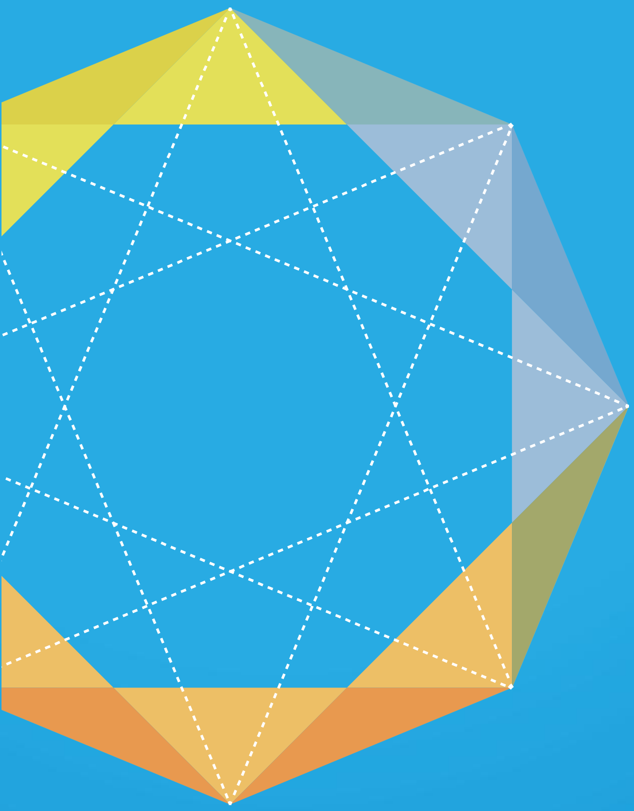
European
Commission

Enhanced System Supervision and Control

ETIP SNET WG 4
Digitalisation of the
Electricity System



ETIP SNET

European Technology and Innovation Platform
Smart Networks for Energy Transition

Authors
Aris Dimeas (NTUA)
Nikos Hatziargyriou (NTUA)
Miguel Ángel Sánchez Fornié (Comillas Univ)
Nuno Souza e Silva (R&D Nester)
Albana Ilo (TU Wien)
Andres Guimaraes Madureira (Sustainable Energy Systems Group)
Metody Georgiev (TU Sofia)
Panagiotis Papadopoulos (Unin of Manchester)
Rajkumar Palaniappan (H&S Hard- and Software Technologies)
Mohammed Al-Saadi (DERlab)

Acknowledgements
The editors would like to acknowledge the valuable inputs from
Mark McGranaghan (EPRI)
George Korres (NTUA)
Laura Grana (ENEL Grids)
Elena Boskov (Bueprintenergy)

EUROPEAN COMMISSION

Directorate-General for Energy
Directorate B – Just Transition, Consumers, Energy Efficiency and Innovation
Unit B5 – Innovation, Research, Digitalisation, Competitiveness

Contact: Mugurel-George Păunescu

E-mail: mugurel-george.paunescu@ec.europa.eu

European Commission
B-1049 Brussels

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PDF Web	ISBN: 978-92-9405-355-8	doi: 10.2926/3049028	HZ-01-25-167-EN-N

Manuscript completed in December 2025
Luxembourg: Publications Office of the European Union, 2025

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1. EXECUTIVE SUMMARY

This document focuses on the enhanced supervision and control requirements of current power systems faced with a large penetration of variable renewable energy sources (RES) into transmission and distribution networks.

A brief overview of current developments and trends in hardware and control equipment and functionalities for energy management and system control at Transmission and Distribution level is provided, including energy management systems, advanced distribution management systems, distributed energy resources management systems, transactive energy systems, phasor measurement units and wide area monitoring systems, advanced meters and flexibility platforms. The key challenges regarding data availability, granularity and compatibility are identified next. Special emphasis is placed on cybersecurity threats.

The available digital solutions, including data analytics, energy data spaces, internet of things, artificial intelligence and machine learning (AI/ML) and digital twins are described together with selected industrial or pilot research applications and good practices. The current and future state of emerging computational technologies, including parallel and distributed computing, quantum computing, GPU computing and edge intelligence is also overviewed.

High level recommendations on R&I support and R&I priorities conclude this document.

2. INTRODUCTION AND SCOPE OF THE DOCUMENT

The large penetration of variable renewable energy sources (RES) into transmission and distribution networks poses multiple operational and planning challenges that require the transformation of existing power system infrastructures, new ways of operation and control and new market structures. The key operational challenges concern the required flexibility to compensate for RES volatility and enhanced forecasting accuracy in a highly uncertain environment. They also include new methods for control to ensure angle, voltage and frequency stability, along with new forms of converter-driven stability.

Distribution networks are becoming active networks as they continue to accommodate an increasing number of distributed energy resources, including distributed generators, storage devices, flexible demand and electric vehicles. As renewable energy sources displace thermal generators that have traditionally provided the necessary flexibility, distributed energy sources now become valuable flexibility resources for managing the system. Alongside the management of the centralized generation units – both thermal and renewable – the management of numerous dispersed resources is gradually making system control more decentralized. Modern control systems – both EMS and DMS – reflect this but they need to be enhanced with new tools and methods.

One key challenge of power network supervision and control is the increased need for observability, defined as the temporal, geospatial, and topological awareness of grid variables and assets. Increased observability provides adequate knowledge about the grid and its behaviour, thus supporting not only the operation of networks but also decision-making for investments.

Regarding power system operation:

- it enhances the efficient use of flexibility resources for voltage control and effective congestion management;
- it ensures stable and efficient power delivery;
- it reduces the risk of outages and bottlenecks;

Observability also enables seamless system integration, facilitating the harmonious operation of diverse energy sources and technologies.

Active asset and system management are also improved, as observability enables predictive maintenance and optimised performance of grid components, ensuring a reliable supply as demand escalates.

Focusing on the challenges for supervision and control, RES, like solar and wind, are inherently variable and weather-dependent, making it difficult to predict and balance supply and demand in real time. Traditional grid systems, originally designed for predictable and centralised power generation, struggle to accommodate the decentralised and intermittent nature of RES. This variability can lead to frequency deviations, voltage instability, and the need for flexible and responsive balancing resources. Supervisory systems must now incorporate advanced forecasting tools, real-time monitoring, and enhanced control algorithms to ensure reliability, stability, and efficiency while managing the complexities introduced by RES.

Digitalisation has become a critical enabler in addressing these challenges. Advanced digital tools, including Internet of Things (IoT) sensors, artificial intelligence (AI), and machine learning (ML), provide means to collect, analyse, and act on vast amounts of data generated by distributed RES. For example, digital twins and predictive analytics allow operators to simulate and prepare for different scenarios, optimising grid operations despite the uncertainty of RES outputs. Moreover, digitalisation facilitates the integration of demand response programs, storage solutions, and decentralised control strategies, creating a more flexible and resilient power system. However, these benefits come with challenges, including cybersecurity risks, the need for robust communication networks, and significant investment in new infrastructure and workforce training. These topics are presented in more detail in the following sections.

3. HARDWARE AND CONTROL SYSTEM REQUIREMENTS FOR REAL-TIME CONTROL

Safety, reliability and efficiency are the main objectives of all electricity grid operators. The latter fulfil their goals in the control centre, the power grid's brain that senses its pulse, controls its state by coordinating its movements and protects against exogenous events. Many transmission and distribution system operators (TSOs and DSOs) operate the power system – the most giant electromagnetic machine ever built by man – within their territories. Usually, one TSO control centre communicates and coordinates with many neighbouring DSO- and TSO-control centres, as shown in Figure 1. Each TSO and DSO is supported by the technology available in the control centres to perform the processes required to fulfil their operational functions. As the electricity grid is the most critical infrastructure in our society, the demands on the availability of technology are very high. It requires a yearly availability of 99.95% or more, meaning the technology supporting the process cannot be out of service by more than 230 minutes or 3.83 hours a year. **The supporting technologies for the operation of power systems in the future should guarantee a yearly availability of 99.95% or more.**

Figure 2 shows the current level of automation in traditional electricity grids and the expected one in smart grids for different fractal smart grid levels. The latter is the high-, medium and low voltage (HV, MV, LV) and customer plant (CP) levels. The supporting technologies in traditional control centres operate online and mainly advise the operator. The load-frequency control is the only control technology in the closed loop used in almost all TSO control centres. The local controls on the grid usually operate uncoordinated, like On-Line Tap Changers (OLTCs), which are widely used at VHV, HV, and MV levels, etc. The distribution transformers (MV/LV) are widely used with fixed tap changers. At the CP level, no automation is available.

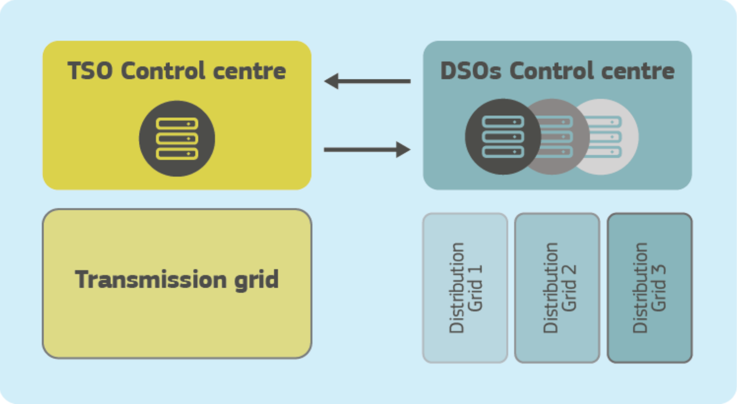

Figure 1 Holistic view of the control centres in the traditional power system

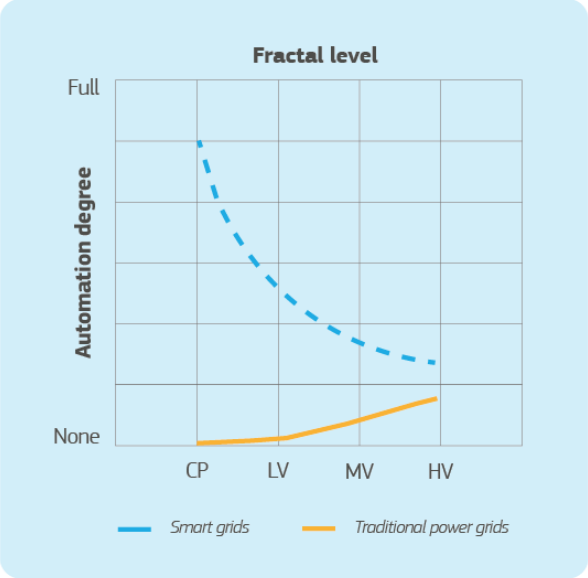

Figure 2 The current level of automation in traditional electricity grids and the expected one in smart grids for different fractal smart grid levels.

