising use case, potentially offering fixed remuneration to providers and fostering local-scale flexibility development. Data privacy and GDPR compliance remain a critical aspect to be considered, with access to smart metering data being an essential component for grid optimization but is currently hindered by complex consent forms and stringent anonymization thresholds. Thus, it is recommended that simplifying consent processes

[12] Universal Smart Energy Framework

and adjusting data aggregation rules without compromising privacy or awareness could reduce the need for additional sensor deployment while ensuring precise localized grid forecasting.

7.11. INTERRFACE

INTERRFACE	TSO-DSO-Consumer INTERFACE aRchitecture to provide innovative grid services for an efficient power system
Coordinator	European Dynamics Luxembourg SA
Duration	2019-2022
Demo locations	
Funding	Horizon 2020
Website	http://www.interrface.eu/restricted.html

The INTERRFACE project [74] aimed to establish a seamless interface between TSOs, DSOs, and customers to facilitate the efficient integration and use of renewable energy in the electricity grid. By developing a common architecture and advanced digital solutions, INTERRFACE sought to overcome barriers that limit the potential of DERs, enabling them to actively contribute to grid operations. With the growth of renewables, interconnected European grids, and local energy initiatives, TSOs and DSOs face challenges requiring enhanced coordination. Thus, the project aligns with EU legislative measures promoting cooperative procurement of grid services to enhance network management efficiency and support demand response and renewable capacity [74]. Through the utilisation of digitalization, including blockchain and big data technologies, INTERRFACE delivered an Interoperable pan-European Grid Services Architecture (IEGSA) to optimize distributed resource use, ensure secure electricity supply, and empower end-users as active market participants, fostering self-generation and demand flexibility [74]. An overview of the IEGSA's architecture is shown in Figure 20 [75].

The IEGSA is an open platform for data sharing across the electricity value chain, from local to pan-EU levels, enabling TSOs, DSOs, and customers to coordinate efforts, maximize renewable energy potential, and foster transparent market mechanisms [76]. This promotes the participation of diverse actors, thereby unlocking and utilizing previously untapped flexibility potential. The IEGSA platform facilitates secure data exchange and communication, enabling transparent coordination and efficient procurement of services through standardized schemes such as those in ENTSO-E and EDSO's Active System Management Report[13].

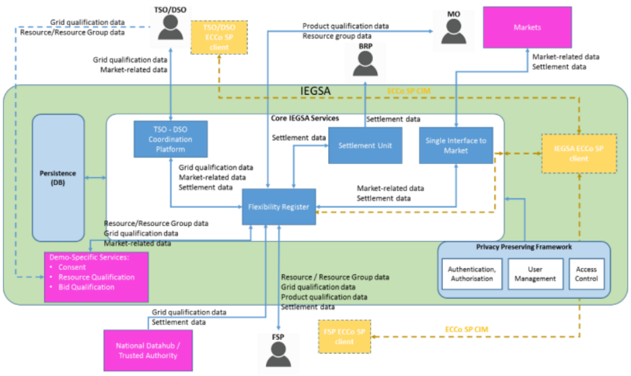


Figure 20 Overview of the IESA Architecture

Through the IEGSA, consumers and aggregators are empowered to efficiently manage their portfolios via a Flexibility Register and submit bids across versatile markets, supporting participation by smaller consumers through innovative tools for peer-to-peer trading and self-consumption. Therefore, the IEGSA fosters a standardized, interoperable ecosystem that enhances market accessibility and streamlines operations for all stakeholders. Based on the lessons learned discussed in [76], the INTERRFACE project highlights that scaling up solutions such as the IEGSA platform requires addressing the diverse characteristics of national power systems, including flexibility portfolios, market maturity, and grid constraints. Additionally, a harmonized European framework is essential to maximize flexibility provision while accommodating local needs. Key challenges identified during the project include defining clear roles across the electricity value chain to ensure efficient coordination, designing flexible and customizable market mechanisms, and integrating cross-border and cross-sector data exchange platforms [76]. Additionally, it was noted that the success of these solutions depends on powerful algorithms and robust interoperability to meet evolving standards and drive the platform's future replication and scalability. INTERRFACE showcased seven large-scale demonstrators in 9 European countries and was divided into three Demo Areas: 1) Congestion Management and Balancing Issues,

[13] https://eepublicdownloads.entsoe.eu/clean-documents/Publications/Position%20papers%20and%20reports/TSO-DSO_ASM_2019_190416.pdf

2) Peer-to-Peer trading and 3) Pan-EU clearing Market. The detailed findings and key lessons learned for each of the Demo Areas can be found in [75] - [77] and are summarised below:

Demo Area 1 Congestion Management and Balancing: explored congestion management and balancing issues through three demonstrators piloted across five countries, emphasizing the integration of flexibility resources into system operations and market frameworks. Key innovations were centred around the IEGSA platform, whose components such as the Flexibility Register, TSO-DSO Coordination tools, and Single Interface to Market facilitated efficient pre-qualification, coordination, and multi-service resource utilization. The DSO and Consumers Alliance demonstrator validated short-term congestion management by using distributed generation technologies, including CHP systems, battery aggregators, and demand response mechanisms, while coordinating renewable energy-producing local communities to mitigate reverse power flows into the TSO network. The Intelligent Distribution Nodes (IDN) demonstrator highlighted the operational versatility of the IDN concept, enabling automated and manual congestion management, with additional applications for TSO balancing services, such as frequency restoration, using the same resources. The Single Flexibility Platform (SFP) integrated existing mFRR and intraday marketplaces to support innovative congestion management services, with minimal technical upgrades, such as locational bid properties, ensuring that TSO market activations did not induce infeasible conditions within DSO networks. Collectively, these demonstrations showcased how IEGSA can enhance resource flexibility by enabling multi-service participation, ensuring optimal TSO-DSO collaboration, and addressing the increasingly critical need for flexibility across Europe's evolving energy landscape. The results further validated the scalability and technical feasibility of these solutions, providing a robust foundation for wider adoption.

Demo Area 2 Peer-to-Peer (P2P): Trading explored innovative market structures and flexibility utilization through two pilots conducted in two countries, emphasizing the role of local electricity trading. The Asset-Enabled Local Markets demonstration aimed to establish P2P trading platforms that integrate real-time distribution grid conditions into the trading process. By leveraging Dynamic Network Usage Tariffs (DNUT), the platform incentivized local transactions to alleviate congestion and improve network flows while ensuring grid reliability and security of supply. The pilot enabled consumers to directly trade energy with local parties, including those with small RES production units, supported by real metering and grid data. A critical component was the Integrated Asset Condition Management System (IACMS), which provided real-time monitoring of network conditions, such as load levels, to ensure voltage stability, minimize losses, and efficiently resolve congestion. The demonstration highlighted the importance of IEGSA as a unified interface for coordination between TSOs, DSOs, and market participants. IEGSA facilitates seamless data exchange, including grid topology changes and real-time market data, essential for managing diverse P2P markets expected to scale across Europe. The use of DSO-provided user databases for grid connection verification streamlined participant registration, while the Flexibility Register demonstrated the ability to manage significant user data volumes with robust security and efficiency. DSOs also shared metering data and historical records via IEGSA, which contributed toward post-operational evaluations and settlement processes. Furthermore, it was shown that real-time communication between the IACMS and IEGSA enabled accurate representation of grid conditions in the marketplace, thereby reinforcing operational reliability. The pilots demonstrated the technical feasibility of integrating localized trading with broader grid management objectives and highlighted the potential of P2P trading to enhance grid efficiency, reduce congestion, and optimize flexibility resources, with IEGSA serving as a pivotal tool for coordination, scalability, and secure market operations.

Demo Area 3: The Pan-EU Clearing Market demonstration explored the integration of local and pan-European energy markets, providing key insights for future market designs. Two pilots conducted across three countries revealed critical findings and recommendations for harmonizing DERs and flexibility within existing market frameworks. The preferred approach for incorporating spatial dimensions is a zonal representation, aligning local flexibility and DER-focused markets with established frameworks such as EUPHEMIA[14]'s single day-ahead market auction. This method ensures compatibility with current trading mechanisms while incorporating DSO-specific congestion management services seamlessly into energy trading auctions, thereby creating a unified and intelligible framework for all participants. The demonstration showed that the inclusion of congestion management services as additional market products allows these services to address multiple grid needs simultaneously, making

[14] Pan-European Hybrid Electricity Market Integration Algorithm

the framework adaptable for diverse use cases. Enabling DERs' participation on a pan-European scale, however, necessitates the harmonization of product definitions and interoperability across markets to unlock their full flexibility potential. The scalability of market algorithms is also critical; by leveraging existing auction platforms, additional constraints can be incorporated with minimal disruption. IEGSA's role was highlighted to be an integral aspect in managing the increased computational load and data handling requirements of integrated markets. Enhanced operational processes and robust data platforms are, thus, essential for processing significant volumes of market and grid data, ensuring efficient operation and scalability of both local and pan-European market frameworks. Therefore, this demonstration validates the feasibility of a cohesive market model that integrates DERs, flexibility, and traditional trading platforms into a scalable and efficient system.

7.12. ATTEST

ATTEST	Advanced Tools Towards cost-efficient decarbonisation of future reliable Energy SysTems
Coordinator	INESC TEC - Instituto de engenhariade sistemas e computadores, tecnologia e ciencia
Duration	2020-2023
Demo locations	
Funding	Horizon 2020
Website	https://attest-project.eu/

The ATTEST project [78] aimed to develop and operationalize a secure platform for smarter energy systems, where TSOs and DSOs can collaboratively plan, operate, and maintain the energy networks of the future. The project addressed technical, economic, and environmental challenges by providing an innovative toolbox of open-source solutions. These tools include optimization strategies for network planning, asset management, and real-time operation, all designed to enhance flexibility, reliability, and efficiency in energy distribution and transmission. The open-source toolbox developed within ATTEST, as shown in Figure 21, was embedded into an ICT platform for TSO/DSO coordination with the aim of providing data access connectors and converters, tools' orchestration functionalities, and visualization interfaces [79].

As described in [72], the ATTEST project evaluated five TSO/DSO coordination mechanisms for ancillary services procurement based on previous projects and developed the hybrid ATTEST TSO/DSO Coordination Approach, which incorporates aspects of Centralized, Local, and Shared balancing responsibility models to address technical and operational challenges [72]. In the Centralized model, only the TSO procures ancillary services from DERs, leaving DSOs unable to utilize these resources for local needs. Conversely, the Local model allows both TSOs and DSOs to access DERs, prioritizing DSO requirements, with unsold offers aggregated for global TSO markets. The Shared Responsibility model assigns independent network operation and balancing duties to each system operator, while the Common Market model focuses on minimizing overall procurement costs through close TSO-DSO collaboration and shared expenses. The integrated flexibility market models incorporate both regulated and deregulated participants, which requires an independent market operator in order to ensure market neutrality. The ATTEST approach prioritizes TSO reservation of ancillary services but enables DSOs to procure services for local grid issues, ensuring greater flexibility than the Centralized model. The DSO ensures that day-ahead market commitments made by DERs are fulfilled in real time, balancing local DG operational constraints with ancillary service schedules. This dual responsibility imposes additional costs on the DSO, which the TSO should partially compensate. Furthermore, the ATTEST model integrates distributed generation (DG) constraints into market-clearing processes, ensuring secure and efficient real-time DG operation. It provides detailed ancillary service schedules for each TSO-DSO connection point or local area, addressing network constraints and facilitating precise coordination. However, it was shown that the approach faces significant implementation challenges, particularly in ensuring rapid data sharing and coordination in real-time scenarios, especially with multiple local DSOs involved. Despite these hurdles, the model offers a scalable framework for improved TSO-DSO collaboration.

Figure 21 Overview of ATTEST open-source toolbox.

