TSO-DSO Challenges & Opportunities for the Digital EU Electricity System

DSO ENTITY
DSOs FOR EUROPE

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Executive summary

The report underscores the critical need for digitalisation to enhance grid operation, planning, and customer integration, which is essential for achieving global and European carbon emission reduction targets. The recommended solution is the development of digital twins (DTs), as virtual replicas of physical systems, tightly connected via indispensable communication interfaces. These cutting-edge technologies enable improved monitoring, prediction, and decision-making across the lifecycle of grid assets, from development and planning to operational monitoring and scenario simulation.

The power system faces several challenges today, including a rapid increase of distributed energy resources that must be integrated into the system, which requires coordinated planning and operational strategies. In addition, rapidly increasing demand in many countries necessitates timely and accurate investment decisions to ensure grid capacity. With increasing weather anomalies and weather-dependent production, advanced forecasting is fundamental for secure and optimal grid operation. Finally, the evolving geopolitical situation requires a robust, data-driven, and resilient cyber defence that safeguards the power system at all times, including when external entities try to sabotage its operation.

Every challenge presents opportunities for the power system and stakeholders. More distributed energy resources help society to electrify consumption and reach carbon emission reduction goals. Higher intermittent production and imbalances make flexibility more valuable and create opportunities for flexible customers to increase their income. Advanced forecasting models enhance stability by handling variations in consumption and production and improve supply security and utilisation of the power grid. Furthermore, a cyber-secure grid strengthens the resilience of critical infrastructure, thereby safeguarding societal well-being.

Implementing DTs will contribute to solving major challenges and exploiting opportunities. They will provide relevant insights for informed decision-making for grid planning and system operation, leading to improved security of supply and grid utilisation, as well as enabling customer integration to increase flexibility. This digitalisation effort supports creating a sustainable, secure, and competitive energy market.

The joint task force emphasises the importance of addressing key challenges to digitalisation for the future of the EU electricity system. Fundamental barriers are connected to data quality, standardisation, and access. The report highlights the need for all system operators to apply existing standards, data availability, and data quality to achieve interoperability and effective decision-making. The task force will develop a roadmap to guide the coordinated implementation of DTs across the European electricity system to further advance efforts.

Acronyms

AC	Alternating Current
ADMS	Advanced Distribution Management System
AG	Average Grade
AI	Artificial Intelligence
APM	Asset Performance Management
BIM	Building Information Model
BRP	Balancing Responsible Party
BSP	Balancing Service Provider
CENELEC	European Electrotechnical Committee for Standardization
CGM	Common Grid Model
CGMES	Common Grid Model Exchange Standard
CIM	Common Information Model
CPS	Cyber-Physical System
DAR	Dynamic Asset Rating
DER	Distributed Energy Resources
DESAP	Digitalisation of Energy System EU Action Plan
DLR	Dynamic Line Rating
DSO	Distribution System Operator
DSR	Demand-Side Response
DT	Digital Twin
EU	European Union
EV	Electric Vehicle
FMM	Fundamental Market Model
GIS	Geographic Information System
HiL	Hardware in the Loop
HILF	High Impact Low Frequency
HV	High Voltage
HVDC	High Voltage Direct Current
IEC	International Electrotechnical Committee
IGM	Individual Grid Model
IoT	Internet of Things
IT	Information Technology
JTF	Joint Task Force
LV	Low Voltage
MARI	Manually Activated Reserves Initiative
MTU	Market Time Unit
MV	Medium Voltage
OPC/STA	Outage Planning Coordination/Short-Term Adequacy
OPDM	Outage Planning Data Management
OT	Operational Technology
PMU	Phasor Measurement Unit
PICASSO	Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation
PV	Photo Voltaic
RES	Renewable Energy Sources
SCADA	Supervisory Control and Data Acquisition
SGAM	Smart energy Grid Architecture Model
SGI	Smart Grid Indicators
SoS	System of Systems
SOTA	State-of-the-Art
TC	Technical Committee
TSO	Transmission System Operator
VAMOS	Varied Market-Model Operating System
WAMPAC	Wide Area Monitoring, Protection, and Control
WP	Work Package

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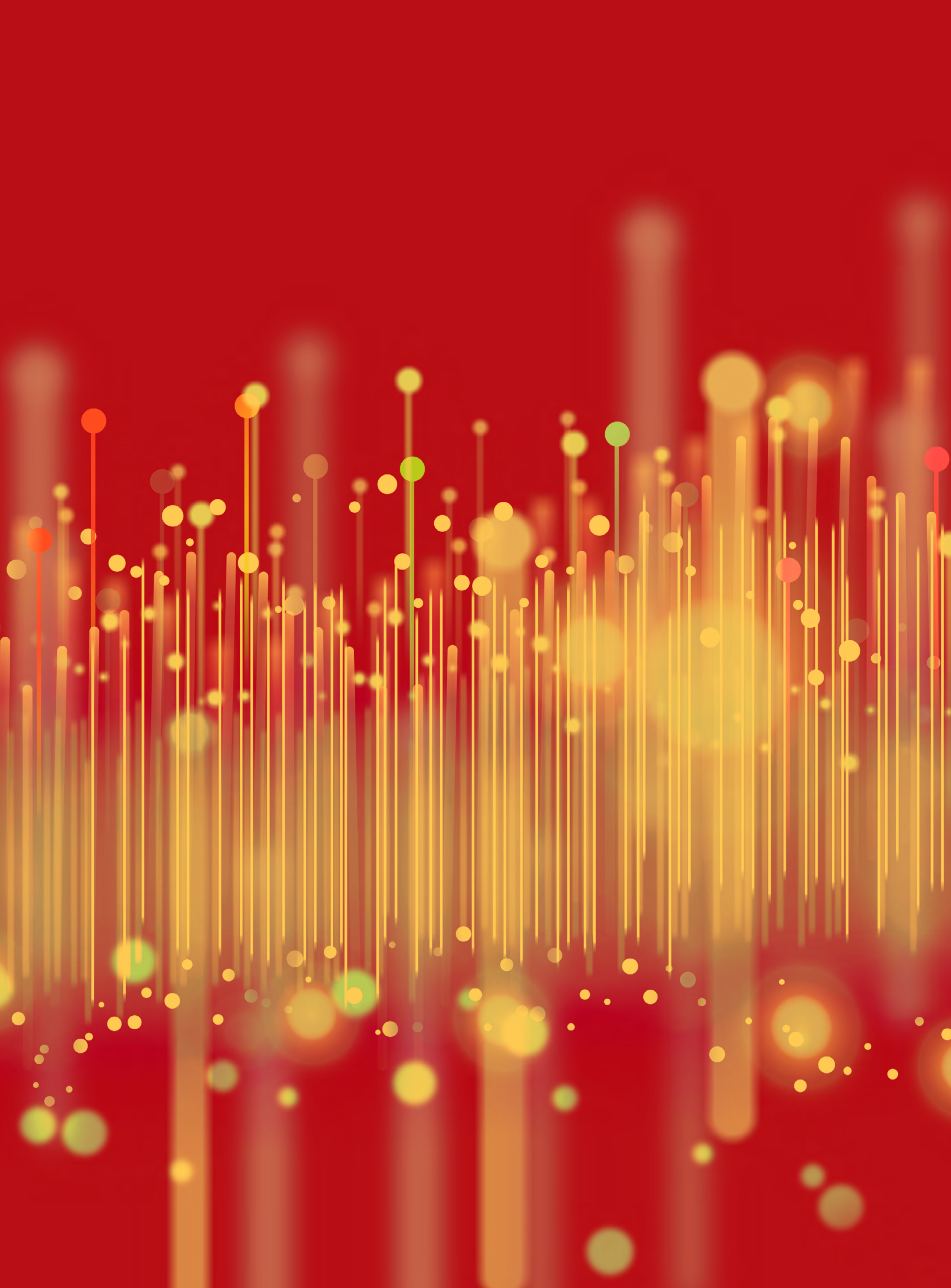


CHAPTER 1

Introduction and background

Digitalisation is an enabler of electrification and the integration of renewable energy, which in turn will contribute to accomplishing global and European carbon emission reduction targets. Digitalisation of the grid enables enhanced system operation, grid planning, and customer integration. Overall, this will create a basis to increase the capacity and utilise the existing capacity by achieving higher interoperability and obtaining more relevant information for decision-making. Digitalisation can benefit from harmonisation and potential standardisation to accomplish interoperability, as well as sufficient data access and quality to create compatible and coordinated information models and decisions.

Requirements and expectations on the digital twin

A digital twin (DT) is a virtual representation of a physical system. The difference between a simple simulation model and a DT is a **data connection** that enables a strong convergence between the states of the physical and digital systems. The DT must have the ability to predict potential issues based on data and scenario simulations for decision-making support and optimising the system and asset performance. The definition and areas of application are ambiguous but should include the entire **lifecycle** of a physical system from initial design to operation and maintenance. It can be used for system planning, developing new products, and solving future problems before the actual physical system exists. It can be used at an operational level for monitoring and predicting faults, as well as simulating different scenarios for deriving optimal operational decisions.

Since the expectations for DTs significantly vary depending on the use case, it is crucial to establish early agreements on DT system approaches, data exchange protocols, and operational boundaries to avoid misalignment. Three different DT system approaches are defined as follows:

- **Local DTs for specific assets or use cases – connected systems:** These are individual systems that can share data. These systems typically have clear operational escalation levels, meaning that there is a defined course of action to take if a problem occurs. For example, a transmission system operator (TSO) might be piloting a DT for a critical high voltage (HV) substation to assess its performance under different load scenarios. A distribution system operator (DSO) could be developing a proof-of-concept for a DT to model the impact of real-time pricing on customer behaviour and overall grid load during peak demand periods.

- **An integrated DT encompassing the entire transmission or distribution network – integrated systems:** These are systems designed to work together as a whole. They share data more seamlessly than connected systems, and their combined functionality creates a new capability. For example, a TSO with a transmission network might be in the early stages of developing a DT that includes all substations, power plants, and transmission lines. A DSO with a large urban distribution network could aim to create a complete digital model of its infrastructure, including all substations, transformers, and connected customer meters.

- **Collaborating with other TSOs and DSOs to develop interoperable DT standards and platforms – system of systems (SoS):** These are groups of independently managed but interconnected systems that connect and exchange data, working together to achieve a shared goal. SoSs differ from integrated systems in that the constituent systems are often managed by different organisations and might have different operational goals. In SoS, operational goals might differ across organisations (e.g., a TSO might prioritise stability across the transmission network, while a DSO might focus on the continuity and quality of supply). Thus, the SoS concept requires mechanisms for cross-organisation communication and alignment on overarching goals, even when internal priorities differ. Furthermore, this complexity requires governance structures and standards (e.g., data ownership, interoperability protocols) that extend beyond the scope of intra-organisational connected systems. For example, the TSO's integrated DT and the DSO's complete network model are connected through a standardised data exchange platform. This platform would form an SoS along with other collaborating systems (e.g., weather forecasting systems and renewable energy integration systems), working towards the common goals of optimising grid operations, managing peak demand, and ensuring overall power system resilience.

Overall, any DT located within each TSO/DSO:

1. Acquires and assimilates observational data from the asset (e.g., data from sensors or manual inspections).

2. Uses this information to continually update its internal models so that they reflect the evolving physical system with its own computing capability. This synergistic multi-way coupling between the physical system, the data collection, the computational models, the decision-making systems, and the digital state allows the DT to adapt and optimise system operations.

3. Subsequently runs these up-to-date internal models for analysis, prediction, optimisation, and control of the physical system thanks to an appropriate computing capacity.

Figure 1 provides an overview of the physical asset and its DT as two closely coupled dynamical systems, time-evolving through their respective state spaces [1]:

1. The state of the physical asset evolves over time.

2. The DT assimilates observational data and updates its state to mimic the physical system.

3. The updated DT enables in-depth analysis of the asset and the prediction of future state evolution.

4. Control inputs informed by the updated DT steer the operator to adjust the physical asset to a favourable state.

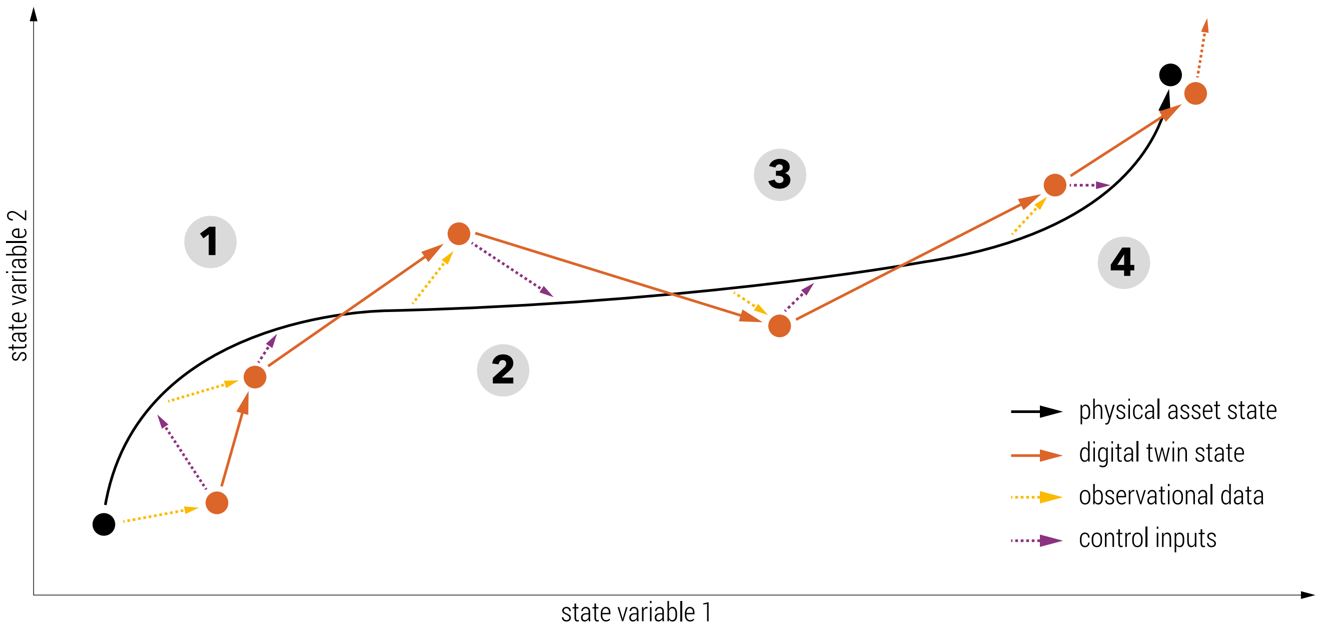


Figure 1: View of the physical asset and its DT as two coupled dynamical systems

Data Interoperability and key functional components

Present DSO and TSO systems were not designed in terms of interoperability, which is relevant to develop effective and operational DTs for each TSO and DSO. This interoperability feature acts as a glue that allows diverse systems, devices, and applications to communicate and work seamlessly. Figure 2 depicts that interoperability must be split into organisational, informational, and technical layers [2].

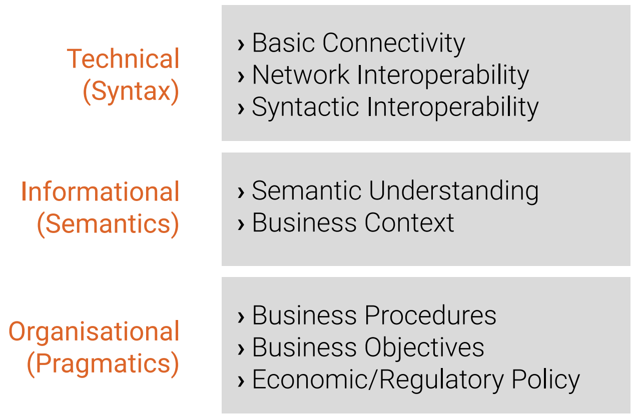


Figure 2: Interoperability categories

When implementing DTs within TSOs and DSOs, it is critical that the individual systems can exchange data and leverage information coherently and efficiently, regardless of the platform on which they are built. This cross-compatibility ensures that DTs can operate within larger ecosystems, connecting with Internet of Things (IoT) devices, enterprise systems, and other DTs to create a comprehensive and interconnected digital representation of physical assets, processes, and systems. The importance of interoperability within DTs and TSOs/DSOs underpins the ability to achieve a holistic understanding of the operational ecosystem. By ensuring that DTs can communicate and share data effectively, organisations can enhance decision-making, optimise operations, and foster an environment for innovation.

Relevant ongoing European projects on digital twins

Brief high-level summaries of other relevant, ongoing European projects on DTs including Twin for Europe (TwinEU), Destination Earth, and InterConnect are provided below.

TwinEU is a Horizon project of 75 partners running from January 2024 to December 2026. The project is mainly funded by the European Union (€20 million) and has a total budget of approximately €25 million [3]. The project will create a concept for a pan-European DT to enable reliable and resilient grid operation based on eight challenges [4]:

1. Lack of consensus defining DT and its functionalities.
2. Insufficient synchronisation of digital models/replicas with real assets.
3. Lack of concrete reusable DT implementation at the pan-European level.
4. Lack of an agreed standardisable approach to grid modelling that fits all actors.
5. Insufficient understanding of interoperable DTs as an effective way of supporting cross-stakeholder cooperation and respective data sharing and exchange.
6. A DT also needs interfaces outside the energy sector to cover challenges such as resilience assessment and planning, whereby a link between a European DT and a European energy data space is critical.
7. A DT cannot be simply developed but needs to be tested at an unprecedented scale.
8. A single project will not solve all challenges but it is important to have a clear and sustainable path for the future.

The project will report key performance indicators (KPIs) and key exploitable results (KERs) for the mapped challenges. Overall, the project will deliver a set of tools through eight pilots in eleven countries, with a total of four different purposes [4]:

1. Cyber-physical grid resilience
2. Grid management, operation and monitoring
3. Forecasting and optimal grid and market
4. Smart, coordinated grid planning

Destination Earth (DestinE) is a European Commission initiative to develop an accurate DT of Earth [5]. The main objectives are to model and simulate both natural and human-related activities on the planet, achieving a full digital replica by 2030. The project will unlock the potential to simulate and forecast different scenarios, which will support developing adaption strategies and mitigation measures[1]. DestinE is an essential pillar of the European Commission's efforts towards the Green Deal and Digital Strategy [5].

InterConnect is a European project funded through the European Commission's Horizon 2020 programme, with 51 participating organisations [6]. The project aims to change how energy is used, exploring smart homes and interconnections between customers and the grid to achieve a more user-centric focus. InterConnect uses edge computing and IoT to optimise energy and launch new services [7].

Kognitwin is a product developed by Kongsberg group [8]. The DT can be built for an asset or system. At present, the development is ongoing in a project called **Kognigrid**, led by SINTEF Energy Research in Norway [9]. A follow-up project named **NextGrid** is currently underway [10]. In NextGrid, grid company's operation centres are being prepared for a future where the operation of the distribution grid is more complex and automated [10].

A comprehensive **study on DT** was recently conducted by VDE and others [11], presenting a reference architecture for the electricity sector. In addition, the task force describes several use cases in the report, which is available online: VDE Study – The Digital Twin in the Network and Electricity Industry. Some of the main recommendations in the report are to create a standardised digital system interfaces to enable vendor-independent, modular systems and develop a standardisation roadmap for DT.

About the report

ENTSO-E and EU DSO Entity work in collaboration on the Joint Task Force (JTF) for Digitalisation of Energy System EU Action Plan (DESAP). The initiative is driven by the European Commission's action plan for Digitalising the energy system – EU action plan (COM/2022/552).

The European digital plan is contributing to achieving parts of the EU's energy policy and aims to develop a sustainable, secure, transparent, and competitive market for digital energy services [12].

Digitalisation of Energy System EU Action Plan (DESAP)

JTF DESAP's main goal is developing a DT of the electricity grid of adequate granularity and developing guidance and support for network operators on sustainable and cost-effective smart investments using smart grid indicators (SGIs) [13].