As part of the energy transition, the structure of the electricity grids changes. A smart grid monitors[1], protects and automatically optimises the operation of its electrical appliances – from the central and distributed electricity production and storage installations through the transmission and distribution grids to customer plants such as

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[1] Ilo, A. (2022). *A holistic solution for smart grids based on LINK–Paradigm* (pp. 68–81). Springer. ISBN 978-3-030-81529-5.

industrial users, building automation systems, and thermostats, electric vehicles, and other household devices. Therefore, it is evident that increased real-time automation is expected in smart grids. While full automation is assumed at the CP level, as shown in Figure 2, the degree of automation of the grid decreases with the voltage level. In these conditions the control centres must constantly evolve to cope with the changes in the operation of the power system.

The interaction between TSOs and DSOs is essential nowadays. Conventionally, DSOs served customers vertically from the transmission system, while now distribution systems are active networks, with DERs contributing to markets and congestion issues. The issues around the area of responsibility between balancing the frequency with DER versus managing voltage and congestion on distribution networks are challenging to resolve. They will require a new architecture, appropriate standardised data exchange, improved data visualisation, and social interaction of the customers with the energy communities and operators in distribution control centres. The latter will probably be more closely linked to complementary aspects, such as telecommunications networks, monitoring of information systems or plant monitoring, market fluctuations or even social networks. Models and procedures for assessing the potential area of application should be shared online across all these interfaces during real-time operation. They could potentially be jointly designed by stakeholders and regularly adapted offline prior to operation.

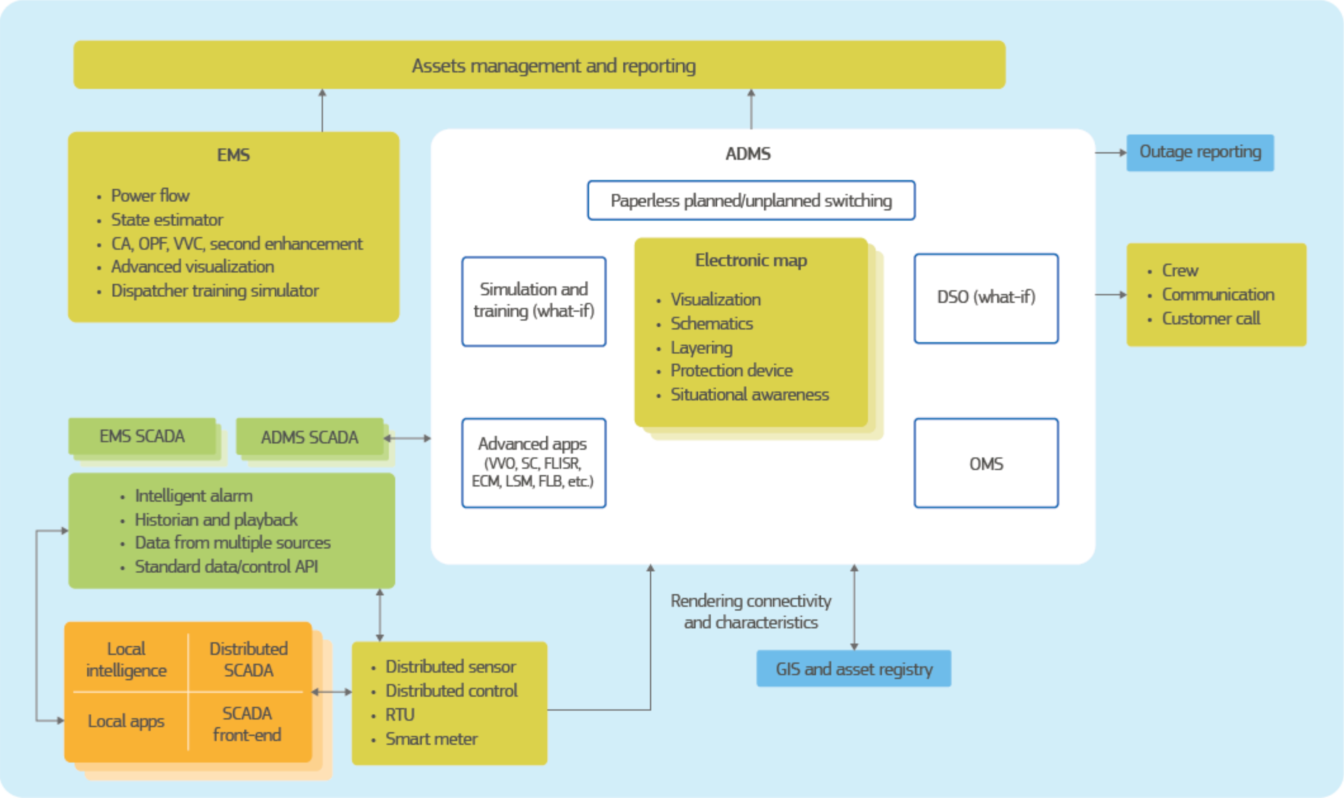

Figure 3 An integrated EMD-ADMS system architecture

3.1 Energy Management Systems (EMS)

Traditiona e l EMS operate in a purely centralized way and were often integrated with supervisory control and data acquisition (SCADA) systems. It was the role of TSOs and large utilities to be the ones responsible for generation, transmission and distribution management using a top-down approach. Nevertheless, with the advancements in computing power and automation technologies, DMS as well as advanced distribution management systems (ADMS) began to emerge. These systems extend the monitoring and control capabilities of traditional EMS to the distribution grid level, particularly at MV and even LV, which improved situational awareness and provided more advanced functionalities for grid operation.

With the growing penetration of DERs, namely solar PV generators, wind power generators as well as battery storage systems and demand-side flexibility, grid management has become more decentralised. This change of paradigm has further advanced due to the increasing digitalisation of the energy sector, powered by artificial intelligence (AI) and distributed ledger technologies such as blockchain, which has enabled peer-to-peer (P2P) energy transactions. These developments made it possible to have improved decision-making at the grid edge, thus allowing for more dynamic operation, close to real time.

Consequently, novel solutions such as distributed energy resource management systems (DERMS) with recent innovations on edge computing as well as decentralised market platforms are now able to complement traditional EMS and DMS. Simultaneously, TSO-DSO coordination is increasingly relevant and necessary to evolve from a rigid, hierarchical model to a more flexible one with a more collaborative structure, which finally enables centralised and decentralised control strategies to coexist. This new operation paradigm is significantly changing modern energy systems, turning the power grid more resilient and adaptive and being able to securely and reliably integrate large amounts of renewable energy.

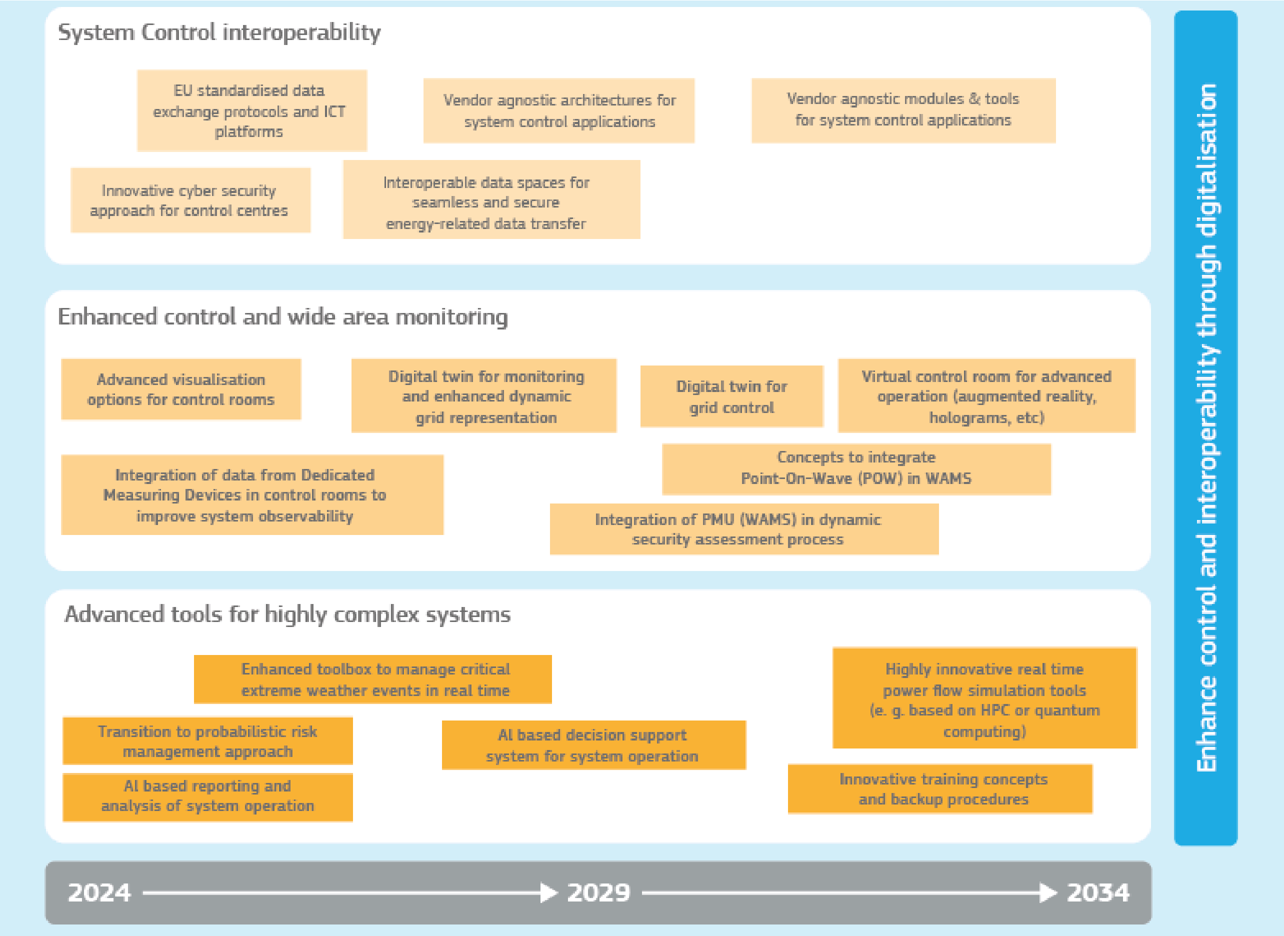

Figure 4 Mission 4 - Enhance control and interoperability through digitalisation

3.2 Advanced Distribution Management Systems (ADMS)

DMSDMS manage the distribution grids in real time, providing monitoring, analytics, and visualisation capabilities. Modern DMS integrate multiple functions, such as an outage management system (OMS), a geographic information system (GIS), and a SCADA system. These integrated platforms are commonly referred to as advanced distribution management systems (ADMS). They also offer advanced functions, such as Volt/VAR optimisation (VVO) and fault location, isolation, and service restoration (FLISR), constraint management, and even look-ahead constraint management applications (proactively solving predicted constraint violations).