The project investigated the tools developed via a number of use cases based on different regions, i.e. UK, Croatia, Spain, and Portugal. In particular, in [80] and [81] the optimization tool designed for planning TSO/DSO shared technologies user guide is presented and the simulation results were evaluated based on two detailed case studies: 1) the Croatian Koprivnica network and 2) standard IEEE test systems. It was shown that the tool effectively generated optimal investment plans for shared energy storage systems (ESSs) and demonstrated robust economic and operational benefits. In the Koprivnica case study, based on the data provided, a €6.00M investment budget was considered. The tool invested €5.02M Net Present Value (NPV) in ESSs, resulting in a significant profit of €38.55M NPV. Operationally, the ATTEST solution ensured that all loads were fully supplied, avoided voltage magnitude and branch flow violations, and also achieved minor cost reductions in conventional generation. In contrast, the Business as Usual (BaU) approach revealed that substantial load curtailment would be necessary to maintain system stability, necessitating major investments in network reinforcements to address voltage and overloading issues. The second case study adapted real profiles from the Koprivnica network to standard IEEE test systems, with a €5.00M investment budget. Here, the tool utilized the entire budget, generating a profit of €21.48M NPV. The ATTEST solution eliminated all voltage violations, which were prevalent and severe under the BaU approach, especially towards the end of the planning horizon. Moreover, the tool enabled the integration of significantly larger amounts of RES generation while ensuring secure network operation. At the transmission level, RES curtailment was completely avoided, leading to a considerable reduction in conventional generation, along with associated cost and Green House Gases (GHG) emission reductions. Additionally, the tool highlighted the potential benefits of diversifying the RES generation mix, showing that in certain periods, the system could operate solely on solar generation. These results demonstrate the tool's capability to enhance power system planning by optimizing investments in shared technologies, improving operational reliability, and facilitating sustainable energy transitions.

The project provided several key lessons as discussed in [72]. Firstly, it was shown that flexibility is essential to accommodate the growing penetration of DERs, making adaptive market structures a cornerstone of modern grid management. Furthermore, real-time and secure data exchange between TSOs and DSOs is fundamental to effective coordination, which further requires advancements in ICT infrastructure. Integrated solutions that combine centralized and decentralized market features strike a balance between cost efficiency and operational flexibility but require clear governance frameworks to succeed. Collaboration among stakeholders (TSOs, DSOs, aggregators, and market operators) is vital to avoid inefficiencies and conflicts. Lastly, scalability and standardization of solutions are also crucial, ensuring that models are adaptable across diverse regulatory environments and capable of integrating multiple DSOs without undermining market liquidity.

7.13. CoordiNet

The CoordiNet project [36] aims to demonstrate how DSOs and TSOs can coordinate and share resources to procure grid services in an efficient and reliable manner. Through large-scale TSO-DSO-Consumer demonstrations involving market participants and end users, the project sought to [82]:

coordiNET	Large scale campaigns to demonstrate how TSO-DSO shall act in a coordinated manner to procure grid services in the most reliable and efficient way
Coordinator	EdistribucionRedes DigitalesSL
Duration	2019-2022
Demo locations	
Funding	Horizon 2020
Website	https://coordinet.netlify.app/

1. To demonstrate to which extent coordination between TSO/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 related key parameters for system 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 open new revenue streams for consumers providing system services.

The project also evaluated various grid services and resources across demonstration sites to achieve these goals. Eight demonstration activities were conducted across three countries: Greece, Spain, and Sweden. Each activity focused on testing various products over different time periods, utilizing flexibility provided by diverse types of DER. An overview of the project is shown in Figure 22 [82].

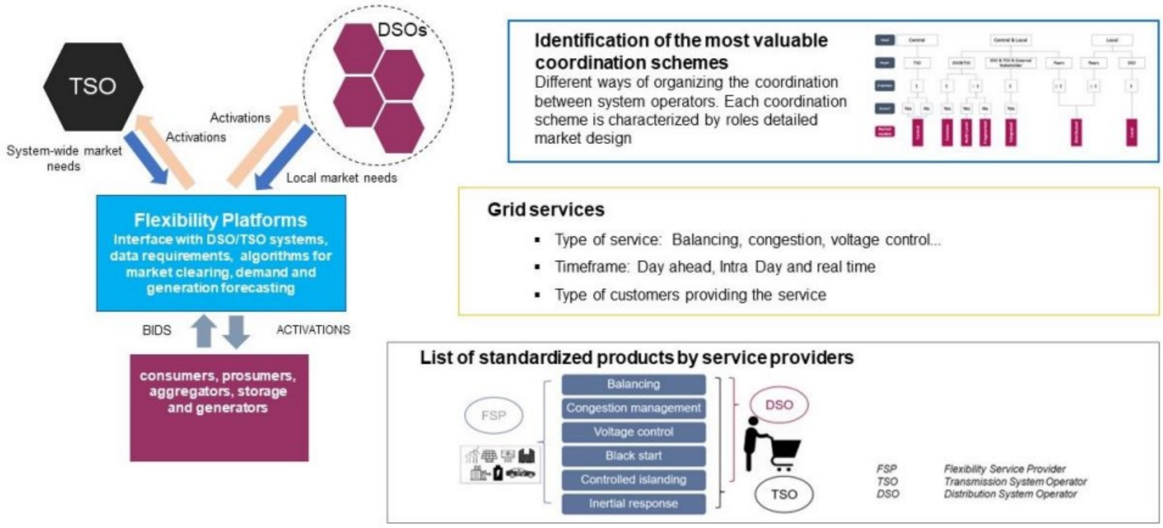


Figure 22 Overview of the CoordiNet approach and key objectives.

Furthermore, in [82] the conclusion and results of the CoordiNet demonstrations, based on the evaluation categories i.e. regulatory, market, technological, and social are presented. This analysis is presented as a CoordiNet roadmap, which comprises five themes outlining the main building blocks of new flexibility markets. Each theme consolidates the key insights includes a set of proposed recommendations and is summarised below.

Theme 1: Incentivising the evolution of SO roles and creation of flexibility markets.

The CoordiNet demonstrations highlight that current national regulations hinder DSOs from recovering investments and costs for new market solutions for system services. To address this, DSO remuneration schemes need to recognize the costs associated with establishing flexibility markets and mobilizing flexibility resources. Since the societal benefits of flexibility solutions are widespread, public institutions should play a more active role in promoting these solutions alongside efficiency measures. Additionally, clear roles and responsibilities must be defined for all stakeholders in flexibility markets, including traditional and new agents, with these definitions standardized at the EU level in network codes for demand-side flexibility at the distribution level. For DSOs, flexibility procurement introduces new responsibilities and necessitates a shift toward proactive, longer-term operational planning. This should be supported by integrating flexibility procurement into the Network Development Plan (NDP) to address structural congestion. Furthermore, it was established that enhanced coordination between TSOs and DSOs is essential to manage the impact of new resources and demand growth, potentially reducing grid reinforcement needs and optimizing planning. Coordinated efforts will minimize adverse effects on different voltage levels, increase procurement efficiency, and scale flexibility markets. Lastly, simple market coordination schemes are recommended during the early stages to attract FSPs and increase liquidity. Thus, over time, a more complex, shared market design, where DSOs and TSOs can access a common pool of flexibility resources, could maximize efficiency and social welfare.

Theme 2: Market access for all flexibility service providers

The CoordiNet findings highlight key challenges in improving the business case for FSPs. High participation costs and market uncertainty, driven by seasonal and annual variability in flexibility demand, were shown to significantly impact FSP profitability. In this regard, the demonstrations suggested that increased automation could help increase market participation and support clear communication from system operators about flexibility needs which consequently can reduce uncertainties. Additionally, transparent, and accurate market prices reflecting the value of services based on location and availability are crucial for enhancing market predictability. Furthermore, based on the outcomes of the scalability and replicability study, it became evident that regulatory barriers are still significant and hinder broader participation, particularly from small-scale distributed DERs. Aggregation, including independent aggregators, is essential for enabling small DERs to meet technical market requirements, but full implementation is currently delayed to the detriment of the stakeholders. In terms of consumer awareness of flexibility service, opportunities are currently perceived to be low. Thus, the importance of providing clear, reliable information is vital for potential FSPs alongside implementable platforms and interfaces are necessary to bridge information gaps.

Theme 3: Managing SO requirements and FSP capabilities through standardisation.

The CoordiNet experience highlights several key considerations for EU-level standardization of flexibility markets. First, while the alignment of flexibility products is crucial to avoid product proliferation and reduce complexity, the outcomes of the demonstrations showed that local applications of congestion management and voltage control require further research before product values or ranges can be standardized. For balancing products, EU-wide harmonization is largely achieved, but further review of standards is needed to facilitate market access for new actors. Regulatory harmonization is recommended to remove barriers that may hinder competition and efficiency, alongside the strive for consistent and harmonized terminology to avoid misunderstandings in flexibility market services. Regarding data flows and platform interoperability, standardization is essential for efficient market functioning. The CoordiNet project's demonstrations show the need for common European frameworks to ensure interoperability between flexibility market platforms, reduce ICT costs, and ensure IT security. Furthermore, standardized processes for data exchange, protocols, and formats are necessary to simplify market participation, with a particular emphasis on metering data and baseline provisions. Additionally, the deployment of smart meters is critical, but in regions with delays, it is recommended that member states establish rules on using sub-meters to support market functionality.

Theme 4: Adaptation of Market Phases for New Products and Actors

The development of new flexibility markets introduces challenges across all market phases, ie prequalification, procurement and activation, and settlement, which requires adaptations to accommodate new participants and roles. Furthermore, the effective integration of flexibility markets with existing markets and processes is critical to minimize disruption and complexity for FSPs, thereby encouraging increased participation. Although the coordination between markets was shown to be necessary to avoid overlapping (which could result in reduced liquidity), CoordiNet advises against EU-level standardization of market timing due to varying local and national contexts. Furthermore, harmonizing prequalification requirements across platforms and automating these processes can enhance liquidity and reduce complexity, with stricter service prequalification potentially enabling automatic qualification for less stringent services. Additionally, prequalification should include testing communication between FSPs and market platforms. For procurement and activation, accurate grid representation is vital, particularly for services like congestion management and voltage control where the location of the FSP is critical as poor grid representation can lead to suboptimal bid selection, pricing inefficiencies, and network constraint violations. Furthermore, it was concluded that currently settlement processes face challenges due to low observability in low-voltage grids, which require robust telemetry and baseline data to ensure fair compensation and accurate verification. Transparency in measurement data is essential to prevent gaming and build trust amongst stakeholders and thus adequate measures should be implemented such as independent third-party auditing.

Theme 5: Enabling FSP contributions to innovative market solutions.

CoordiNet examined two emerging concepts in system service provision 1) flexible services for reactive power and 2) peer-to-peer markets, both of which remain in early testing stages and were not fully developed within the project. It was shown that reactive power provision faces inherent limitations due to its localized nature and existing regulatory frameworks, making large-scale market organization unfeasible. A hybrid approach combining market-based and rules-based methods is, therefore, recommended, with regulatory sandboxes proposed to explore optimal conditions for implementation. Similarly, P2P markets, while showing potential for more efficient grid use and reduced renewable energy curtailment, require further investigation to evaluate their feasibility, scalability, and economic viability. CoordiNet emphasized the need for regulatory sandboxes and incentivization mechanisms to assess and support the development of these concepts.

