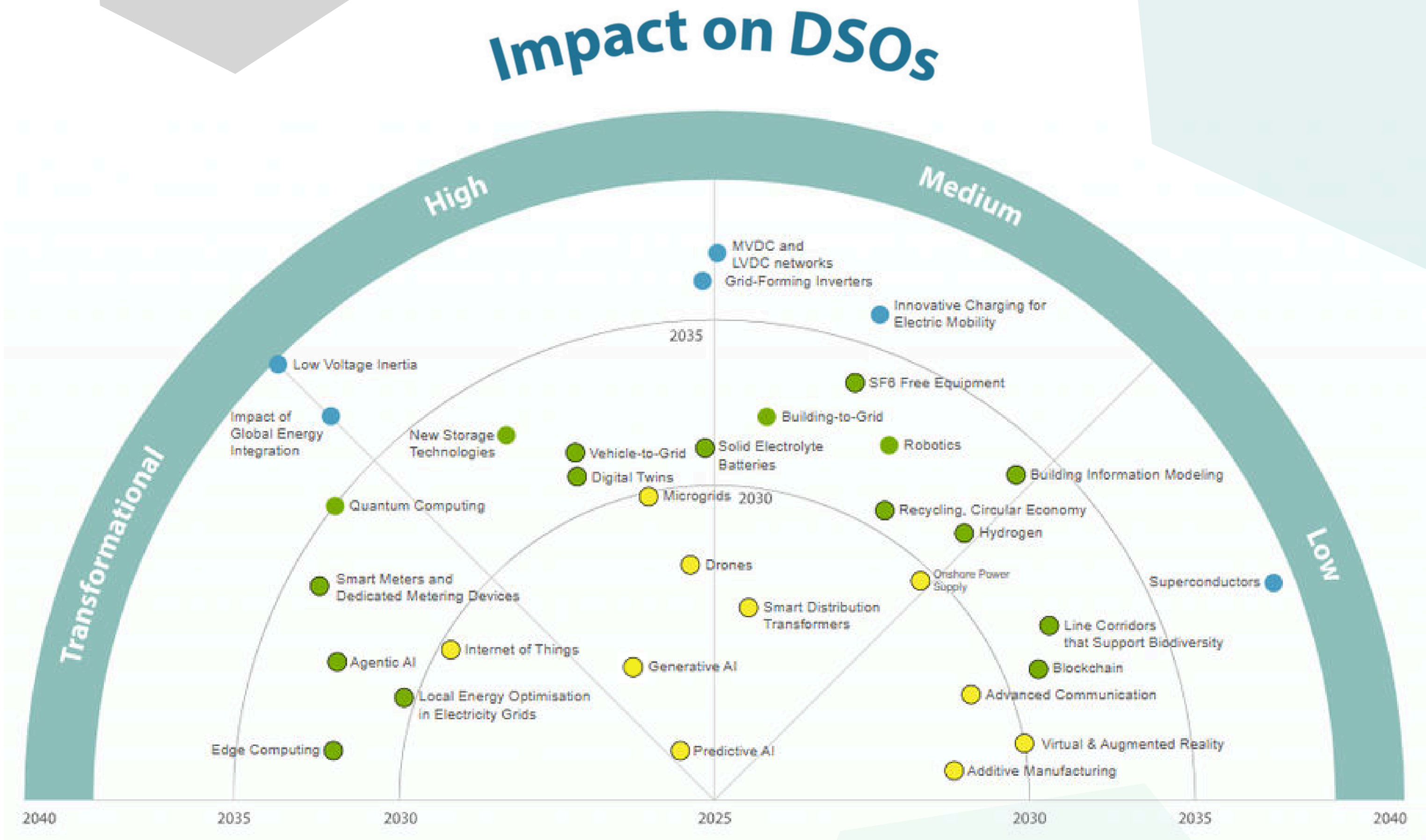
E.DSO Technology Radar



September 2026

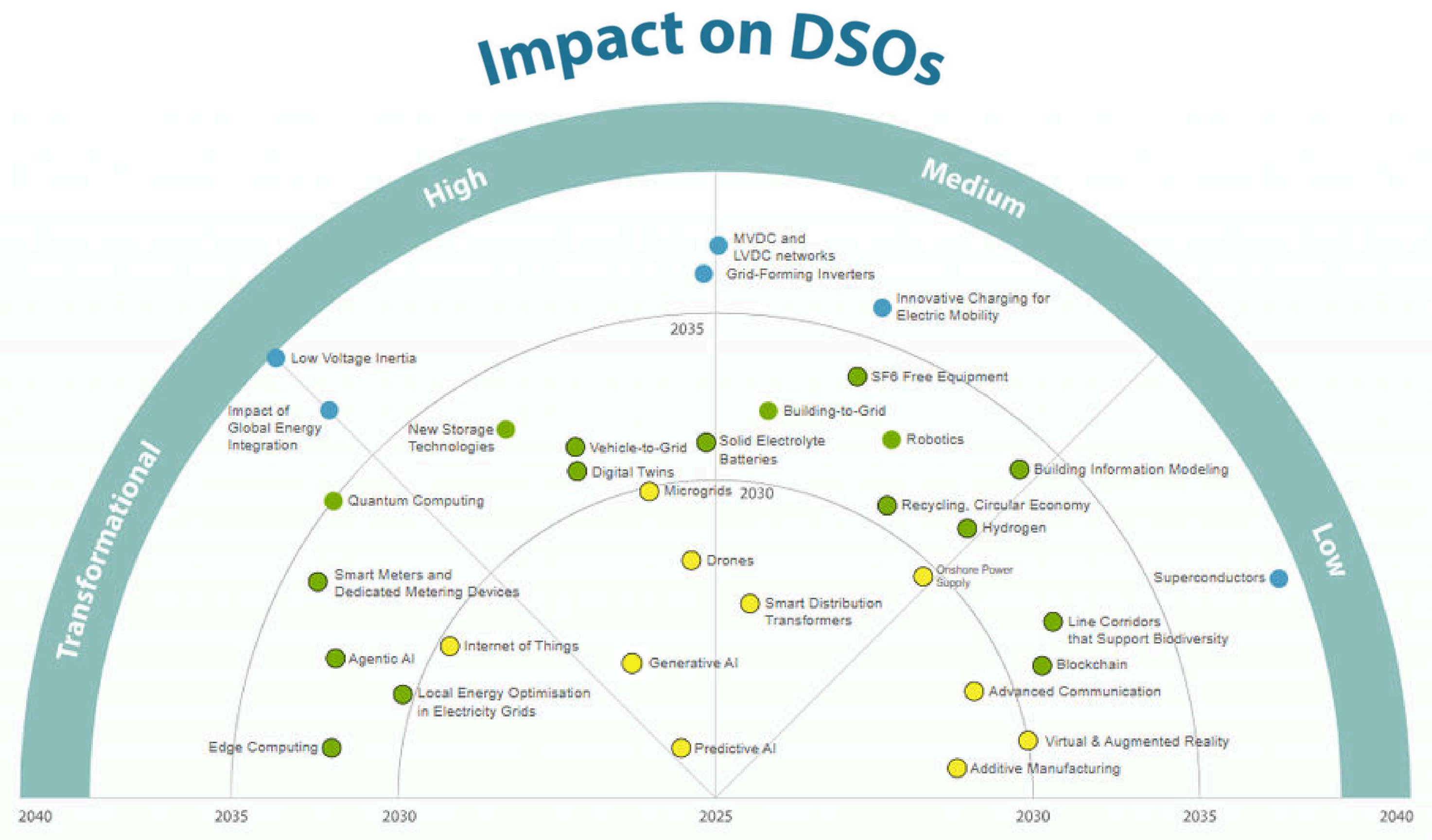
Table of contents

European Distribution System Operators (E.DSO) gathers 37 leading electricity distribution system operators (DSOs), including 2 national associations, cooperating to ensure the reliability of Europe's electricity supply for consumers and enabling their active participation in our energy system.

This is the eighth edition of the E.DSO Technology Radar. You can submit comments and suggestions on this work at techradar@edsoforsmartgrids.eu.

Publishing date of this document: **15 September 2026**
Last update of the Technology Radar: **12 September 2026**

About the Technology Radar



European Distribution System Operators (E.DSO) promotes and enables customer empowerment and the increase in the use of clean energy sources through electrification, the development of smart and digital grid technologies in real-life situations, new market designs and regulation. E.DSO and its members are committed to taking on the huge challenges associated with realising the Energy Union, built on the EU's ambitious energy, climate, security of supply, jobs and growth objectives. This involves ensuring the reliability and security of Europe's electricity supply to consumers while enabling them to take a more active part in our energy system.

The current technological landscape is very uncertain, marked by numerous and rapid developments.

The current period is characterised by numerous and rapid technological developments and possible disruptions, particularly in the energy and Information Technology (IT) sectors. These transformations potentially have a significant impact on DSOs. They must therefore prepare for it, which sometimes imposes difficult choices between the subjects on which to work as a priority.

A Technology Radar has been prepared with the objective of identifying and analysing trends and stimulating innovation.

The Technology Radar's ambition is to evaluate technological topics that have a potential impact on DSOs and their ecosystem (public authorities, suppliers, customers, and employees).

The objectives are:

- Early identification of new technologies, technological trends and potential disruptions
- Increased awareness of the opportunities and threats associated with emerging technological developments
- Stimulation of innovation by combining technology reports with business potential assessment.