Accordingly, it is pursuing several objectives to achieve these objectives [13]:

- Enlist a set of business user requirements of the DT addressing present and future challenges of energy systems from both TSO and DSO perspectives.
- Define a set of use cases addressing the current and future challenges of a digitalised European electricity grid and helping to enhance the grid's smartness.
- Identify the current state of implementation of DT technologies in the power sector to guide prioritising challenges and developing requirements.
- Define the interoperability requirements based on the Smart Energy Grid Architecture Model (SGAM) reference architecture, which will support the implementation of the DT use cases.
- Provide a shared definition of DT platforms for the TSO/DSO sector.

1 The project has a use case catalogue online, available at: Use Cases Catalogue Archive – Destination Earth (destination-earth.eu).

- Define a set of smart indicators depicting the level of smartness and effectiveness of network operations.

This report is a deliverable from work package (WP)2 of the JTF DESAP project, denoted as D2.1 (deliverable 1 in work package 2) in Figure 3. WP1 focuses on administration and management, while WP2 is dedicated to identifying challenges and opportunities in DT development, including conducting a state-of-the-art (SOTA) and gap analysis. WP3 concentrates on creating use cases, DT solutions, and SGIs. Finally, WP4's main task is to develop a roadmap for digitalisation and to enhance DT capabilities.

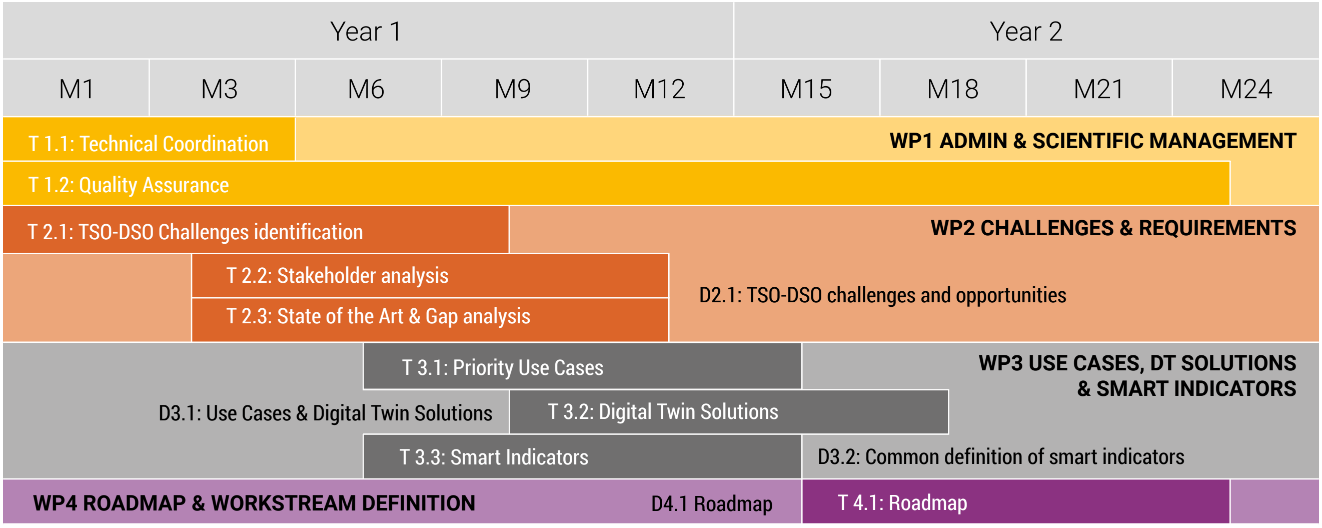


Figure 3: JTF DESAP work programme

According to the DESAP project plan, this deliverable shall provide [13]:

"A comprehensive compilation of anticipated challenges in the transition toward a fully digitalised electricity system, categorised into clusters, encompassing challenges specific to TSOs, DSOs and shared TSO/DSO challenges. These clusters are further divided into areas of focus, including Customers, Business, Market, Data & Information Exchange; System Planning, Future Flexibility & Assets Lifecycle; and System Operations, Dynamics & Control Rooms of the Future. The report would gather insights and expectations on DT solutions from various stakeholder engagement mechanisms (workshops, interviews, surveys, and focus groups) involving representatives from the energy sector. The report would also capture improvement opportunities based on a review of the current state of digital solutions, and decision-making support areas, guiding challenges prioritisation and requirement development".

This report is the deliverable for this objective in JTF DESAP.

Structure of the report

Chapter 1 outlines the requirements and expectations for DT development, introduces the DESAP JTF initiative, and provides an overview of the report's structure. Chapter 2 describes the methodology used. Chapter 3 analyses the prioritised opportunities and challenges facing DSOs and TSOs in Europe based on the initial survey results. Chapter 4 discusses ongoing initiatives and the current state of DT development. Chapter 5 provides a forward-looking perspective, focusing on identified gaps and based on a second survey mapping implementation rates across various DT projects in relation to key challenges. Finally, chapter 6 summarises the main conclusions, key insights into the current landscape, prioritised challenges, and identified gaps.

CHAPTER 2

Methodology for analysis and data description

This chapter outlines the methodology used for the analysis, along with the data sets involved. The analysis in this report draws on several key inputs:

- **Survey 1** (conducted in early spring 2024) focused on identifying and prioritising challenges.
- **Survey 2** (conducted in late summer 2024) – known as the "gap survey" – gathered insights on project maturity and addressed the specific challenges identified in survey 1.
- **Meetings and discussions** among JTF expert groups provided additional perspectives and insights.

Each of these inputs contributed to a comprehensive understanding of the issues and opportunities analysed in the report.

Definition of clusters

The JTF experts defined three clusters to structure the work:

- **Cluster 1:** Customers, business, market, data and information exchange
- **Cluster 2:** Planning, future flexibility and assets lifecycle
- **Cluster 3:** System operations, dynamics and control rooms of the future

Cluster 1 includes sub-areas supporting the work of deep electrification through interoperable solutions for the seamless data and information exchange among TSOs and DSOs, as well as other relevant actors. This also entails the work related to the standards and requirements of a cyber-secure smart system.

Cluster 2 includes sub-areas related to grid planning and development, aiming to anticipate the future needs of an efficient and smart infrastructure. This involves planning and optimisation strategies of integrated systems while ensuring the consistent provision of flexibility services in collaboration with electricity system operators.

Cluster 3 comprises sub-areas related to the operational requirements of a digitalised future system. It involves everything related to enhanced observability and controllability supported by necessary operational procedures and simulations, ensuring a high level of resilience of smart electricity networks.

First survey on identifying and prioritising challenges

TSO and DSO experts were tasked with drafting challenges they see as bottlenecks for reaching a fully digitalised electricity system. The initial identification of challenges was performed by TSO and DSO experts, whereby ENTSO-E Vision: A Power System for a Carbon Neutral Europe [14] served as a basis for defining an initial list of challenges, containing key challenges to address for each of the four main building blocks: energy infrastructure and investments, operating future grids, energy system flexibility, and market design for a carbon-neutral energy system. This approach was also reconciled with the internal identification of challenges and subsequent clustering conducted within the EU DSO Entity in the JTF DESAP. Experts took challenges defined in this document as a starting point to draft sub-challenges for each of them, which resulted in around 140 suggested sub-challenges.

After analysing the suggestions, it was concluded that not all defined entries were strictly challenges, as some of them were enablers, functions, scenarios, or non-functional requirements. This led to triggering a pre-screening exercise in which sub-challenges were separated from enablers (technologies, tools, resources), functions (specific scenarios), and non-functional requirements. Appendix 1 provides the final list of sub-challenges.

After aligning on the list of sub-challenges, a group of TSO and DSO experts for each cluster performed an evaluation of each challenge's strategic impact, expected effort, and relevant timeframe of occurrence. The strategic impact was evaluated by assigning grades 1 to 5 in terms of smartness, interconnectedness and efficiency. Table 1 shows the structure of the expert responses.

	Strategic impact (1-5)	Expected effort (1-4)	Relevant timeframe (1-3)
Challenge 1			
Challenge 2			
…			

Table 1: Structure of the expert responses in the survey

Figure 4 shows the process of identifying and prioritising challenges.

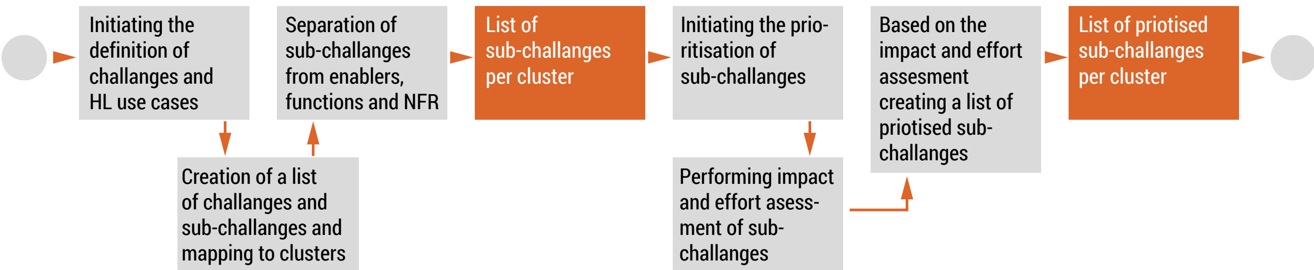


Figure 4: Challenge identification and prioritisation process

Based on the individual ratings provided by the experts on the smartness, interconnectedness and efficiency areas, the impact and effort scores were estimated according to the methodology in Appendix 1 by an average grade (AG). This was then subject to categorisation of the challenge's impact and effort – if solved – as indicated in Figure 5.

The impact score was used as the main parameter to select the set of key challenges from the list defined by the experts. The formula for calculating a prioritisation score is described in Appendix 1.

Appendix 1 outlines the impact, effort, prioritisation score and expected timeframe scores for all defined sub-challenges. In the following chapters, the key challenges for each of the three clusters are presented and described.

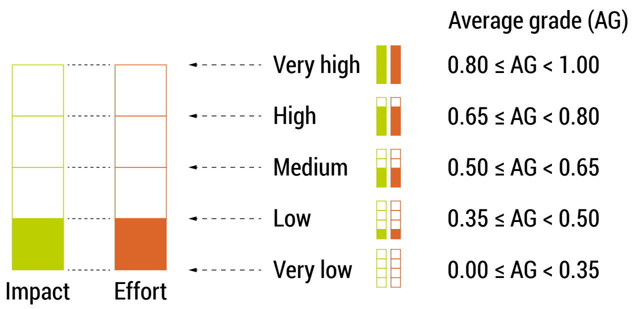


Figure 5: Grading system and visualisation for assessing impact and effort for each challenge

Second survey for gap analysis

A SOTA and gap analysis survey was created and sent to JTF members with the main goals of:

- Evaluating existing DT solutions employed by TSOs and DSOs to identify gaps between the desired and current state requiring attention. The results should define which regulatory and technological gaps exist and estimate the necessary efforts to resolve them.
- Analysing areas in which these solutions can provide the most significant improvements, benefits, and support for decision-making processes for both DSOs and TSOs.
- Identifying existing solutions developed through similar EU-funded projects that can serve as a basis for developing and enhancing digital solutions.
- Evaluating these solutions to determine their applicability and potential for integration into the project framework.

The survey questioned TSO and DSO experts to name ongoing implementations and already implemented DT solutions within their company. For each solution, the experts were tasked with answering the following set of questions:

- What is the concept of DT implementation (connected systems; integrated system; SoS)?
- Which interactions are being facilitated (DSO-DSO; TSO-DSO; TSO-TSO; SO-industry association; other)?
- What is the maturity level (stage) of the DT (conceptualisation; development; integration; diagnostics; predictive analysis; prescriptive/autonomous optimisation)?
- What outcomes have been achieved and are expected with the DT solution?
- Which priority challenges from each of the three clusters are addressed with the DT solution?
- What challenges has the organisation faced during the implementation of the DT solution?
- How do national and EU policies and funding programmes address the gaps in achieving fully integrated DT for the European electricity grid?
- List some DT solutions developed outside of the organisation that experts are aware of, with a focus on solutions with strong potential for integration in their organisation.

A total of 37 answers were received from TSO and DSO experts, out of which 25 were from TSOs and 12 from DSOs. The answers were very beneficial, mostly for creating an overview of existing and future DT solutions in European TSOs and DSOs, and defining areas in which these solutions can provide the most significant improvements, benefits, and support for decision-making processes for DSOs and TSOs.

Definitions of DT maturity

The maturity of the DT represents the functionality and capabilities of the digital solution. Table 2 shows the different maturity stages of the DT with a description of each stage [15].

Stage	Explanation
A. Conceptualisation	Basic idea with the initial data collection plan, although not connected to real-time data.
B. Development (descriptive)	Digital representation focuses on replicating physical characteristics, which includes sensor data but not used for analysis or decisions.
C. Integration	Connects to real-time data and monitors health and performance, but limited analysis.
D. Diagnostic	Analyses sensor data to identify trends and issues, providing basic alerts or reports on anomalies.
E. Predictive analysis	Uses advanced analytics for predictive performance and failure to recommend maintenance and optimisations.
F. Prescriptive/ autonomous optimisation	Predicts and autonomously optimises, adjusts settings, triggers maintenance, and can control the asset directly.

Table 2: Definitions of maturity level for DTs

CHAPTER 3

Prioritised challenges for TSOs and DSOs

An electric power system is a substantial physical system with a vast number of components and different ways in which they can be represented in the digital world. It was decided that prioritisation of the fields of action is necessary from a TSO and DSO perspective to adequately streamline the focus of future DT development. The first step was to identify TSO-DSO challenges and opportunities related to digitalisation.

The methodology has been described in chapter 2, and the following chapters provide more details about the key challenges and the effort and impact analysis performed.

Key challenges for the clusters

Customers, business, market, data and information exchange (cluster 1)

As only nine challenges were defined for the first cluster, all of them ended up being key challenges. Effort and impact analysis were still performed and Figure 6 shows the challenges for cluster 1 sorted by the expected timeframe of occurrence.

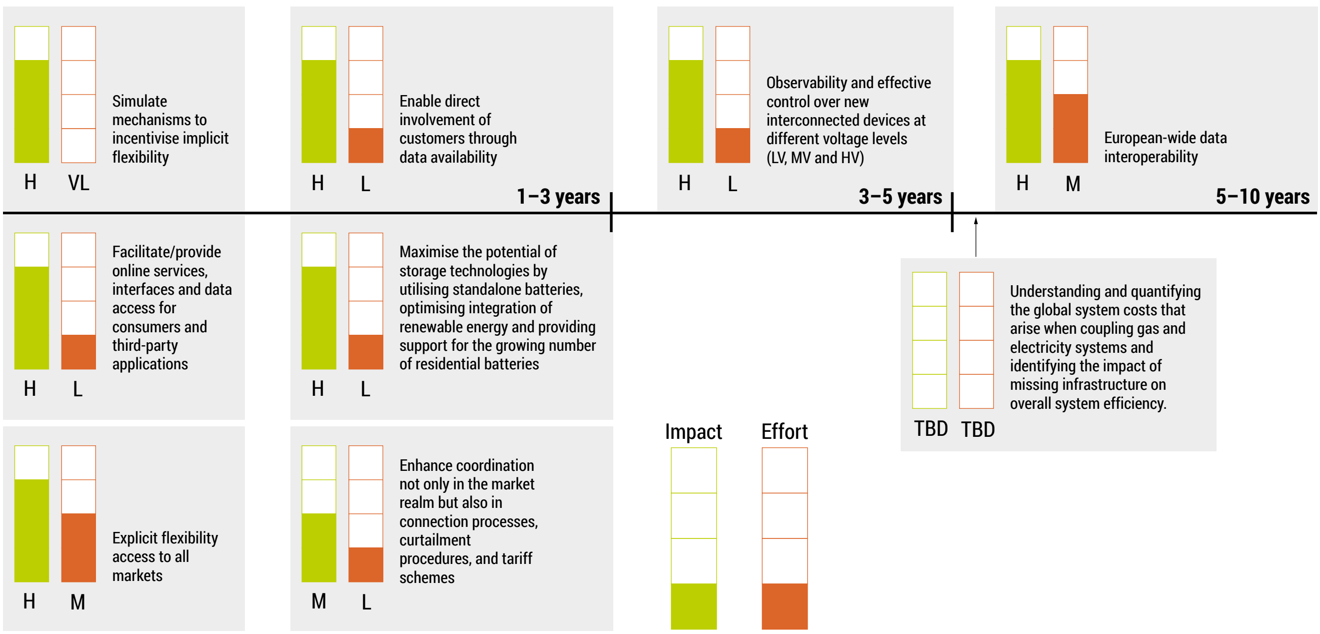


Figure 6: Key challenges for cluster 1

After discussion with JTF members, it was decided to change the expected timeframe for the occurrence of the "explicit flexibility access to all markets" challenge to 1–3 years, as after the experts' initial evaluation, the expected timeframe for this challenge was long-term. Moreover, in the later stage, after further evaluation by the experts, one additional sub-challenge was added, namely "understanding and quantifying the global system costs that arise when coupling gas and electricity systems and identifying the impact of missing infrastructure on overall system efficiency".

From the prioritised challenges in this cluster, based on the expected timeframe score, six challenges are sorted as short-term, one as medium-term, and two as long-term challenges.

Short-term challenges for cluster 1

Throughout the prioritised short-term challenges of the first cluster, the primary focus is placed on developing **demand flexibility** through various approaches, such as the direct involvement of customers or through independent aggregators. One of the important aspects is allowing customers to participate in day-ahead, intraday, and balancing markets. Customers can be incentivised to be flexible by responding to price signals from the markets or grid tariffs.

Some other challenges focus on increasing **TSO-DSO coordination and cooperation** to reduce costs and administrative burdens by streamlining, and – where needed – aligning processes such as connection and curtailment.

The remaining challenge focuses on introducing various **advanced battery usages**, such as improving system stability and help with the integration of renewable sources.

Most of these challenges are graded as quick wins as the estimated effort is low and the impact is high.

Medium-term challenges for cluster 1

The only challenge in this cluster that falls into the medium-term timeframe is "observability and effective control over new interconnected devices at different voltage levels (LV, MV and HV)". This challenge is graded as a quick win as visibility on power flows and market parties' actions is important to ensure the safe operation of the system while the effort is not too considerable. The observability is a key challenge and a prerequisite for well-functioning DTs.

Long-term challenges for cluster 1

One of the long-term challenges in this cluster is **data interoperability** and **standardisation** of data models, formats and protocols. The interoperability between TSOs and DSOs as well as other relevant entities enables advanced coordination and data exchange between several entities. This is a major project with high impact and effort that involves standardising data formats and protocols across multiple countries. Standards for data exchange and communication already exist as a basis for solving the challenge of higher interoperability. Another long-term challenge is "understanding and quantifying the global system costs that arise when coupling gas and electricity systems and identifying the impact of missing infrastructure on overall system efficiency". Coupling different systems with the electricity system is an important challenge that will become increasingly relevant in the future.

System planning, future flexibility, and asset lifecycle (cluster 2)

For the second cluster, fourteen sub-challenges were defined, ten of which were prioritised during the effort versus impact analysis. The effort score had a higher weight when prioritising sub-challenges, and hence the four sub-challenges with the lowest impact score (0.37 – 0.52) were omitted. The remaining ones were defined as key challenges and are shown in Figure 7, together with their impact and effort scores.