7.14. OneNet

The OneNet [39] project was designed to create a unified and scalable European electrical grid architecture, enabling seamless operation across diverse markets and stakeholders. The project's objective was to build a consumer-centric system by leveraging demand response, storage, and distributed generation while ensuring fairness, transparency, and inclusivity across all market levels. OneNet's vision was based on three pillars: 1) Definition of a common market design for Europe, 2)

Coordinator	Fraunhofer gesellschaft zur forderung der angewandten forschung ev
Duration	2020-2024
Demo locations	
Funding	Horizon 2020
Website	https://www.onenet-project.eu//

Definition of a common IT Architecture and common IT Interfaces, and 3) Verification of the proposed solutions in large field tests. The project comprised four regional cluster demonstrations to showcase the project's solutions [39]:

- Northern Cluster (Ireland, Norway, Sweden, Finland, Estonia, Latvia, Lithuania): Focused on market-driven flexibility and coordination across multiple networks, utilising frameworks from prior projects like INTERRFACE and EU-SysFlex to enhance network needs management and scalability.
- Southern Cluster (Greece, Cyprus): Addressed balancing and congestion management challenges in compliance with OneNet's architecture. Pilot projects in this region aimed to inform future market reforms and regional harmonization for a Pan-European electricity market.
- Western Cluster (Portugal, Spain, France): Tested a wide range of flexibility mechanisms to improve renewable integration, anticipate operating scenarios, and manage balancing, congestion, voltage, and critical situations. Use cases spanned from real time grid to long-term planning.
- Eastern Cluster (Czech Republic, Poland, Hungary, Slovenia): Develops interoperable flexibility platforms, focusing on standardized services, market-based products, grid prequalification processes, and the coordination of local and system-level service access. It also defines technical requirements for flexibility providers and aggregators.

The project also focussed on community engagement and consensus-building beyond its consortium through initiatives such as the GRIFOn [83] forum which facilitates collaboration within the European energy community.

Based on the project results, significant lessons learned, and insights related to collaboration, market design, and enhancing customer engagement have emerged and are discussed based on interviews found in [84]. Herewith, it was demonstrated that the effective collaboration between TSOs and DSOs is paramount, emphasizing the need for open communication, a shared common language, and unified efforts to address both system-level challenges and localized issues. This collaborative approach mitigated inefficiencies caused by administrative and regulatory divisions. Furthermore, understanding and evolving the market design is considered to be essential. Flexibility markets require tailored products for capacity, energy, and power, with varying timescales and data needs. This highlights the importance of robust data exchange frameworks and tools such as flexibility registers and TSO-DSO coordination platforms. These enable efficient information sharing and facilitate market participation by lowering entry barriers and ensuring fair cost distribution. Customer engagement also plays a critical role. Surveys conducted as part of the project indicated that there is generally a strong interest in participation but emphasized the need for improved facilitation, including education and awareness campaigns, as many participants do not fully understand the important role they play. In terms of service provision, the shared platforms that integrate device and market connections through the flexibility register, were shown to effectively empower customers to act on their flexibility potential. This is due to the lowering of the barrier of entry, which encourages increased participation. Thus, involving stakeholders throughout the process was shown to be highly impactful. This can be achieved through regular engagement, trust building, and enthusiasm, and enabling the establishment of TSO-DSO coordinated flexibility markets. Real-world demonstrations with diverse stakeholders also demonstrated the practical benefits of collaboration and thus TSOs and DSOs are encouraged to work closely together to maximize the potential for an efficiently evolving energy market that integrates distributed renewable assets.

Insights for Electricity Market Design: Lessons Learned
The OneNet project advanced electricity market design by proposing a standardized framework for six flexibility products, streamlining TSO-DSO coordination for balancing and congestion management. The project successfully developed methodologies to quantify the efficiency, procurement, and equipment costs of coordination models, enabling data-driven policymaking tailored to grid requirements. Novel tools, such as a flexibility register, and enhanced processes such as pre-qualification, baseline management, and settlement, were shown to provide support for future implementation of Network Code on Demand Side Flexibility and robust market functionality. Furthermore, it established that future research should address sector coupling (e.g., gas and heat), implicit flexibility mechanisms (e.g., tariffs), and consumer-centric models like peer-to-peer energy sharing to establish a sustainable, multi-energy pan-European market ecosystem.

Flexibility markets and TSO-DSO cooperation

OneNet, building on the findings from INTERRFACE [74] and CoordiNet [36], advanced flexibility market design and TSO-DSO cooperation, emphasizing robust collaboration among stakeholders to create a unified European electricity system. The project tested value-stacking ancillary service markets and identified key enablers such as a flexibility register and TSO-DSO coordination platforms to streamline data exchange and market access. The findings revealed that current data systems are inadequate for handling diverse flexibility products across timescales, and thus require the development and implementation of enhanced solutions. Flexibility markets were identified to be essential for mitigating grid congestion, balancing supply-demand variability, and managing decentralized energy resources. The project explored TSO-DSO coordination models and highlighted the trade-offs between common and multi-layered market designs in efficiency, grid safety, and local optimization. Consumer centricity was identified as a cornerstone of the project, with reduced entry barriers, aggregation, and tailored local market layers empowering small-scale users while ensuring their participation aligns with technical and market requirements. The project also emphasized that value stacking is vital to maximizing resource efficiency, ensuring robust coordination to safeguard grid stability, and consumer engagement through aggregators. Thereby enhancing trust, transparency, and equitable access for all stakeholders. Real-world testing validated the practical benefits of integrated flexibility markets, emphasizing the need for sustained stakeholder collaboration to drive the energy transition.

Pilots

A major technical advancement was the introduction of flexible market products and bidding formats. Demonstrators tested mechanisms such as bid forwarding, which allowed market bids to be submitted across different platforms, enabling seamless integration and value stacking for flexibility providers. These tests showed how tailored market designs could accommodate dynamic requirements, such as rebound effects in storage and demand-side resources, which necessitate precise modelling of temporal constraints to ensure operational stability. Interoperability was a key aspect of the project and was achieved through the deployment of the OneNet system. This platform facilitated data exchange across markets and systems for critical processes such as pre-qualification, registration, bidding, result processing, and settlement. The system demonstrated its capability to handle diverse requirements, supporting integration across platforms while maintaining high levels of scalability and reliability. The demonstrators also provided insights into system-wide data management. The project validated the feasibility of harmonizing datasets across platforms, which has been identified as a key requirement for interoperable markets. Additionally, the project highlighted the technical complexities of integrating multiple market layers and optimizing cross-market interactions in real-time scenarios. Key technical lessons included the need for enhanced decision-support tools to address real-time operational challenges and the importance of modular system architectures that can adapt to regional differences in grid configuration and market requirements. Lastly, it was noted that future work should focus on developing advanced analytics and machine-learning-driven algorithms to further refine market operations, optimize system constraints, and improve the reliability of integrated electricity markets under varying grid conditions.

Eastern Cluster

The lessons learned and key outcomes of the demonstrations in the Eastern Cluster can be found in [85] and are summarised below.

Poland

The OneNet project in Poland aimed to develop and test market solutions to enhance flexibility in network operations, to improve the reliability and efficiency of the distribution network while fostering coordination between DSOs and TSOs for future flexibility services markets. Due to the absence of existing regulations on flexibility in Poland, the project developed market mechanisms and their integration with the Balancing Market from the foundation. Key achievements include defining the scope of flexibility services and products, which were tested through business and system use cases (BUC and SUC) to model market processes and stakeholdersinteractions . A prototype flexibility platform was created, serving as an open-access environment for market participants, including TSOs, DSOs, FSPs, aggregators, and market operators. The platform incorporates a critical coordination mechanism between DSOs and TSOs, supported by an algorithm optimizing resource utilization while ensuring distribution network security. The demonstration provided significant insights into the regulatory, technical, and organizational barriers to implementing a flexibility market in Poland. Solutions developed include the flexibility platform and optimization algorithms, which are prepared for large-scale implementation. However, it was noted that their adoption depends on future national regulations and network codes aligning with the project's framework. The project's outputs, such as coordination mechanisms and market process procedures, were shown to hold potential for standardization and broader adoption in Poland, based on discussions with other DSOs and regulatory alignment. These findings highlight the necessity of regulatory amendments and the integration of future network codes to enable the successful establishment of a flexibility market in Poland.

Hungary

The Hungarian demonstration focused on developing a DSO-centric flexibility market platform capable of managing multiple products across various voltage levels and congestion zones. Despite challenges, the demonstration validated the platform's feasibility and adaptability across different national contexts. Key findings include the resource-intensive nature of data pre-processing and network modelling for DSOs, which, while demanding, can synergize with advancements in smart metering, AI, and data quality. The platform's optimization algorithm addresses highly nonlinear tasks, managing flexibility needs in localized network areas where volumes may not reach TSO levels. The integration of market-based and redispatch bids via pseudo-pricing was also a notable achievement, which enables DSOs to respond to congestion issues rapidly in the short and medium term. Collaboration with potential flexibility service providers (FSPs) and aggregators was an integral part of the project but was shown to cause complications due to the immaturity of the flexibility market and structural heterogeneity within stakeholder organizations. The demonstration also revealed limitations in market timing, with delayed bid activation leading to uncertainty and reduced attractiveness for FSPs. This timing issue, common in emerging markets, impacts liquidity and revenue potential. The lack of immediate business benefits from individual use cases highlights the need for service optimization and coordination among market participants. However, it was mentioned that introducing an independent market operator could streamline processes and incentivize market growth. Furthermore, regulatory challenges persist, including the absence of flexibility-focused tariff structures and horizontal stakeholder alignment. While the platform and its extensions offer a viable alternative to traditional CAPEX-heavy solutions, current corporate and regulatory frameworks prioritize short-term objectives. Thus, addressing these barriers is crucial for harnessing the flexibility market to meet future energy demands effectively.

Slovenia

The Slovenian pilot focused on DSO-centric flexibility services and establishing a local flexibility market integrated into the national data hub for customer access. This approach ensures uniform access for all consumers, which promotes sustainability as the platform continues to operate post-project. Key achievements include the successful setup of a flexibility market platform addressing low-voltage (LV) network congestion and voltage violations. Slovenia's LV network, which constitutes 72% of its distribution network, presents significant challenges due to its length and associated voltage problems. The market primarily targets flexibility from households and small commercial enterprises equipped with heat pumps, battery storage, and similar systems. The platform received positive feedback from the national regulatory authority (Energy Agency), which viewed it as a sandbox for advancing flexibility services. However, a tender for flexibility services at 30 overloaded MV/LV substations yielded no participants, which indicates economic and technical barriers. From the aggregator's perspective, there was limited business incentive due to low power per customer (<4 kW) and the limited value of flexibility compared to network reinforcement costs. Additionally, customers' preference for automatic remote control of loads was impeded by the requirement for physical modifications, such as two-wire connections to meters. Despite an adequate regulatory and legislative framework and the development of a functional market platform, the Slovenian demonstration revealed critical gaps. These include insufficient business viability for aggregators and low consumer engagement. Further technical enhancements and adjustments to the market design are necessary to reach the platform's full potential and facilitate the broader adoption of flexibility services.

Czech

The Czech demonstration implemented components of the flexibility platform into real operations, including a "traffic light scheme" for centralized outage reporting and flexibility coordination. This system facilitates data exchange among DSOs, TSOs, and service providers, supporting flexibility management and ensuring supply quality in nodal areas. A flexibility register was also developed to catalog data for aggregators and suppliers. Aggregators in the demonstration engaged customers to test the platform for non-frequency services and the traffic light scheme. The DSO conducted direct testing with its EV charging infrastructure, highlighting the need for advanced charging management to accommodate growing EV adoption while minimizing grid reinforcement costs. The results showed that flexibility is critical for integrating renewables, and the demonstration provided valuable insights into data exchange requirements, including granularity, frequency, and architecture. These findings will assist the national flexibility platform's design and the integration of the traffic light scheme as an interim solution. Furthermore, regulatory updates were noted to be essential to operationalizing these solutions.

Western Cluster:
The Western Cluster demos successfully addressed complementary aspects of flexibility provision, including operational planning, flexibility needs identification, FSP prequalification, and flexibility activation from loads and RES generation, complemented by monitoring. The key findings and lessons learned were presented in [86] and are summarised below.