For each trend, a factsheet has been drawn up summarising the key elements relating to the technology considered, the developments in progress as well as the analysis of potential impacts for the DSOs. These may consist, for example, of a change in their business model, prospects for productivity gains or opportunities to develop new services.

An aggregated view of all ongoing trends has been constructed by positioning each technology on a diagram according to estimates of industrial maturity time and magnitude of impact on DSOs. This helps to visualise key technologies as they relate to DSO activities. It should be noted that the position of each technology on this diagram is often only indicative and could be the subject of endless debate, in particular for technologies, such as artificial intelligence, which are already widely used and which however are subject to potentially disruptive new developments.

The trends analysed cover in particular energy systems, digital technologies, and the various emerging solutions serving operational performance.

The task was carried out in an effective way by a network of high-level experts.

A dedicated Task Force organised within the E.DSO Technology & Knowledge Sharing Committee and including high-level experts from a large set of European DSOs was set up to produce the Technology Radar. The sourcing and analysis of technologies has been facilitated by reaching, through the network of technology scouts, the best sources of information.

The members of the Task Force are:

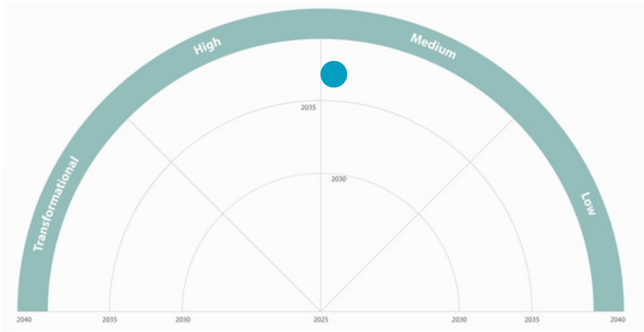
- Convenor: Anne-Laure Popelin (Enedis).
- Members: Alessandro Cirocco (Unareti), Angeliki Gialketsi (HEDNO), Antonio Castellanos (Enel Grids), Aris Baumgarts (Sadales tīkls), Dan Catanase (ESB Networks), Diego Raggini (Unareti), Dimitrios Selimis (HEDNO), Enrique Garcia (i-DE), Eugenio Maria Mazza (Unareti), Ewa Mataczynska (PGE Dystrybucja), François Dispot (Enedis), Gerald Käferle (Netz NÖ), Hynek Mencl (ČEZ Distribuce), Javier Hernandez (i-DE), Johannes Stürmer (Westnetz), Karolina Kowalska-Balmas (PGE Dystrybucja), Konstaninos Mammasis (HEDNO), Mariano Gaudó (UFD), Mark den Brok (Stedin), Olivier Goethals (Fluvius), Raquel Gómez Martín (E-REDES), Rolands Agofonovs (Sadales tikls), Samuele Giovannetti (Enel Grids), Sjors van der Heijden (Stedin), Thomas Börmans (E.ON), Thomas Buisseret (ORES), Wilfried Pichler (EVN), Wouter van den Akker (Alliander).

Regular updating is essential.

Given the rapid evolution of technologies, E.DSO plans to carry out a regular update of its Technology Radar.

Last update: 12 September 2026

Network Technologies



Although the transmission and distribution of electricity is almost exclusively carried out in alternating current (AC), certain trends call for a reconsideration of the interest in **direct current (DC)**:

1. The uptake of renewable energy (photovoltaic and wind) and batteries (in particular electric vehicles), which natively operate in DC, is accelerating.
2. The proportion of energy consumed in DC at home is high (50% in 2018) and growing sharply (80% projected by 2030).
3. Innovation and fast-decreasing costs in power electronics are making the use of DC increasingly economical.

The use of direct current could allow limiting conversions on the distribution network, representing a source of simplification and improving the energy efficiency of the electrical system.

Highlights

DC solutions, in particular for the distribution network, are raising great interest, with numerous demonstrators around the world and, as it appears, a proactive industrial policy in China. Standardisation of DC networks is of critical importance, even more so for low voltage DC (LVDC) to enable the development of appliances. The International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) have all started standardisation work on medium voltage (MV) and LV DC networks.

Opportunities for DSOs

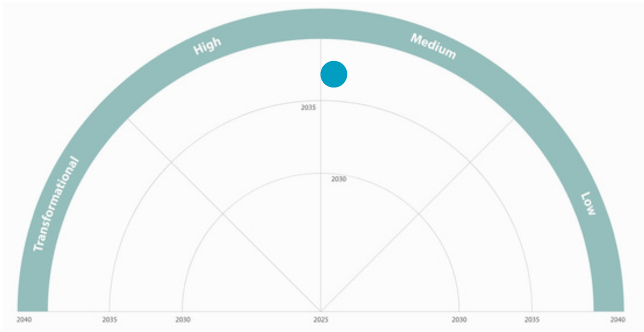
DC grids are a solution of interest for some relevant use cases.