DERMSDERMS are emerging software technologies providing DSOs tools to manage DERs and to maximise their benefits. The increasing penetration of DERs not owned by the distribution company leads to significant changes in distribution operations and the role of a distribution utility. DSOs need to compensate the services provided by DER operated by customers and third-party resources from DER aggregators or other energy service providers. The role of DER aggregators is to aggregate small-scale DERs into DER groups and, consequently to enable their services using the aggregated DER power. Aggregators, however, may not be fully aware of the grid model, its conditions and its technical boundaries, and so they cannot rule out congestion, voltage violations, or protection issues. Thus, to enable the safe use of the services offered by DER aggregators, DSOs must be able to observe the real-time grid conditions as well as the ability to validate—and modify, if necessary—the DER aggregator schedules to avoid causing constraint violations on the grid assets [14]. The presence of behind-the-meter resources is usually not represented in detail in ADMS and might further complicate the system operation.

3.3 Distributed Energy Resources Management Systems (DERMS)

The transition from traditionally passive distribution grids to increasingly complex active distribution grids requires the modernisation of control centres and the development of highly intelligent software systems to enable the real-time observability, control, aggregation, constraint management, and protection of such grids. DERMS technology needs to be developed to provide different services to different stakeholders, including DER aggregators and DSOs. The role of DER aggregators includes enabling the participation of small-scale DERs in electricity markets, the engagement of DERs and prosumers in energy-saving and energy-efficiency programs, the provision of demand response and load-shedding services, as well as the provision of other mostly customer-related services.

DERMS solutions for DSOs are grid-aware software packages that enable the full awareness, control, and optimal management of medium- to large-scale DERs and DER groups (consisting of behind-the-meter DERs), with the goal of using all these resources to achieve system-wide benefits without violating grid constraints, e.g., solving existing violations or predicted constraint violations and keeping the system in a stable and optimal state in real time.

Different approaches exist in using DERMS in DSOs' control centres, i.e., they can operate as a logical entity whose functionalities are integrated into the ADMS, or they can have a separate DERMS platform that complements the ADMS. A properly designed and implemented DERMS addresses both the grid reliability operations and the commercial aspects of dealing with DERs and the associated transactions with customers and other third-party DER asset owners.

3.4 Transactive Energy Systems and Energy Blockchain

Transactive energy systems are a distributed form of control and coordination that may be used to orchestrate the integration of DER and other assets in distribution systems and of the interactions between distribution systems and the transmission system. There have been multiple field demonstrations of transactive energy systems in the United States and Europe. Blockchain technology in transactive energy systems provides distributed ledgering to meet bookkeeping and audit requirements for transactive energy systems.

The heart of transactive energy systems is the use of distributed control and coordination implemented via local markets to use the flexibility associated with DER to deal with variable RES. As we move to decarbonised energy systems with increasing quantities of DER deployed in distribution systems, the distributed control and coordination of transactive energy systems becomes increasingly important. However, there are several barriers to the wide deployment of transactive energy systems, including regulatory. Indeed, regulators are often concerned that they expose customers to risk that should be borne by utilities, integration costs and customer acceptance.

3.4.1 Project Example: U2DEMO

The U2DEMO project contributes significantly to advancing transactive energy systems and blockchain-enabled energy trading. At its core, U2DEMO develops an open-source platform that facilitates peer-to-peer (P2P) trading and energy sharing. This platform integrates blockchain and distributed ledger technologies to ensure transparency, security, and traceability of transactions, adhering to principles of openness, interoperability, scalability, and trustworthiness. By providing robust, user-centric tools, the project reduces barriers to participation for consumers and prosumers, empowering them to actively engage in energy markets. U2Demo's detailed mapping of social, business, and regulatory landscapes enables tailored approaches to address challenges like regulatory hesitancy, customer acceptance, and integration costs. By understanding the motivations and concerns of diverse stakeholders including prosumers and energy communities across Europe, the project ensures that its solutions are both relevant and impactful. The U2DEMO project is positioned to provide critical advancements to overcome the barriers to scaling transactive energy systems, contributing significantly to their widespread adoption and operational efficiency. One of the project's key contributions lies in its focus on the integration of advanced control strategies that enable coordination and forecast of DER based on real-time information.

3.5 Phasor Measurement Units (PMUs) and Wide Area Monitoring Systems (WAMS)

Wide area measurement systems (WAMS) are vital for acquiring real-time grid information. They are built on real-time measurements collected from sophisticated digital recording devices, called synchronised phasor measurement units (PMUs), installed at substations. WAMS is a technology that assists TSOs in daily operations, prevents widespread blackouts, and improves observability and situational awareness in electricity grids. It collects, stores, transmits, and analyses critical data from key points across a power network and across large geographical areas.

The PMU records and exports dynamic power system data that is GPS-synchronised with a sampling rate of 5-50 samples/second. This data typically includes branch current and bus voltage phasors, local frequency, rates of frequency changes, harmonics measurements, negative and zero sequence quantities. Three main constitutive parts can be identified in a WAMS: phasor measurement unit, phasor data concentrator, and communication system. Phasor data concentrator (PDC) has a very crucial role since it receives synchrophasors from several PMUs or other PDCs and feeds them as a single stream by implementing several checks on data consistency.

The state-of-the-art WAMS functions are designed to detect abnormal system conditions and evaluate large-area disturbances. They do this to preserve system integrity and maintain suitable power system performance while offering improved scalability and higher flexibility. WAMS brings new, advanced indications into the operator environment and enables operators to directly use data from PMU devices and high-frequency WAMS calculations in energy management system (EMS) applications. WAMS enhances EMS applications – like state estimation, parameter estimation, and voltage stability analysis, by providing high-fidelity, accurate measurements with high-resolution data. Combined, these features greatly enhance operators' awareness of the dynamic state of the power system and provide an early warning of unsafe operating conditions and work to avoid catastrophic power blackouts. WAMS integrates renewables and helps operating the network closer to its physical limits to maximise energy delivery from existing resources, increase transmission capacity, and postpone investments in new equipment. WAMS can detect and evaluate what happened and use the insights for improved planning with playback scenarios, post-mortem analysis, and the high-resolution historian database.

3.6 Advanced Metering Infrastructure (AMI)

Advanced metering infrastructure (AMI) is a system that measures, collects, and analyses energy usage while facilitating two-way communication with metering devices, such as electricity meters. This communication can occur either on demand or on a predetermined schedule. AMI systems consist of various components, including hardware, software, communication networks, consumer energy displays, controllers, customer-related systems, meter data management (MDM) software, and supplier business systems. **AMI plays a key role in enhancing the monitoring, supervision, and control of modern electricity systems, especially since it provides insights into electricity consumption patterns across various voltage levels, from HV down to LV networks, enhancing overall grid visibility and operational efficiency.**

While smart meters are installed across much of the LV network, the integration of this data into advanced monitoring and control systems remains a challenge. Current smart meter deployments are largely designed to collect data at set intervals, typically ranging from minutes to an hour, but often lack the capability for continuous, near real-time data transmission necessary for proactive grid management. Additionally, data communication technologies such as 4G networks have limitations in handling large volumes of information generated by millions of smart meters, further constraining DSOs' ability to fully leverage AMI for network control purposes.
Some DSOs have therefore begun experimenting with the latest generation of smart meters, that are capable of collecting and transmitting high-resolution data, often at the rate of gigabytes per day, allowing for far more granular monitoring of electricity consumption and grid conditions. To overcome the limitations of existing communication infrastructures and achieve higher data transmission capacity and lower latency, 5G is expected to support real-time data collection from large numbers of smart meters and IoT devices, in order to manage effectively the increasing complexity of modern electrical systems. Additionally, AI and machine learning (ML) technologies are being incorporated into AMI systems to enhance data processing and predictive analytics. These technologies allow DSOs to identify patterns, predict equipment failures, and optimise grid performance with greater precision, while supporting the shift towards predictive maintenance and demand-side management (DSM).

3.7 Flexibility Platforms

Recent years have seen significant progress in TSO–DSO collaboration across Europe, driven by real-world pilots and EU-funded projects that have improved the integration DERs. EU funded research projects like INTERRFACE and CoordiNet have piloted large-scale coordination schemes between TSO, DSO, and consumers, establishing new mechanisms for procuring flexibility from DERs. For example, CoordiNet have defined standardised grid service products and tested multiple TSO–DSO–consumer coordination models in Spain, Sweden, and Greece. These trials have demonstrated how local flexibility platforms can relieve grid congestion and avoid renewable curtailment by enabling DER providers and aggregators to sell services to the grid. Likewise, the INTERRFACE project has developed a common interoperable architecture (IEGSA) acting as an interface between TSOs, DSOs, and customers to exchange data and activate new ancillary services. Building on these successes, the OneNet project has created a fully replicable and scaleable architecture that enables the whole European electricity system to operate as a single system in which a variety of markets allows the universal participation of stakeholders regardless of their physical location. Together, these collaborative efforts have proven the viability of joint TSO–DSO platforms and market-based coordination, paving the way for more resilient and efficient management of a high-DER grid (INTERRFACE , CoordiNet and OneNet project results available on cordis.europa.eu).