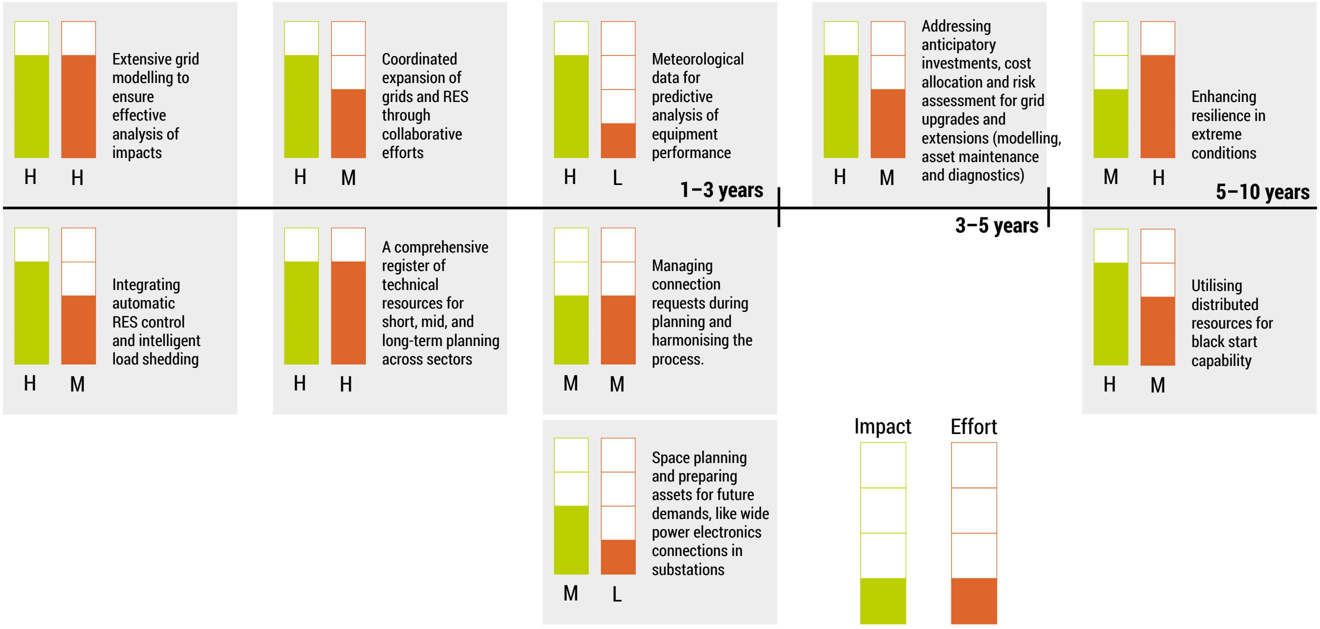


Figure 7: Key challenges for cluster 2

In the second cluster, seven challenges are short-term, one is medium-term, and the other two are long-term, based on the estimation performed by the experts.

Short-term challenges for cluster 2

In the second cluster, many challenges are focused on **infrastructure development planning**, i.e. planning the grid expansion by considering various factors such as population growth, urbanisation, industrial expansion, charging infrastructure, electrification of transport and other sectors, etc. An important precondition is **modelling**, which needs to become more sophisticated. It is also emphasised that infrastructure development needs to be coordinated with the planning of the location and size of renewable energy sources.

Asset maintenance is also highlighted in several priority challenges. Developing **predictive analytics** algorithms can identify early warning signs of equipment failure using meteorological data, while building information models (BIMs) can be used for optimising maintenance activities, such as shutting down only parts of substations during maintenance. Prioritising asset maintenance and diagnostics can optimise grid operations by emphasising the utilisation of the assets (e.g. by using dynamic line rating; DLR).

Five out of seven short-term challenges have a high impact in cluster 2, such as "extensive grid modelling to ensure effective analysis of impacts", which also has a high effort as it involves modelling other coupled sectors (transport, heat, gas, hydrogen). Furthermore, the impact is high due to the importance of high-quality grid models for the safe operation of the electricity grid. Two challenges with high impact and medium effort are "integrating automatic renewable energy resources (RES) control and intelligent load shedding" and "coordinated expansion of grids and RES through collaborative efforts". With medium effort, the RES can be integrated into operation environments through automatic control, and the RES volume can increase through a collaborative effort on grid expansion.

Two short-term challenges are graded as quick wins due to their high impact and low effort. The first is "meteorological data for predictive analysis of equipment performance" as the effort is not too demanding due to the accessibility of artificial intelligence (AI) methods for analysing historical data (e.g. machine learning). The second is "space planning and preparing assets for future demands", where the impact is high as it involves strategic consideration and long-term visioning of factors such as population growth, urbanisation, industrial expansion, and the electrification of sectors (e.g. through the use of BIM to optimise maintenance activities).

Medium-term challenges for cluster 2

The only medium-term challenge in this cluster is "addressing anticipatory investments, cost allocation and risk assessment for grid upgrades and extensions (modelling, asset maintenance and diagnostics)". This is officially a major project challenge, although it is on the borderline with quick win status with a 0.53 effort score (0.5 is the border). Many organisations already have tools and data that can be repurposed to create a preliminary assessment.

Long-term challenges for cluster 2

Enhancing resilience is one of the important long-term challenges that can be faced by increased monitoring for early identification of problems, redundancy planning, automatic network reconfiguration, and intentional islanding. Other possible measures include taking resilience into consideration when planning infrastructure development, introducing digitalisation in the grid operation, and using HVDC converters or aggregated EV batteries for the black start capability. This challenge is a major project due to the relevance of establishing high network resilience in extreme conditions and the necessary effort involved.

System operations, dynamics and control rooms of the future (cluster 3)

The highest number of sub-challenges was identified for cluster 3 (22). Although the impact score was high at over 0.6 for all defined sub-challenges, the list of prioritised challenges was created by selecting the eight sub-challenges with the highest impact score. The list of high-priority challenges was subsequently expanded with the inclusion of one additional sub-challenge, namely "critical elements vulnerable to high impact low frequency (HILF) events". Figure 8 presents the resulting set of nine key challenges, along with their corresponding impact and effort scores.

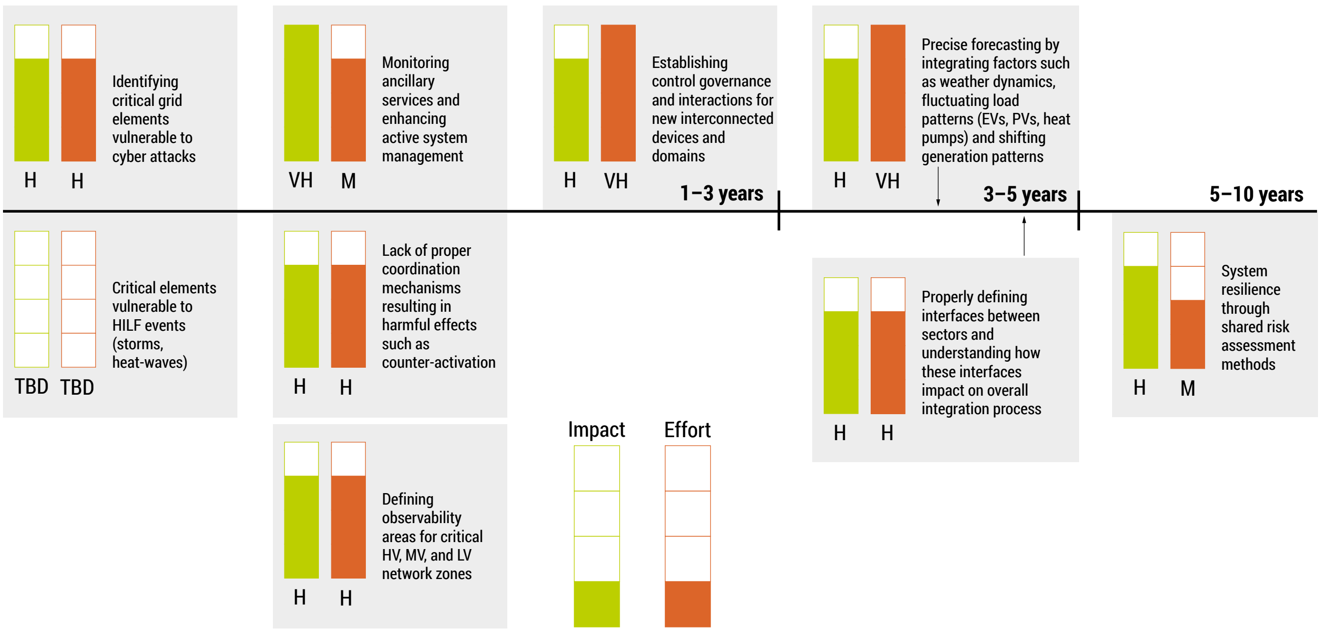


Figure 8: Key challenges for cluster 3

Out of nine prioritised challenges in this cluster, six are short-term, two are medium-term, and one is long-term.

All challenges in this cluster are graded as major projects (even those that are not prioritised).

Short-term challenges for cluster 3

High-quality measurements are essential for operating the power system. Several short-term key challenges focus on **advanced monitoring** with the goal of **facilitating system operation**. The number of sensors in the grid and their capabilities are increasing, which leads to different challenges and opportunities. There is a considerable increase in the volume of data that needs to be processed, as well as other using these data with advanced (e.g. AI) algorithms to improve monitoring, forecasting and operation by:

- improving **load and generation forecast**;
- using **predictive models** for short-term planning;
- using **optimisation algorithms** to increase the performance and grid reliability in critical network zones.

One of the challenges classified as short-term is “establishing control governance and interactions for new interconnected devices and domains”. This challenge likely involves developing new frameworks, policies, and technologies that promote intricate coordination and oversight. Establishing control governance is often an iterative process, requiring continuous evaluation and refinement.

Other important topics described in short-term key challenges are increasing resilience to cyber attacks and introducing **risk assessment** for identifying weak components in the system.

The final key challenge is coordinating the usage of resources for congestion management and balancing by both TSOs and DSOs, such as **avoiding counter-activation**.

Medium-term challenges for cluster 3

Two challenges in this cluster that are envisaged as medium-term are “precise forecasting by integrating factors such as weather dynamics, fluctuating load patterns (EVs, PVs, heat pumps) and shifting generation patterns” and “properly defining interfaces between sectors and understanding how these interfaces impact on overall integration process”. Improving forecasting is an important topic that is also mentioned for some short- and medium-term challenges as well. This challenge has increased in recent years considering observed weather anomalies such as floods, extreme heat, etc.

Interfaces between sectors also appear in several challenges for this cluster, albeit none within the short-term timeframe.

Long-term challenges for cluster 3

“System resilience through shared risk assessment methods” is the only challenge classified as long-term, and it is a major project as it requires developing new risk assessment models, data-sharing infrastructure, and coordination across multiple stakeholders.

Priority challenge analysis using gap survey

As part of the second survey, participants were tasked with linking their DT initiative with one or more of the prioritised challenges. Some of the initiatives are linked to a single challenge, and others to multiple ones (up to fifteen different challenges).

This subchapter provides an overview of how initiatives relate to challenges based on answers from TSO and DSO experts from the second survey and highlights areas with high and low implementation rates.

Customers, business, market, data and information exchange (cluster 1)

According to the survey, "Observability and effective control over new interconnected devices at different voltage levels (LV, MV and HV)" was the overall mostly addressed challenge in the first cluster, but also when looking at TSO and DSO responses separately. This challenge seems to be comprehended as very broad as applications vary among virtual substations, renewable energy source management, congestion management, DLR, network modelling, etc.

Regarding TSO DT initiatives only, other than the mentioned challenge, "European-wide data interoperability" was also highlighted by nine TSOs (50Hertz, Terna, Transelectrica, TenneT Netherlands, Amprion, HOPS, Svenska Kraftnät, ČEPS, and Energinet). Initiatives are facilitating data exchange with other TSOs, DSOs, and market participants, which are becoming an important party in TSO and DSO activities.

While European interoperability is a concern concentrated on TSOs, a common challenge is to "facilitate/provide online services, interfaces and data access for consumers and third-party applications" and "enable direct involvement of customers through data availability". These are opportunities to increase the flexibility available for system services and grid utilisation. The challenges together present the importance of data availability. The opportunity is presented by initiatives such as European Data Spaces [15] as collaborative frameworks designed to promote data sharing and interoperability in a secure, standardised, and transparent manner. One of its initiatives – Omega-X – works on the same topics with an energy-specific implementation of these principles, focusing on creating federated and interoperable energy data spaces to support secure and efficient data exchange among TSOs, DSOs, and market participants, enabling broader stakeholder collaboration and customer engagement.

Apart from the common most targeted challenge, DSOs' solutions mostly target the challenges to "enable direct involvement of customers through data availability" and "simulate mechanisms to incentivise implicit flexibility". These challenges show that DSOs are seeing active participation of customers in the market or actively responding to grid tariffs as an important milestone.

Figure 9 lists all cluster 1 challenges with the percentage of DT initiatives that are addressing them, separated into TSO, DSO, and all solutions.

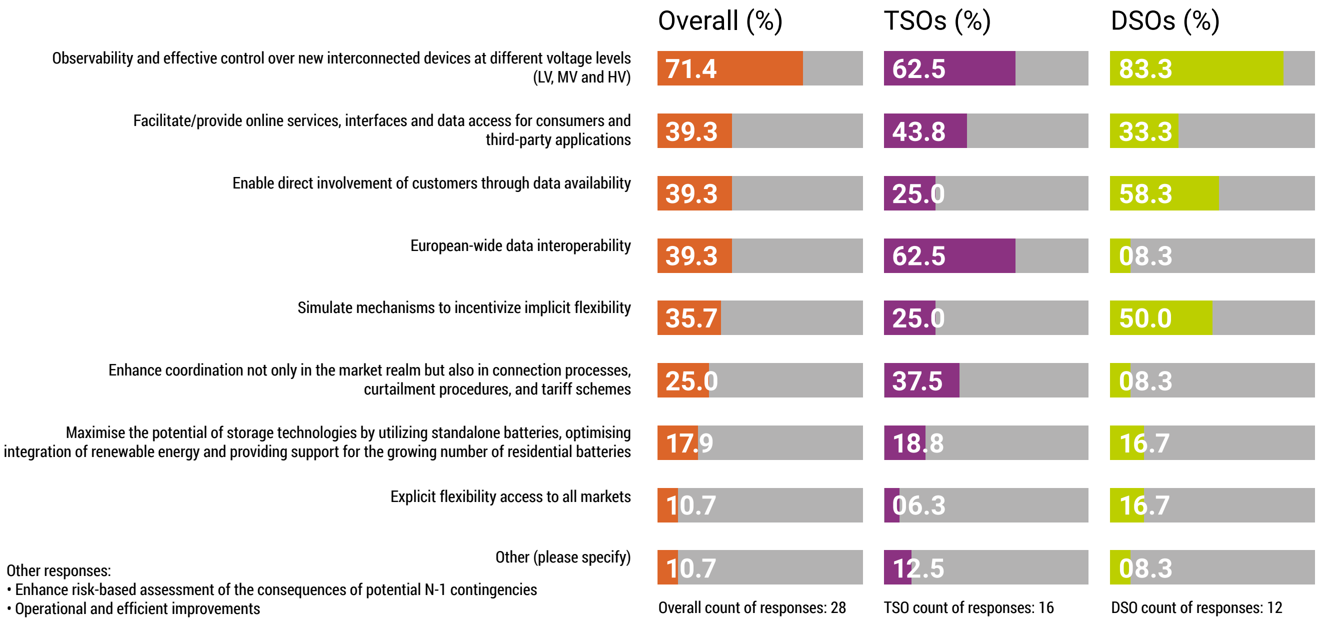


Figure 9: Percentage of challenges from cluster 1 addressed by TSO and DSO solutions

While some areas show promising adoption rates, certain fundamental challenges continue to have implementation rates below 20 %, indicating gaps in the industry's progress.

Most concerning is "explicit flexibility access to all markets", with a minimal implementation rate of just 10.7 % across both operator types. This low adoption rate suggests that significant barriers still exist in creating truly open and accessible market structures for flexibility services, which are fundamental requirements for efficient network operation in future energy markets. Further testing is still needed to improve the understanding of the different use cases where flexibility is beneficial.

"Maximise the potential of storage technologies by utilising standalone batteries, optimising integration of renewable energy and providing support for the growing number of residential batteries" similarly shows low adoption at 17.9 %. This indicates that despite the growing importance of energy storage in modern power systems, both TSOs and DSOs remain in the early stages of implementing solutions to fully utilise these technologies.

System planning, future flexibility, and asset lifecycle (cluster 2)

Of the 32 DT initiatives addressing challenges from the second cluster, 78 % are addressing the challenge of "extensive grid modelling to ensure effective analysis of impacts", as can be seen in Figure 10. This is a very broad and fundamental challenge, and it also shows the importance of precise grid modelling for various types of analysis and planning for both TSOs and DSOs.

For TSOs, "enhancing resilience in extreme conditions" is one of the often-tackled challenges, which includes warning and prevention systems, real-time simulators, advanced power system strategies, and other solutions.

Regarding DSOs, other than the already mentioned challenge related to grid modelling, there are a few challenges tackled by different solutions, most notably "coordinated expansion of grids and RES through collaborative efforts" and "a comprehensive register of technical resources for short, mid, and long-term planning across sectors". Both challenges are related to the vast increase in renewable energy sources connected to the distribution grid, and therefore it makes sense that DSOs are tackling issues related to this.

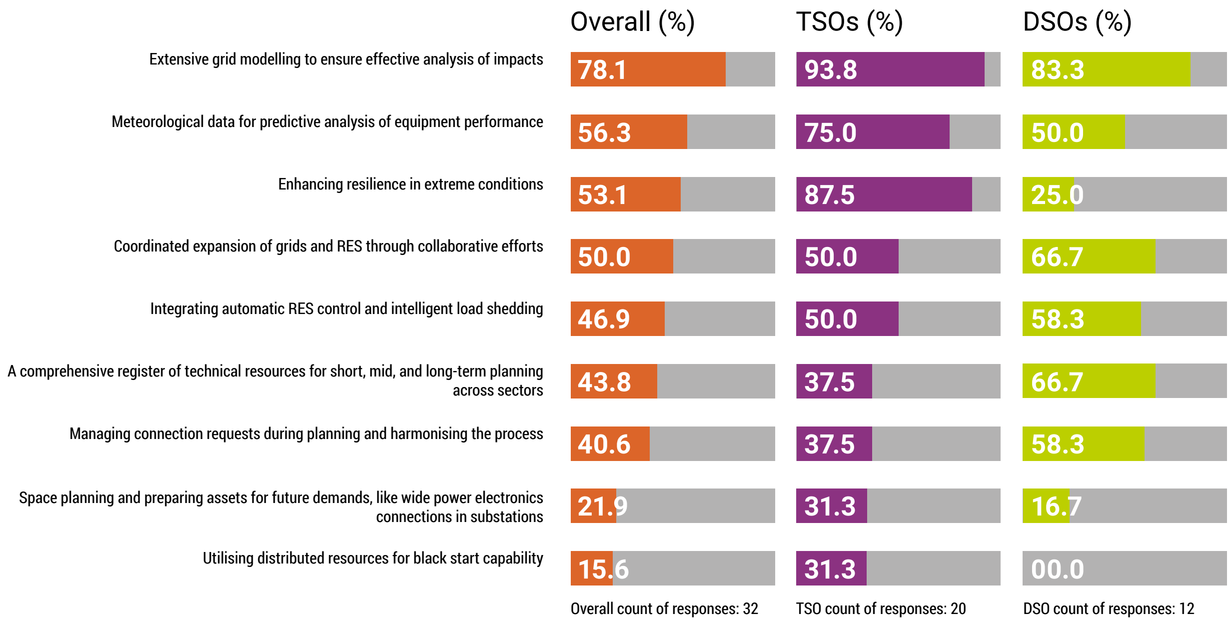


Figure 10: Percentage of challenges from cluster 2 addressed by TSO and DSO solutions

The findings reveal notably low implementation rates for several critical challenges, with "utilising distributed resources for black start capabilities" ranking the lowest, with an overall implementation rate of 15.6 %. Among TSOs, 31.3 % reported initiatives in this area, while none of the twelve DSOs that responded indicated any ongoing initiatives focused on this topic.

The data indicates limited progress in "space planning and preparing assets for future demands, like wide power electronics in substations", with only 21.9 % overall implementation. The DSOs show a lower implementation of 16.7 %, which probably reflects that their networks comprise smaller geographically dispersed assets with more standardised components.