Spain
The results from the Spanish demonstration showed that in most cases, flexibility providers consistently delivered contracted amounts on time and for the required durations. Key performance indicators (KPIs) from demo site tests showed positive outcomes in cost efficiency, load forecast accuracy, and asset load impact. However, challenges included limited customer engagement, maintaining comfort levels, baseline calculation, adapting market production needs for industrial providers, and regulatory gaps in incentives and penalties. Due to low customer participation, demo site selection prioritized engaging flexibility providers over addressing specific network needs, which were then simulated instead. Coordination with FSPs, transparent market processes, and the involvement of Market Operators were instrumental in mitigating operational and technical barriers. By engaging FSPs early and collaboratively defining demonstration schedules, potential disruptions to building users and industrial operations were minimized, ensuring smoother participation. Transparent market processes, facilitated by the Market Operator, enhanced trust and clarity among stakeholders, reducing uncertainties related to market operations. Furthermore, the Market Operator's active involvement streamlined IT requirements for participants by simplifying the integration of wholesale and local flexibility markets. This approach not only minimized technical complexities but also provided participants with a clearer understanding of market mechanisms, enabling their effective engagement in the demonstrations. Identified gaps, such as the absence of intraday market notifications and incomplete platform information, were noted as areas that require improvement, however to achieve this regulatory development in terms of definition needs to be made. The demonstrator highlighted the potential of local flexibility markets to cost-effectively resolve DSO-detected network constraints while emphasizing the need for further efforts to address participation, regulatory, and operational barriers. These findings provide valuable guidance for designing and implementing local flexibility markets, supporting wider adoption in Spain's electricity market and shaping European energy policy to build resilient, cost-effective systems.

Portugal
The Portuguese demonstrator aimed to define information exchange processes between system operators (SOs) to facilitate flexibility provision and enhance operational planning. For business use cases (BUCs) related to flexibility, the corresponding stages of the ASM report were used to establish coordination processes between the TSO and DSO, excluding the settlement stage to focus solely on information exchange. For the BUC related to operational planning, the demonstrator targeted improvements in SO operational processes through enhanced information exchange between network operations. The Portuguese demo faced challenges due to several factors. These included insufficient FSP engagement to provide data caused by delays in identifying substations, which hindered targeted recruitment efforts. Additionally, a mismatch between reported flexibility availability and substation capacity arose because the flexibility perimeter encompassed only a limited number of installations (3 to 10 stores), resulting in aggregate flexibility values significantly lower than HV substation requirements. Moreover, delays in developing the DSO Data Exchange Platform (DDEP) prevented full integration with the TSO, necessitating a second demo run planned. Despite these challenges, the demo successfully demonstrated all chosen BUCs and SUCs, achieving its core objectives of specifying and exchanging coordinated information for flexibility provision, grid operation, and planning.

France
The French demonstration consists of two main components: the implementation of STAR (System of Traceability of Renewables Activations) and a study on innovative methods for TSO-DSO information exchange related to DER activation. The STAR project aimed to enhance the integration of FSPs into the French electricity grid. It envisioned a decentralized platform connecting France's TSO, DSO, and RES producers. The primary focus was to build trust and demonstrate the potential of STAR in managing simple congestion scenarios by optimizing the management of renewable production curtailments by addressing the entire lifecycle of flexibility offers. This included formulating offers, controlling their activations, invoicing, and using blockchain technology for transparency and accuracy. As an outcome, the demonstrator emphasized in improving coordination between the TSO and DSO to prevent undesirable constraints during the flexibility provision process. Flexibility must be activated while ensuring that the impacts on each system operator's (SO) perimeter are carefully monitored to maintain the safe and secure operation of the networks and the overall power system. However, greater cooperation between SOs will be required to fully realize the flexibility potential of renewable energy

sources. The goal is to explore future coordination strategies that would optimize the use of flexibility, enhancing its effectiveness without compromising the individual prerogatives and responsibilities of each SO. The demonstration successfully achieved robust test coverage, executing planned tests and implementing production data. The STAR platform was effectively designed to meet use case requirements for data modelling, shared governance, and architecture. Blockchain technology played a pivotal role in ensuring transparency and data uniqueness, with a detailed analysis of its advantages and limitations documented in [87].

Northern Cluster

The document [88] provides comprehensive lessons learned across customer engagement, technical operations, and market challenges in deploying DER flexibility solutions. A significant obstacle identified in the demonstrations was limited customer participation, with some participants leaving the demonstrations due to unmet expectations or discomfort during flexibility activations. This underlines the need for transparent communication, clear baselines, and incentive mechanisms that align with consumer expectations. Challenges in operationalizing flexibility included insufficient advanced metering infrastructure, hindering real-time validation and monitoring, and baseline inaccuracies requiring the development of AI-driven, use case-specific calculation methodologies. Furthermore, it was shown that data exchange protocols like MQTT demonstrated feasibility for real-time operations but require further refinement for scalability and reliability. On the market side, the lack of harmonized products, tools, and APIs across regions caused integration inefficiencies. Additionally, regulatory uncertainties, particularly around incentives and penalties, were observed to have limited the scope of implementation. Demonstrations revealed the technical feasibility of automating flexibility transactions using IoT and real-time data exchange, however, in contrast, it was noted that scaling such solutions proved challenging due to high costs, technical complexity, and limited pilot timelines. Additionally, the absence of a unified European framework for flexibility operations has been shown to intensify silos between TSOs and DSOs, which consequently restricts the seamless integration of the developed solutions and coordination approaches. Despite these barriers, the demonstrations highlighted the potential of flexibility markets in addressing grid needs and reducing operational costs. Future recommendations include enhanced consumer engagement strategies with clear communication and transparent incentives, promoting regulatory support through sandboxes to test innovative solutions, and providing investment in interoperable and standardized technologies to enable cross-border scalability.

Southern Cluster

The evaluation of the Southern Cluster demos in Greece and Cyprus, as described in [89], highlighted critical advancements in managing high-RES penetration and optimizing power grids. The approach was used to assess the innovative solutions implemented, with the Cypriot demo focusing on grid monitoring, pre-qualification of operational limits, and flexible resource participation. Key findings include the effectiveness of real-time monitoring in improving transmission and distribution grid stability, enhanced frequency support by flexible RES, and congestion management with measurable improvements in thermal loading, energy losses, and asymmetries. Market participation metrics further demonstrated active engagement of DERs and FSPs, alongside seamless stakeholder collaboration. The Greek demo showcased strong FSP participation, accurate forecasting of technical constraints, and robust early warning systems for weather and cyber threats, thereby addressing grid uncertainties introduced by variable RES. Lessons learned from both demos emphasize the importance of real-time monitoring, robust communication infrastructure, secure protocols to mitigate cyber risks, and prequalification schemes for distributed flexibility offers. These findings provide a foundation for informed decision-making and policy development, supporting the green energy transition in Southern Europe while advancing cost-effective and resilient grid management practices.

7.15. FLEXGRID

FLEXGRID	A novel smart grid architecture that facilitates high-RES penetration through innovative markets towards efficient interaction between advanced electricity grid management and intelligent stakeholders
Coordinator	Erevnitiko panepistimiako institouto systimaton epikoinonion kai ypologiston
Duration	2019-2022
Demo locations	
Funding	Horizon 2020
Website	https://flexgrid-project.eu/

The FLEXGRID project [90] [91] developed a holistic smart grid architecture to address the challenges of high-RES penetration by integrating advanced grid models, flexibility asset management, and market-data analytics. The project incorporated game theory to improve trade-offs across energy market requirements (e.g., real-time efficiency, fairness, and scalability), applied optimization theory for efficient market clearing and robust power flow algorithms and implemented AI-driven business models for modern Energy Service Providers (ESPs) and RES Producers (RESPs). The approach enabled cost-effective grid management for DSOs/TSOs, supported competitive ESP operations, and enhanced RESPs' economic and operational performance by enabling effective RES generation dispatch. An overview of the FLEXGRID framework is depicted in Figure 23.

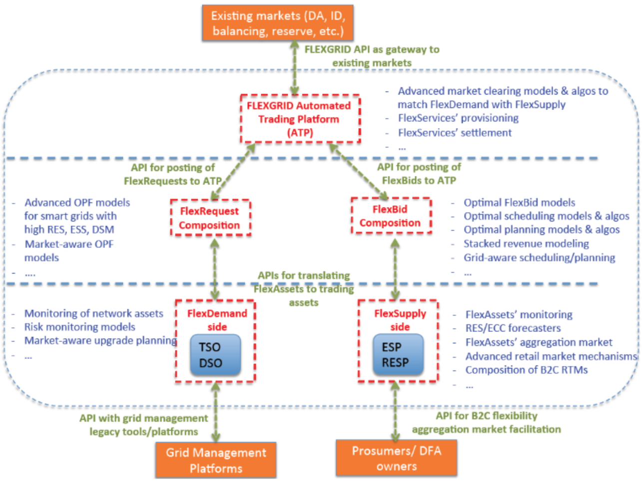


Figure 23: Hierarchical FLEXGRID framework and S/W architecture (APIs for modular-by-design approach)

In [92] the lessons learned and outcomes from the comparison of various Distribution-Level Flexibility Market (x-DLFM) architectures are presented. The findings reveal insights for improving flexibility market designs to accommodate the rising penetration of RES. For example, it was shown that the No-DLFM architecture, representing current EU regulatory frameworks, struggles to address local contingencies as RES penetration increases. These limitations were shown to result in a higher Value of Lost Load (VoLL) and increased renewable curtailment. To mitigate these issues, it was recommended that DSOs adopt market-based procurement of active and reactive power reserves and prioritize areas that are prone to more contingencies in the short term while also establishing robust communication protocols with TSOs. Furthermore, it was shown that the Reactive DLFM (R-DLFM) architecture is effective under conditions of high flexibility liquidity or slower RES penetration compared to the growth in flexibility resources. Furthermore, its compatibility with existing EU regulatory frameworks makes it a practical choice, particularly with the TSO's leading market operations. However, the approach requires that regulatory advancements such as Redispatch 3.0 be implemented, thereby enabling DSOs to allocate redispatch orders efficiently and ensuring FlexOffer (see GOFLEX) accuracy to prevent market distortions. The Proactive DLFM (P-DLFM) architecture was shown to perform optimally in scenarios where distributed RES capacity exceeds peak local loads or in grids with high-RES penetration. However, its effectiveness depends on highly accurate market price forecasts (Mean Absolute Percentage Error, MAPE ≤ 5%). This architecture is particularly suitable for small, remote, or islanded grids, where DSOs can leverage advanced optimization algorithms to generate local dispatch schedules. The requirements include enhanced monitoring, control systems, and sophisticated optimization capabilities. The Interactive DLFM (I-DLFM) architecture was shown to deliver the highest performance in high-RES penetration scenarios due to its iterative real-time communication framework between TSOs and DSOs. This architecture facilitates coordinated decision-making but requires significant investments in ICT infrastructure to support complex data exchanges and computational capabilities in substations. While highly effective, its short-term implementation may not be economically viable for systems with less intense flexibility and RES integration needs.