3.8 Key Challenges for TSO-DSO Cooperation

Despite these achievements, several challenges must be addressed to scale up TSO–DSO cooperation in the coming years. Regulatory harmonisation is a top priority: current national rules and legacy practices differ widely, and aligning these frameworks is essential for replicating flexibility markets across the EU. Data exchange and interoperability also remain obstacles – agreeing on common data standards, and standardised products is crucial to ensure that IT systems of TSOs, DSOs, and market platforms can seamlessly work together. In addition, robust cybersecurity protections are needed as grid operations become more digital and interconnected; shared platforms must enforce strong cyber defences and data privacy measures to safeguard critical infrastructure. Another core challenge is clarifying roles, responsibilities and governance in this evolving landscape. The rise of prosumers, energy communities, and independent aggregators blurs traditional boundaries, calling for clear definitions of each actor’s duties and interactions.

3.8.1 Project example: i-Autonomous

In the German research project i-Autonomous, a comprehensive framework was developed using standardised tools for the integration of smart grid features. The fundamental idea was to create a template that enables uniform incorporation of smart grid facilities in the distribution grids. Protection and control algorithms based on the IEC 61850 standard were developed and then tested on hardware devices from several vendors to prove the independence between the hardware and software. Various partners such as hardware providers, DSOs, technology providers and research institutions were involved to include aspects such as hardware, software, communication protocols, resilient communication strategies, control functionality and robustness of the developed application.

These requirements helped in creating a detailed system specification documented in the integration guide. Based on this, both hardware and software components were developed to facilitate the necessary protection and control applications. This included interface adaptations, a suitable engineering process, and automated testing procedures. An example of the overall implementation of the hardware-independent software is explained in Fig. 5.

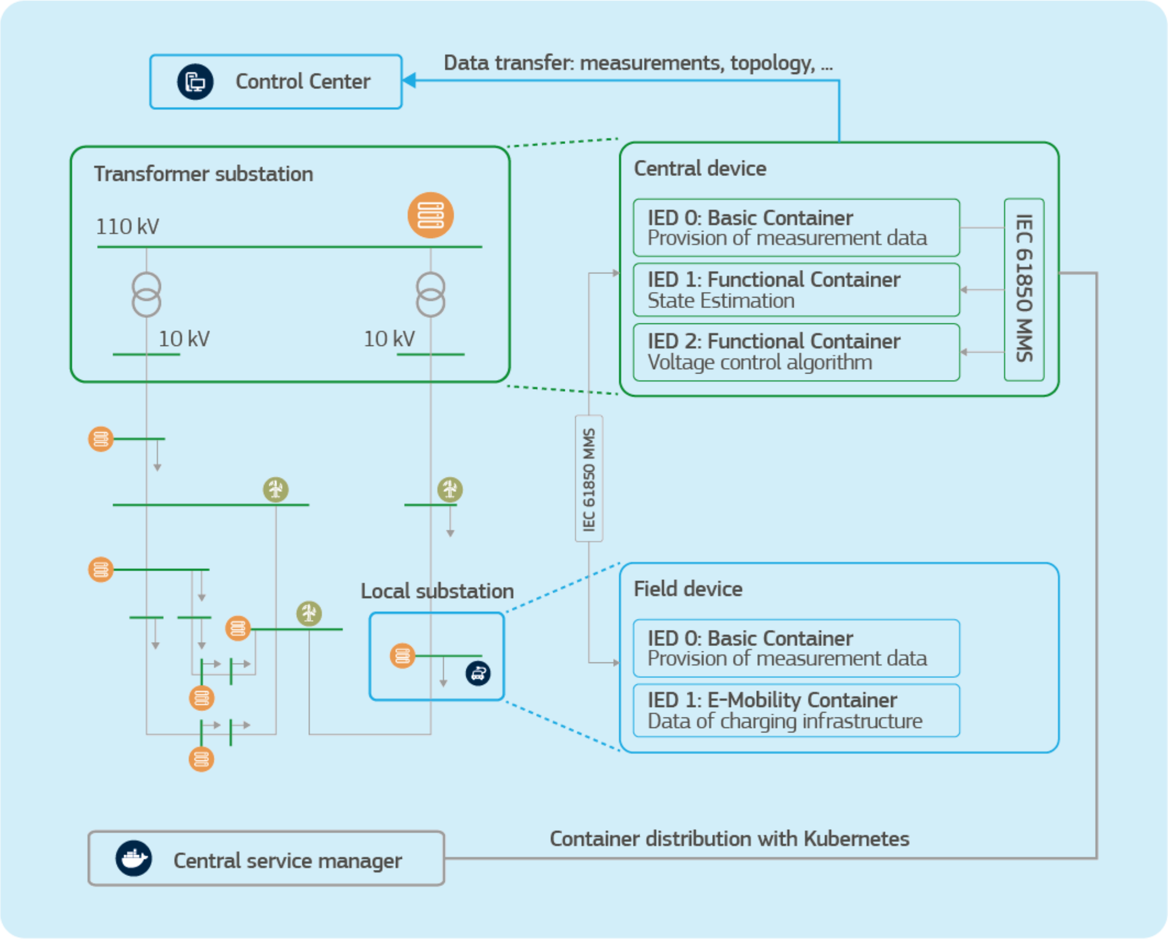

Figure 5 The integration process of hardware-independent software implementation[2]

The project ultimately focused on determining if the developed applications using standardised software could be independently implemented on other hardware. It turned out that it was indeed possible. The implemented functionalities operated effectively within their designated environments on specified hardware and communicated with the other entities as required. This proved that software applications can be developed for the DSOs regardless of a particular hardware provider. This further establishes that various other automation functions from independent developers can be sourced to evaluate their performance. This collaborative approach aims to address the complexities of the evolving energy landscape and ensure a seamless transition to more advanced and adaptable grid management systems. The implementation was tested on various international grids in future publications[3].

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[2] Raczka, S., et al. (2022). A novel software applications rollout and monitoring strategy for enabling the transition to electromobility in future smart grids. In *CIRED Porto Workshop 2022: E-Mobility and Power Distribution Systems*. https://doi.org/10.1049/icp.2022.0760

[3] Palaniappan, R., et al. (2022). Experimental verification of smart grid functions on real-world grids using a real-time simulator. *IET Generation, Transmission and Distribution, 16*(13), 2747–2760. https://doi.org/10.1049/gtd2.12486

4. KEY CHALLENGES

4.1 Data Challenges

4.1.1 Lack of measurement in distribution grids

Historically, distribution grids were the final link in the electricity supply chain, characterised by relatively simple (radial) structures. Compared to transmission networks, distribution networks have traditionally had poor observability due to limited metering data, primarily for economic reasons and a lack of automation. In terms of data collection, smart meters have significantly increased the volume of available data. These devices provide the ability to monitor and control consumption at various voltage levels, extending down to LV networks. However, many DSOs still lack comprehensive knowledge of the detailed topology and electrical characteristics of their networks, particularly in LV systems.

Regarding automation, DSOs have made significant progress in modernising MV and HV networks in recent years, but LV networks have largely been overlooked. The electrical topology of LV networks is often reliant on basic infrastructure, such as fuses, and cannot be actively operated or controlled from DMS. As a result, supply disruptions are typically managed reactively, often only after customer complaints.

To address these deficiencies, it is crucial to obtain near real-time data for effective monitoring and control. While smart metering infrastructures provide some of the necessary operational data, they need to be complemented with advanced technologies. AI and MLtechniques offer promising solutions, enabling the development of algorithms for proactive actions and predictive management of LV networks. These approaches can greatly enhance the reliability and economic efficiency of the system.

4.1.2 Limited observability and monitoring

Limited observability and monitoring in distribution grids result in significant inefficiencies in management and operations. With insufficient data available, grid operators are forced to rely on rule-of-thumb approaches to make decisions. This type of management fails to address the complexities of modern grids, especially in real-time operations where undetected congestion and voltage issues can compromise system reliability. The challenges extend to long-term planning, where the lack of necessary information leads to rough estimations of key parameters such as peak load and transformer loading. These approximations often lead to either underinvestment or overinvestment in grid infrastructure. Moreover, to mitigate risks associated with the uncertain nature of RES, conservative limits are imposed on RES penetration to avoid the violation of grid constraints. This not only restricts the integration of RES, but also hinders the grid's ability to use flexibility from RES/DER. The limited visibility makes it difficult to implement effective DSM programs, further limiting the potential for optimising energy consumption and improving grid efficiency.

4.1.3 Low data granularity

Smart meters typically capture energy measurements at 15-minute intervals. This coarse data resolution hinders the effective management and operation of flexibility resources, especially for processes requiring rapid response times. For instance, demand response programs and participation in balancing markets necessitate faster and more precise data to operate efficiently. Furthermore, the 15-minute data intervals can hide critical variations in load, such as spikes or rapid fluctuations, impacting the planning and operation of the distribution grid and posing risks to grid stability. Additionally, very short-term forecasting (e.g., 5-minute forecasts) for RES like PV systems cannot rely on such low-resolution data, as solar production can change significantly within minutes.

4.1.4 Difficulties of TSOs in handling the large amount of distribution network data

Typically, TSO SCADA systems manage thousands or tens of thousands of measurement points, including buses, production units, transformers, and switches. However, in distribution grids, particularly with the full deployment of smart meters, the number of measuring points increases exponentially, reaching into the millions. Additionally, the distribution network spans a much greater length compared to the transmission network, significantly expanding the volume and complexity of GIS data required for effective monitoring and management. As a result, the current infrastructure of a typical TSO is not designed to handle and process such an enormous volume of information from the distribution network. The significant differences in data scale and complexity pose challenges for TSO-DSO real-time data acquisition, storage, and analytics.

4.1.5 Compatibility between legacy/old and new control systems

Legacy control systems were designed to perform a limited set of tasks and operations without consideration for integration into a broader, interconnected ecosystem. For instance, a traditional DMS was built specifically for managing the distribution grid and lacks the functionality needed to manage flexibility resources for balancing markets or cross-sector integration. This narrow design focus inherently limits the openness and interoperability of these systems, making it difficult to integrate them with modern solutions. As a result, legacy systems often struggle to support the evolving needs of the energy sector, such as real-time data management, flexible market participation, and the integration of distributed energy resources.

4.1.6 Limited openness of systems

One significant reason for the limited openness of systems is the prevalence of their proprietary solutions tailored to the specific needs of individual stakeholders. Proprietary solutions often come with unique modifications of standard communication protocols, creating interoperability challenges and reducing system openness. Stringent cybersecurity policies and strategies can further restrict openness, particularly for older systems that were not designed with modern cybersecurity principles in mind. These legacy systems often require restrictive measures to safeguard against cyber threats. Lastly, regulatory frameworks and market rules can impose additional restrictions, limiting data sharing and integration between different entities to ensure compliance and maintain market integrity.