- For **wind or photovoltaic (PV) plants, storage units and charging stations**, a DC connection could be a relevant solution from a technical-economic point of view.
- **Microgrids**: MVDC or LVDC hybrid microgrids could be developed.
- **Control of power flows**: DC lines could allow connecting two areas by controlling the flows between them.

Challenges for DSOs

DC grids have several challenges to overcome:

- **Technical aspects**, in the absence of global standards and within an incomplete international regulatory framework, including:
  - Definition of voltage levels; conversion topologies and electrical architectures; connection, operation, and protection.
  - Availability and sustainability of suitable hardware offerings, and equipment interoperability; metering and communication chain.
  - Concept of power quality, definition of a point of delivery (POD) in DC.



Challenges for DSOs (continues)

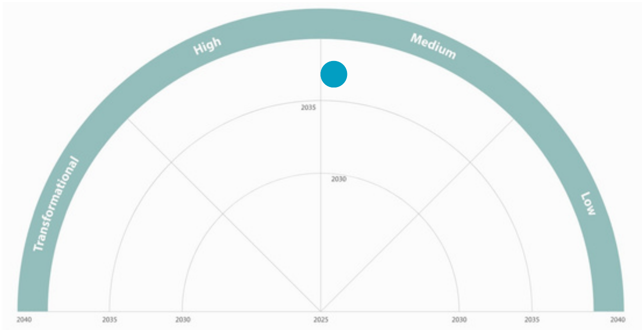
- **Non-technical aspects**, within a regulatory, normative, contractual, and insurance framework built for AC systems:
  - Energy Code, quality decree, and technical decree.
  - European standard EN50160 (characteristics of voltage supplied by the DSO).
  - Suppliers' general terms and conditions.
  - Commissioning and insurance guarantees for installations.
- **Issues related to network economics and planning**:
  - Need for clear identification of use cases where DC could be part of the reference solution catalogue, based on robust comparative cost-benefit analyses.
  - Integration of DC solutions into the existing AC network and consideration of long-term impacts. Equipment robustness. Scalability.

E.DSO Considerations

- DSOs should carry out the analyses and implement the demonstrators necessary to identify the relevant use cases of DC links.
- DSOs should master the technical and economic aspects of DC networks and the related regulatory aspects.
- DSOs should mobilise to play an active role in the development of standards for DC distribution networks.
- Experience needs to be gained via pilot projects to ensure the safety of operations (power protection and control, etc.).

Potential use cases

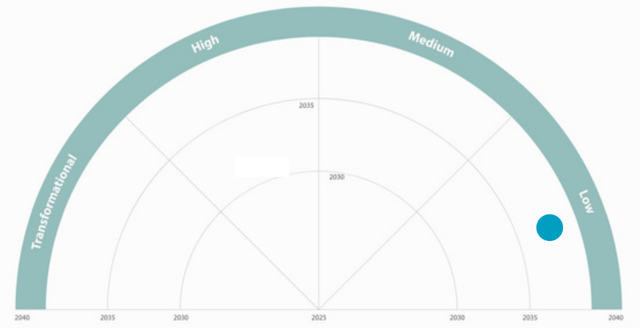
- AC/DC network hybridisation for greater energy efficiency.
- High-power and/or long-length connections.
- Controlling power flows between electric zones.
- Connection of linear transport operators.
- Solutions for recharging all types of electric mobility.
- Networks for specific applications (e.g., data centres).
- Hybrid AC/DC indoor distribution.
- Connections for wind or PV plants, storage units or charging stations.
- Microgrids.
- Control of power flows.



Ongoing projects

- **ORES** (Belgium) conducted a study on DC connections with the Laborelec research centre. Broadly speaking, the study shows that a DC connection for wind generation units is technically feasible but does not yet offer a sufficient cost-benefit ratio for the use case to be exploited. At lower voltage levels, the problem was a too great difference in standards between the various devices to be able to create an effective DC network (many DC-to-DC converters were needed).
- The ASTRA-CC project was developed by **i-DE** (Spain) to explore the conditions for the creation of DC networks with an operation equivalent to the LV and MV AC networks. The project is currently investigating new DC secondary substation designs, converters and public DC network architectures that reduce barriers for the connection of direct current loads to the MV grid, such as renewable generation and storage systems. ASTRA-CC aims to further assess the feasibility of deploying DC public networks as a complement to the AC networks for specific applications.
- **Enedis** (France) is *considering* implementing a project (“DC Douai”) with a field demonstrator. This would involve an LVDC line to which one PV production and two EV charging stations would be connected.
- **Enedis** is also working through academic partnerships on different aspects of the DC networks and has been financing several PhD and postdoctoral works:
  - “Hybrid AC/DC distribution network architectures: Analysis of power quality and protection aspects” (PhD, ESTIA 2020-2023).
  - “Optimisation of the architecture of a hybrid AC/DC MV/LV distribution substation: Design and sizing” (PhD, Centrale Supelec 2020-2023).
  - “DC network protection” (Post-doc, INPG 2024-2025).
  - “Stability of multi-source DC power networks” (PhD, Centrale Supelec 2025-2028).