System operations, dynamics, and control rooms of the future (cluster 3)

A total of 33 DT initiatives from the survey are linked to the challenges from the third cluster. The challenges addressed are considered more even than in previous clusters, as Figure 11 shows. Hence, no challenges clearly stand out as particularly addressed in the ongoing initiatives.

"Precise forecasting by integrating factors such as weather dynamics, fluctuating load patterns (EVs, PVs, heat pumps) and shifting generation patterns" has the most widespread adoption, being addressed by 45.5 % of survey respondents. This highlights the importance of accurate forecasts, mostly due to the growing share of renewables and the rising use of electric heating and cooling systems. The forecasts are important for grid operation, grid optimisation, and the energy and balancing markets. The effects of climate change have heightened the focus on weather forecasting as a vital tool for enhancing climate resilience and preparing the grid for extreme weather events.

For DSOs, "defining observability areas for critical HV, MV and LV network zones" is clearly the most commonly tackled challenge. Solutions are mainly related to grid monitoring, congestion management, and fault location detection. The observability of LV and MV zones allows DSOs to detect and address outages, voltage fluctuations, and other local issues more efficiently, which is less of a concern for TSOs dealing with larger regional networks.

From the TSO perspective, we can highlight "monitoring ancillary services and enhancing active system management". Solutions are related to real-time system monitoring and control, including dynamic analysis system, network modelling, digital simulators, etc.

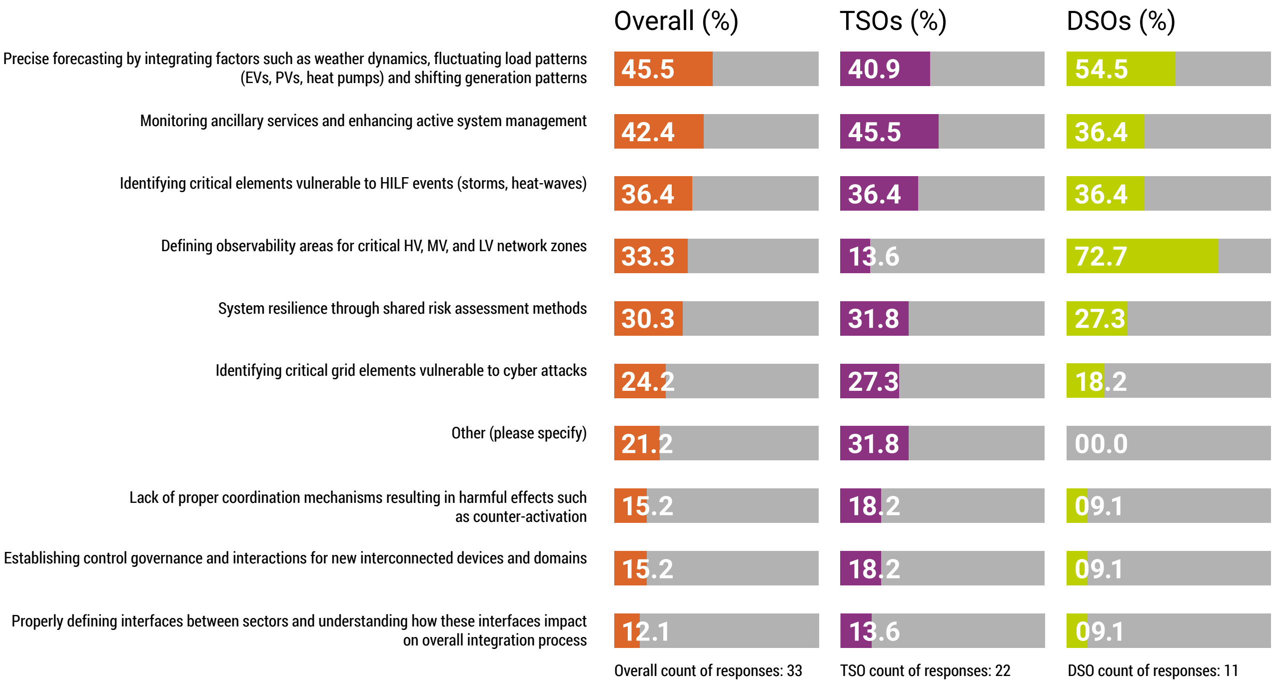


Figure 11: Percentage of challenges from cluster 3 addressed by TSO and DSO solutions

"Lack of proper coordination mechanisms resulting in harmful effects such as counter-activation" and "establishing control governance and interactions for new interconnected devices and domains" have very low implementation rates of 15.2 %, which contrast with identifying both challenges as short-term and having high and very high impact, respectively.

Cross-cutting challenges

During the discussions among the JTF members, some of the challenges mentioned were more general ones and related to all three clusters. These challenges are separated from the others as cross-cutting challenges, shown in Figure 12. As they were not identified at the beginning of the challenge identification process, and as they are too general to be compared to other more specific challenges, they do not have impact and effort scores. However, these challenges must not be neglected during the next stages of the project.

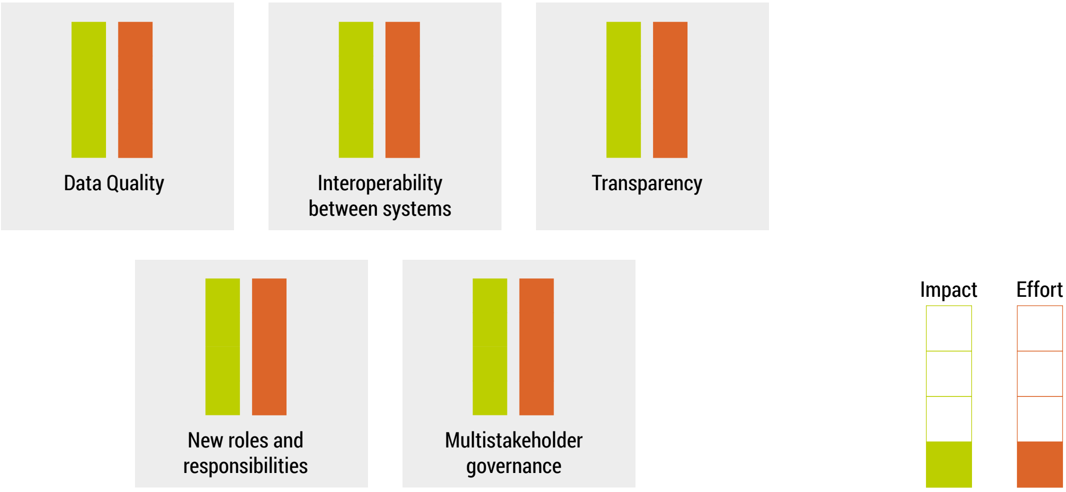


Figure 12: Cross-cutting challenges

Data quality challenges are crucial for a well-functioning DT, independent of the applications. Such challenges include dealing with inconsistent or incomplete data, leading to inaccurate analysis and decision-making. Ensuring data accuracy and reliability over time can be difficult due to human error or system issues. High-quality data holds strong importance for all processes to achieve and maintain the confidence of all stakeholders in the processes.

Interoperability challenges between systems often arise from differences in data formats and protocols, making seamless data exchange difficult. Ensuring compatibility and integration across diverse systems requires significant effort in standardisation and middleware solutions. Additionally, security and privacy concerns can complicate interoperability as data must be protected while being shared across various platforms. As indicated in chapter 1, interoperability operates across three layers – organisational, informational, and technical – and serves as the foundational "glue" that allows systems to exchange data and integrate efficiently, regardless of their platform. This cross-compatibility connects DTs with IoT devices, enterprise systems, and other digital representations, creating a holistic view of physical assets and processes.

Transparency challenges often stem from the lack of clear and accessible information about data sources, processes, and decision-making criteria. This opacity can lead to mistrust and reduced accountability as stakeholders struggle to understand and verify the actions and intentions behind decisions. Achieving transparency requires consistent and thorough documentation and communication, which can be resource-intensive and difficult to maintain.

Challenges related to **new roles and responsibilities** can often lead to a lack of accountability and reduced productivity. DTs involve significant data sharing across stakeholders, often regulated by privacy and security standards. For example, establishing clear roles for data ownership and access control is critical to ensure compliance. TSOs might handle aggregated system data while DSOs manage more granular data, ensuring that each stakeholder only has access to the necessary data for their role. Clear role delineation with external parties – such as balancing responsible parties (BRPs) and forecast providers – also helps to maintain compliance by defining data-sharing boundaries.

Challenges related to **multistakeholder governance** include coordinating diverse interests and priorities, which can lead to conflicts and slow decision-making processes. Achieving consensus among various stakeholders requires extensive communication and negotiation, often resulting in delays and increased complexity. Ensuring equitable participation can be difficult, potentially leading to dissatisfaction and disengagement among certain groups.

CHAPTER 4

Current development and ongoing initiatives

This chapter analyses and structures the survey responses regarding ongoing activities and initiatives.

Survey responses indicate significant activity from both TSOs and DSOs in implementing DT solutions across various applications. Many applications are covered, and in the following text the initiatives from the survey are sorted by application area and represented with a brief explanation of their main features. The following sections organise DT initiatives into areas based on their application in the TSO and DSO companies, with these areas spanning across multiple previously defined clusters, as shown in Table 3. Each area is accompanied by a brief description of its key features and a glance at specific TSO and DSO solutions.

Application area	Cluster 1	Cluster 2	Cluster 3
Grid and market modelling	X	X	X
System operation and operational planning		X	X
BIM and 3D modelling		X	
Real-time monitoring and control			X
Grid flexibility and customer interaction	X	X	
Centralised data platforms and data exchange	X		
Grid optimisation and asset health		X	X

Table 3: Application area and clustering

As some solutions have multiple goals, the same solution might be assigned to more than one area. One such example is EDG West SCADA, which is part of the grid and market modelling application area as one of its goals is to have a "complete network model" and exchange it with other companies, but it is also an ADMS system, which is a real-time monitoring and control system.

The maturity level of each application area will be shown based on the survey responses. Maturity levels have already been described in chapter 2 (A – conceptualisation, B – development/descriptive, C – integration, D – diagnostic, E – predictive analysis, F – predictive/autonomous optimisation).

It is important to emphasise that the results presented in this section are based solely on the survey responses and might not provide a comprehensive overview or exhaustive list of all solutions being implemented. Even among the operators that participated in the survey, these results should not be considered all-encompassing.

Grid and market modelling (clusters 1, 2, and 3)

Modelling of the electricity grid and market for various analyses is one of the key underlying processes on which many other TSO and DSO business processes rely. High-quality modelling holds strong importance for TSOs and DSOs, as emphasised by the fact that many of them highlighted it as one of the challenges faced while implementing all kinds of different solutions relying on either grid or market models. Although modelling is part of many initiatives listed in the survey, Table 4 contains initiatives predominantly focused on modelling.

Country	TSO/DSO	Organisation	DT solution	A	B	C	D	E	F
AT	DSO	Energienetze Steiermark	DT of the grid including data from all possible sources (including near-time).						
IT	TSO	Terna SpA	Terna is working on the TwinEU developing a pilot for HiL simulations and automatic validation of designs.						
DE	TSO	50hertz	Modelling of substations and creating virtual scenarios for training and analysis.						
AT	TSO	Austrian Power Grid	Varied market-model operating system (VAMOS) modelling environment for European electricity market model, capacity and redispatch calculations.						
PT	DSO	E-REDES	Development of the DT of the low-voltage network, using AI and street view images to map LV assets and data from smart meters to complete the model.						
BG	DSO	EDG West	ADMS implementation with one of the goals of having a complete network model and exchanging it with other companies.						
PL	TSO	PSE	The fundamental market model (FMM) enables advanced simulations of the European electricity market with a dedicated module that integrates transmission and market data from across the EU.						

Table 4: Initiatives for grid and market modelling

This area showcases a well-balanced distribution of solutions developed by both DSOs and TSOs. The TSO solutions are distinguished by two markedly different focus areas: APG and PSE prioritise European-scale market modelling, while 50Hertz and Terna concentrate on detailed substation-level modelling.

On the other hand, DSO solutions tend to exhibit a higher level of maturity, with E-REDES standing out for its innovative use of AI. E-REDES significantly enhances its modelling capabilities by leveraging smart meter data and street view imagery.

System operation and operational planning (clusters 2 and 3)

This application area focuses on initiatives supporting real-time operations of the system by providing various analyses that are part of short-term operational planning processes across TSOs and DSOs. The initiatives listed by TSOs and DSOs in the survey related to this area are predominantly focused on DLR.

DLR is a system used in power grids to adjust the capacity of transmission lines in real time, which can be achieved through a direct or indirect method [16]. The direct method is based on direct measurements of power line characteristics, i.e. conductor temperature, wind speed, solar radiation, line tension, and line sag. By measuring these factors, DLR allows utilities to optimise the power flow and increase the efficiency of energy transmission without overloading the lines. The indirect method estimates the line ratings based on weather data. There are several initiatives focusing on DLR implementation, many of which use sensor data, forecasts, SCADA data, etc. to inform DLR, whereas an initiative from MAVIR is developing DLR without sensors by leveraging artificial neural networks (ANNs).

While most initiatives focus on DLR, it is noteworthy that APG is also using a similar concept on their transformers. The transformer load management initiative leverages the thermal reserves using precise knowledge and adjustment of transformer conditions. Additionally, there are also initiatives focusing on outage planning and security assessment.

Table 5 shows all relevant initiatives for applications related to system operation and operational planning.

Country	TSO/DSO	Organisation	DT solution	A	B	C	D	E	F
DK	TSO	Energinet System Responsibility	Implementing risk-based N-1 security assessment, which will be used for asset management and grid planning.						
NL	TSO	TenneT TSO B.V.	Dynamic transformer rating initiative to study overloading capacity utilising sensor data, oil data, weather forecasts, and SCADA measurement data.						
AT	TSO	Austrian Power Grid	DLR implementation using sensors and data from SCADA and weather forecast providers.						
AT	TSO	Austrian Power Grid	Dynamic transformer load management.						
DK	TSO	Energinet System Responsibility	Model-based DLR, with models calibrated using movable sensors on sample lines of each type.						
CH	TSO	Swissgrid	Implementation of smart outage planning by enabling access to the common system to all partners connected to the network.						
HU	TSO	MAVIR	Development of DLR without sensors but using ANNs (part of TwinEU project).						
CH	TSO	Swissgrid	DLR implementation utilising sensor data, weather forecasts, and SCADA data.						

Table 5: Initiatives for system operation and operational planning

Most solutions in this area show a very high level of maturity, which might be related to multiple TSOs having a similar focus. However, the solutions in this area are concentrated in central Europe, which might indicate a greater potential for cooperation with TSOs of other regions. The lack of initiatives from DSO in this area might reflect the comparatively lower DSO participation rate in the survey, as well as the differing operating characteristics.

BIM and 3D modelling (cluster 2)

BIM is a digital process that creates and manages detailed models of assets (e.g. buildings, equipment, infrastructure) throughout their lifecycle. It enables collaboration among architects, engineers, contractors, and stakeholders by providing a shared, accurate, and up-to-date representation of the project. BIM helps to improve design efficiency, reduce construction errors, and streamline project management. Given that BIM is also an asset management tool, it is not only used at the design stage but also throughout the asset lifecycle.

There are already existing projects among TSOs and DSOs to create BIM models. Each organisation tailors its approach, whereby some focus on specific components such as substations or lifecycle management, while others aim for comprehensive digital representations across all grid assets.

This area shows a stronger presence of TSOs, aligning with expectations as BIM offer particular value for managing complex assets and stations, which is typical in transmission systems. Additionally, the geographic diversity of these solutions suggests that they can deliver widespread benefits across various environmental conditions. However, most solutions still exhibit relatively low maturity levels. Notably, 50Hertz distinguishes itself by focusing explicitly on training and scenario analysis, which is a well-suited application for a solution at an early maturity stage.

By contrast, Enel stands out not only as the sole initiative led by a DSO but also for achieving the highest maturity level in conjunction with Fingrid. Enel reports that detailed modelling – enhanced by thermography and image analysis – is unlocking new potential for predictive maintenance. This approach could provide a valuable model for other DSOs.

Table 6 shows all initiatives related to BIM and 3D modelling.

Country	TSO/DSO	Organisation	DT solution	A	B	C	D	E	F
CH	TSO	Swissgrid	BIM virtual representations of substations.	■					
NO	TSO	Statnett SF	Initiative to develop BIM for all grid assets.	■					
DE	TSO	50hertz	Modelling of substations and creating virtual scenarios for training and analysis.	■	■				
IT	TSO	Terna SpA	BIM implementation for lifecycle management of assets.		■				
FI	TSO	Fingrid Oyj	Elvis solution in which 3D model of assets is being created.				■		
IT	DSO	Enel	3D modelling of the system within a tool for storing and accessing the up-to-date physical characteristics of its grid.				■		

Table 6: Initiatives for BIM and 3D modelling

Real-time monitoring and control (cluster 3)

The real-time monitoring and control area is the application area with the strongest focus among TSOs and DSOs based on the survey results. TSOs are focused on improving their monitoring and control with advanced solutions for real-time simulators, system stability, management of renewable energy sources and substations, etc. On the other hand, DSO solutions are more focused on low-voltage grids (digitalisation, fault detection) and customer monitoring.

The solutions from the survey response include typical systems such as SCADA and ADMS, as well as some other solutions utilising advanced sensors, smart meters, advanced monitoring and control, and various automations. Solutions from the survey are shown in Table 7.

Country	TSO/DSO	Organisation	DT solution	A	B	C	D	E	F
DK	TSO	Energinet System Responsibility	Early warning early prevention systems covering dynamic analysis of the electric system.	■					
HR	TSO	HOPS Ltd	Real-time digital simulator (OPAL RT) for monitoring dynamic behaviour of the system and testing of voltage regulation settings.		■				
SE	TSO	Svenska kraftnät	Power system hub programme containing solution for advanced data analysis and system monitoring and control.		■				
RO	TSO	Transelectrica	Using virtual substations for event simulation and training.		■				
LT	TSO	LITGRID AB	SCADA module for renewable energy source management.			■			
BG	DSO	EDG West	ADMS implementation with one of the goals of having a complete network model and exchanging it with other systems.			■			
ES	DSO	Cuerva	Technology provided by Adaion, which collects data from sensors, smart meters, and SCADA to create a model and perform power flow calculations, hosting capacity analysis or real-time voltage and current monitoring.			■			
AT	DSO	Wiener Netze	SCADA system and its development to cope with the upcoming challenges (integration of renewables, EVs, heat pumps, etc.) and fulfil the legal framework requirements.			■			
IT	DSO	Enel	ADMS implementation.				■		
AT	TSO	Austrian Power Grid	Use of sensors for monitoring different substation components.				■		
IT	DSO	E-REDES	DT for detection of phase interruption on the MV feeders using smart meter data.				■		
DE	DSO	E.ON SE	Intelligent grid platform solution, with the primary goal of digitalising the distribution grid (LV and MV), and one of the functions being grid monitoring.					■	

Table 7: Initiatives for real-time monitoring and control

According to the survey results, this area also distinguishes itself with a comparatively high level of maturity and a significant number of DSO solutions. For instance, E.ON stands by using a intelligent grid platform, to fully digitalise its low- and medium-voltage grids, enabling real-time monitoring through measurements and state estimation. This approach lays the foundation for flexibility and congestion management solutions. Similarly, Cuerva employs a competing solution from Adaion. However, their implementation is at an earlier stage of maturity, with a focus on connection requests, fault detection, and restoration.

While the use cases converge for the DSOs, a varied range of use cases can be observed among the TSOs. Among them, the example with the highest maturity level comes from APG, which uses advanced sensors for comprehensive condition monitoring to run predictive diagnoses and action recommendations.

Grid flexibility and customer interaction (clusters 1 and 2)

Table 8 shows DT initiatives that prioritise grid planning and flexibility to cope with the growing complexity of increasing participation of distributed energy resources (DER) and electric vehicles (EVs) in the electricity network. This is also closely connected with the evolving energy market, where customer participation is becoming increasingly active.