4.2 Cyber Security

An inclusive definition of cyber security is: “The continuously improved application of people, processes, and technologies to the power grid for:

1. Preventing intentional or unintentional manual or automatic, digital or analog, and logical or physical malevolent acts;
2. Minimising risks that compromise integrity, availability, and confidentiality of data in transit and at rest;
3. Detecting such acts as or before they occur;
4. Responding to such acts;
5. Implementing actions that remediate or mitigate the threat or vulnerability so that reliability and resilience are maintained.

The different types of cyberattacks include false data injection attacks, replay attacks, time-delay attacks, denialof-service attacks, ransomware attacks, man-in-the-middle attacks and spyware attacks.

It can be reasonably assumed that all the ICT parts that compose a remote automation system are directly threatened by cyberattacks. Accordingly, the power system components susceptible to digital threats are the sensors, measurement channels, the Control Center, as the cornerstone of an automation system, the control command channels and the actuators.

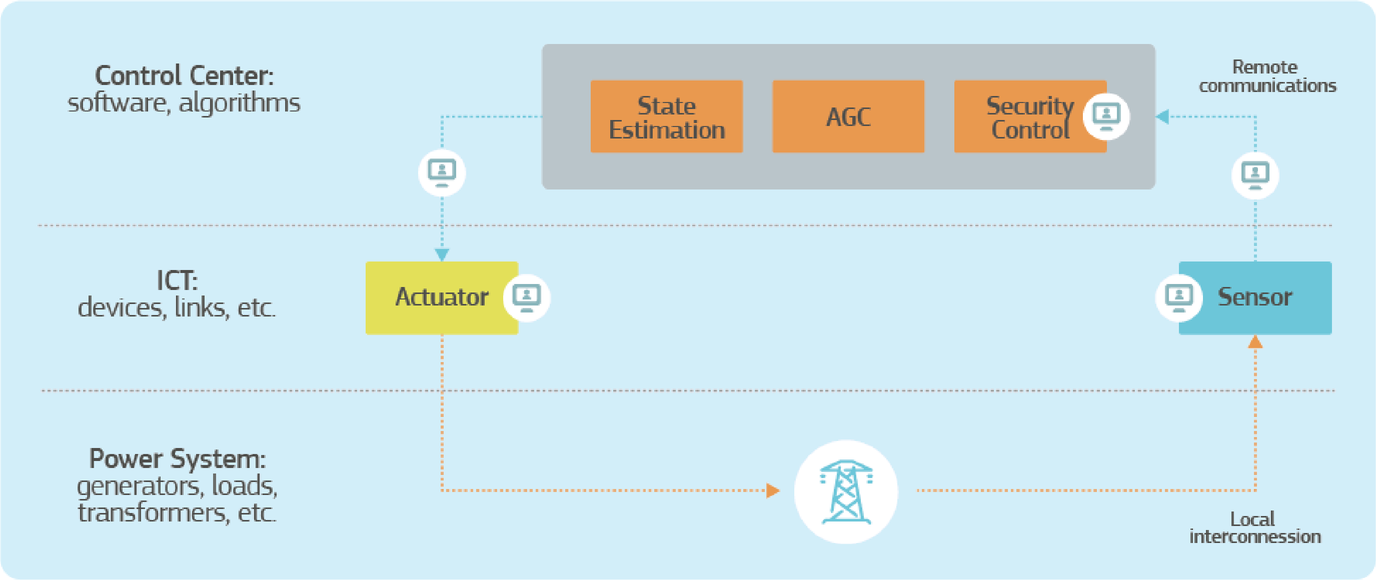

Figure 6 Overview of potential cybersecurity threats in power system supervision and control

The methods used for cyber defense are:

- Model-based methods: in this category, the defense methods extract system knowledge/information and properly process it in order to identify underlying patterns that can reveal insights about the attacking strategy. Some indicative examples in power system control are the use of load forecasting to approximate the correct generator setpoints in case of cyberattack, the deployment of sophisticated Kalman filters that leverage the system modelling to estimate cyberattacks and the implementation of statistical methods to predict the healthy behaviour of the frequency control signals.
- Observer-based methods: this group of research methodologies leverages a special type of system, called observers, to estimate and mitigate attacks on control systems. Observers can accurately estimate the state vector of the real-world control systems that they are designed for. The observer design generates a formula for the estimation error, which represents the difference between the actual and the estimated state vector. Depending on the assumed conditions, different variations of this formula are applied, in order to accurately estimate cyberattacks and employ attack-tolerant control strategies.
- Data-driven methods: instead of using an analytical model of the power system control loops, these methods use the data that are generated by the actual control systems in order to approximate their healthy or abnormal behaviour. Data-driven methodologies typically use historical databases, which keep track of past values of the control signals, in order to train their learning models. In this way, they can determine if the status of the control system is healthy or not, and extract information about the compromised signals. These historical databases serve as input to the developed data-driven models.

4.2.1 End-to-end cybersecurity frameworks

End-to-end cybersecurity frameworks provide unified rules, strategies and guidelines to manage cybersecurity risks, including prevention, detection and reaction to cyberattacks. In July 2020, the EU Security Union Strategy[4] presented aims to ensure European security in both the physical and the digital world in all parts of society. Acknowledging the need for sector-specific initiatives, particularly in the energy sector, the strategy outlines an upcoming initiative to make critical energy infrastructure more resilient against physical, cyber and hybrid threats[5]. Key among the Commission's actions is the establishment of a comprehensive legislative framework that builds on

- the EU Cybersecurity strategy (JOIN/2013/01)
- the Directive on Security of Network and Information Systems (the NIS Directive) EU/2016/1148, EU/2022/2555
- the Cybersecurity Package (JOIN/2017/450 final) from September 2017, which also includes the Cybersecurity Act

The NIS 2 Directive (Directive (EU) 2022/2555)[6] is a legislative framework designed to enhance cybersecurity across the European Union by establishing a high level of security for network and information systems. It upgrades the original NIS1 Directive, expanding its scope and strengthening requirements to better address evolving cyber threats.

Under NIS2, entities are categorised as essential within existing sectors depending on the turnover and the employment. The sectors are divided into two groups “Sectors of High Criticality” and “Other Critical Sectors”. The energy sector is classified as a Sector of High Criticality.

Other cybersecurity frameworks are the ISO/IEC 27001:2022[7], ISO/IEC27002:2022[8], CSA Cloud Controls Matrix (CCM)[9], Center for Internet Security (CIS) Critical Security Controls[10], COBIT 5[11], NIST Cybersecurity Framework 2.0 (USA)[12], Cybersecurity Risk Information Sharing Program (CRISP)[13], etc.

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[4] European Union. (2013). *Regulation (EU) No 52013JC0001*. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1553779410177&uri=CELEX:52013JC0001

[5] European Commission. (n.d.). *Critical infrastructure and cybersecurity*. https://energy.ec.europa.eu/topics/energy-security/critical-infrastructure-and-cybersecurity_en

[6] European Union. (2022). *Directive (EU) 2022/2555*. https://eur-lex.europa.eu/eli/dir/2022/2555/oj

[7] International Organization for Standardization. (n.d.). *ISO 27001*. https://www.iso.org/standard/27001

[8] International Organization for Standardization. (n.d.). *ISO 75652*. https://www.iso.org/standard/75652.html

[9] Cloud Security Alliance. (n.d.). *Cloud controls matrix*. https://cloudsecurityalliance.org/research/cloud-controls-matrix

[10] Center for Internet Security. (n.d.). *CIS controls*. https://www.cisecurity.org/controls

[11] ISACA. (n.d.). *COBIT 5*. https://www.isaca.org/resources/cobit/cobit-5

[12] National Institute of Standards and Technology. (n.d.). *NIST.CSWP.29*. https://doi.org/10.6028/NIST.CSWP.29

[13] Splunk. (n.d.). *Cybersecurity frameworks*. https://www.splunk.com/en_us/blog/learn/cybersecurity-frameworks.html

5. DIGITAL SOLUTIONS

5.1 Data analytics

The energy sector generates an enormous amount of data through every phase of the supply chain. The data consist of values for energy production and consumption, network states, event registration, customer and producer information, pricing and trading details. Data analytics provides the opportunity to identify gaps and innovative approaches for energy production and distribution. It also involves the consumers in the energy supply process by turning them into prosumers or just by demand response improvement and participation in trading platforms.

Large amounts of valuable data are available in energy systems, but they are often underused.[14] There is no single data platform connecting data from the generation, transmission, distribution and consumption domains in Europe's electricity sector or across the various energy vectors – electricity, gas, heat, etc.

According to the Common European Energy Data Space Report (https://op.europa.eu/en/publication-detail/-/publication/43b8d2d1-6975-11ee-9220-01aa75ed71a1) from October 2023, the following issues should be taken into account working with the energy data:

- Data formats: energy data is often collected, stored, and shared using different formats, protocols, and semantics. This makes it difficult to integrate and share across systems, creating challenges for companies that need to exchange data with other companies or regulators.
- Data access: energy data is often owned by different parties, including energy providers, grid operators, manufacturers of various equipment and products, and regulators. This can make it difficult for some companies to access the data they need to operate their businesses effectively.
- Data privacy: metering data and further data on flexibility provision are often tied to a person as an electricity consumer. Thus, it is personal data and, as such, governed by the EU data protection regulations, such as the General Data Protection Regulation (GDPR).
- Cyber security: sharing data across different systems and organisations can increase the risk of cyber security breaches.

The data collection also needs a strong communication infrastructure to ensure data integrity (avoiding gaps in data records) and valid data for real-time monitoring and control.

5.2 Energy Data Spaces

Data space is defined as a decentralised infrastructure for trustworthy data sharing and exchange in data ecosystems based on commonly agreed principles (Common Energy Data Space, Common Energy Data Space Nov.2024, ENTEC Full Report[15].

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[14] International Data Spaces Association. (n.d.). Omega-X: An energy data space to boost the European data economy. https://internationaldataspaces.org/omega-x-an-energy-data-space-to-boost-the-european-data-economy/

[15] European Commission. (n.d.). *Common European Energy Data Space*. https://energy.ec.europa.eu/publications/common-european-energy-data-space_en

To address the above-mentioned issues mentioned, the EU has launched several initiatives to promote the sharing of energy data, such as the EU Action Plan on digitalising the energy system (Commission 2022), which supports the energy-related objectives of the European Green Deal (European Commission 2019) and includes a key action area to create a common European data space for energy. This initiative aims to facilitate the sharing of energy data across different organisations and systems along the energy value chain by promoting interoperability, standardisation, and data protection.