Last update: 26 June 2025



Some metals cooled to very low temperatures (typically between -272 and -240°C) acquire the superconducting state, i.e. the ability to conduct electric current without resistance and, thus, without energy loss. **Superconductivity** has reached the industrial stage in some sectors for the production of intense magnetic fields such as medical imaging, particle accelerators and tokamaks. The applications of superconductivity to grid cables and current limiters have been the subject of experiments after the discovery in the mid-1980s of "high temperature" superconductivity (-196°C) which allows the use of liquid nitrogen for cryogenic purposes. Superconducting cables carry up to 5 times more energy than standard cables.

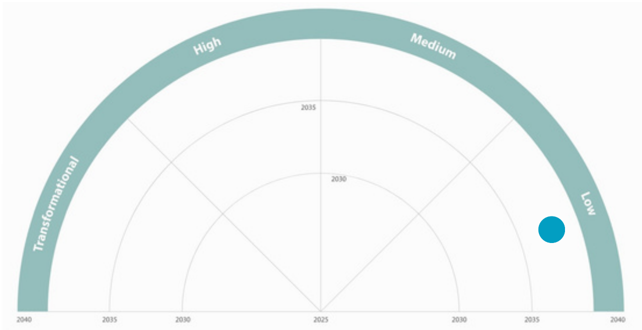
Highlights

Superconducting technologies can be used for power lines, current limiters and transformers.
A large number of tests of **superconducting power lines** have been conducted. Some of them took place many years ago (Long Island 2008: 600 m, 138 kV, 574 MW; Essen 2014: 1000 m, 10 kV, 40 MW), but others are recent (Shingal/Korea 2019: 1000 m, 23 k, 50 MW; Shanghai 2021: 1200 m, 35 kV, 80 MW; Chicago 2021: ~ 100 m, 12 kV, 62 MW) and several are currently under development (Paris/Gare Montparnasse 2025 / 2 links of 60m, 1500V DC, 5 MW; Munich 2025: 150 m/15 km,110 kV AC, 500 MW). We are therefore seeing a renewed interest in this technology. Many experiments with **current limiters** (10 kV to 138 kV, from a few MVA to a few tens of MVA) have taken place in the USA, Asia (Korea, Japan, China), Germany and the United Kingdom since the 2010s, without leading to a significant deployment of these solutions. Superconducting transformers have also been tested, but it appears that no further work has been done on this solution for about ten years.
These real-world projects provide crucial data on the performance, cost, and operational challenges of superconductor technology, forming the evidence base for any future DSO business case.

Opportunities for DSOs

The opportunities offered by superconductor technologies directly address some of the most pressing strategic challenges facing modern distribution networks.

- **High-Capacity Power Transfer in Congested Environments:** The primary advantage is the ability to transmit significantly more power through a very small right-of-way. This may allow DSOs to upgrade capacity in dense urban centres while avoiding the extremely high costs, long timescales, and public disruption associated with major civil engineering works for multiple new conventional cable circuits.
- **Enabling Renewable Integration and Grid Modernisation:** Superconducting Fault Current Limiters (SFCLs) may offer a strategic solution to rising network fault levels, which are a direct consequence of connecting more Distributed Energy Resources (DERs). An SFCL can allow a substation to host more generation without requiring a prohibitively expensive, full-scale replacement of its switchgear and busbars, thereby deferring massive capital expenditure.
- **Enhanced Network Resilience and Flexibility:** Superconducting cables can be used to create high-capacity interconnections between primary substations. This may strengthen the network topology, provide valuable redundancy, and give operators more flexibility to re-route power during outages or maintenance, improving overall supply security.



Challenges for DSOs

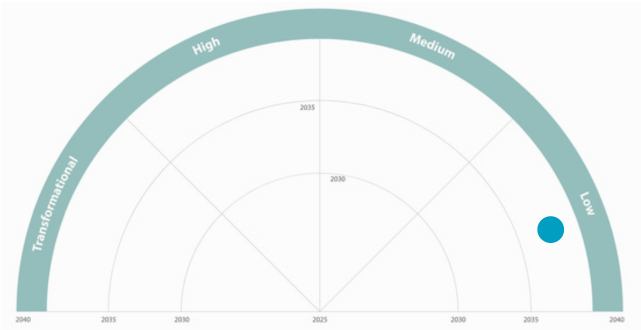
While promising, the technology presents significant economic, operational, and technical hurdles that must be thoroughly evaluated before any investment.