Country	TSO/DSO	Organisation	DT solution	A	B	C	D	E	F
AT	DSO	Energienetze Steiermark	DT of the grid including data from all possible sources offering customers a map with grid capacities at the HV level.	■					
SI	DSO	ELES, d.o.o.	DigiElProm project that combines electricity, market, and traffic data to define optimal locations for future charging parks.		■				
NL	DSO	Alliander	Initiative to implement a solution for customer integration.			■			
ES	DSO	Cuerva	Technology provided by Adaion to know the hosting capacity in different scenarios, reducing the time to answer connection requests for both demand and generation.			■			
IT	TSO	Terna SpA	Participation in Equigy's Crowd Balancing Platform solution, a common platform allowing market parties access to ancillary services markets.		■	■	■		

Table 8: Initiatives for grid flexibility and customer interaction

This area still shows a relatively low number of examples and a higher presence of DSOs. This can be explained by their much higher demand for customer-facing solutions due to their high volume of interactions, especially with residential and small businesses. A remarkable point is that the Equigy project mentioned involves a total of five countries with different TSOs, revealing a wider reach of this area than is initially evident.

It is noteworthy that the solutions from Energienetze and Cuerva are part of a broader solution – also appearing in other areas – while ELES and Alliander chose to have a more focused approach for this area.

Common data platforms and data exchange (cluster 1)

DSOs and TSOs operate a wide range of systems, each generating diverse types of data, often in incompatible formats. A critical enabler for successful DT implementations is the establishment of a common data platform that consolidates and harmonises data from these various sources, making it easily accessible for multiple use cases. This is especially important for grid operators, which face the challenge of bridging the historically rigid divide between operational technology (OT) and information technology (IT). Additionally, they must meet the stringent cybersecurity and data protection requirements typical of critical infrastructure. Notably, this common platform – a single source of truth – can itself be considered a foundational DT, representing the integrated state of the grid's data ecosystem. Table 9 shows the ongoing initiatives related to these topics.

Country	TSO/DSO	Organisation	DT solution	A	B	C	D	E	F
SE	TSO	Svenska kraftnät	Power System Hub programme containing a solution for advanced data analysis, data exchange, and system monitoring and control.		✓				
NL	TSO	TenneT TSO B.V.	DT solution as the representation of a real power system, which enables informed decision-making across different domains through interconnected databases and models, as well as developing interoperable DT standards as part of TwinEU.		✓				
BG	DSO	EDG West	ADMS implementation with one of the goals of having a complete network model and exchanging it with other systems.			✓			
IT	TSO	Terna SpA	Participation in Equigy's Crowd Balancing Platform solution, a common platform allowing market parties access to ancillary services markets.			✓	✓		

Table 9: Initiatives for common data platforms and data exchange

The examples highlighted in this section draw attention due to their diverse approaches, with each respondent presenting a unique strategy. For instance, EDG West emphasises the central role of an advanced distribution management system (ADMS) in DSO operations, leveraging it as a hub for data exchange with other systems. This approach could serve as a viable alternative for other DSOs, reducing the need to develop a separate parallel platform.

While TSOs share the overarching objective of facilitating data exchange at least partially with external stakeholders, their contexts and implementation strategies significantly differ.

Although not directly mentioned in the survey, it is important to acknowledge several European initiatives, such as PICASSO, MARI, CGM/OPDE and OPC/STA which aim to provide common platforms for data exchange within specific contexts. These initiatives could lay the groundwork for a more comprehensive exchange platform in the future, capable of supporting a wide range of use cases across the energy sector. In this context, the transition to a fifteen-minute market time unit (MTU) in the wholesale markets (day-ahead and intraday) from March 2025 to reduce imbalance and connect the markets and the physics closer together is increasing the data amounts and automatisation, hence increasing the need for digitalisation and standardisation. These fundamental changes will improve the impact of some challenges and reduce others. For example, it will increase operational RES integration and hence reduce the impact of some challenges addressed regarding operational RES integration and imbalances. On the other hand, it will probably increase the impact of facilitating higher consumer integration into markets.

Grid optimisation and asset health (clusters 2 and 3)

Grid asset optimisation and asset health are essential in the context of the massive investments required to decarbonise energy systems and meet climate goals. These practices integrate **asset management**, **investment optimisation**, and **predictive maintenance** to maximise grid performance and lifespan. With decarbonisation driving significant infrastructure expansion, financial sustainability becomes crucial, as improving efficiency helps to reduce costs while ensuring or enhancing grid **resiliency** and **reliability**. By optimising asset health, grid operators can better allocate resources, minimise risks, and support the transition to a clean energy future without compromising service quality.

The relatively high maturity of most solutions coupled with a balanced mix of contributions from DSOs and TSOs underscores the critical importance of digital advancements for operators across all levels. Outstanding examples include **Swissgrid** and **E-REDES**, which lead the group with their highly mature solutions. Meanwhile, despite a lower maturity level, **Amprion's** lifecycle management approach is noteworthy for its comprehensive data integration from design to maintenance. Table 10 summarises the results of the survey.

Country	TSO/DSO	Organisation	DT solution	A	B	C	D	E	F
DE	TSO	Amprion GmbH	Lifecycle management solution that combines data from the design, construction, operation, and maintenance stages of an asset to establish predictive maintenance and asset optimisation.	■					
DK	TSO	Energinet System Responsibility	Electrical and digital asset health solution.		■				
NL	TSO	TenneT TSO B.V.	Asset performance management tool for data-driven grid maintenance.			■	■		
IT	DSO	Enel	Initiative to have predictive maintenance technologies by 2027.				■		
AT	TSO	Austrian Power Grid	Condition monitoring for predictive maintenance using sensors and APM tools.				■		
IT	DSO	E-REDES	DT being developed to integrate asset conditions, failure risks, and renewal strategies for risk mitigation.				■	■	
CH	TSO	Swissgrid	Systematic, risk-based planning optimises maintenance through proactive solutions for plant-specific issues. Simulations and forecasts improve asset performance and reliability.					■	

Table 10: Initiatives for grid optimisation and asset health

Summary of the maturity stage of ongoing projects

Table 11 shows the average maturity level for each application area based on the reported ongoing projects that are sorted and considered in this chapter. The highest maturity is for system operation and operational planning, where mostly one technology is widely implemented in many countries: DLR. Completed projects are not a part of this maturity assessment. For example, the general maturity level –hence not only counting ongoing projects as here – of grid and market modelling is higher than a conceptualisation state for many system operators in reality. The system operators must all have SCADA systems for operations, many own models for grid planning and development, and most TSOs have grid models for market analysis. Therefore, the maturity level in Table 11 does not reflect the overall maturity but rather the maturity in the ongoing projects developing DT.

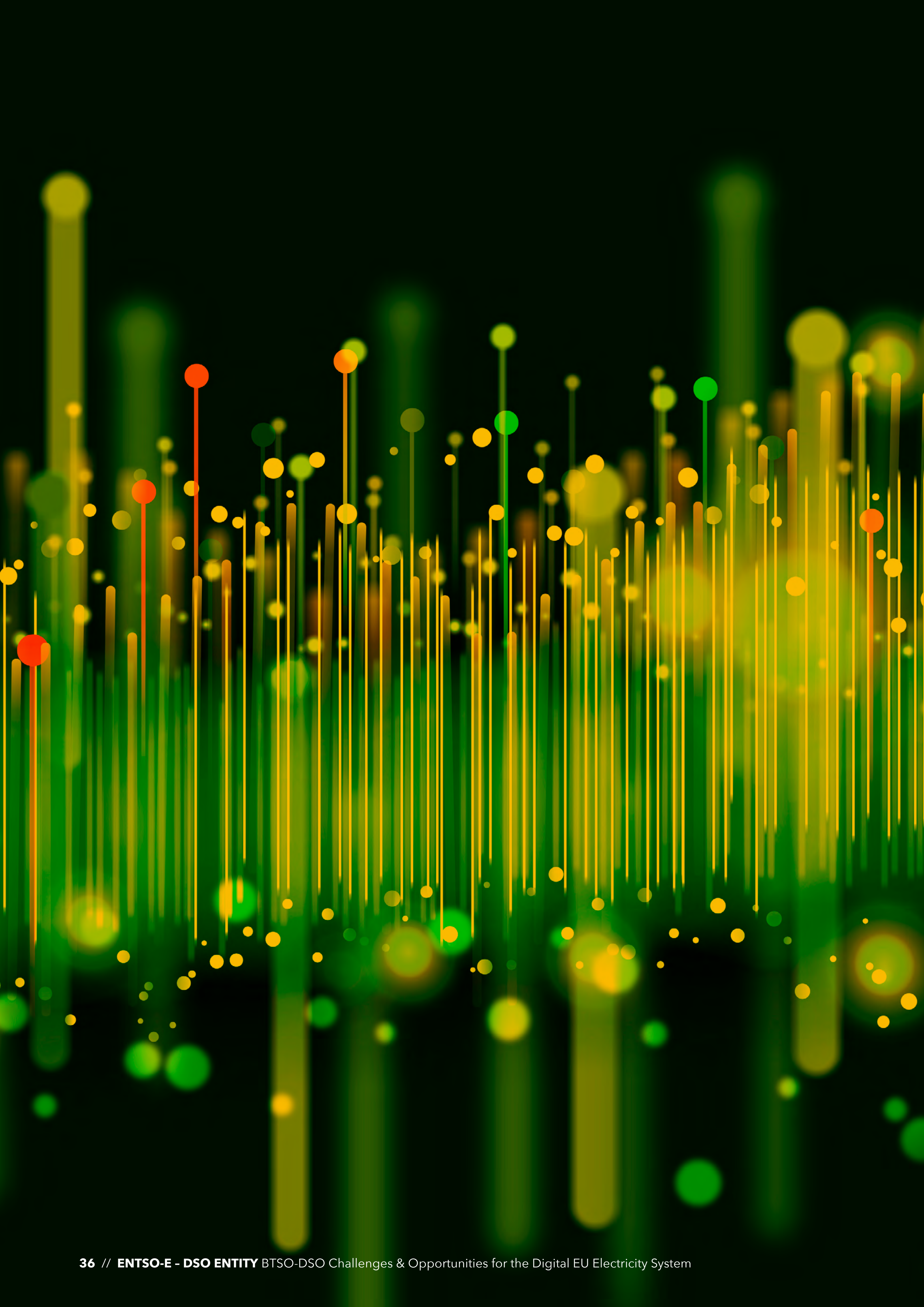
Overall, the lowest maturity is evident for grid and market modelling, BIM and data exchange, which remain in the conceptualisation and descriptive phase (phase A and B). Real-time monitoring and control, grid flexibility, and customer interaction are in the integration phase (phase C). The highest maturity is registered for system operation and operational planning, as well as grid optimisation and asset health, which are in the diagnostic maturity phase (phase D).

Application area — Maturity stage	A	B	C	D	E	F
(Advanced) Grid and market modelling (7)	36 %	23 %	29 %	0 %	14 %	0 %
System operation and operational planning (9)	0 %	16 %	6 %	34 %	22 %	11 %
BIM and 3D modelling (6)	38 %	28 %	0 %	33 %	0 %	0 %
Real-time monitoring and control (12)	8 %	25 %	34 %	25 %	8 %	0 %
Grid flexibility and customer interaction (5)	20 %	26 %	46 %	6 %	0 %	0 %
Centralised data platforms and data exchange (4)	0 %	58 %	33 %	8 %	0 %	0 %
Grid optimisation and asset health (7)	14 %	14 %	7 %	43 %	22 %	0 %

Table 11: Average maturity for different application areas based on ongoing projects.

Note: The total number of projects within each application area is noted in parentheses.

While this overall picture shows the average maturity, individual deviations from this will emerge when considering isolated companies. It is also visible in Table 11 that some application areas have higher variability and individual deviations than others. For example, system operation and operational planning, real-time monitoring and control, and grid optimisation and asset health have a large spread in maturity, while BIM and 3D modelling and data platforms and data exchange have more concentrated maturity levels.



CHAPTER 5

Outlook and measures required for the digital EU electricity system

Building on the earlier analysis of existing DT implementations among power system operators, this section explores potential next steps, areas for improvement, and priority challenges that remain under-adopted relative to their planned timelines and strategic importance. While the previous chapter highlighted current implementations, this chapter focuses on identifying existing gaps and outlining actionable steps to drive higher adoption and maturity, which are essential for guiding the industry's future efforts and investments.

The analysis is divided into the same application areas of the previous chapter and will help to identify potential barriers to implementation and areas requiring immediate attention to ensure a comprehensive digital transformation of the power sector.

Grid and market modelling (clusters 1, 2, and 3)

Survey respondents are advancing their DT initiatives in this application area with a focus on expanding scope and enhancing integration. One common next step is the scaling of existing DT projects from the system operators to cover larger portions of the grid that they operate and handling the different priorities of DSOs and TSOs. For instance, 50Hertz plans to extend its virtual substation simulator to all substations, enabling a unified simulation environment for network-wide analysis. Similarly, E-REDES aims to complete a comprehensive low-voltage network model within 3 to 4 years, leveraging DT technology for enhanced geographic information system (GIS) representation and asset management.

A notable trend is the focus on interoperability and collaborative models, as demonstrated by Terna's demo in the TwinEU project. This initiative aims to create a pan-European DT framework to enhance power system defence strategies and improve substation design validation. Another critical next step involves the addition of new use cases to DT platforms. For example, EDG West is planning to integrate asset management into its existing ADMS DT initiative as a next step.

Data integration and system interoperability are important requirements to succeed in developing well-functioning DTs, as highlighted by 50Hertz and E-REDES. Terna emphasises the need for standardisation in software and communication protocols, which is critical for scaling DTs and ensuring seamless collaboration between stakeholders. It is vital to adopt and implement a common ground for processes and data to be exchanged, and the standards already exists but simply need to be adopted.

The power system representation standards for tools for the design, operation, and operation of power systems are established by the IEC Technical Committee (TC) 57 committee, including IEC 861850 and the IEC Common Information Model (CIM) standard.

Initiatives such as the CIM-based common grid model exchange standard (CGMES) – based on EN 61970 – would help by implementing a European-wide framework for grid-related data in many contexts, although its implementation has been slowed by some of the same issues aggravated by limited support from fragmented vendors. European TSOs have implemented this to exchange individual grid models (IGMs), develop common grid models (CGMs), and perform regional coordination analysis. The adoption of CGMES creates interoperability and enables data exchange across SOs in Europe, which creates an opportunity for stronger cooperation in planning and operation to increase grid utilisation and security of supply. Applying existing standards from CENELEC – such as EN 61850 – is a clear opportunity for progress in DT development, data integration, and data exchange.

Developing and implementing DT is an opportunity to eliminate the reliance on outdated systems and legacy infrastructure. E-REDES highlighted the difficulties of connecting legacy GIS systems to modern DT platforms, requiring substantial investment in both hardware and software upgrades. While some organisations such as APG have received substantial support through EU programmes, others such as E-REDES report insufficient incentives for DT-specific projects. The complexity of DT models themselves also presents challenges, with APG noting the difficulty in setting up highly complex models that require advanced computational power and expertise. This complexity can slow down deployment and increase costs, particularly when adapting existing infrastructure to meet new operational and regulatory standards. While computational power is a limiting factor, continuous technological advancement is generally increasing the affordability and availability of computing power.

System operation and operational planning (clusters 2 and 3)

The TSOs and DSOs in this area demonstrate a clear focus on implementing advanced DT solutions to optimise grid management and asset performance. Common next steps include leveraging data for predictive analysis and operational improvements. For example, Swissgrid aims to integrate virtual modelling in 2D and 3D environments, focusing on the entire lifecycle of infrastructure projects. It plans to utilise these DTs to enhance planning, maintenance, and risk management, with full integration into daily operations expected within the next few years.

Dynamic asset rating (DAR) is another critical development area with high upside potential regarding grid utilisation. Organisations such as MAVIR are focusing on improving the transfer capacity of overhead lines by utilising DTs without strongly relying on sensor installations, instead leveraging data from existing weather and SCADA systems. The TwinEU project continues to play a pivotal role, with Swissgrid collaborating on this initiative to develop advanced outage planning and risk-based asset management systems. The aim is to refine tools that support asset longevity and enhance grid resilience, with expected implementations over a three- to five-year timeline.

The process of achieving these next steps is a challenge, particularly regarding data quality and integration. Many organisations report difficulties in merging data from different sources such as operational data and weather forecasts into a cohesive DT framework. This integration is further complicated by the existence of data silos within organisations, as noted by Swissgrid and Energinet, which hinders developing a necessary unified data platform for effective DT operation. This barrier presents another example where the adoption of European-wide standards presents a major opportunity to increase internal and external coordination.

Relevant technological and financial opportunities have also been identified. MAVIR has highlighted uncertainties regarding weather data accuracy, which affects the reliability of its DLR models. By reducing weather forecasting errors by introducing DT or AI for data assimilation and advanced forecasting, the certainty in the DLR models will increase. The costs associated with implementing IoT sensor platforms and other infrastructure upgrades potentially pose a barrier, and thus innovative solutions such as the model-based approach being tested by MAVIIR present an opportunity for companies starting with their DT journey. With comprehensive policy support and standardised guidelines aggravating these issues, the overall implementation will be accelerated.

The projects in "system operation and operational planning" are making substantial progress towards integrating DT solutions into their operations. By addressing data integration issues and leveraging collaborative initiatives such as TwinEU, TSOs and DSOs can unlock the full potential of DTs for grid management and asset optimisation. The next few years will be crucial in demonstrating the scalability and reliability of these technologies, ultimately driving the European energy grid towards greater efficiency and resilience.

BIM and 3D modelling (cluster 2)

In this area, the development of DTs strongly focuses on operational improvements and enhanced asset management. Organisations such as Fingrid are leading efforts to implement DT solutions across various asset groups, with a primary goal of creating a "single source of truth" for asset data. This strategy ensures that accurate and up-to-date information is available for all stakeholders, enhancing decision-making and operational efficiency.

Similarly, Enel is working on advanced 3D modelling and thermographic analysis to improve the management of physical assets such as substations. The integration of these DT solutions is expected to facilitate better condition monitoring and fault detection, with plans to roll out these systems across key operational areas within the next few years. For 50Hertz, the focus remains on expanding their virtual substation simulations to cover the entire network, thereby improving training and operational readiness.

Adopting the necessary advanced modelling technologies for BIM and 3D modelling involves high costs, especially in terms of OPEX for software licensing and digitising operations. Enel notes this financial burden as an important factor limiting the pace of deployment. Additionally, the challenge of data integration remains significant, particularly when working with legacy systems and diverse data sources. For instance, Fingrid emphasises the need for seamless data sharing across all asset management platforms to achieve the desired "single source of truth".

Related to the financial challenge is the perception that the funding possibilities at the EU level are limited and do not target large-scale projects. Adopting the financial incentives will ensure harmonisation and an even playing field, leading to a fast implementation pace.