Based on the outcomes highlighted in [93] and [94], the FLEXGRID project assessed the performance, scalability, and replicability of three DLFM architectures: Reactive (R-DLFM), Proactive (P-DLFM), and Interactive (I-DLFM), using simulations on test grids like the IEEE 30-bus system and real-world data from the DSO's (bnNETZE) 20 kV grid in Germany. The methodologies employed include Optimal Power Flow (Class C) and LinDistFlow[15] with DisgSilent PowerFactory for realistic grid behavior analysis. The key findings show that R-DLFM, while compatible with existing market structures and minimizing flexibility costs, is affected by suboptimal social welfare and operational inefficiencies due to its lack of grid awareness. P-DLFM integrates grid constraints into the market clearing, reducing costs at the Distribution Network (DN) level, but incurs higher re-dispatch costs and is impacted by renewable energy forecasting errors. I-DLFM maximizes social welfare through advanced coordination between TSOs and DSOs, offering decentralized, scalable solutions close to centralized optimization, though it faces regulatory and infrastructure challenges. Scenario analysis reveals that R-DLFM is unaffected by grid loading, while P-DLFM and I-DLFM face higher costs under high-loading conditions. High renewable energy and DG penetration lower TSO flexibility costs, with I-DLFM demonstrating the most efficient grid use but at higher TSO costs when flexibility is limited. Increased EES penetration was shown to

[15] Linearized distribution flow

reduce TSO costs, which provides benefits R-DLFM due to its simpler structure. Furthermore, various challenges were identified including the need for improved grid integration, forecasting accuracy, and regulatory and infrastructure improvements for I-DLFM. The findings in [94] further emphasize that there is significant potential for FLEXGRID's market architectures, including enhanced liquidity and profitability for DER investors, improved grid stability, and reduced operational costs for DSOs and TSOs. Through innovative market designs—such as interactive, reactive, and proactive DLFMs—the project demonstrated the capability to mitigate network constraints dynamically, balance supply and demand effectively, and optimize the deployment of DERs across the energy ecosystem.

7.16. Platone

Platone PLATFORM FOR OPERATION OF DISTRIBUTION NETWORKS	PLATform for Operation of distribution NEtworks
Coordinator	RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN
Duration	2019-2023
Demo locations	
Funding	Horizon 2020
Website	https://www.platone-h2020.eu/

The Platone [95] introduced an innovative approach to joint data management, tailored to the needs of DSOs related to network observability, and procurement of flexibility [96]. The project developed the Platone Open Framework (as shown in Figure 24 [97]), which is a layered platform architecture compliant with regulatory frameworks, which facilitates data collection, processing, and exchange to support the operations of DSOs, TSOs, and other market participants [96]. By investing in an open, standardized, and non-discriminatory infrastructure, Platone aims to empower DSOs to enhance customer and aggregator participation in flexibility markets, reinforcing their role as market enablers [96] [98]. The platform's capabilities were validated through three large-scale pilots across Europe [96] [98]. In Italy, the demonstration evaluated a complete local flexibility environment within a metropolitan area, involving virtual energy communities and smart electric vehicle charging facilities. Here, the primary focus was based on facilitating distributed flexible resources connected to the medium and low voltage levels of the DSO's grid to deliver services within an integrated TSO/DSO flexibility market that includes all stakeholders. In Greece, the demonstration focused on optimizing renewable energy use, enhancing grid observability, and advancing automation to improve system security and resilience. In Germany, the platform was implemented and tested in a rural low-voltage network with high renewable penetration, demonstrating effective flexibility coordination and decoupling of low and medium voltage networks to enhance local and regional balancing.The lessons learned are collected and presented in [99] and are summarised below.

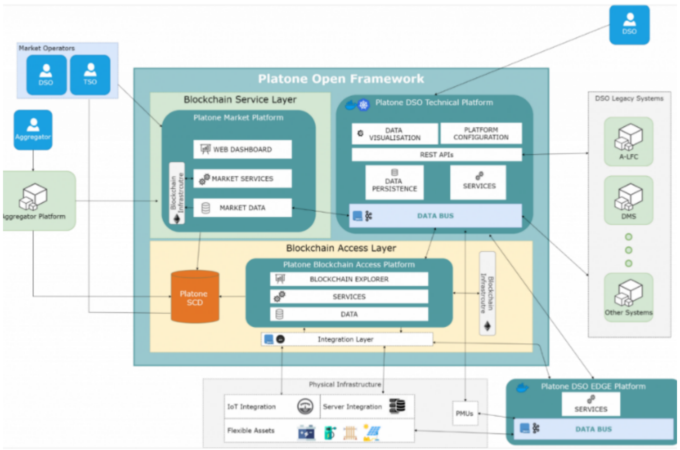


Figure 24: Overview of Platone Framework architecture.

The Platone project provided critical insights into developing smart grid systems and integrating Distributed Energy Resources (DERs). A notable achievement was the deployment of a two-layer blockchain architecture: an Access Layer for customer-DSO interactions and a Service Layer connecting DSOs, customers, and flexibility markets. This architecture enhanced data security, transparency, and market integration, with certified blockchain data ensuring trust among stakeholders. For example, the Light Node device, implemented in the Italian Demo, enabled real-time data certification, ensuring secure data exchange between DSOs and customers.

One significant challenge that was identified was aligning EU directives with national regulatory implementations. For instance, while EU policies encourage flexibility markets, countries like Greece lack regulatory sandboxes to test variable Distribution Use of System (DuoS) tariffs, limiting innovation. Dissemination activities highlighted this gap and facilitated knowledge sharing across regions. Tailored customer engagement strategies were also essential to address diverse cultural contexts, privacy concerns, and resistance to device installations. Examples included workshops with energy-conscious communities in Italy and Abbenhausen's open-day events in Germany, which boosted local trust and participation.

Greece
The Greek demonstration marked the first installation of Phasor Measurement Units (PMUs) in Greece's distribution network, which was considered to be a significant step toward enhanced grid observability. However, the PMUs' non-plug-and-play nature required substantial design modifications, including voltage and current transformers to scale signals for measurement. This additional signal processing introduced phase angle errors, highlighting the need for future designs that support isolated direct sensing to minimize inaccuracies.

Integrating PMU data into the Distribution System Operator Technical Platform (DSOTP) faced challenges due to data format incompatibilities. Grid topology data in CIM format required conversion to a compatible format for the State Estimation Tool (SET). Python-based data converters addressed this issue, however, the importance of early-stage planning for data harmonization is to be noted.

Regulatory limitations hindered real-world testing of the variable DUoS tariffs tool. Nonetheless, stakeholder workshops and surveys revealed significant interest among consumers in adjusting energy usage for cost savings and environmental benefits. The Greek NRA's shift toward capacity-based tariffs further supports the future integration of flexibility mechanisms, making remote electricity meters a key enabler for broader adoption.

Germany
The German demonstration showcased the efficacy of Virtual Islanding and Bulk-Based Energy Supply in reducing power exchange at the Point of Common Coupling (PCC). For example, schedule-based operations reduced power export peaks using day-ahead PV generation forecasts, achieving significant reductions in energy exchange. However, cloudy weather caused forecast inaccuracies, which could be mitigated through localized cloud monitoring, such as cloud cameras installed in Abbenhausen.

The rural community of Abbenhausen, with 445 kW_p PV capacity, provided key insights. During sunny days, the community exported up to 2.33 MWh, emphasizing the importance of managing surpluses. Bulk-based energy supply effectively reduced MV line loads, with testing identifying optimal export times (8 p.m.–12 a.m.) and import times (0 a.m.–4 p.m.). These findings offer a replicable framework for similar communities.

Regulatory barriers posed significant challenges, particularly restrictions on DSOs owning or operating storage systems. These constraints limited the scalability of community batteries, such as the 300 kW CBES in Abbenhausen, which required extensive approvals from local authorities. Early collaboration with respective departments and councils streamlined the process, offering a model for future deployments.

Standards-related lessons highlighted inconsistent APIs and data fields across household battery storage systems. These inconsistencies complicated integration, underscoring the urgent need for industry-wide standardization to simplify future projects.

Italy
The Italian Demo focused on designing a Local Flexibility Market, defining system architecture, actor roles, functional and technical requirements, market clearing mechanisms, and TSO-DSO coordination schemes. The demo aimed to integrate blockchain and platform technologies, with an emphasis on establishing the necessary standards and protocols. It also explored the flexibility services market as a complementary addition to Italy's existing ancillary service market for local congestion management. A key part of the work involved examining relevant regulations, laws, and the IEC-62559 and SGAM[16] frameworks to define use cases and data exchange processes. It was identified that compliance with privacy regulations caused critical concern, particularly regarding the sharing of user consumption data, as non-compliance could lead to legal issues related to unbundling and antitrust laws.

Furthermore, due to the nascent stage of blockchain technology and the lack of certification for new energy storage systems, the demo had to resort to the use of non-rigidly standardized protocols and introduced a custom data model, particularly for energy market communications. Initially, the Light Node procurement faced delays due to Italian public tender requirements, which were managed through proactive scheduling.

[16] Smart Grid Aricitecture Model

The user-engagement strategy involved targeted workshops for retail and business users, which allowed for a strategic approach to identifying their specific needs.

Due to the engagement of multiple users, a contractual framework was established to facilitate installations, and an internal governance document was developed to ensure compliance with privacy regulations, emphasizing pseudonymization for data protection.

The adoption of the MQTT protocol optimized communication with other platforms, while a multi-band communication module with 4G ensured reliable uptime. The Blockchain Access Layer successfully maintained certified measurements without increasing block creation frequency, even with increased data volumes. Despite challenges with the distributed cloud infrastructure causing communication lapses, integration adjustments to retry mechanisms helped mitigate these issues.

The introduction of the Local Flexibility Market highlighted challenges such as the importance of DER locations for efficient operation and the need for improved coordination between system operators. Customer engagement revealed installation difficulties due to user dispersion and the need for availability in private areas, but the DSOs (Areti) involvement enriched their understanding, leading to the application of Platone's solutions in the future.

Scalability efforts included a systematic monitoring process to mitigate computational load issues under increased user volumes and ensure system performance. The demonstrated success of the Italian Demo's architecture and methodology led to its adoption in new projects like Flow (enhancing EV flexibility using market mechanisms and shared databases), Beflexible (TSO-DSO coordination via traffic light mechanisms), and RomeFlex (local flexibility market experimentation). Delays in self-consumption community activities, caused by administrative bottlenecks related to national incentivization policies, highlighted the critical need to account for bureaucratic uncertainties in project planning.

7.17. OSMOSE

OSMOSE	Optimal System-Mix Of flexibility Solutions for European electricity
Coordinator	RTE RESEAU DE TRANSPORT D'ELECTRICITE
Duration	2018-2022
Demo locations	
Funding	Horizon 2020
Website	https://www.osmose-h2020.eu/

The OSMOSE project [100] [101] developed and demonstrated advanced flexibility solutions for integrating high shares of renewable energy into the power system. By considering synergies among flexibility needs and sources, the projects included investigations including hybridization and multiservice utilization to optimize cost-efficiency and reliability. The project consisted of four demonstrations, which address key applications: synchronization of large systems using hybrid storage, multiservice control of storage and FACTS devices, coordinated management of grid assets, demand response, RES generation, and cross-border energy market integration. Simulation studies forecasted the optimal flexibility mixes for 2030 and 2050 scenarios and proposed regulatory and market improvements to enable scalable, sustainable flexibility solutions. The project also addressed aspects related to interoperability, TSO-DSO coordination, and knowledge sharing. Although the project's primary focus was that of the TSO perspective, the project developed a tool (i.e. the Flexibility Scheduler) to enhance voltage control by optimizing the flexibility levers at the TSO/DSO interface and the distribution level. The test results, along with the conclusions, are documented in [102] and are summarised as follows.

The results identified that transparency of communication and synergies between system operators are key elements in facilitating a harmonized and efficient collaboration. Furthermore, it is paramount that the activation of flexibility services does not cause a negative impact on the grid operation, especially when it comes to cross-border grid impacts or conflicts of interest. Thus, it is recommended to define a prioritization order based on a holistic system view. The flexibility scheduler (FS) was primarily designed to consider the needs and constraints of the transmission system, where selected flexibilities are activated according to their defined set-point for each hour based on a day ahead schedule, however, the tool was shown to operate in various time horizons i.e. real-time and operational planning. The tool also proved to be successful in the mitigation of congestion management and voltage control in distribution challenges networks, through the execution of optimal reactive power management. This was achieved with consideration of the TSO-DSO interface and was validated based on 16 simulated test cases. The outcomes of the simulations indicated that the operational schedules generated by the FS tool were able to ensure that voltage levels at the TSO-DSO interface (DSO observability area) remained within acceptable limits. These solutions also observed a reduction in system losses and improved cost efficiency, except in one instance where losses increased due to limited control variables on the TSO side.