- **Economic Viability and Total Cost of Ownership (TCO):** The business case is not yet clear-cut. A DSO must conduct a rigorous TCO analysis comparing a superconducting solution to conventional alternatives. This must include not only the high initial CAPEX (cable, complex cryogenic plant, terminals) but also the continuous OPEX, particularly the significant energy consumption of the cooling systems and the costs of specialist maintenance contracts.
- **System Reliability and Maintenance:** The reliability of the entire system is paramount. The cryogenic cooling plant represents a critical single point of failure; its failure is equivalent to a cable fault. Furthermore, the time required to repair a fault can be substantially longer than for conventional cables, requiring specialised equipment and skills that are not widely available. To make investment decisions, DSOs need robust data on the Mean Time Between Failures (MTBF) and the Mean Time to Repair (MTTR) of these systems, data that is not really available for these emerging technologies.
- **Grid Integration and Protection:** Superconducting cables have fundamentally different electrical characteristics (e.g., near-zero impedance) compared to copper or aluminium cables. Integrating them into a hybrid network requires sophisticated engineering studies. Existing grid protection schemes may need to be completely redesigned to ensure that faults can be correctly detected and isolated without causing mis-operation or instability elsewhere in the network.

E.DSO considerations

A proactive and structured approach is required. DSOs must regularly assess the maturity of superconductive technologies through a strategic roadmap.

- **Phase 1 - Monitor & Learn:** Actively monitor the operational data, reliability metrics, and real-world costs emerging from key demonstrator projects like Munich's "SuperLink". Engage with manufacturers to understand the technology's development trajectory and supply chain maturity.
- **Phase 2 - Identify & Model:** Proactively identify specific, high-value "problem locations" within the DSO's own network where conventional reinforcement is exceptionally difficult or expensive. Conduct detailed desktop studies and business case modelling for these specific scenarios to understand the potential TCO benefits of a superconducting alternative.
- **Phase 3 - Pilot & Develop**: For DSOs facing imminent and severe grid constraints, collaborating on a smaller-scale pilot project could be a strategic step. This would build invaluable in-house expertise on the practical engineering, installation, and operational realities of the technology before committing to a major, business-critical deployment.



Potential use cases for DSOs

- **Urban Centre Infeed:** Replacing ageing, capacity-limited fluid-filled cables in dense city centres to meet very high future load growth from electrification of heat and transport.
- **Substation Deferral or Avoidance:** Using a single superconducting link to provide a massive capacity upgrade to an existing primary substation, thereby deferring or completely avoiding the multi-million-euro cost of acquiring land for and building a new substation.
- **Connecting Power-Intensive Loads:** Providing high-capacity, low-footprint grid connections for new large loads such as data centres, gigafactories, or major electric vehicle fleet charging hubs.
- **Grid Reinforcement for Renewables:** Deploying SFCLs at substations with high penetrations of DERs to manage fault levels and unlock additional capacity for renewable connections.

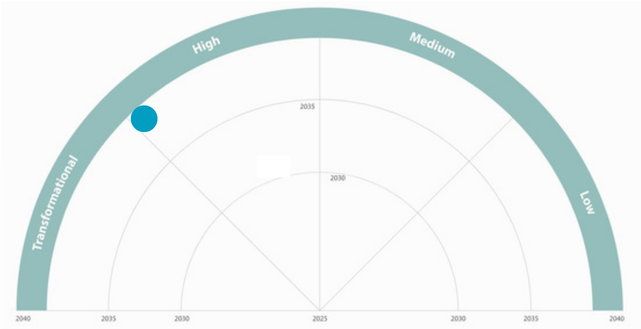
Ongoing projects

The following projects are key sources of the data needed for the 'Monitor & Learn' phase of the DSO strategic roadmap.

- **Test operation of an innovative high-temperature superconductor cable has begun in Munich** (150 m/15 km, 110 kV AC, 500 MW). A 15-kilometer-long superconducting cable is the subject of ongoing design and testing as part of the "SuperLink" research project. The first 150 meters of the project have been put into operation in 2025 under real conditions to test the functionality and suitability of this technology for everyday use. The cable is being supplied by NKT. The line owner is Stadtwerke München Infrastruktur, a subsidiary of the utility Stadtwerke München.
- A **new connection** (2 links of 60m, 1500V DC, 5MW) **has been installed and is expected to be commissioned in 2025 in Paris**, at Montparnasse railway station. The cable is being supplied by Nexans. The line will not be operated by a DSO, but by SNCF-Reseau, the French rail network operator. Superconducting technology was chosen because the space available for the connection was very small.