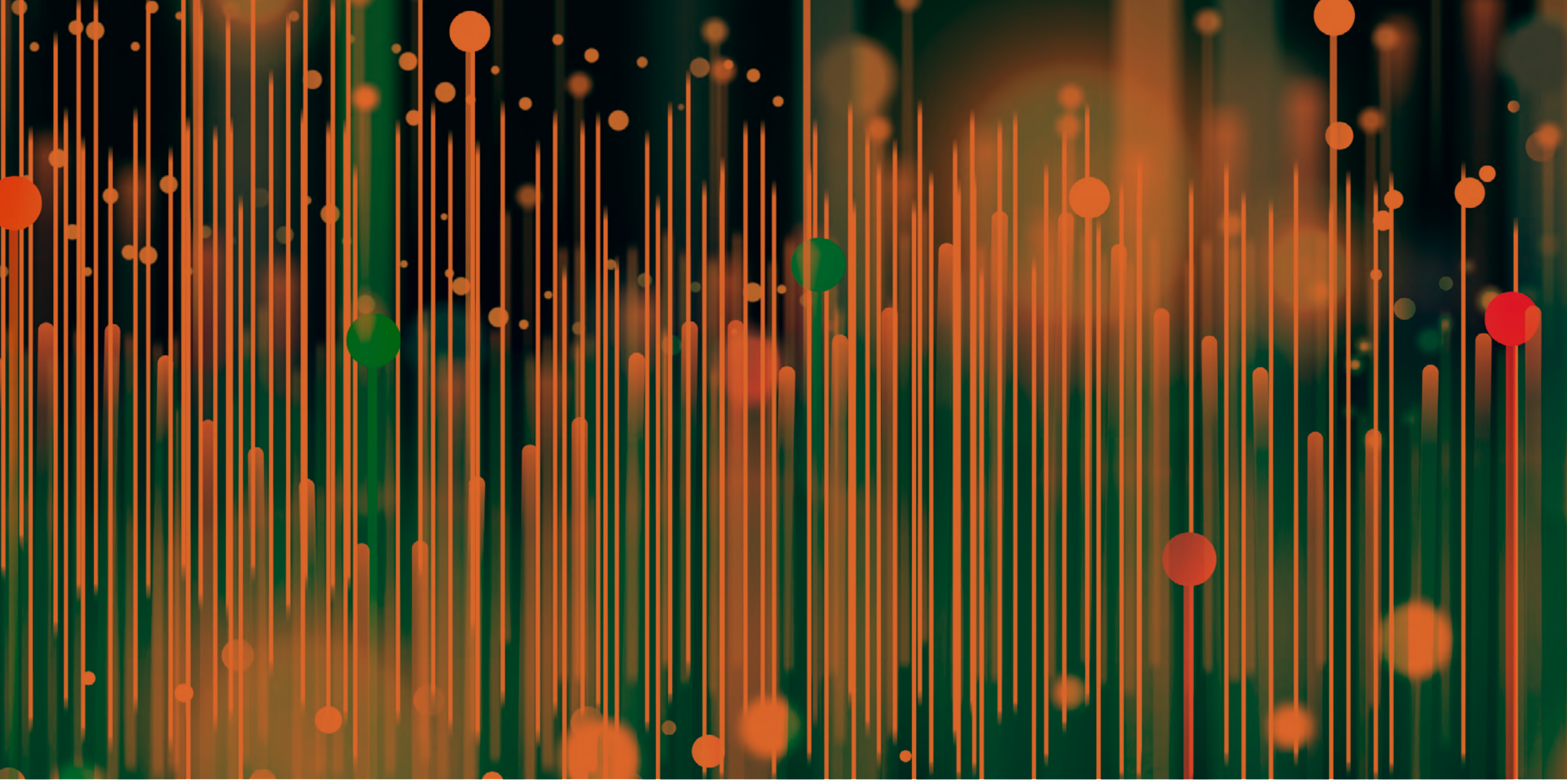
The grid operators are leveraging the use of BIM and 3D modelling to enhance grid operations and asset management. Despite challenges related to costs and data integration, these TSOs and DSOs remain committed to their long-term vision.

Real-time monitoring and control (cluster 3)

System operators working on real-time monitoring and control through DT technologies have outlined clear next steps aimed at operational improvements and enhanced asset management. Enel plans to leverage its ADMS integration by scaling the use of DTs for 3D modelling and advanced monitoring of grid assets. Litgrid AB emphasises the need for greater visibility into distributed generation assets and aims to improve its operational control systems to handle the increasing penetration of renewables. The implementation of DTs can contribute to enhanced real-time monitoring and control, which will make the integration of more RES possible.

APG is focusing on testing and refining predictive maintenance systems and dynamic load management tools, with plans to scale these systems based on their effectiveness. Meanwhile, Transelectrica intends to integrate the lessons from its pilot virtual substation into day-to-day operations, aiming for full-scale implementation within the next year.

Despite the clear benefits presented by real-time monitoring and control, its implementation frequently depends on the rollout of advanced sensors and intelligent devices, which have a significant impact on CAPEX. On the other hand, advanced software and highly qualified personnel are necessary to leverage this additional information and controllability, which also means higher costs in the form of OPEX. However, it is reasonable to expect that the cost of sensors should continue to decrease, especially as the technology matures and gains scale, while advancements in AI technology could support training new professionals and interpreting more complex data.



As in the previous area, Enel identified the financial burden as a significant barrier. Additionally, data quality issues and integration challenges persist, which might delay the actual benefits of advanced solutions. For example, APG highlights difficulties in merging operational and sensor data into cohesive DT frameworks due to the complex nature of their models.

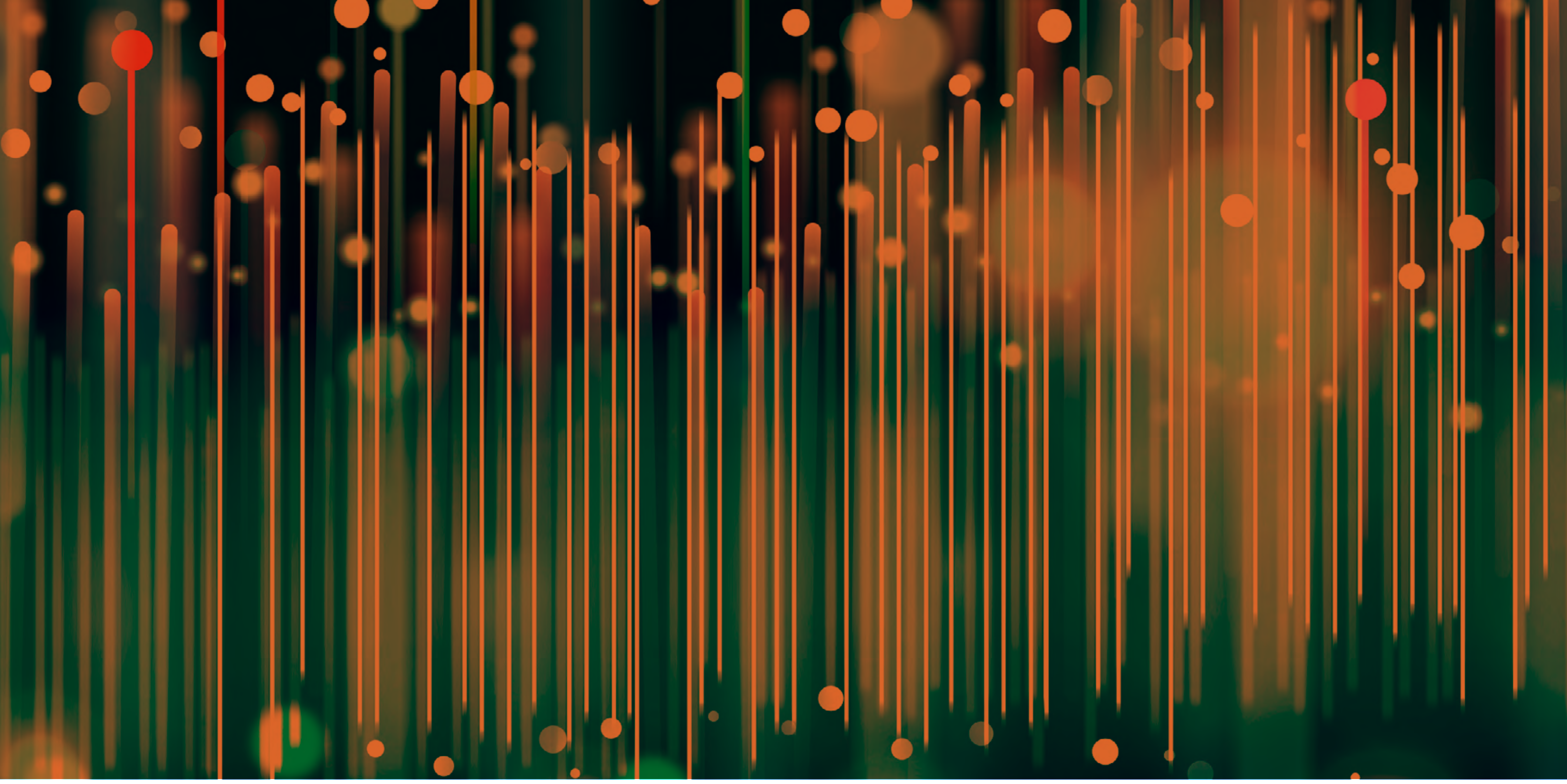
Policy and funding gaps again further complicate the deployment of these technologies. Organisations such as Transelectrica and Enel note the limited availability of targeted regulatory frameworks or funding mechanisms to support the specific needs of DT projects. While EU funding initiatives such as the modernisation fund offer some support, there remains a need for more specialised and widespread funding to bridge the gap between pilot projects and full-scale implementation.

DT technologies are expected to have a significant impact on real-time monitoring and control. While organisations are making strides towards integrating these systems, overcoming challenges related to costs, data integration, and policy support will be key to achieving widespread adoption.

Grid flexibility and customer interaction (clusters 1 and 2)

Organisations have identified key next steps to enhance their DT initiatives in the area of grid flexibility and customer interaction,. Energienetze Steiermark plans to develop a map for available grid capacities for new grid customers, while ELES is developing something similar for future EV charging stations. Alliander aims to create a customer interface to support grid connection requests and load forecasting, which will increase new customers' opportunities to strategically locate their businesses.

Through its involvement in the Equigy platform, Terna is preparing for the platform's broader rollout in Italy, Germany, and Switzerland, with go-live timelines extending to 2025 and beyond. Cuerva is working on integrating its DT solutions for HV and LV systems to reduce response times for customer requests and improve overall grid interaction capabilities. Along with other similar initiatives, this will increase the opportunities to realise the existing flexibility.



The implementation of these solutions faces significant hurdles, particularly around data quality and integration. Many organisations – including Energienetze Steiermark and Cuerva – report challenges in collecting and standardising data from various sources. This issue is compounded by a mismatch in data formats and incomplete datasets, which can slow down the development and deployment of DTs.

As for other application areas, another major challenge is the lack of use of standardised models for customer interaction and flexibility services. Terna and other organisations involved in the Equigy project note that progress is evident, although there remains a need for harmonised communication protocols across all TSOs and DSOs to ensure seamless integration across different systems and regions.

Common data platforms and data exchange (cluster 1)

The survey indicates that the next steps in this area revolve around expanding and refining data integration frameworks. A primary focus is placed on establishing standardised data platforms capable of supporting seamless data exchange between stakeholders. This includes the development of granular and closer to real-time data-sharing systems that enhance situational awareness and grid performance. Many organisations also plan to adopt advanced data analytics tools to extract actionable insights, which will play a crucial role in optimising grid operations and planning.

Another significant next step is harmonising data exchange protocols across different regions and organisations, which involves adopting common standards and practices to ensure interoperability. Several initiatives also aim to integrate external data sources such as weather and market data into their platforms to enrich decision-making processes. These enhancements are expected to drive efficiency and resilience in grid operations, providing a holistic approach to energy management.

The survey also highlights that ensuring data quality and consistency across diverse systems is a critical barrier and represents a challenge in advancing in this area. Interoperability remains a complex issue, compounded by the need to align different regulatory frameworks and legacy systems. Moreover, achieving consensus on data standards across a broad range of stakeholders poses a significant obstacle. Overcoming these challenges will be essential for the successful implementation of common data platforms.

The next steps point towards a concerted effort to create standardised, interoperable data platforms that facilitate seamless information sharing across stakeholders. The challenges of data consistency, interoperability, and regulatory alignment must be addressed to unlock the full potential of these platforms. By overcoming these hurdles, organisations can lay the groundwork for a more integrated and resilient energy system, supporting both operational and strategic goals.

Grid optimisation and asset health (clusters 2 and 3)

For this area, system operators emphasise the operational integration of DT solutions to enhance grid optimisation and asset health monitoring. The challenges in this area are primarily technical and organisational. The survey highlights difficulties in integrating DT solutions with legacy grid infrastructure and ensuring real-time responsiveness. Financial constraints and regulatory hurdles also add to the complexity of scaling these initiatives.

DSOs and TSOs are focusing on leveraging DTs to improve maintenance capabilities, enabling the early detection of potential failures and the optimisation of asset lifecycles. These solutions are also expected to play a critical role in simulating grid operations under various conditions and supporting optimal investment planning, helping operators to make more informed decisions.

Another priority is scaling these technologies to cover a wider range of assets and operational scenarios, which includes integrating DTs with existing operational systems to create a unified framework for grid management and ensuring that the system operators or operational planners have a higher degree of observability and control. Such integration will enable more dynamic and responsive grid operations, ensuring that utilities can adapt quickly to changing demands and conditions. Several initiatives also plan to use DTs for long-term strategic planning, providing insights into future infrastructure needs and investment priorities.

In this area, the focus on integrating DT solutions into daily operations marks a pivotal step in optimising grid performance and asset health management. These technologies promise to enhance maintenance strategies, enable dynamic grid control and optimise investment planning, contributing to improved reliability and efficiency.

Cross-cutting challenges

One of the most pressing challenges for DSOs is the lack of resources, which encompasses both human and technical aspects. Many DSOs operate with limited staff and expertise in cutting-edge technologies such as DTs, which makes it difficult to allocate the necessary time and personnel to fully develop and implement DT solutions. Moreover, these constraints extend to ongoing operations, where the maintenance and evolution of DT systems require specialised knowledge that might be scarce within the organisation.

Financial constraints also pose a significant hurdle. The high cost of technology – from acquiring advanced hardware and software to integrating existing systems, i.e. smart metering deployment –often exceeds the budgets of DSOs, which are unable to cover it through the tariff. These organisations are also required to justify the return on investment for implementing DT, which can be challenging in the early stages when benefits such as improved efficiency or predictive maintenance might not yet be fully realised. This financial burden can delay or limit the scale of DT projects. This means that apart from creating targeted funding opportunities, providing an adequate regulatory and remuneration framework holds considerable importance, allowing the SOs to effectively recover the costs with digitalisation and providing them with the necessary tools – i.e. increased observability through smart meter deployment – to respond to the different use cases.

For TSOs, data quality remains a significant challenge when implementing DT solutions. Digital models strongly rely on accurate and comprehensive data to mirror the physical grid accurately. However, TSOs frequently encounter issues with inconsistent or incomplete data, which can lead to inaccurate simulations and unreliable predictions. These data quality issues not only affect the current operation but also hinder the long-term strategic value of the DT system.

Data integration complexity is another common issue for DSOs. Given that legacy systems – on which many DSOs rely – were not designed to be interoperable, integrating data from disparate systems into a unified digital environment is both time-consuming and technically challenging. The lack of standardised protocols exacerbates this problem, making it difficult to create a seamless flow of data, which is critical for the success of DT initiatives. This often results in fragmented data that limits the effectiveness of the digital models. The existing standards developed by CENELEC and IEC can be used by all SOs and reflect an opportunity to simplify data and system integration and enable SOs to handle the complexity.

Another key challenge identified is the prevalence of data silos. TSOs often manage complex networks where different departments or systems operate independently, each holding valuable but isolated data. This separation creates barriers to data sharing and collaboration, which are essential for developing an integrated DT. This problem is further complicated by the usage of outdated systems that were not designed to support interoperability and create a unified digital environment across different domains. Breaking down these silos requires cultural and procedural changes within the organisations. The success of DT implementations hinges on these operators' ability to cultivate a more collaborative and data-centric organisational mindset.

Mapping operational processes into a digital framework is also a daunting task for TSOs. Translating the complexities of real-world operations into a DT involves significant effort in standardising processes and aligning them with digital capabilities, which is essential to ensure the DT can accurately represent and simulate real-time operations, although it requires extensive coordination and expertise. As discussed in previous sections, adopting industry-wide standards and CGMES represents a remarkable opportunity for progress that stretches over multiple areas.

DSOs highlighted that the availability of resources – in terms of both personnel and funding – remains a significant barrier. Current national and EU-level policies and funding programmes are insufficient to bridge the gaps in resource allocation necessary for developing and implementing DT solutions. This lack of support hinders their ability to advance technological capabilities and integrate systems efficiently. The persistence of these barriers underscores the critical need for knowledge-sharing platforms at the European level specifically dedicated to DT use cases. Such platforms would enable the iterative exchange of successful initiatives and best practices while fostering learning from shared mistakes. This approach would lead to more efficient use of resources and significantly benefit smaller operators, particularly DSOs, helping them to achieve higher levels of maturity in their DT initiatives.

TSOs noted that their work in projects such as Horizon Europe initiatives is ongoing, although they emphasised the need for clearer policy frameworks and enhanced funding mechanisms to support the broader adoption of DT technologies. Existing policies provide some foundational support but do not fully address the operational and integration challenges faced by TSOs.

Both DSOs and TSOs agree that current policies and funding mechanisms – while beneficial – do not adequately cover the technical and operational demands required for the effective deployment of DT solutions. This highlights the need for more targeted regulatory and financial interventions to ensure widespread and efficient implementation across Europe.

CHAPTER 6

Conclusion

The European electricity system stands at a pivotal moment, poised to undergo a radical transformation driven by digital technologies. This transition is imperative to meet the escalating demands of a low-carbon and highly integrated energy future. Digitalisation is key to accomplishing the goals of electrification and renewable energy integration, which will support global carbon reduction. Digitalisation will enhance grid operations, planning, and customer engagement. DT technology has emerged as a powerful tool for meeting the European society's challenges by increasing capacity utilisation, improving interoperability, and enabling data-driven decisions.

The report highlights critical challenges faced by TSOs and DSOs in managing customer interactions, planning, and maintaining systems. It calls for a strategic approach to DT implementation, starting with immediate operational issues while building long-term goals for interoperability, resilience, and collaborative solutions across stakeholders.

The report emphasises the need for clear governance structures, high-data quality, and enhanced interoperability at the organisational, informational, and technical levels for DT adoption to succeed, ensuring seamless data exchange across diverse platforms and devices. The key barriers to overcome are summarised with five main topics:

- **Data integration:** Limited data harmonisation across regions and legacy systems impedes efficient DT deployment. Achieving interoperability requires aligning data protocols with the standardisation of data and communication. The standards for data and communication already exist and should be adopted by all system operators. This barrier exists for all application areas.
- **Scaling and interoperability:** Internal reductions of organisational data silos are necessary for scaling and internal coordination between asset management, grid planning, market analysis, operational planning, and operation. In addition, coordination across entities will require interoperability and standardisation of data and communication. This barrier exists for grid and market modelling, system operation and operational planning, real-time monitoring and control, grid flexibility, and customer integration.
- **Forecasting accuracy:** Reducing errors in forecasting of demand, production and grid capacity (i.e. DLR) will increase the grid utilisation and security of supply. This can be achieved with more data sharing from balancing service providers (BSPs)/BRPs or other relevant entities and can also be enhanced using several data sources and AI models.
- **Stable and supportive regulatory framework:** Adequate regulatory and remuneration frameworks are critical to support digitalisation efforts, enabling system operators to recover costs effectively. Alongside targeted funding, these frameworks should equip operators with essential tools such as enhanced observability through smart meter deployment to drive the broader rollout of smart grids. Rolling out smart meters enables opportunities for realising increased flexibility if customers have dynamic price contracts and data for analysis.
- **Resource capacity:** High capital and operational costs, a shortage of skilled personnel, and funding limitations hinder progress, particularly for smaller DSOs facing budget constraints and limited EU funding support. This is an opportunity for collaboration, as not every single entity has to develop its own systems. This barrier can be overcome by cooperation in developing solutions together.

A collaborative approach among TSOs, DSOs, policy-makers, and industry leaders is essential To maximise DT potential, including establishing harmonised data formats, interoperability standards, and strong cyber-security protocols. With DT technologies, the European electricity system can become more resilient, customer-focused, efficient, and sustainable, leading the way towards a low-carbon future. This shift not only aligns with the European Green Deal but also offers a model for global energy systems in the digital age.

The key benefits of DT implementation include enhanced grid visibility and control, data-based insights that allow optimised maintenance, early identification of potential issues, as well as enabling more informed decision-making and investment planning. Additionally, DTs optimise operations by enabling coordinated analysis and control, improving power flow calculations, reducing system disruptions, and enhancing overall operational efficiency. They also accelerate renewable integration by enabling accurate forecasting and demand response, which supports the seamless integration of DER into the grid.