Furthermore, the project's main takeaways were presented in [103]. In summary, it was concluded that advanced simulations of the European power system are crucial for informed decision-making on investment, incentives, and market design. Additionally, since flexibility needs and sources are interdependent, they should be considered for long-term studies. Simulations are, therefore, a vital component in investigating the impact of flexibilities in various time scales as well as sector coupling. This includes the integration of other flexibility technologies such as power to gas, BESS, and RES. In particular, BESS have become increasingly favourable as flexibility solutions to support system security and stability. Therefore, it is recommended that they be considered for synchronisation services when there is no additional cost for the provider. In terms of RES and industrial flexibility, wind farms were shown to provide ancillary services, however, there are still barriers such as grid code updates and industrial developments that need to be implemented. Industrial loads were shown to be capable of providing flexibility however, due to their optimised processes and retrofitting challenges, the available flexibility is somewhat limited. Lastly, while advanced sensors and tools often serve as a means to improve operational cost optimization, their deployment is often faced with challenges in industrial practices.

7.18. Redispatch 3.0

The Redispatch 3.0 research project [38] [104] investigates the potential of the increasing spread of photovoltaics, heat pumps, and electric mobility in the context of congestion management. Controllable resources such as photovoltaics, heat pumps, and electromobility can offer flexibility in their operating behaviour. One aim of the project is to make this flexibility usable for congestion management in the upper voltage levels [105]. To this end, various components in the low-voltage grid with flexibility potential in the grid are being modelled in two field test areas using smart meters, among other things. In addition to forecasting technologies, the Institute ie³ at TU Dortmund University is optimizing operational planning for congestion management.

Redispatch 3.0	
Coordinator	OFFIS e. V.
Duration	2022-2024
Demo locations	
Funding	Federal Ministry for Economic Affairs and Climate Action
Website	https://www.redispatch3.eu/

The flexibility potential is first calculated in all subordinate distribution grids, which describe the possible power transfers at the connection point to the transmission grid (aggregation). This is done utilizing optimization methods, taking into account the bottlenecks in the distribution grid [106]. The flexibility potential in the higher-level grid is also used in an optimization algorithm to find an optimal solution to the bottleneck. In the final step, an optimization problem is solved in the downstream grid to find target values for all controllable resources (disaggregation). The optimum power value previously calculated by the higher-level network at the connection point is specified as a boundary condition. The determination, aggregation, and retrieval of flexibility potential is becoming increasingly important. Thus, the SIMONA energy simulation framework has been further developed to include energy management functionalities [107], [108]. In particular, the SIMONA framework enables the simulation of end consumers with energy management systems and intelligent local grid systems with power limitations require the development of an energy management agent, these functions within the framework. Within the project, energy management functionalities were integrated into SIMONA, and a heuristic method was developed to consider batteries in the process through aggregation efficiently.

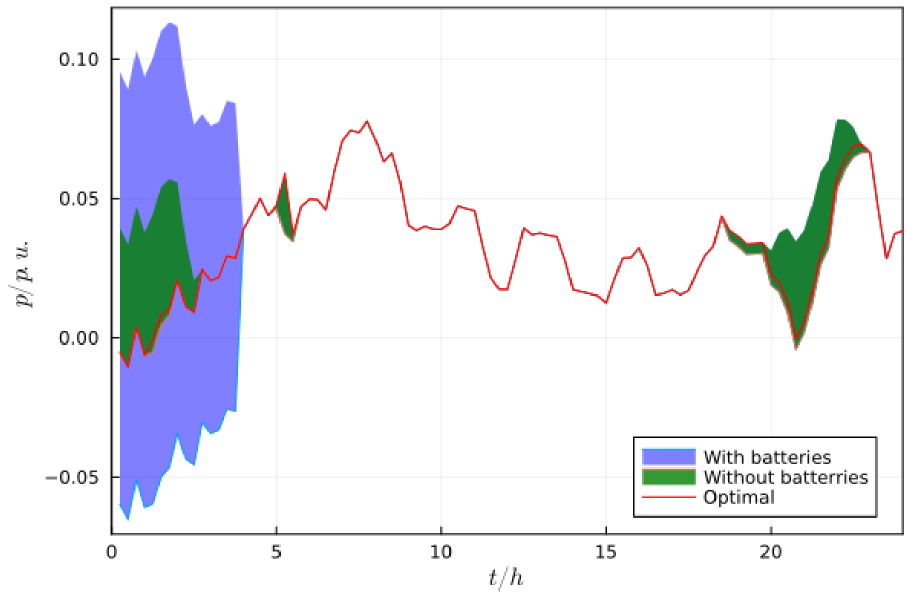


Figure 25: Flexibility potential with and without batteries over a time period.

7.19. Industry4Redispatch

Industry4Redispatch	
Coordinator	AIT Austrian Institute of Technology GmbH
Duration	2021-2025
Demo locations	
Funding	NEFI, klima energie fonds, Vorzeigeregion Energie
Website	https://w w w .nefi.at/de/projekt/industry4redispatch

The flagship Austrian project Industry4Redispatch (I4RD) [35] is designed as a key project within the model region NEFI – New Energy for Industry. I4RD is the first NEFI project that develops innovative solutions enabling (i) the provision of flexibility from the demand and supply side at the distribution network level for redispatch and (ii) the demonstration of an online, predictive and holistic control concept for industrial energy supply systems, which optimizes a company's market participation while ensuring its energy supply. Within I4RD, redispatch service and processes are developed and the related tools for the exchange of technical restrictions between the DSOs and the TSO, as shown in Figure 26. In addition, I4RD set up industrial demonstrators/virtual power plants (VPPs) at the distribution system level to efficiently address industrial customers with control systems with different levels of maturity and lay the groundwork for the future engagement of different industrial sectors and flexibility volumes. A cost-benefit analysis was conducted to determine the distribution of costs and benefits among the stakeholder groups. Furthermore, a scalability analysis for TSO-DSO interaction was conducted to identify the impact on the distribution system caused by large-scale demand and supply-side management for redispatch in the transmission system and required information flows between TSO and DSO. Finally, a guideline is provided including a step-by-step tutorial for transforming a conventional existing industrial energy supply system into a more flexible, more decarbonized, optimally operated one as well as the guidelines for the TSO-DSO coordination process. The detailed descriptions of the key lessons learned are summarised below.

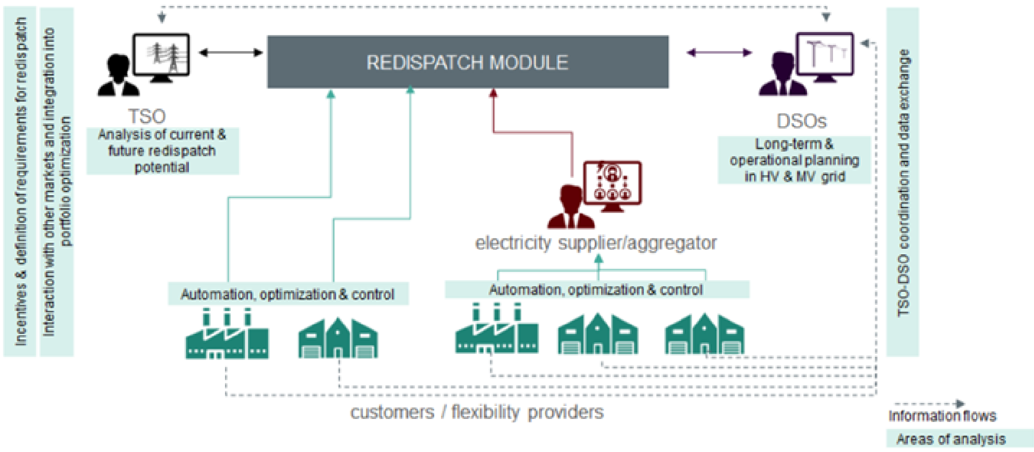


Figure 26 Overview of the project architecture, stakeholders and main research areas

Key lessons learned:

- Flexibilities of distributed industries, connected at the distribution networks, may be utilized to mitigate transmission congestions, thus holding the potential to reduce redispatch costs. The activation of distributed flexibilities may cause violations of the operational distribution network constraints (loading and voltage) due to high coincidence. Therefore, TSO interaction process is needed to provide the TSO with a day-ahead access to the most cost-effective flexibility bid combinations that maintain limit compliance at the distribution level.
- The process shall be fair, practicable, accurate, scalable, and replicable. Confidentiality of the DSOs, transparency, and short calculation times are integral parts of these requirements.
- Transparency, confidentiality, and accuracy span a trilemma in which only two out of the three requirements can be simultaneously maximized at the expense of the remaining one. An adequate trade-off needs to be specified as the basis of process design.
- The process shall identify feasible (i.e., distribution network limit-respecting) bid combinations that are pareto optimal in terms of cost and power and do not contain any XOR-conflicts and forward them to the TSO.
- The feasibility of bid combinations shall be validated across multiple dimensions: time intervals, contingency cases, and elements. The complete 24-hour time horizon allows accounting for anticipatory and catch-up effects of flexibility providers. Examining diverse contingency scenarios guarantees limit compliance even for outages at the high-voltage part of the distribution network.
- From a physical perspective, validating the feasibility of bid combinations requires an adequate degree of bid aggregation:
- Several assets behind a single delivery point of the distribution network may be aggregated.
- Bids related to different delivery points cannot be aggregated.
- The proposed sensitivity-based distribution system model accuracy depends on the linearity of the distribution system and the bidden power.
- Distribution systems contain several sources of non-linearity, including network- and control-related ones. Control-related non-linearities are relevant when distributed energy resources are controlled to adapt their (active/reactive) power contributions depending on the distribution network state. Their accurate consideration is crucial to obtaining meaningful results because such controls are often employed to increase the network's hosting capacity.
- The linearity of any real distribution system should be analysed prior to implementation and re-evaluated after network reinforcements/expansions and adjustments of the applied controls.
- Low-quality forecasts and non-unity bid power factors significantly degrade calculation accuracy, leading to misjudgements concerning the feasibility of bid combinations and ultimately to increased redispatch costs.
- Non-unity bid power factors generally tend to provoke higher redispatch costs due to their high impact on the distribution network voltages.

- Network state calculations for bid combinations that contain XOR-conflicts should be avoided during the optimization process when using heuristic algorithms to improve the performance of the solver.
- The proposed solution approach, which is based on a modified NSGA2[17] algorithm and limited to a runtime of 15 min, does not support the consideration of voltage limits in large networks with many redispatch bids due to calculation speed issues.
- An improved load and generation forecasting, an accurate consideration of non-unity bid power factors, a systematic reduction of critical network elements prior to optimization execution, and the consideration of other solver algorithms than NSGA2 are identified as key measures to improve the performance of the proposed process.
- Network expansion or reinforcement cannot be fully replaced, and the process becomes complex when the distribution overloaded.

7.20. InterConnect

interconnect	Interoperable Solutions Connecting Smart Homes, Buildings and Grids
Coordinator	INESC TEC
Duration	2019-2024
Demo locations	
Funding	Horizon 2020
Website	https://interconnectproject.eu/

The InterConnect project [109] aimed to advance the digitalization of the electricity sector by developing and demonstrating advanced solutions that enhance energy efficiency and promote sustainable consumption behaviours among users. Through seven large-scale pilot sites in Belgium, France, Germany, Greece, Italy, Portugal, and the Netherlands, the project demonstrated practical solutions for connecting platforms to deliver cost-effective, sustainable energy and non-energy services. By incorporating advancements in Smart Grids, Smart Homes, and ICT, InterConnect advances digital marketplaces where prosumers can efficiently trade energy and services. The project focused on three main objectives [110]:

1. Implement a semantic interoperability framework within large-scale pilots with interoperable devices, services, and platforms.
2. Engage citizens and other stakeholders in the co-creation and implementation of innovative energy and non-energy services and their business models.
3. Enhance efficiency in energy use, integrate digital platforms and services, and drive energy sector innovation.