Common European Data Spaces are currently being developed across 14 sectors/domains. In the energy sector, the following data spaces are available:

- IntNET – Developing, testing and deploying interoperable energy services to further pave the path for a carbon-free European society in 2050
- OMEGA-X – The proposed concept and architecture heavily rely on the approaches adopted by both IDSA and GAIA-X as major EU references regarding data spaces, including also additional references such as FIWARE, BDVA/DAIRO and SGAM (purely on the energy sector). The IDSA approach defines data sovereignty, as the ability of a given actor (corporate or person) to act as self-determined for its own data. Therefore, the primary goal of its reference architecture relies on deriving appropriate requirements for sound, secured and trusted data trading.
- EDDIE (European Distributed Data Infrastructure for Energy) introduces a decentralised, distributed, open-source data space in alignment with the efforts of the EU Smart Grids Task Force on Implementing Acts on Interoperability and other European initiatives. EDDIE significantly reduces data integration costs, allowing energy service companies to operate and compete seamlessly in a unified European market. Additionally, an Administrative Interface for In-house Data Access (**AIIDA**) ensures secure and reliable access to valuable real-time data based on customer consent.
- Enershare defines a data-driven reference architecture for the energy domain, which is compliant with FIWARE, IDSA and GAIA-X. It creates a marketplace based on blockchain and smart contracts with the aim of improving mutual trust among the actors of the ecosystem and increasing the security of the shared data. It also enables a compensation system (even non-monetary) of assets and resources related to data (e.g., datasets, algorithms, models) with energy assets and services (e.g., maintenance of heating system, surplus transfer of locally self-produced energy).
- Synergies
- Data cellar aims to create a federated energy data space that will support the creation, development and management of local energy communities in the EU. The data space population will be facilitated via an innovative rewarded private metering approach, with a focus on easy onboarding and interaction, guaranteeing a smooth integration with other EU energy data spaces and providing LEC stakeholders services and tools for developing their activities.

5.3 Internet of Things (IoT)

The Internet of Things (IoT) is an infrastructure of interconnected objects (mainly sensors and equipment) that contains embedded technologies to sense, communicate, process information, react and interact with each other or the external environment to create value from this interaction. IoT solutions encompass sensors, information technology (IT) and operational technology (OT) systems, communications, data storage and analysis, including AI. Increasingly, various industries are using IoT to operate more efficiently, deliver enhanced customer service, improve decision-making and increase the value of the business. With IoT, data are transferable over a network without requiring human-to-human or human-to-computer interactions.

IoT can facilitate real-time supervision of power systems (power quality, asset characteristics, etc.). IoT enables powerful asset management solutions (power transformers, overhead lines, partial discharges, etc.).

In the future, IoT could be used for the implementation of decentralised flexibilities, including V2G. Its applications could sharply increase with the development of smart secondary substations and smart LV networks. IoT will bring the most benefits at low and medium voltage levels. The greatest benefits from IoT will come from substation monitoring, followed by monitoring of transformers and power quality measurements, congestion management and implementation of flexibilities.

Currently, the deployment of IoT devices in the energy sector faces significant challenges, including high implementation costs, interoperability challenges, regulatory and policy barriers, and cybersecurity concerns. Many utilities encounter difficulties in integrating IoT infrastructure into existing systems due to the complexity of aligning OT with IT. Retrofitting legacy systems with IoT capabilities requires substantial investment and technical expertise, which slows down adoption. The absence of widely adopted standards for communication and data exchange further complicates efforts to scale IoT solutions. Regulatory and policy barriers significantly limit the deployment of IoT devices in the energy ecosystem due to the variability and ambiguity in regulations across regions. The lack of harmonised frameworks and legislation regarding data ownership, cybersecurity, and interoperability adds uncertainty for stakeholders. Policies around data sovereignty and restricted data sharing further hinder innovation, especially for services relying on shared IoT data like demand response and flexibility markets.

5.3.1 Indicative EU R&I projects

The HEDGE-IoT project tackles the above challenges by offering scaleable, secure, and interoperable solutions that demonstrate the transformative potential of IoT. By leveraging edge computing for real-time analytics, standardised architectures, and robust cybersecurity protocols, the project provides a blueprint for effective IoT deployment, enhancing flexibility, resilience, and grid optimisation. It promotes the adoption of widely recognised standards like SAREF and GAIA-X to resolve interoperability challenges, ensuring seamless integration of devices and systems across borders and energy domains. HEDGE-IoT also develops cost-effective IoT solutions by leveraging advanced edge and cloud intelligence with AI and ML tools to enhance data processing and operational efficiency, reducing the economic barriers to adoption. Furthermore, it fosters collaboration among stakeholders to establish trust, provides real-world use cases to highlight economic benefits, and advocates for market-ready IoT solutions tailored to energy applications.

5.3.2 Edge computing for real-time analytics

Edge computing is transforming IoT applications in the energy sector by enabling real-time data processing and analytics at or near the source of data generation. Unlike traditional cloud-based systems, where data must travel to centralised servers for processing, edge computing reduces latency by handling critical computations locally. This capability is vital for dynamic and time-sensitive operations in power systems, such as grid balancing, fault detection, and demand response, where continuous monitoring and rapid decision-making are essential.

By processing data locally, edge computing supports faster decision-making, reduces network congestion, and enhances system resilience by ensuring continued operation even during connectivity disruptions. It also improves data privacy and security by limiting the transfer of sensitive information to external servers.

The HEDGE-IoT project capitalises on edge computing to deliver advanced analytics and real-time insights across the energy system. Through its federated architecture, the project enables distributed intelligence and computational sharing, ensuring scalability and enhanced flexibility and efficiency of the system. This approach is especially beneficial for managing decentralised energy resources and implementing flexibility mechanisms, making it a key element for next-generation smart energy systems.

5.4 Machine Learning (ML) and AI

AI involves the use of information systems, data within management systems and dedicated algorithms and is often applied in classification, prediction and forecasting use cases. AI performance is based on the combination of the availability of a large amount of data, large computing capacity, and machine learning algorithms. As transmission and distribution networks are generating a large and growing amount of data, AI techniques can provide several solutions to power system monitoring and control problems. In particular, current challenges are related to the need for improved situational awareness, fast assessment of a large number of computationally intensive tasks, and optimal planning and operation.

AI and ML have the ability to use data and speed up processes; depending on the application this can be up to 100s of times faster compared to conventional techniques. Data can come from various systems and sensors, ranging from SCADA/EMS and PMUs at the transmission level, smart meters at the distribution level, or even from other sources or sensors (e.g., weather data, temperature sensors, etc.). This can consequently enable fast assessment and screening of a large number of scenarios or the ability to solve large computationally intensive problems (e.g., related to optimisation or time domain simulations). This is useful at the planning stage when there are too many scenarios to analyse/assess (millions or even billions) and not enough to do so otherwise. It is also useful in operational timescales (close to real time) when there is not enough time to analyse a –still high– number of scenarios/cases.

AI/ML can help system operators and planners to have increased situational awareness (close to real time) and gain insights into complex underlying behaviours. In particular, recent advances around explainability/interpretability can be useful in this respect, among others. AI/ML can also provide decision support while taking into consideration details related to the system behaviour (e.g., through optimisation routines that consider constraints related to dynamic behaviour). Finally, AI/ML can also be envisaged to enable automated control. This can be particularly useful in cases where current tools can’t perform fast enough or capture the level of detail needed. For example, when there is a need to control millions of devices (e.g., EVs, distributed generation, batteries, etc.) or act very fast, beyond what human system operators can do alone (e.g., to address challenges related to power system dynamics). As an example, reinforcement learning can be a useful approach in this respect.

Potential use cases for DSOs (non-exhaustive list)

- Renewables (wind and solar) production and load forecast in minutes, hours, days, months ahead
- Distributed Energy Resources (DER)/Flexibility: AI allows handling the increasing complexity of network control due to DER variability, e.g., determining the available power for charge point providers.
- Network development studies: AI enables the undertaking of network development studies accounting for technical constraints and technological and sociological hypotheses.
- Asset management: the performance of AI in image processing enables automatic diagnosis to enhance programmed renovation. The learning capacity of AI allows predictive maintenance to be performed in some cases.
- Image recognition: for instance, electricity energy meter & components recognition from meter photos, detecting assets on technical drawings. Lines inspection, identification of faulty components
- Operation and employee support: AI could augment the capabilities of maintenance technicians, customer advisors and support function employees.

- Network control & outage prediction: AI could augment the capabilities of control rooms (fault location, DER integration). AI solutions will enable precise LV massive control.
- State estimation in the distribution grids: ML techniques have shown great potential for addressing the limited availability of measurements in distribution grids. Typically, training datasets for ML models are generated through offline power flow simulations. Additionally, in many cases, ML-based methods are employed to create a topology identification system as a preliminary step. This system aims to determine the status of sectionalising switches and accurately map the network topology. Among the various neural network architectures, CNN (Convolutional Neural Networks) and GNN (Graph Neural Networks) have emerged as particularly promising approaches. CNNs are effective in capturing spatial patterns from grid measurements, while GNNs excel at handling the graph-like structure of distribution networks, allowing for more accurate and efficient state estimation and topology identification.

Potential use cases for TSOs (non-exhaustive list) [Ref. CIGRE C2.42 WG TB]

Focusing on the use of AI/ML on power system operations specifically, CIGRE has identified the following broad categories: forecasting and risk assessment, grid monitoring, operations and processes, simulation, market management, emergency and extreme events, and reporting assistance. A non-exhaustive list of **potential use cases**[16] follows:

- Forecasting: AI/ML is proposed and used for both load and renewable generation (wind and solar) forecasting in various timescales (minutes, hours, days, months) and also covering locational aspects. This is a relatively mature application being used by some utilities.
- Dynamic Security Assessment[17] under increasing complexity and uncertainty: AI/ML can systematically characterize mechanisms of instability and offer decision support (e.g., through security-constrained optimisation). Data-driven approaches can be used to investigate multiple operating conditions and understand sensitivities.
- One of the key advantages of ML-based methods is the ability to significantly speed up security assessment through the use of proxy models, with reported cases of up to hundreds of times faster. This can allow fast screening of more scenarios and help improve the understanding of potential underlying risks or even flag cases that need to be further investigated with traditional tools (e.g., time domain simulations) in more depth. This can be helpful in both planning and operational timescales.
- ML can also help to improve situational awareness in close to real time due to the capability to quickly compute an output metric related to power system stability after it has been trained. For example, current SCADA/EMS systems can provide close to real time understanding of how far we are from thermal and static voltage limits, but doing this for specific stability metrics is still challenging due to the computational implications. ML can use close to real-time measurements as they become available and quickly compute stability-related metrics (e.g., the critical clearing time across several locations in a system).
- Moving one step further, ML can also help human system operators by offering decision support. ML can help provide useful insights into complex behaviours, e.g., through explainability or graph-based methods. In addition, ML can help consider aspects related to detailed dynamics in optimisation routines for

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[16] CIGRE C2.42 Working Group. (2024). *The impact of the growing use of machine learning / artificial intelligence in the operation and control of power networks from an operational perspective* (Technical Brochure 946).