Finally, DTs improve customer engagement by offering consumer-centric solutions that empower individuals to participate actively in energy markets, contributing to grid stability and fostering a more resilient and dynamic energy system. Through these advancements, DTs have the potential to reshape Europe's energy landscape, driving it towards a resilient and sustainable future. The following work packages in JTF DESAP – detailed in chapter 1 and illustrated in Figure 3 – focus on developing concrete use cases for DTs (WP3) and outlining a roadmap for their implementation and development (WP4). WP3 will identify and create use cases that address specific, real-world challenges and needs, while WP4 will establish a roadmap to highlight the interconnections and dependencies between these challenges and the proposed use cases, as well as providing a structured sequence of recommended activities.

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APPENDIX 1

Calculating impact and effort scores for survey results

Equations 1 and 2 show the formulas for calculating the impact and effort scores, respectively. The normalised average impact score is a parameter showing the average impact considering grades from the mentioned areas of smartness, interconnectedness, and efficiency. The sum of the grades for each challenge is divided by 15, as the sum of maximum grades. The normalised average effort score is calculated by dividing effort grade with the maximum effort grade, which is 4.

Normalised Average Impact Score = (Smartness+Interconnectedness + Efficiency) / ImpactMaxScore

Equation 1: Impact score calculation

Normalised Average Effort Score = Effort / EffortMaxScore

Equation 2: Effort score calculation

After the evaluation, each challenge was placed in one of the following four quarters, as shown in Figure 13: Low impact, low effort = Nice to have / Low impact, high effort = Question marks / High impact, low effort = Quick wins / High impact, high effort = Major projects (necessary activities)

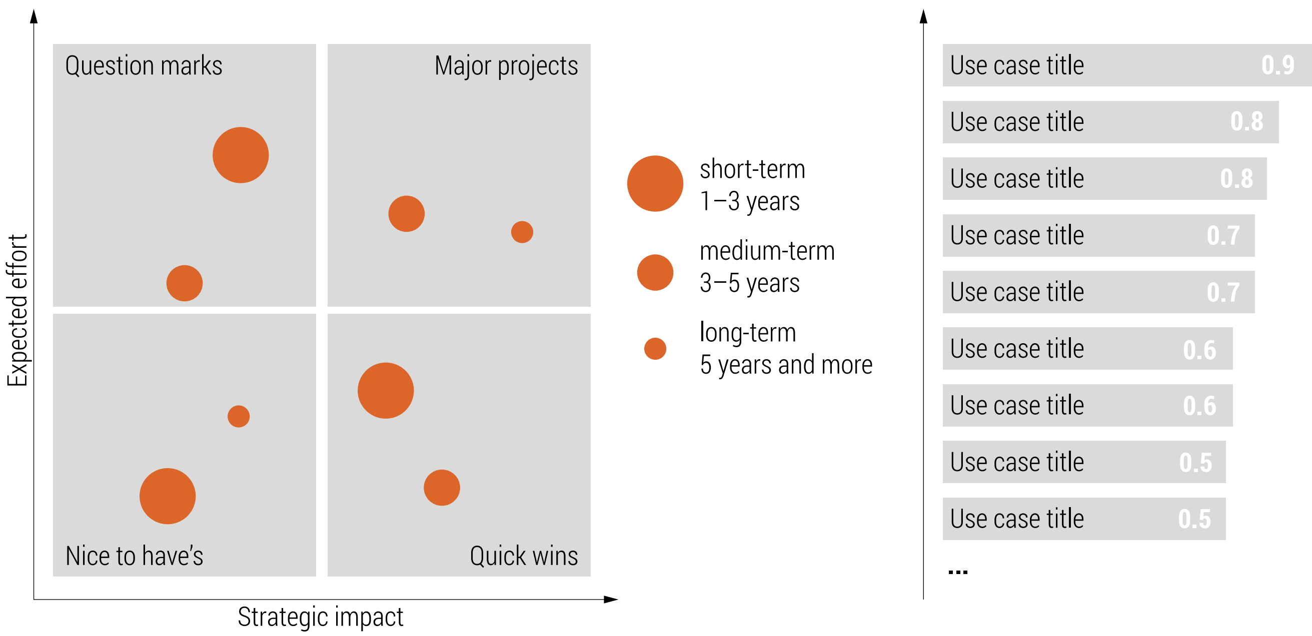

Figure 13: Grouping challenges based on experts' evaluation

The formula for calculating the prioritisation score involves dividing the normalised average impact score by the normalised average effort score. Regarding the relevant timeframe for the occurrence of the challenge, after grading performed by the experts, the AG is calculated and used to classify sub-challenges in one of the following three categories:

- Short-term challenges: 1 < AG ≤ 1.5
- Mid-term challenges: 1.5 < AG < 2
- Long-term challenges: AG ≥ 2

APPENDIX 2

Impact and effort scores

As only nine challenges were defined for the first cluster, all of them ended up being key challenges. Effort and impact analyses were still performed, as shown in Figure 14. For all challenges, the impact score was above 0.5. Therefore, in the graph only the quadrants for quick wins and major projects are shown, as the other two quadrants are empty.

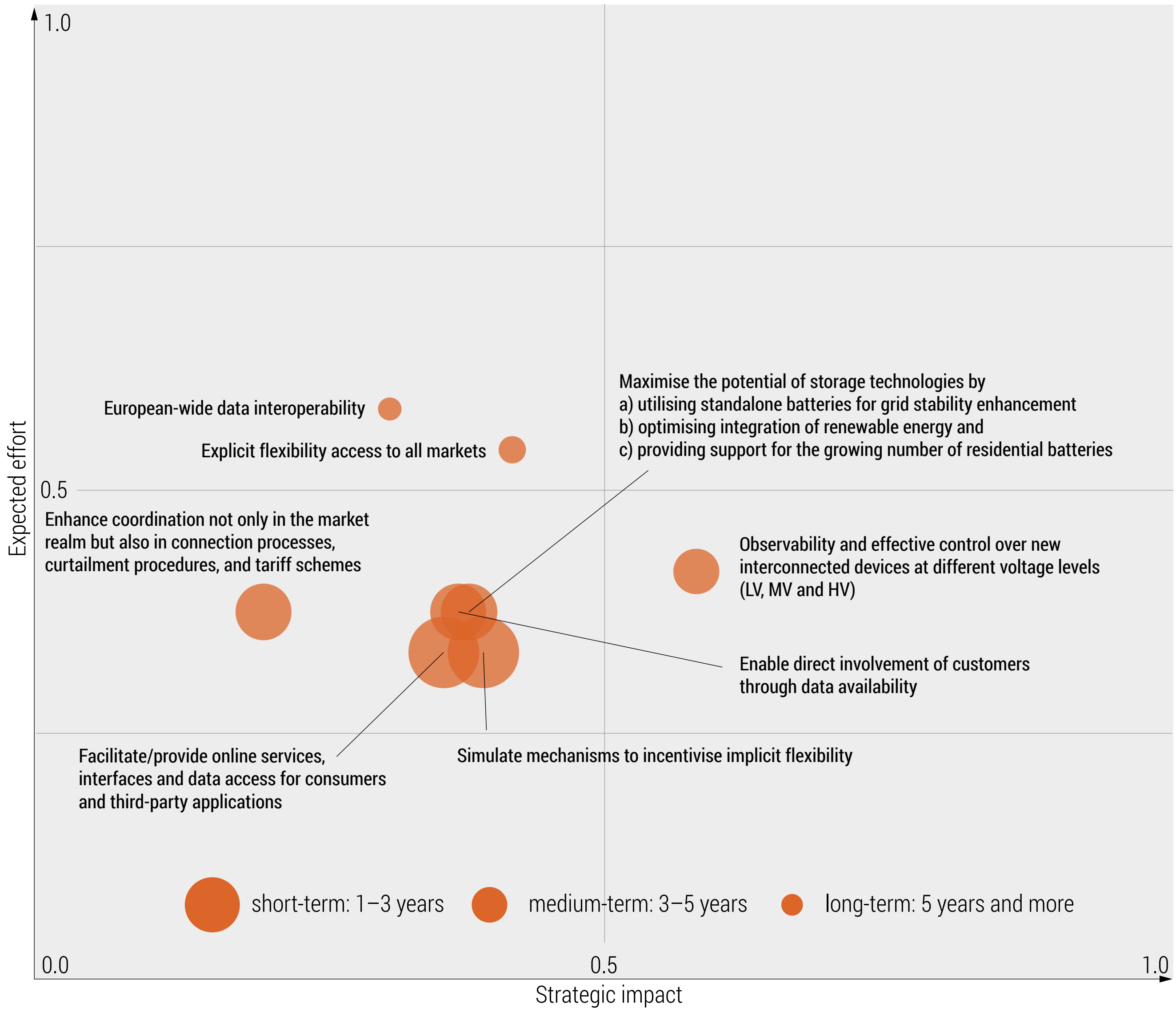

Figure 14: Result of effort versus impact analysis for cluster 1

For the second cluster, fourteen sub-challenges were defined, ten of which were prioritised during the effort versus impact analysis. The effort score had a larger weight when prioritising sub-challenges, and hence the four sub-challenges with the lowest impact score (0.37–0.52) were omitted. Figure 15 shows the results of the effort versus impact analysis for the second cluster, where all four quadrants are shown.

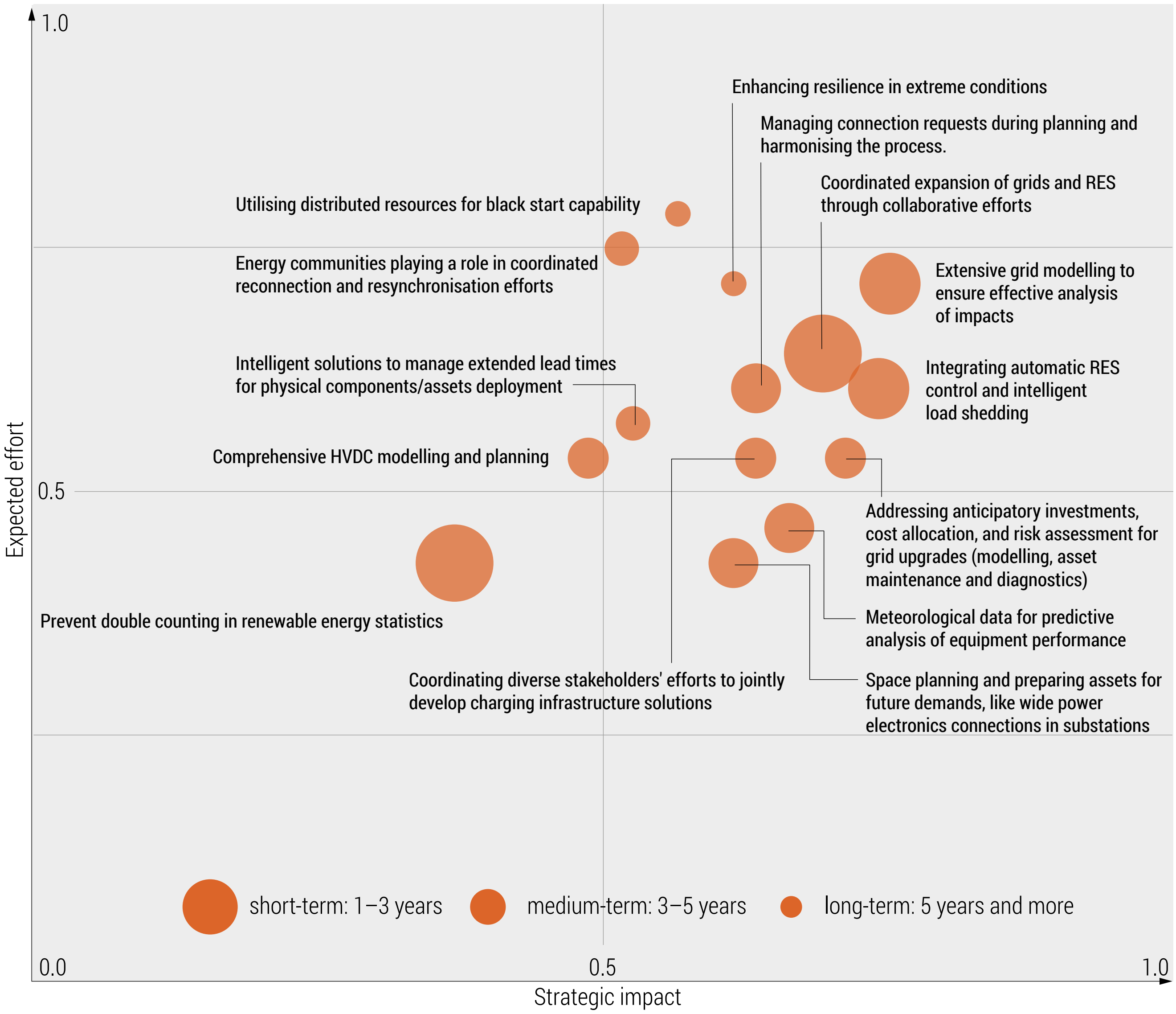

Figure 15: Result of effort versus impact analysis for cluster 2

The largest number of sub-challenges was identified in cluster 3 (22). Although the impact score was high at over 0.6 for all defined sub-challenges, it was necessary to create a list of prioritised challenges based solely on the impact score. Figure 16 below shows the impact and effort score, although the representation is focused on the upper-right quadrant as all the challenges fell in that category as major projects, with high impact and high effort. As for the second cluster, prioritisation was performed based on the impact score, whereby the eight sub-challenges with the highest impact (≥0.71) were taken as high-priority ones. In the later stage, after further evaluation by the experts, one additional sub-challenge was added ("critical elements vulnerable to HILF events").

Figure 16: Result of effort versus impact analysis for cluster 3

APPENDIX 3

Aligned list of sub-challenges per cluster

JTP DESAP identified relevant bottlenecks foreseen by both TSOs and DSOs towards a future and fully digitalised electricity system. Three clusters categorise the identified challenges:

- Customers, business, market, data and information exchange
- Planning, future flexibility, and assets lifecycle
- System operations, dynamics, and control rooms of the future

The identified challenges consider all relevant short- and long-term bottlenecks for securing the planning and operation of electricity networks. The insights gathered from brainstorming sessions conducted prior to the summer were carefully reviewed and refined, ensuring that the identified sub-challenges are not overly broad and initially understood as issues that can be directly or indirectly addressed by DT solutions and SGIs. These sub-challenges and their prioritisation will thoroughly be described in a standalone deliverable (D2.1 in WP 2) and specific requirements will be outlined for the selection of the most interesting challenges, giving priority to problems addressing power system digitalisation.

Customers, business, market, data and information exchange

Challenge	#	Sub-challenge	Description	Impact score	Effort score	Exp. time-frame score	Prior. score
TSO-DSO coordinated access to distributed resources	1	Enhance coordination not only in the market realm but also in connection processes, curtailment procedures, and tariff schemes	Identify opportunities to optimise connection timelines, reduce administrative burdens, and ensure that the connection process aligns seamlessly with evolving grid needs. Address curtailment challenges by designing coordinated procedures that balance the needs of both TSOs and DSOs. Analyse existing tariff structures and propose harmonised schemes that align with the interests of both TSOs and DSOs.	0.60	0.38	1.5	1.60
New load and demand patterns	2	Maximise the potential of storage technologies by a) utilising standalone batteries for grid stability enhancement, b) optimising integration of renewable energy and c) providing support for the growing number of residential batteries	From a grid management perspective, electrochemical batteries are suitable for frequency balancing, voltage stability or congestion management. Exploring challenges comprehensively with a focus on applications: standalone battery solutions that demonstrate measurable improvements in grid capacity and stability, storage solutions that optimise the integration of renewable energy into the grid, and the prevalence of residential batteries and their integration into broader energy infrastructure.	0.69	0.38	1.5	1.84

Challenge	#	Sub-challenge	Description	Impact score	Effort score	Exp. time-frame score	Prior. score
	3	Observability and effective control over new interconnected devices at different voltage levels (LV, MV and HV)	The observability and controllability of resources connected at the distribution level and grid system conditions will also become increasingly crucial. The visibility of power flows and market parties' actions is important in all timeframes to ensure the safe operation of the system. The increased time and geographical granularity of information are important but also more challenging to obtain (observability and management of flexibility from other energy carriers, such as molecules, heat, etc.). Accessing more granular and timely information about the performance and condition of assets would help to improve energy network modelling and allow for more accurate optimisation of the network.				
	4	Understanding and quantifying the global system costs that arise when coupling gas and electricity systems and identifying the impact of missing infrastructure on overall system efficiency	Sector coupling technologies such as electrolysis, heat pumps, and EVs will foster a more integrated energy system with the electricity sector in the centre. At the same time, decentralised generation and storage – along with higher and more dynamic loads – will bring the distribution networks more into focus. It is important to develop methodologies to accurately measure costs, considering factors such as investment requirements, OPEX, and the long-term implications on both energy systems. By considering transmission and distribution infrastructure, storage facilities, and interconnection capabilities, missing links on reliability and resilience could be explored and the full potential of coupling gas and electricity systems could be harnessed.				
Flexibility assessment and development (incentives for demand side, optimal build-up and use of flexibility portfolio)	5	Explicit flexibility access to all markets	• Independent aggregation • Harmonisation of flexibility products • Demand-side participation in day-ahead and intraday markets • Resource registration • Standardised communication	0.71	0.54	2.2	1.31

Challenge	#	Sub-challenge	Description	Impact score	Effort score	Exp. time-frame score	Prior. score
Consumers' prices, roles, needs, and preferences	6	Enable the direct involvement of customers through data availability	End users require access to near real-time information on their energy consumption and/or generation to actively engage in the European energy market. Such data can be sourced from smart meters and supplemented with dedicated measurement devices for detailed granularity. This data availability enables customers to modify their energy behaviours; for example, based on signals received from market actors. Moreover, it is crucial to empower these customers to share their near real-time data with approved innovative energy service providers for involvement in activities such as aggregation, peer-to-peer trading, and energy communities. To facilitate this exchange, either DSOs, TSOs, or specific roles designated by member states should provide digital means for data sharing.	0.69	0.38	1.5	1.83
	7	Simulate mechanisms to incentivise implicit flexibility	Implicit flexibility programmes that are embedded in the energy supply contract, and consumers can use demand-side response (DSR) by adjusting their consumption without being triggered by a control signal. Implicit DSR is adjusting consumption triggered only by price signals via static or dynamic pricing. This challenge calls for developing sophisticated simulation tools that not only model implicit flexibility but also test and refine incentive mechanisms.	0.68	0.33	1.3	2.04
	8	Facilitate/provide online services, interfaces, and data access for consumers and third-party applications	In our increasingly digitalised world, individuals have grown accustomed to managing a wide array of services online, from their bank accounts and credits to booking flights and more. It is imperative that every step of customers' grid interaction processes becomes seamlessly paperless, digital, and readily accessible online for all market participants to foster efficient customer relationships in the energy sector. This transition begins with the online application and ordering processes for all energy-related services, including applications for services such as charging points, facilitating easy access to and sharing of meter data, providing direct online access to information regarding application or account statuses, and offering online self-services for service alterations or additions. Furthermore, both customers and energy service providers require public access to pertinent information, such as the availability of nearby grid connection points, system operators' flexibility needs, the spectrum of energy services needed in specific areas, and details regarding the rollout of new services (e.g. demand response programmes) in terms of location and schedule.	0.66	0.58	1.3	1.12

Challenge	#	Sub-challenge	Description	Impact score	Effort score	Exp. time-frame score	Prior. score
	9	European-wide data interoperability	Addressing challenges in smart infrastructure involves tackling key aspects such as standardisation (data models, formats, communication protocols). Establishing one-stop shops for data provision and access is crucial, demanding robust technological solutions and comprehensive frameworks for governance. The development of a pan-European infrastructure (Data Space) adds complexity, requiring harmonised governance and technological integration across diverse landscapes for successful implementation.	0.70	0.33	2.3	2.09