The InterConnect multidomain approach interconnects Multi-Service Provider (MSP) platforms to enhance energy efficiency, drive innovation, and lower adoption barriers, while citizen co-creation ensures user-centric design and sustainability. The project is centred around the concept of semantic interoperability, which refers to the capability of digital systems to exchange data with a clear and well-defined meaning. With this in mind, the project's Semantic Interoperability Framework (SIF) for buildings and homes implemented the concept of semantic interoperability on a large scale [111]. The DSO Interface (DSOi) concept and platform which utilizes the SIF to facilitate communication between DSOs and household devices, enables data exchange between DSOs and service providers, promoting more efficient system operations and integrating consumers into the energy value chain. Furthermore, the Interoperable Recommender (IR) was also designed to connect the SIF and DSOi domains, offering energy recommendations derived from predicted scenarios and real-time grid measurements.

As part of the project outcomes, the definition of a blueprint for the energy application based on the Common European Reference Framework (CERF) is presented in [112], which focuses on the challenges and insights related to data sources, data repositories, and exchange, consumer applications, and scalability. The document provides an overview of the challenges encountered and the lessons learned obtained from pilot implementation and proposes a series of recommendations to

[17] Non-dominated Sorting Genetic Algorithm II

address the technical, regulatory, social, and economic aspects. In particular, the analysis was based on a mapping according to four categories, i.e. Data sources, Data repository and exchange, Consumer application, and Replicability and Scalability are summarised as follows.

Data sources

The InterConnect pilots highlight challenges in accessing and integrating public energy data, primarily due to data fragmentation, interoperability issues, and limited access resulting from proprietary formats and legacy system constraints. Incompatibility in data schemas and varying standards across stakeholders were shown to emphasize this concern. Public data sources like the ENTSO-E Transparency Platform[18] provide some support in data availability, however, it was observed that there are still a number of inconsistencies for specific data points, especially in cross-border interconnection data. Additionally, data accessibility regulations remain largely undefined, with no unified EU guidelines related to smart meter data access and sharing. The ongoing smart meter rollout in the EU further indicated the significant disparities across Member States. Furthermore, based on the outcomes from the pilots, near real-time consumption, generation, and grid status data were identified to be critical for optimizing energy and grid stability decision-making processes. Low availability and inaccuracy in LV topology data from DSOs, which might not be linked to Geographic Information Systems (GIS) pose a further challenge. Thus, accurate topology information is recognized to be a key aspect in the generation of accurate demand response grid signals. The establishment of centralized data hubs was found to reduce integration complexity and provide free data access. Lastly, the absence of data marketplaces and unclear monetization models was shown to hinder the establishment of the CERF since there is a lack of economic incentives for data providers, in addition to the non-clarity of intellectual property.

Data repositories and exchanges

The integration of diverse data sources into developed solutions posed significant challenges for the pilots, primarily due to the heterogeneity in data sources and Application Programming Interfaces (APIs), data semantics, formats, and communication protocols. One example is associated with the ENTSO-E TP where it was identified that there was an inconsistency in the duration of data reporting periods from different TSOs, requiring separate analysis and handling at the TSO level. The implementation of CERF and InterConnect solutions was shown to facilitate simplified access to grid-related data, which reduces integration efforts across disparate data sources. The project, thus, showed that a uniform interoperability approach could support all tested energy applications, aligning with CERF's objective to foster agnostic interoperability. For example, in the Slovenian pilot, the FlexTrade platform leverages both the DSOi and IR services to access and integrate carbon intensity data, prosumer information, and electricity prices sourced from the ENTSO-E Transparency Platform. Furthermore, the pilots highlighted that data exchange formats and methods used by TSOs and DSOs still lacked standardization. Thus, the DSOi tool was identified as crucial for accessing distribution grid data and generating demand response signals with higher geographical granularity. While more accurate grid and demand response signals could be derived from specific electricity delivery points, this approach raised two primary concerns: technical complexity in scaling up and potential risks to personal data privacy. To mitigate these concerns, the Portuguese pilot opted to utilize zip codes to refer to geographical locations, based on a cost-benefit analysis. This approach enabled the collection of district-level data, and the provision of recommendations tailored to the local grid state while maintaining user anonymity. Lastly, concerns were raised regarding the adequacy of existing communication infrastructure. It was highlighted that public internet, communication, and cloud services were not designed to meet minimum latency requirements, ensure cybersecurity, or provide reliable failure response, which poses challenges to the scalability and security of the system.

Consumer applications

The InterConnect pilots provided critical insights into effectively engaging energy consumers through applications, emphasizing the importance of monetary incentives, social responsibility, and user-centered design. Dynamic tariffs were shown to create monetary benefits that encourage users to shift consumption periods and thus consequently result in highly effective in optimizing grid operations. However, their limited availability across the EU necessitated alternative approaches. For example, the Italian pilot leveraged wholesale electricity prices and carbon emission data to create price signals.

[18] https://transparency.entsoe.eu/

Furthermore, it was shown that increasing customer awareness and promoting social responsibility is pivotal for user engagement. For example, In the Greek demo, users accessing the energy application are welcomed on the landing page with daily grid recommendations. These recommendations served as a reminder of their potential to contribute to grid stability and effectively encourage them to modify their consumption habits accordingly. Furthermore, it was shown that social responsibility is closely associated with environmental impact awareness. As shown in the Italian pilot, combining energy consumption data with information about the associated carbon footprint proved effective in enhancing user engagement.

In addition to providing adequate incentives to encourage customer engagement, it is also necessary to ensure that customers remain enthusiastic to continue to participate. Therefore, it is important that demand response programmes do not entail undesired and unnecessary complexities. Automation of demand response mechanism was identified to be a critical finding, as demonstrated by the German pilot, where financial incentives were tied to automated device responses, such as rescheduling appliance operations. In the Dutch pilot, the introduction of a push notification mechanism, where users receive alerts about upcoming overload situations, instead of a pull mechanism that requires customers to open the energy application to access grid signals was implemented. This approach eliminates the need for users to actively check the application.

Furthermore, it was emphasised that not all customers can be considered identical. There is a clear variation in customer consumption and demographics. Different user demographics required distinct approaches: wealthier households, equipped with PV systems, EVs, and smart home appliances, had greater potential for offering demand-side flexibility compared to lower-income households facing energy poverty. Additionally, the consideration of energy literacy should be considered. For example, the Spanish found that users engaged more readily when data was presented in monetary terms (euros) rather than technical units like kWh.

Replicability and scalability
For replicability and scalability, the pilots underscored the need for standardized ontologies and protocols to ensure seamless integration across diverse regulatory and technical landscapes. The challenges associated with data in energy systems were shown to be multifaceted and require technical attention. It was highlighted that the absence of common, interoperable grid datasets and limited accessibility, often due to the lack of public APIs, restricts the scalability and replicability of solutions across Europe. Furthermore, unresolved issues surrounding data ownership, particularly for customer-generated data such as smart meter readings, EV charging statistics, and IoT device outputs, create significant barriers to data sharing. From a scalability perspective, processing the massive volumes of data generated daily by over six million LV grid delivery points across Europe presents substantial computational challenges. Additionally, the lack of a standardized recommendation ontology and the limited availability of open-source Smart System Architectures (SSAs) inhibit interoperability and the widespread adoption of innovative solutions. Addressing these challenges requires a concerted effort-in data standardization, advanced processing capabilities, and improved accessibility frameworks. From a technical design perspective, modular and flexible approaches emerged as critical factors for scaling energy applications, ensuring adaptability across diverse operational scales. For example, in Denmark and France, the pilots demonstrated the value of such adaptability by enabling seamless integration of varied energy systems, benefiting grid operators and industrial users. Lastly, it was also highlighted that scalability and replicability also depend heavily on regulatory alignment, as divergent transpositions of European Directives into national regulation contain many barriers. Countries with forward-looking regulations enabling DSOs to enhance network management more effectively were shown to successfully support technological integration.

7.21. National Grid Electricity Distribution: UK

An example of such DSO-TSO collaboration can be seen in the way National Grid Electricity Distribution (NGED) collaborates with the Electricity System Operator (ESO) in Great Britain to facilitate this energy transition. One notable service is MW Dispatch, which maximizes DER participation through effective communication between system operators. MW Dispatch manages transmission constraints and connects DERs to the distribution network. By instructing DER units to reduce output during system constraints, they receive payments for the electricity they would have generated. MW Dispatch offers a cost-effective alternative to the Balancing Mechanism, potentially resulting in consumer cost savings. It also provides flexibility and visibility beyond existing generators.

The deployment of MW Dispatch began in the Southwest region of England and has since expanded to other regions, facilitating over 7.3 GW of generation connection offers and 500 connections. The interaction between DSOs and the ESO is crucial for the success of MW Dispatch. Data sharing and coordination protocols enable the ESO to gain visibility of new DERs. NGED and UK Power Networks work closely with the ESO to ensure effective communication and information exchange. Technical capabilities are being developed to coordinate the dispatch of generators during transmission constraints.

This project on MW dispatch has directly fed into the work NGED is feeding into on implementing primacy rules in collaboration with the ESO through the Open Networks project. Primacy establishes agreed-upon rules to manage conflicts between the ESO and DSO. It ensures that actions taken by both operators are effective and coordinated, thereby avoiding inefficiencies. NGED specifically focuses on addressing conflicts between DSO procurement and ESO constraint management. The implementation of primacy rules prioritizes improved data sharing and decision-making based on the overall value to the entire system.

In summer of 2024, further enhancements for NGED included expediting the implementation of primacy rules. The aim was to enhance collaboration, coordination, and data sharing between the ESO and DSO, supporting the optimization of the power system and the integration of DERs. These initiatives serve as exemplary models for other jurisdictions. The collaborative approach, data-sharing protocols, and coordinated efforts provide valuable insights. The UK's experience demonstrates the benefits of leveraging DERs and smart technology between energy stakeholders to effectively manage transmission constraints, increase renewable generation connections, and reduce costs.

7.22. TDFlex

TDFlex	T&DFlex – TSO-DSO Flexibility: towards integrated grid control and coordination in Switzerland
Coordinator	ETHZ
Duration	2018-2022
Demo locations	
Funding	SFOE
Website	https://www.fen.ethz.ch/activities/system-operation/tdflex.html

The Swiss project TDFlex performed an analysis of the practical use of flexibilities within distribution grids. The goal was, to quantify the economic value of flexibility of distributed energy resources (DER) such as electric demand (e.g. heat pump, EV charging), solar PV generation and distributed battery energy storage systems (BESS) at low voltage level to minimize or defer infrastructure investments in distribution grids while considering the impact of the technical capability and availability (reliability) of such resources. The project was performed in close collaboration with utilities from regions with different characteristics (rural, city). Their feedback on practicality, the realistic utilization and the secure grid integration of flexibilities allowed to narrow down the realistic flexibility options and to robustly assess their potential.

Proliferation of PV with or without BESS, personal electric vehicles and electric heat pumps is gaining traction in Switzerland. Massive amounts of such DER will be mainly deployed in low-voltage distribution networks, resulting in challenges to the network infrastructure investment planning and daily operation. The technological transformation is also accompanied by new solutions based on novel flexibility options.