Last update: 30 September 2025

Power System Technologies



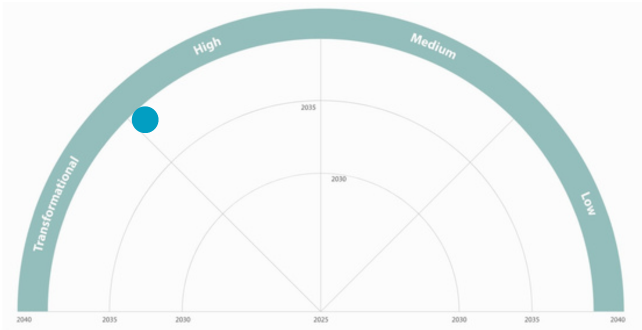
As conventional power plants with large rotating turbines are replaced by inverter-based Distributed Energy Resources (DERs) like solar PV and batteries, the power system is losing its natural physical **inertia.** This inertia is critical for stabilising the grid's frequency immediately following a fault or sudden change in load. Low Voltage (LV) Inertia, also known as **Synthetic or Virtual Inertia**, is the solution to this challenge. It is a capability provided by advanced power electronics (specifically **grid-forming inverters**) that enables DERs to actively mimic the stabilising behaviour of traditional generators. This decentralises grid stability, moving it from large transmission-connected plants to the medium and low-voltage grids edge where the new generation is located.

Highlights

The need for virtual inertia is rapidly accelerating as renewable penetration targets increase. System operators globally are beginning to recognise inertia as a critical ancillary service that must be actively managed. Regulatory bodies are starting to update grid connection codes to mandate grid-support functions, including inertia, from new DER connections. This represents a fundamental shift from a passive distribution network to one where a significant number of small assets actively contribute to the stability of the entire power system.

Opportunities for DSOs

- **Increased DER Hosting Capacity:** By providing local stability, LV inertia allows DSOs to safely connect significantly more solar PV, batteries, and EV chargers onto their networks without violating technical limits or causing instability, unlocking new revenue streams.
- **Enhanced Grid Resilience:** DERs with grid-forming capabilities can create stable, self-sufficient **microgrids.** This enables intentional islanding to keep power on for critical facilities or communities during a wider grid outage, dramatically improving reliability.
- **Improved Power Quality:** Grid-forming inverters provide a strong, stable voltage waveform locally. This helps to mitigate voltage sags, swells, and other disturbances on the LV network, improving the quality of supply for all customers.
- **New Ancillary Service Markets:** DSOs could play a role as market facilitators or aggregators, procuring inertia as a paid service from customers with capable DERs. This creates a new value stream for customers and a new tool for the DSO to manage their network.



Challenges for DSOs

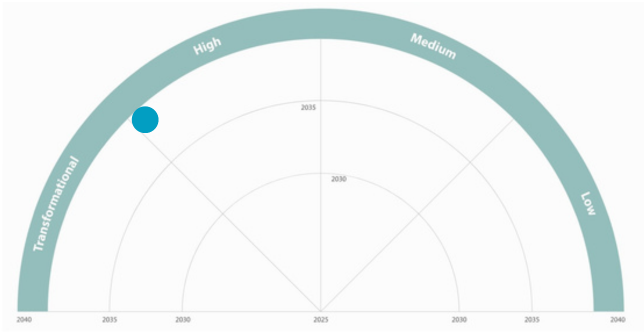
- **Technology Cost and Maturity**: Grid-forming inverters are more complex and currently more expensive than the standard grid-following inverters that dominate the market. A clear business case is needed to justify the incremental cost.
- **Control and Coordination Complexity:** Managing the stability contributions of thousands or millions of distributed devices is a major technical challenge. It requires advanced Distribution Energy Resource Management Systems (DERMS) to ensure they work in harmony and not against each other.
- **Lack of Standards and Interoperability:** There is an urgent need for industry-wide standards to ensure that grid-forming devices from different manufacturers are interoperable and their behaviour is predictable.
- **Protection System Redesign:** Grid-forming inverters have different fault current characteristics than traditional generators. Existing LV network protection schemes (e.g., fuses and circuit breakers) may not operate correctly and will likely require re-evaluation and redesign. Anti-islanding protections may not be effective with generators equipped with Grid-forming inverters. New protections will have to be designed and installed.