Planning, future flexibility, and assets lifecycle

Challenge	#	Sub-challenge	Description	Impact score	Effort score	Exp. time-frame score	Prior. score
Grid and system resilience	1	Enhancing resilience in extreme conditions	Climate change-induced environmental turbulence raises the likelihood of incidents that can affect not only the physical integrity of grid components – potentially resulting in issues such as ground faults – but also the overall system's stability. This instability might lead to situations involving partial disconnection from the grid, among other disruptions. Additionally, the system faces heightened loads due to diverse weather conditions such as extreme heat, cold, wind, snow, and more. To address these challenges, grid components must be designed with greater resilience in mind or undergo strategic restructuring, such as the replacement of overhead lines with underground ones for added protection. Other strategies can further bolster grid resilience, including increased monitoring for early identification of problems, redundancy planning, and implementing solutions such as automatic network reconfiguration and intentional islanding. Moreover, it is imperative to incorporate resilience considerations as an integral part of planning activities, accounting for the probability of events and potential cascading effects. This entails introducing risk-based matrices into investment planning scenarios. On the other front, the digitalisation of grid operations offers grid operators enhanced efficiency, transparency, and observability through data loggers, measuring devices, and remote asset control. However, this remote accessibility to critical grid components introduces the risk of potential cyber threats, underscoring the importance of a comprehensive approach to deploying and configuring IT infrastructures to ensure compliance with essential cybersecurity standards.	0.61	0.71	2.0	0.85
	2	Energy communities playing a role in coordinated reconnection and resynchronisation efforts	This challenge focuses on harnessing the potential of energy communities to actively participate in coordinated reconnection and resynchronisation efforts following disruptions to the energy grid, thus creating a more decentralised, adaptable, and resilient energy ecosystem that can effectively navigate and recover from disruptions.	0.51	0.75	1.7	0.69

Challenge	#	Sub-challenge	Description	Impact score	Effort score	Exp. time-frame score	Prior. score
	3	Meteorological data for predictive analysis of equipment performance	By analysing historical data, weather patterns, and network conditions, predictive analytics algorithms can identify early warning signs of equipment failure or degradation by extracting valuable insights from large datasets to predict future trends and events. Moreover, these analytics prove instrumental for "innovative" digital solutions such as DLR and play a pivotal role in the strategic planning of the system, encompassing aspects such as vegetation management, soil erosion, rights of way, etc. This integration with asset management is essential, serving as a proactive measure to reduce potential future problems, including congestion and bottlenecks, particularly concerning DLR and thus fostering more effective and comprehensive planning.	0.66	0.46	1.4	1.42
	4	Utilising distributed resources for black start capability	New approaches to grid resilience will need to be developed, e.g. black start capability from new flexibility resources. An example is the use of HVDC converters and their control for black start capability especially for meshed offshore grids where both generation and load are connected. Technical requirements for potential interaction with the alternating current (AC) grid system are considered, along with appropriate protection systems during restoration conditions and HVDC fault ride-through capability. Another example is the coordinate use of aggregated EV batteries as distributed bottom-up process for black start, which shall require a deep and fast cooperation between DSOs and the incumbent TSO.	0.56	0.79	2.0	0.72
Additional network (TSO-DSO) infrastructure	5	Coordinating diverse stakeholders' efforts to jointly develop charging infrastructure solutions	This challenge calls for a scalable and well-integrated strategy for charging infrastructure deployment, including aligning future grid expansion plans with charging infrastructure requirements, ensuring a harmonised and future-proof approach. This involves assessing grid capacity, demand response capabilities, and potential grid upgrades to accommodate increased charging loads without compromising overall grid stability. All of the above must pursue smart charging by default, and V2G whenever viable, requiring digital platforms and tools for jointly exploiting the flexibility from EVs being charged on either distribution or transmission grids.	0.63	0.54	1.6	1.17

Challenge	#	Sub-challenge	Description	Impact score	Effort score	Exp. time-frame score	Prior. score
Coordinated TSO-DSO grid planning (exchange of necessary info)	6	Coordinated expansion of grids and RES through collaborative efforts	This challenge calls for integrated plans for the simultaneous expansion of grids and integration of RES. A more efficient infrastructure development process could be facilitated by aligning grid expansion strategies with the geographical distribution and capacity of RES projects. The same is applicable to EV charging infrastructure, which needs to be coordinated with RES penetration to avoid lacking the desired decarbonisation effect.	0.69	0.64	1.1	1.07
	7	Integrating automatic RES control and intelligent load shedding	• This challenge calls for a joint assessment of RES capacity, load profiles, and grid infrastructure requirements to design and implement automatic RES control algorithms that dynamically adjust renewable energy generation in response to grid conditions. It is intended that the modulation of variable RES is compensated by sector coupling energy conversion plants. • Furthermore, algorithms prioritise non-critical loads and shed them in a controlled manner, preventing cascading failures and maintaining grid stability during periods of high demand or unexpected disturbances. More generally, Load shedding must become smart, i.e. linked and managed through market mechanisms. Partial shedding should be applied with a merit order logic, where the merit is the hourly bid for accepting a progressive reduction in maximum withdrawal capacity at the given connection point.	0.73	0.61	1.3	1.21
	8	Addressing anticipatory investments, cost allocation, and risk assessment for grid upgrades (modelling, asset maintenance and diagnostics)	It is important to develop methodologies for anticipatory grid planning considering factors such as the electrification of transportation, increased renewable energy adoption, and emerging technologies that might affect grid requirements. It is also important to explore grid enhancement strategies and multi-year investment plans that align with the anticipated needs of both TSOs and DSOs, minimising the total cost of ownership while ensuring grid reliability. This will entail more sophisticated modelling of complex systems, with many interrelated variables, most of them of stochastic nature (load, generation, equipment failure, external parameters, etc.). DTs of complex systems here shall hold paramount importance here. It is also important to optimise current grid operations by prioritising asset maintenance and diagnostics, emphasising the utilisation of existing assets, and fostering data exchange among TSOs to enhance knowledge-sharing and improve overall efficiency.	0.70	0.54	1.6	1.32

Challenge	#	Sub-challenge	Description	Impact score	Effort score	Exp. time-frame score	Prior. score
	9	Comprehensive HVDC modelling and planning	This challenge calls for advanced models for HVDC systems that accurately simulate their behaviour under various operating conditions, incorporating factors such as converter technologies, and control strategies, and responding to dynamic grid events. A multi-objective planning framework should consider the diverse requirements of grid integration, RE integration, and system resilience.	0.49	0.54	1.6	0.91
Development of RES infrastructure (incl. Offshore grids)	10	Intelligent solutions to manage extended lead times for physical components/assets deployment	This challenge calls for developing predictive procurement strategies that leverage data analytics, forecasting techniques to anticipate future demand for critical components, BIM models of power equipment for faster, and precise project design. Thereby, uncertainties in lead times could be minimised (potentially if virtual replicas of physical components and assets are designed, it could enable the simulation and analysis of deployment scenarios, thereby identifying potential challenges, optimising logistics, and fine-tuning deployment strategies).	0.52	0.57	1.7	0.92
Rapid Integration of RES	11	Prevent double counting in renewable energy statistics	This challenge calls for a transparent tracking system that provides a clear and auditable trail of renewable energy attributes from generation to consumption (through the use of blockchain or other distributed ledger technologies, secure and tamper-resistant records could be generated, ensuring the authenticity and uniqueness of reported renewable energy statistics). A similar need applies for CO_2 accountability.	0.37	0.43	1.1	0.87
	12	Space planning and preparing assets for future demands, such as wide power electronics connections in substations	The development of a strongly interconnected and hybrid AC/DC power system with high renewables penetration and power electronics integrated devices will result in the magnification of stability phenomena. By considering factors such as population growth, urbanisation, industrial expansion, and the electrification of sectors, strategic space planning in substations and related infrastructure could be pursued. Space planning could also use BIM models (3D models of substations) to optimise maintenance activities by checking with the 3D model if it is possible to ascertain which parts of the substation need to be shut down during the maintenance and ones which can continue to operate.	0.61	0.43	1.4	1.42

Challenge	#	Sub-challenge	Description	Impact score	Effort score	Exp. time-frame score	Prior. score
	13	Extensive grid modelling to ensure effective analysis of impacts	This challenge focuses on developing and utilising sophisticated grid models to ensure a comprehensive and effective analysis of impacts on the energy grid. Modelisation must extend to other coupled sectors, including transport, heat, gas, and hydrogen.	0.74	0.71	1.3	1.04
	14	Managing connection requests during planning and harmonising the process	This challenge calls for creating a unified platform that facilitates communication and collaboration among stakeholders, streamlining the process of evaluating and approving new grid connections. Prioritising grid reinforcement and expansion is crucial. To synchronise development pace with increasing demand, a shift from a reactive, incremental approach to a proactive, future-oriented strategy is essential for both TSOs and DSOs. Such an approach mandates DSOs to foresee future connections and anticipate demand surges for improved network upgrade planning and collaborate with TSOs to ensure the readiness of all voltage levels of the electricity infrastructure. It is also vital for DSOs to possess accurate asset information, including specifications of cables, transformers, and other system components, and understand the load factors affecting these assets. Furthermore, network planning methodologies should be tailored to champion a consumer-centric model, which entails discerning future consumer needs to construct scenarios that optimise capacity and minimise limitations. Enhanced collaboration and data exchange between DSOs and TSOs will be instrumental in shaping a cohesive vision for the future grid.	0.63	0.61	1.4	1.04

System operations, dynamics, and control rooms of the future

Challenge	#	Sub-challenge	Description	Impact score	Effort score	Exp. time-frame score	Prior. score
TSO-DSO coordinated access to distributed resources	1	Monitoring ancillary services and enhancing active system management	incorporation of additional measuring points and devices yields an increased volume of data points. This raises specific operational challenges as it makes forecasting, observability and controllability complex and requires coordinated access to resources between TSO and DSO for sourcing ancillary services. These data points can be employed to discern the unseen physical states of system components that are either not directly measured or inherently immeasurable. By combining this with refined weather forecasting, customer behaviour modelling, and comprehensive knowledge of virtually all grid-connected DER – inclusive of their online status and physical parameters – shall become feasible to predict day-ahead behaviours with minimal safety margins. Such predictive models enhance the dispatch and redispatch capabilities of major power plants, connected renewable generation, and flexibilities, thereby optimising the renewable contribution. Furthermore, the heightened observability and controllability facilitated by this data-centric approach provide robust countermeasures in the event of system component failures. These countermeasures include the swift redirection of power flows through alternative switches or grid connection points and the rapid activation of flexibility solutions, such as bidirectional charging.	0.81	0.75	1.4	1.08
Exponential growth in grid complexities	2	Lack of proper coordination mechanisms resulting in harmful effects such as counter-activation	One single asset – if appropriately pre-qualified – might be able to provide flexibility for congestion management in the DSO grid, congestion management in the TSO grid or balancing performed by the TSO. Therefore, there is a need to ensure coherence between all congestion management and balancing bids. For system operators to communicate their needs in different timeframes, proper interaction is required between two merit order lists (MOLs) or joint optimisation allowed to enable value-stacking, avoid double activation of the same asset and ensure secure operation of grids by performing coordinated grid impact assessment.	0.77	0.78	1.4	1.00

Challenge	#	Sub-challenge	Description	Impact score	Effort score	Exp. time-frame score	Prior. score
	3	Precise forecasting by integrating factors such as weather dynamics, fluctuating load patterns (EVs, PVs, heat pumps) and shifting generation patterns	The quality of load and generation forecasting must improve due to its expected technical and economic impacts on the efficiency of the whole electricity system. Forecasts of injection and withdrawal of energy and power can be improved if observed connected resources are measured. The use of improved weather forecasts and AI (self-learning algorithms) will enable an effective energy system state forecast for all timeframes. The introduction of improved modelling of the energy system in which all forecasts are included will also offer the possibility to almost continuously perform load flow security and dynamic stability analysis calculations. At the same time, a better wind power forecast also reduces the need for balancing energy from the reserve markets, which often incurs a high cost that in turn reduces the profitability of the wind power producers. Measures for trusting the measurement data and baselines provided by flexibility service providers need to put in place.	0.76	0.80	1.7	0.95
Wider, deeper and greater grid visibility, predictability and controllability	4	Defining observability areas for critical HV, MV, and LV network zones	This challenge calls for prioritising areas where observability is crucial for maintaining grid stability, minimising downtime, and ensuring the reliable operation of the power network. TSOs and DSOs can proactively address issues, optimise performance, and maintain the reliability of the entire electrical network through advanced sensors within defined observability areas, optimisation algorithms and by considering factors such as network topology, critical nodes, and potential points of failure.	0.75	0.68	1.4	1.12
	5	Establishing control governance and interactions for new interconnected devices and domains	This challenge calls for creating a governance framework to facilitate seamless interactions and coordination – especially for the new interconnected devices – to enhance overall grid visibility, predictability, and controllability.	0.75	0.85	1.5	0.89
	6	Defining interfaces with other sectors to facilitate seamless sector coupling and interoperability	Defining standardised data exchange protocols to enable interoperability between the energy sector and other sectors. Establish common formats and communication standards for sharing data related to energy consumption, demand response, emissions, and other relevant parameters	0.73	0.70	1.9	1.04

Challenge	#	Sub-challenge	Description	Impact score	Effort score	Exp. time-frame score	Prior. score
	7	Identifying critical grid elements vulnerable to cyber attacks	Comprehensive vulnerability assessments are necessary to identify potential weaknesses in critical grid elements as well as detailed maps of critical grid infrastructure, highlighting key elements and their interdependencies. This includes substations, control systems, communication networks, and any interconnected devices. It involves evaluating susceptibility to cyber threats and potential points of entry for attackers. In the event of a detected cyberattack, it is important to adhere to established guidelines and implement varying levels of TSO/DSO response based on the specific infrastructure or software under attack.	0.73	0.68	1.3	1.08
	8	System resilience through shared risk assessment methods	This challenge calls for a standardised risk assessment framework that includes common methodologies, risk categories, and metrics, providing a unified approach for evaluating risks to different components of the energy system.	0.71	0.83	2.2	0.86
Grid stability (PEs, new loads, storage, sector coupling) / Increasing power electronics	9	Shared portfolio of countermeasures to mitigate risks and enhance overall system resilience	By establishing consensus on the most critical risks that require targeted countermeasures, a standardised framework for countermeasures could be developed, which would potentially enhance the resilience of the energy system.	0.71	0.70	1.5	1.01
	10	A comprehensive register of technical resources for short, mid, and long-term planning across sectors	With the increase of RES, there is an increased risk that disturbances due to a change in demand or generation (e.g. loss of a circuit or generator) propagate more rapidly through the network. Bringing together data on the topology of the network, electric characteristics, power system generation models, network conditions, and variance of energy production from renewable in a register will enable a better understanding of the network's stability and how to mitigate potential system instability. Ensuring high resolution in the measurements is crucial to capturing the dynamics of power system phenomena with the increase of RES. This might necessitate the expansion of phasor measurement units (PMUs) installed in the system.	0.71	0.78	1.3	0.91

Challenge	#	Sub-challenge	Description	Impact score	Effort score	Exp. time-frame score	Prior. score
	11	Ensure network power quality	Power quality is the extent to which the power frequency, voltage, electric current, and power factor lie between the dimensioned values. If we take a close look at this response to the driver, we can identify that it is not only a one-dimensional problem. There is a need to have an effective overview of the assets regarding location, dimensions, etc. Furthermore, sensoring and real-time monitoring of the assets to gain knowledge of the load factors during each day of the year holds vital importance. Effective models are also needed to predict where to expect the highest increase of DER in our network, e.g. in case of PV in urban grids, information such as available roof surface, roof orientation, and the capability of the owner to invest can be useful. With this information, DSOs are more capable of planning and prioritising civil engineering measures and performing other operations, such as maintenance works.	0.70	0.63	1.4	1.12
Predictive behaviour of future systems	12	Effective asset management despite incomplete or unreliable data from emerging technologies	Traditional reactive asset management practices entail replacing components only upon the occurrence of an incident. By contrast, proactive asset management seeks to pre-empt such incidents, minimising durations where customers or market participants might be adversely affected. With this approach, statistical data and predictive models are utilised to automate the processes of equipment ordering, commissioning, and the necessary civil work for anticipated replacements. Beyond mere statistical replacements, the integration of active equipment monitoring and advanced techniques such as deep learning or fault analysis permits early detection of potential damages to system components. This foresight empowers DSOs to enact preventive measures, ensuring that component functionality is maintained without reaching the point of failure. In a parallel effort, there are also projects leveraging predictive analytics – including weather data and satellite information – to plan measures for protecting electrical lines, power plants, and other utility assets from unwanted vegetation.	0.69	0.78	1.9	0.89

Challenge	#	Sub-challenge	Description	Impact score	Effort score	Exp. time-frame score	Prior. score
Sector integration (with DSOs and other sectors) including governance	13	Uncoordinated processes in grid planning, operation, and market coupling, including risk assessment, connection requests, and generation/load forecasting	Streamlining connection procedures, implementing collaborative forecasting models, and creating unified risk assessment frameworks are essential for addressing uncoordinated processes.	0.67	0.65	1.8	1.04
	14	Interoperability challenges with sectors like heat, gas, transportation, health, and manufacturing	To facilitate effective interoperability and data exchange, it is necessary to define agreed taxonomies and ontologies, including metadata standards.	0.67	0.73	1.4	0.93
Predictive behaviour of future systems	15	Using AI to forecast future system behaviour and performance with the integration of new technologies.		0.67	0.75	1.4	0.90
	16	Using asset reliability and risk-based methodology to assess the health and potential risks of assets	This challenge calls for a system that can remotely display the state of equipment and components, the severity of the problem, the description of the fault, the processing method, etc. in real time. Thus, remote and online diagnosis of equipment can be realised.	0.67	0.60	1.1	1.11
New grid capabilities (grid forming, modular multi-level converters, synch condensers)	17	Precise and reliable measurement techniques to monitor grid performance	Expansion of PMUs on the grid is crucial for real-time monitoring and control. With synchronised data, PMUs enhance grid reliability and can prevent failures.	0.67	0.65	1.3	1.03
	18	Conceptual framework for the grid architecture that outlines the arrangement of components and their interactions.		0.67	0.75	1.5	0.89
Automated controls (for system response and decision-making support)	19	Trustworthiness and reliability of automated control systems in real-time grid operation	As the number of PMU network on the grid expands, the grid's observability will improve. Wide area monitoring, protection, and control (WAMPAC) could harness real-time data from PMUs to not only monitor the grid but also implement control actions, enhance system stability, and optimise power flow in response to dynamic conditions.	0.67	0.78	1.7	0.86

Challenge	#	Sub-challenge	Description	Impact score	Effort score	Exp. time-frame score	Prior. score
	20	Interactions between different control systems to ensure coordination and efficient operation	Unified data models that ensure consistency in the representation of information across different control systems.	0.63	0.70	1.4	0.90
Sector integration (including governance)	21	Properly defining interfaces between sectors and understanding how these interfaces impact on overall integration process, including technical, operational, and regulatory considerations.	Ensuring compatibility and standardisation of data formats and communication protocols across sectors. It is important to design interfaces that allow for seamless integration between different systems.	0.63	0.60	1.1	1.04
Coordinated TSO-DSO grid operation (exchange of necessary info)	22	Standardising the grid operation processes, including voltage control, congestion management, outage scheduling, power flow control, balancing, and restoration to enhance system efficiency.	exchange data from both internal and external systems across their enterprise (e.g. planning, operations, etc.) to effectively plan and operate the grid. However, the input from these systems typically has its own data formats and team of experts to manually maintain each model. Inconsistencies in model data across these domains result in model inaccuracies, sub-optimal system performance, possible regulatory violations, excessive manual labour, and other additional resulting losses. For optimal grid performance, utilities require a solution that can provide seamless/unified data exchange between internal and external utility domains. This also holds true for the fundamental parameters and standardised data of power equipment. The adoption of a common data format would significantly facilitate knowledge and experience sharing within the power industry.	0.61	0.60	1.5	1.02

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