[17] Papadopoulos, P. N., Chatzivasileiadis, S., & Marot, A. (2024). Can machine learning help keep the system secure? Power systems and change addressing the increasing complexity and uncertainty during the energy transition. *IEEE Power and Energy Magazine, 22*(6), 100–111. https://doi.org/10.1109/MPE.2024.3421388

dispatching units or for topology alteration actions, something that requires significant computational effort with current tools. This can, in turn, enable preventive securing of the system while incorporating detailed dynamics.

- Finally, even full automation and control can be envisaged. This can be useful in situations where human operators cannot act within the timescales of the phenomena to be addressed, e.g., for phenomena in the millisecond/second range. This can enable new types of corrective control or last-resort defence mechanisms. Reinforcement learning, for example, can be used in such a setting.
- Congestion management: AI/ML can provide decision support on potential remedial actions to alleviate congestion. This is usually a very large optimization problem that needs to be solved close to real time (especially under N-k security considerations).
- Alarm management and reporting: Alarms can be overwhelming in control rooms. AI can help in grouping and contextualising alarms and also in report preparation/summary (e.g. through the use of LLMs).
- Visual Inspection: Visual inspection of power system equipment (e.g., substations, transmission line towers, conductors, transformers, etc.) is labour-intensive and expensive. ML-based methods combined with unmanned aerial vehicles or robots and appropriate sensors/cameras can aid in this direction
- Predictive maintenance: AI/ML can also be used to predict failures, remaining lifetime of assets, asset health monitoring, etc. This can be useful for power system equipment and also in offshore installations (e.g. offshore wind farms).

5.4.1 Good Practices (non-exhaustive list)

Several DSO initiatives make use of AI combined with drone visual inspections to detect anomalies on HV and MV overhead lines. Examples include the GridDrone project by E-Redes, the DALI project from UFD and Enedis’ DORA platform.

E-REDES network in Portugal has fully deployed the Analytics4Vegetation initiative to predict vegetation growth with respect to the surrounding electrical infrastructure to automatically plan, prioritise and generate vegetation cut orders.

The Enedis AI-based tool ARIIA analyses requests for field intervention and assigns a probability of non-success (e.g., due to poor definition), limiting unnecessary travel for field operators.

Enedis uses the Windy tool to predict the number of outages on overhead power lines before a storm using meteorological data with 90% accuracy, enabling better crisis preparation and faster restoration.

E-Redes developed a solution to predict possible neutral losses based on the events generated by smart meters before their occurrence.

ESO created a machine learning-based system that provides alerts for potential large-scale mass power outages in the 10 kV overhead line network, considering weather forecasts, historical data, and technical network parameters.

Enedis’ Cartoline Low Voltage uses AI to analyse voltage-related data observed by Linky smart meters to foresee future incidents that could lead to power outages and schedule preventive interventions from field technicians.

5.5 EU BRIDGE projects (non-exhaustive list)

TWAIN Integrated, Value-based and Multi-objective wind farm control powered by Artificial Intelligence,

https://cordis.europa.eu/project/id/101122194

The project aims to enhance wind farm control using digital innovations to achieve stable, secure, and cost-effective energy production. Key objectives include developing advanced control systems to optimise energy output, reduce maintenance costs, extend turbine lifespan, and enhance cybersecurity. Measurable outcomes include improved farm performance, reduced operational costs, and increased reliability of wind energy systems. This project contributes to advancing renewable energy technologies for sustainable energy production.

RESONANCE Replicable and Efficient Solutions for Optimal Management of Cross-sector Energy

https://www.resonance-project.eu/

- Creating a plug-and-play framework for tailored Customer Energy Manager (CEM) solutions.
- Implementing hybrid modelling approaches for flexible assets and baseline loads.
- Developing consumer-centric Artificial Intelligence for automated demand response.
- Enhancing interoperability, trust, security, and privacy in energy management.
- Measurable outcomes include increased efficiency in demand-side flexibility, consumer empowerment, reduced carbon emissions, and technological advancements in energy management.

5.6 Digital Twins

A digital twin (DT) consists of three essential elements: a tangible object, its corresponding virtual representation, and the data link that enables seamless communication between these two. There has been substantial attention given to DT applications spanning various fields, including manufacturing, aviation, healthcare, telecommunication networks and transportation systems. In the power systems industry, numerous DT applications have been proposed; some of the most promising ones are highlighted next.

DT is anticipated as a key technology for the evolution of power system control centres. Integrating DT can facilitate dynamic observability, real-time disturbance analysis and testing of future scenarios that include new critical equipment. In general, DT can offer advanced decision support, enhancing functionalities, e.g. for system planning and security assessment.

A DT of the electricity grid is a virtual replica of the physical grid, offering insights for facilitating continuous monitoring. It can be implemented with varying data resolution and calculation frequencies. While real-time monitoring is not essential for planning, functionalities such as state estimation and flexibility deployment in network operations require near real-time capabilities. These systems are engineered to manage and process far larger volumes of data than conventional SCADA systems. Developing a DT for grid monitoring, operation, optimisation, and control can drive future advancements in grid control centre technology, leading to enhanced system efficiency and reliability.

DT can also assist system operators or power production plant owners in performing planned or predictive maintenance of their assets. Using real-time measurements, as well as historical data and detailed models, a system operator can estimate the health condition of the network assets, which can lead to proactive measures and timely maintenance actions.

A useful application of a DT is in the education and training of system operators. DT can be used to simulate conditions that involve significant threats in modern power systems, i.e., cyberattacks or natural disasters, to teach system operators how to address them more effectively.

5.6.1 Good Practices (non-exhaustive list)

Building the trust of operators in AI

Adopting a data-driven approach for dynamic security assessment in power systems holds the potential to enhance the accuracy and computational speed of security evaluation. Despite the benefits, system operators may be reluctant to embrace these solutions, as the models may be challenging to interpret and perceived as black boxes. Additional concerns may arise regarding the adequacy of testing under realistic conditions.

A digital twin is applied for the realistic testing of dynamic security assessment based on ML applications (Optimal Decision Trees) in Rhodes, a Greek non-interconnected island. The developed digital twin incorporates two options for the virtual model of the island: an interface with commercial RMS/EMT software and a real-time simulator together with industrial under-frequency load shedding protection equipment. The settings of the current field devices on the island are tested through a hardware-in-the loop interface. The virtual models are updated with near real-time data obtained from the SCADA, and the dynamic security algorithm is also executed in real time using online data.

EU BRIDGE projects

TwinEU Digital Twin for Europe.[18] This project aims to produce a pan-European digital twin (DT) based on a federation of local twins.

ICONIC Smart, Aware, Integrated Wind Farm Control Interacting with Digital Twins[19]

This project develops digital and physical tools for the integrated control of wind farms, considering the whole physical system at farm, turbine, and component levels, and in particular, the complex aerodynamic interactions between turbines. The integrated control solutions are demonstrated by an extensive validation study via high-fidelity simulation models, experiments at a national-level wind tunnel, historical operational data, and real-world wind farm field tests

ERANET-project AISOP

DTs and Internet of Things (IoT) technologies are used to create a modular framework that executes specific workflows designed to enhance grid observability and analyse the effects of dynamic tariffs in mitigating grid violations[20]. Data-driven approaches have been used for anomaly detection in low-voltage grids using several machine learning techniques.

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[18] CORDIS. (n.d.). *Project 101136119*. https://cordis.europa.eu/project/id/101136119

[19] CORDIS. (n.d.). *Project 101122329*. https://cordis.europa.eu/project/id/101122329

[20] Barahona, B., et al. (2024). A framework for data-driven decision support for operational planning in active distribution networks. *IET Conference Proceedings, 2024*(5), https://doi.org/10.1049/icp.2024.1979

5.7 Emerging Computational Technologies [4]

5.7.1 Parallel and Distributed Computing

Parallel computing and distributed computing are techniques for accelerating computation problems by decomposing computation workload into subtasks that can run simultaneously on multiple cores or processors on a shared memory computer. Distributed computing refers to the use of independent computers that are networked to collaborate on a common computing task. Both techniques can improve performance, increase efficiency, and help solve very large-scale problems.

The adoption of parallel and distributed computing requires a profound understanding of both the domain-specific problem and the underlying computing hardware in order to guarantee efficiency; it requires theory and practice to develop parallelisable algorithms, determine the optimal granularity of tasks, manage data dependencies, ensure synchronisation, and minimise communication overheads.

Current State

Parallel and distributed computing has gained momentum in power system analysis, planning and optimisation, and real-time operations.

Regarding supervision and control, the main fields of application in steady-state analysis include power flow analysis, optimal power flow (OPF) (temporal and spatial decomposition), state estimation and contingency analysis. In system dynamic analysis, approaches exist in parallelising transient stability simulations, electromagnetic transient simulations and small signal stability analysis (e.g., accelerating the solution of sparse linear equations or increasing the integration time steps). Other applications for monitoring, control, and data analysis include real-time monitoring, synchrophasor applications, and wide-area control and applications in Blockchain technology, also known as distributed ledger for storing and processing data across the network.

Future State

General trends for future applications include designing algorithms and frameworks that:

- Efficiently use heterogeneous computing resources, such as CPUs, GPUs, FPGAs, and specialised accelerators that can dynamically adjust their granularity based on real-time computational loads, ensuring optimal use of computational resources across diverse scenarios. Development of standardised and open platforms and benchmarks that allow researchers and industry professionals to compare different parallel computing methods, promoting transparency, replicability, and continuous improvement in the field. Explore the potential of quantum computing (section 5.7.2) for solving computationally intensive power system problems, like optimisation or eigenvalue analysis

5.7.2 Emerging Computational Technologies - Quantum Computing

Current State

The application of quantum computing in power system engineering is mostly in the theoretical or very early experimental stages. However, its potential to vastly outperform traditional computers for certain tasks, has been recognised, and preliminary research has been conducted on its possible uses in power system optimisation, simulation, fault detection, and grid security.