Current regulation in Switzerland motivates the electricity distribution utilities to invest in the infrastructure (e.g., increase the capacity of the transformers, cables) when needed rather than paying for and utilizing the flexibilities of DERs owned by end-users. However, the pace of DER proliferation is expected to be higher than the speed of replacement of cables and/or transformers. The need for flexibility emerges for the utility to maintain the reliability of electricity supply (e.g., avoid power outage) by ensuring a secure grid operation. The cause of the flexibility needs of a distribution utility are potential grid violations, including (1) thermal overloading of the transformer, cables and overhead lines, (2) over-voltage at the point of power injection and at electrically nearby nodes of the excess generation, and (3) under-voltage at the demand connection and at electrically nearby nodes due to high simultaneity factors of the new loads (i.e., HP, EV charging). Note that the violations have temporal and spatial characteristics. That means, unless the DERs are coordinated or controlled, violations will occur in some parts of the grid at certain times on certain days. In addition, the spatiality of the violations implies that the need for flexibility is location-dependent.

Figure 28 shows the power profile (red line on the left denotes the net demand) and line loadings of a future rural grid in a touristic region without the utilization of flexibility. It can be observed that PV dominates the grid loading, leading to overloading of the transformer and distribution cables. A low proliferation of BESS is assumed in the demonstrated scenario.

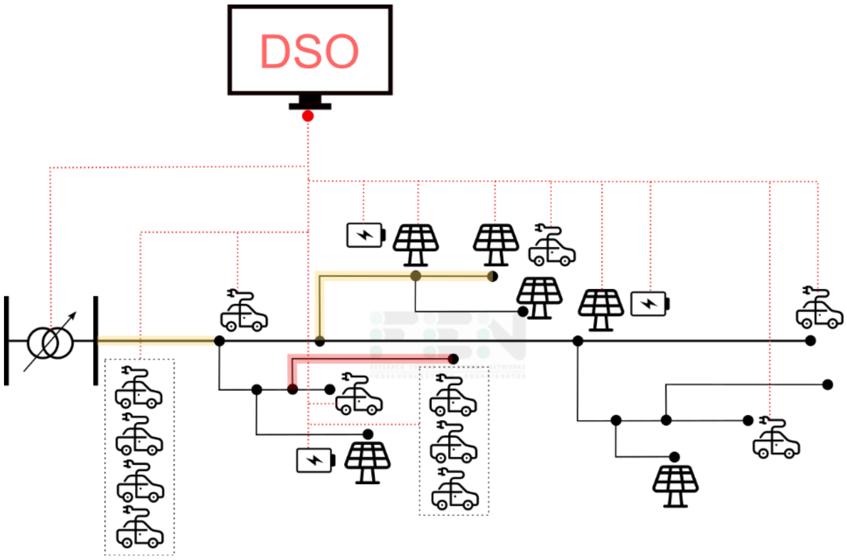


Figure 27: Relief of future congestions: Invest in grid infrastructure and/or exploit the flexibility of DER?

The following rule-based flexibilities were considered:

- PV flexibility through curtailment
- EV-charging flexibility by slowing down or delaying charging (i.e., night-charging or peak-shaving /valley filling)
- Heat pump flexibility by shifting the operation ±2 hours
- BESS charging strategies with local control through (i) charging at times of excess generation and discharging at times of positive demand and (ii) delayed charging to cover the peak of the excess generation and delayed discharging to cover the maximum demand.

As a result of these simple flexibilities, the following figure shows, that the congestion in the example can be relieved. The use of BESS allows to maintain the level of PV-utilization.

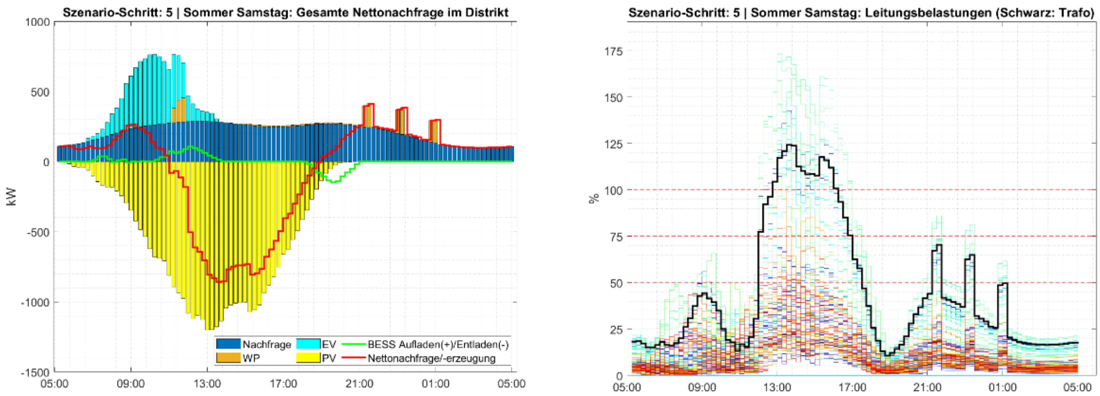


Figure 28: Daily Power profile of future rural grid (left) and resulting loading of cables and transformers (right) without the use of flexibility. Several cables and the transformer are overloaded.

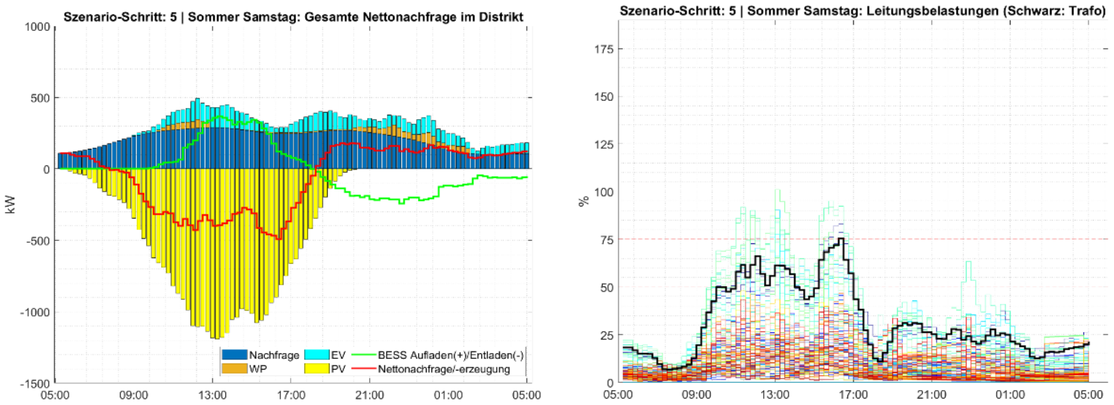


Figure 29: Daily Power profile of future rural grid (left) and resulting loading of cables and transformers (right) with the use of flexibility. The congestions are mitigated.

The results were reproduced for a wide range of Swiss distribution grids with varying characteristics. They show that utilization of flexibilities is a potential alternative to defer grid investments. The trade-off between the two approaches is investigated in the subsequent section on economics. For urban and industrial grids, similar results are obtained when using flexibilities, with two differences. First, peak grid loading occurs during the evening and is mostly driven by the loads, not PV-units unless a very aggressive PV proliferation scenario is considered. Secondly, there are more under-voltage violations determining the need for flexibility usage.

Data exchange and cyber security

It has been found that the main potential use of flexibilities for the mitigation of congestion in the grid can be achieved without a centralised real-time coordination with the necessary data exchange. Instead, local flexibility control based on time schedules or local measurements has been found to be sufficient to unlock the potential of flexibilities. For example, BESS systems can be scheduled to charge during the forecasted excess PV-peak hours (e.g., 13:00 – 14:00) and discharge during the forecasted evening consumption hours (e.g., 18:00 – 20:00), without any reduction of local self-consumption on the side of the customer, and without any communication requirements. This also reduces the number of communications exchanges and simplifies the implementation of flexibility support – an inherent feature of cyber security.

Economy: Putting a price on a modern grid

The planning and cost assessment of the future electricity grid should naturally account for the use of flexibilities. The potential of utilizing DER flexibility to postpone grid investment is assessed by comparing the cost of investment (annualized capital expenditure – investment cost, CAPEX + operational expenditure, OPEX) and the cost of flexibility to alleviate the violation.

- If the cost of flexibility in a year is smaller than the cost of investment, it favors a deferral.
- The assessment provides a basis to estimate the order of magnitude for the cost of the necessary ICT infrastructure.

It is assumed that the flexibilities are available without causing any loss of comfort to the owner. The cost of flexibility is then estimated by using the minimum flexibility remuneration that is required to convince the DER owner to commit to flexibility provision (compensating the loss of opportunity). The customer's opportunity cost is therefore highly dependent on electricity retail prices and solar feed-in tariffs. The scenarios were tested for a range of price developments, to ensure the robustness of the results.

Figure 30 illustrates the trade-off between grid investments and flexibility usage. The horizontal axis gives the future peak loading of the existing branch for three scenario years (starting with 90% in 2034 and ending with 157% in 2046). The vertical axis gives an estimate of the annualized cost to use flexibility for the congestion mitigation (no costs in 2034, since the branch is not overloaded and up to 6800 CHF in 2046, since the branch is often overloaded). The annualized cost for doubling the capacity of the branch is indicated by the red dashed horizontal line at about 1'000 CHF. It can be observed that flexibility is the cheaper option until ~2040 but is then becoming more expensive than upgrading the branch. The same assessment can be made of each asset of the existing grid, allowing efficient and secure grid planning taking into account the temporality and spatiality of the flexibility needs. Individual assumptions for the flexibility usage (e.g., permitted curtailment level for PV) can be compared against one another.

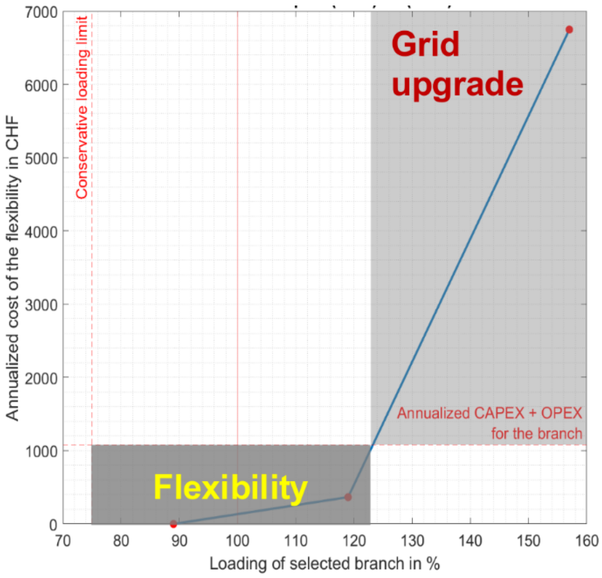


Figure 30: Trade-off between grid investments and flexibility usage. Flexibility usage can defer or avoid grid upgrades, depending on the cost, usage frequency and spatial availability of the flexibility.

Flexibility utilization, itself, cannot completely avoid investments on every branch and transformer; however, it can reduce the number of investments and can help defer (i.e., postponing) the investments to a later stage. Compared to traditional approaches, relying on simultaneity factor estimation and point forecasts, the asset investment analysis exploiting time-series analysis is especially beneficial and utilization of flexibilities demonstrate potential because the pace of proliferation is expected to be faster than the pace of upgrading the grid infrastructure.

Overall, the results demonstrate that the need for DER flexibility is location-dependent. Only those DER, which can alleviate the violations are utilized and remunerated.

- The violations due to excess solar PV can only be alleviated if solar curtailment is allowed by regulation.
- Grid violations in urban grids are expected to be mainly due to demand (i.e., HP and EV charging) on winter workdays unless a very aggressive solar proliferation scenario is considered.
- Grid violations in rural grids are expected to be mainly due to solar PV since the excess generation (if not stored) in summer can be higher than the winter workday evening demand due to EV and HP operation.
- Mechanisms for demand-side flexibility are a valuable solution for distribution utilities to defer grid investments when electrification of demand takes place at a faster pace than anticipated (and faster than PV proliferation). In such cases, the utility may not be able to catch up with the required network investments. This is especially valid for electromobility, which, in some regions, is growing the fastest.