Future State

The future of quantum computing in power system engineering could be revolutionary. Quantum algorithms have the potential to significantly enhance the performance of critical tasks. This could result in more efficient power generation and distribution and improved grid security and resilience. There may be an exploration of the use of quantum computers on the cloud for edge computing purposes and/or for small-scale optimisation in the field.

GPU Computing Current State

Graphics processing units (GPU) are specialised computing hardware with highly parallel processing capabilities that were originally designed for rendering images and graphics in video games and multimedia applications. In the power system field, GPUs have been studied to analyse single and batch power flow problems and closely related problems such as static security analysis and contingency screening to achieve parallel computing and reduce computation time. Researchers have also attempted to use GPUs in state estimation, small-signal stability analysis, transient stability analysis and optimal power flow. In the literature, high parallelism and significant speedup have been demonstrated in these works.

Current challenges include the inherent difficulties in algorithm parallelisation for some power system algorithms, the data transfer bottlenecks between GPU and CPU for applications with large datasets and the GPU memory limitations.

Future State

Potential future directions may include the evaluation of the performance scalability and energy efficiency in more advanced GPU/CPU hardware, GPU clusters, cloud computing and new computing platforms, including quantum processors and the development of solutions for edge devices to enable localised processing and decision-making for critical tasks.

5.7.2 Edge Intelligence

Current State

Edge intelligence is emerging as a transformative technology that changes the way we manage and optimise electricity distribution. It provides significant opportunities for power grids since it is positioned where decisions need to be made, often directly at the source of data production. Thus, it is characterised by low latency, which is crucial for real-time decision-making. This approach offers the potential to improve operational efficiency and functional safety, to seamlessly integrate renewable energy sources and bolster grid resiliency, etc.

Edge intelligence has played a pivotal role within the broader scope of the IoT (Section 5.2). With increasing decentralisation and real-time decision-making of power systems, edge intelligence can play a key role thanks to its localised processing and decision-making capabilities. Technologies like edge computing, advanced sensors, and machine learning algorithms are being strategically deployed at the edge of the power grid. This deployment facilitates quicker responses to dynamic changes and enhances overall system efficiency. The integration of edge intelligence in power systems presents notable advantages, e.g. in the exploitation of distributed energy resources, optimising virtual power plants based on local data and constraints, etc.

Future State

The future trajectory of power systems is probably linked to the ongoing evolution of edge intelligence by elevating the intelligence of edge devices, empowering them to locally process and analyse data. This evolution is geared towards diminishing latency, improving reliability, and laying the groundwork for autonomous decision-making within the power grid. The synergy between edge intelligence and emerging technologies, such as 5G and the IoT, is expected to substantially augment the capabilities of power systems. To render edge computing scaleable, automation becomes critical, and human intervention should be minimised. Decisions need to be proactive and predictive in nature, aligning with the dynamic and complex nature of the edge of power systems.

Indicative Good Practices

The E4S Alliance (Edge for Smart Secondary Substation) works on defining a standards-based, open, interoperable, and secure architecture to enhance the automation, scalability, security, and manageability of secondary substations worldwide. Involved DSOs are i-DE, E-EDES, Enedis and UFD.

Stedin is piloting AI on the edge with high-frequency or real-time data collection (from sensors, microphones and thermal cameras) in substations primarily for asset management and prediction. Piloting modular architectures on edge computers to test security risks and flexibility benefits.

6. RECOMMENDATIONS

6.1 TSO-DSO-DER coordination

The increasing penetration of renewable and distributed energy resources at the transmission and distribution networks make the operation of modern power systems extremely complex. In order to face these challenges grid operators need to enhance the capabilities of supervision and control of their networks by applying advanced methods and technologies. The core of these activities is performed at their control centres, namely EMS and ADMS. Lately, the increased penetration of DER has made the installation of DERMS highly desirable in order to deal with their dedicated management. The close coordination of these control systems at different levels and with different responsibilities is essential and requires well established procedures and efficient and timely data sharing to allow efficient scheduling operation and coordinated control activities. This is particularly important for the provision of ancillary services by DER. Modern ADMS operation should carefully consider the capabilities of Grid Forming (GFM) inverters, including their black-start capabilities. ADMS and DERMS optimisation algorithms will have to manage increased uncertainty as more non-dispatchable DERS are integrated. Finally, cybersecurity concerns are an area where increased efforts need to be devoted.

6.2 Regulatory support for novel solutions

Only TSOs and DSOs are responsible for power system supervision and control, and they are the main beneficiaries of the admirable technological achievements in these fields. In order to face the increased complexities, operators should be encouraged to adopt novel methods and tools. Experimentation with novelties is essential at the first stages of their application to a particular system, but this does not guarantee success of this application. Operators should be allowed to finance such efforts without the stringent regulatory restrictions of proven performance of the relevant investments. Regulatory restrictions, in general, should be relaxed for specific areas and periods in the case of novel technologies applications that show promising results, even if they entail certain risk and their performance is not guaranteed. The application of regulatory sandboxes is a step in the right direction.

Power systems are part of critical infrastructure and there are initiatives like the EU AI Act that are working towards implementing a legislative framework or regulations for such applications. This can potentially enable de-risking of such applications for operators if implemented in such a manner that does not inhibit innovation. There are also several technical developments/aspects that can help in this direction.

6.3 Support in ML and AI technologies

An important aspect that needs to be addressed when discussing ML-based methods is trust. ML models, especially the ones that tend to have powerful predicting capabilities like large neural networks, are usually black box in nature. This can be a hindrance in real-world implementation. However, there are recent advances around explainability/interpretability that allow us to explain what drives the outputs of the models. The explainability/interpretability of ML models can help understand how models work and reach decisions. This can enable trust but also help in gaining useful insights into complex underlying behaviours. Verification methods for ML methods can also be useful in offering some performance guarantees.

Some particular areas that need to be especially considered are:
The scalability of ML-based methods to ensure ML models can be trained efficiently for very large real networks. To this end, it is important to develop proof-of-concept applications in close collaboration with academia, research organisations and industry. Physics informed methods have shown to be helpful in this respect.
Data quality and access/availability have also been flagged as a challenge, especially when consumer or sensitive data might need to be exchanged between industry participants. Data collection and management is a challenge due to the current lack of existing processes/expertise to handle tools relying on data quality (and quantity). This mainly refers to applications that depend on real-world data and where bad data might cause unwanted or unexpected behaviours. The availability of open datasets and competitions can help in this direction.

Lack of in-house expertise and relevant skills concerning AI and data science is a general challenge that can hinder the adoption of such methods by the power industry.

6.4 R&I in emerging computational technologies

Emerging computational technologies (Section 5.6) are certainly worth considering; however their practical application in power system operation and control is mostly in its infancy. Undoubtedly, their application can provide several advantages regarding speed of data processing; however, more R&I is needed in order to prove their added value for power system control functionalities. Some examples are:

- Quantum Computing: Research is needed to showcase the feasibility of using quantum computers for developing applications in the power grid. Developing quantum algorithms for power system applications is a complex task and a major challenge since it requires a deep understanding of both power engineering and quantum physics. Additionally, while theoretical analyses have shown that quantum algorithms could enhance certain power system tasks, more research is needed to determine how these theories can be translated into practical applications in the real world. Finally, quantum algorithms for basic functionalities like linear solvers, optimisers, etc., need to be produced that will enable to development of quantum algorithms for power grid applications.
- GPU Computing: The value of GPUs in power system applications such as unit commitment, dynamic state estimation, fault detection, cyber-physical system security, co-simulation of transmission-distribution, EMT simulations, etc., needs to be explored by pilot GPU-computing projects. Newer computer technologies such as a system on a chip (SoC) need to be explored for their enhanced memory and speed capability. Also standardised test cases and benchmark studies need to be developed to evaluate and compare the performance of different solutions and GPU/CPU hardware.
- Edge Intelligence: the main challenges concern data security, the interoperability of diverse edge devices, and the necessity for standardised protocols. Coordinating real-time data extraction proves to be particularly challenging due to the variety of data streams and the bidirectional flow of data/decision traffic. R&D efforts are particularly needed for robust encryption and authentication mechanisms for data security, standardisation towards creating interoperable frameworks, enhance scalability by advancements in edge computing infrastructure and collaborative efforts between stakeholders.

7. Conclusions

The European energy transition demands increasingly digitalised, intelligent, and resilient power systems.
Enhanced system supervision and control are at the core of this transformation. The large-scale integration of

renewable energy sources, the decentralisation of generation, and the active involvement of consumers require a new technical and organisational architecture built on interoperability, observability, and cybersecurity. Digitalisation, through artificial intelligence, digital twins, the Internet of Things, and real-time data analytics, enables optimised operation, improved efficiency, and strengthened resilience of the grid. These technologies must be complemented by flexible regulatory frameworks, transparent TSO–DSO–DER coordination schemes, and robust data protection and cybersecurity strategies.

A truly digitalised European power system will be one capable of anticipating events, adapting to changing conditions, and recovering rapidly from disturbances or threats. The ultimate vision is an interconnected, intelligent, and trustworthy energy network that combines advanced automation, distributed intelligence, and human oversight, ensuring a sustainable, secure, and affordable electricity supply for all European citizens.

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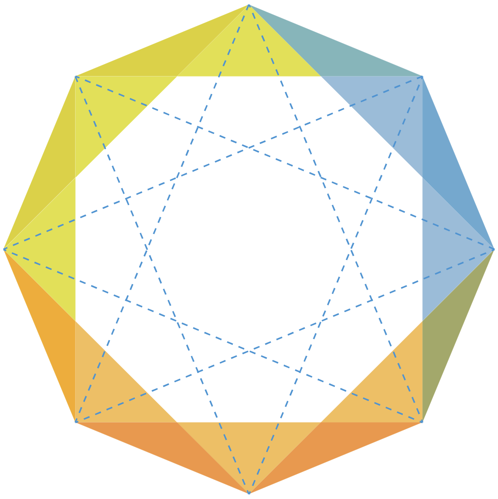

The Service Contract (n. CINEA/2023/OP/0001/SI2.901723) supports BRIDGE activities, funded by the EU.

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