E.DSO Considerations

- **Advocate for Updated Grid Codes:** DSOs must actively participate in regulatory discussions to update national and European grid connection codes, ensuring that new DERs are required to have grid-forming capabilities.
- **Develop New Connection Agreements:** Connection agreements should be revised to specify the required grid support functions, including inertia provision, from new and existing DERs.
- **Invest in Digitalisation and Skills**: DSOs must invest in the DERMS platforms, communications infrastructure, and engineering skills necessary to monitor, control, and validate the performance of these distributed stability resources.
- **Launch Pilot Projects:** It is crucial for DSOs to engage in pilot projects to gain hands-on experience, test control strategies, and understand the real-world costs and benefits of deploying virtual inertia solutions on their networks.

Potential Use Cases

- **High-Penetration Solar Feeders:** Deploying grid-forming community batteries on LV circuits with high solar PV saturation to absorb excess generation while ensuring the local grid remains stable and within voltage limits.
- **Weak or Rural Grids:** Using a grid-forming battery system to "stiffen" the grid at the end of long, rural feeders, improving power quality and enabling the connection of new renewable generation or EV charging.



Potential Use Cases (continues)

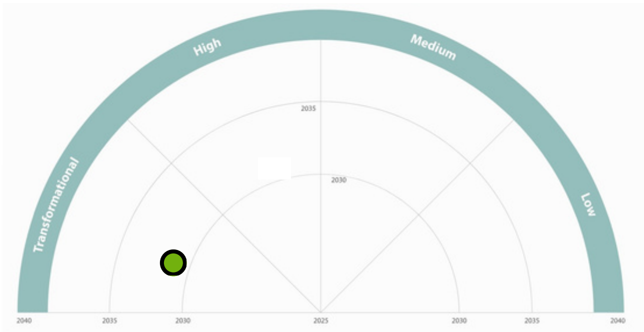
- **Resilient Critical Infrastructure:** Creating stable microgrids for hospitals, airports, or data centres that can seamlessly disconnect from the main grid during an outage and continue to operate reliably.
- **Large EV Charging Hubs:** Requiring new, large-scale EV charging depots to include integrated grid-forming battery storage, making them self-sufficient in terms of stability and capable of providing support services back to the grid.

Ongoing Projects & Initiatives

- **UK Power Networks (UK):** The "Constellation" project is a trial to manage DERs as a coordinated group to provide a range of services, including stability, by creating a virtual synchronous machine.
- **A-P-P-L-A-U-S-E Project (Germany)**: A research initiative focused on developing control strategies for large populations of grid-forming inverters to ensure stable operation of future power systems.
- **National Grid ESO (UK):** The "Pathfinder" programme, while at the transmission level, is a world-leading initiative procuring inertia and other stability services from non-traditional sources like batteries, setting the market precedent for DSOs.
- **SUREVIVE Project (Germany):** A lighthouse initiative testing grid-forming inverters and intelligent battery storage under real grid conditions to validate their role in providing instantaneous reserve and stabilizing distribution networks. The project explores innovative control concepts and aims to enable black start capability, frequency support, and energy balancing in future renewable-based grid
- **National Grid ESO – Stability Pathfinder Phase 2 (UK):** A strategic response to the growing low inertia challenge in Scotland, driven by the retirement of synchronous generators and the rise of renewables. The programme awarded £323 million in contracts to innovative technologies that can deliver inertia and short-circuit current without relying on traditional spinning machines. This initiative is key to maintaining grid stability in low-inertia conditions and sets a benchmark for future DSO-level services.
- **Enedis (France):** Enedis has financed and supervised several PhD theses and research projects on the operation of microgrids, particularly on the control of inverters (Grid Forming / Grid Following). The objective is to design innovative solutions to reduce the cost of implementing micro-grids (small systems without rotating machines and, if possible, without batteries, or with only a as small as possible battery). Furthermore, Enedis finances and contributes to the monitoring, together with the French TSO (RTE), of a thesis on the global system recovery after a widespread incident using renewable energy production means connected to the MV network.

Last update: 8 December 2025

4. Local Energy Optimisation in Electricity Grids



Local energy optimisation in electricity grids encompasses all technologies on the low voltage (LV) network that help ensure the **integration** of energy is carried out with minimal impact on supply quality. In the case of **photovoltaic (PV) generation** in LV networks, issues such as overvoltages and network instabilities may arise due to excessive generation during peak hours, which often coincide with low demand. Similarly, the gradual deployment of **electric vehicle (EV) charging points**, with increasingly higher power, can cause instabilities. In the current scenario of growing **electrification of demand**, all these aspects should be addressed.

Highlights

The total **PV energy capacity** in Europe is experiencing substantial growth, with annual additions hitting record highs and the total capacity projected to reach **405 GW by 2027**. Similarly, the number of EV charging points is expanding rapidly and is expected to exceed **1.2 million by 2025** due to significant investments and supportive policies in the sector. These developments reflect Europe's strong commitment to enhancing renewable energy infrastructure and aligning with broader climate and energy security goals (source: IEA).

Opportunities for DSOs

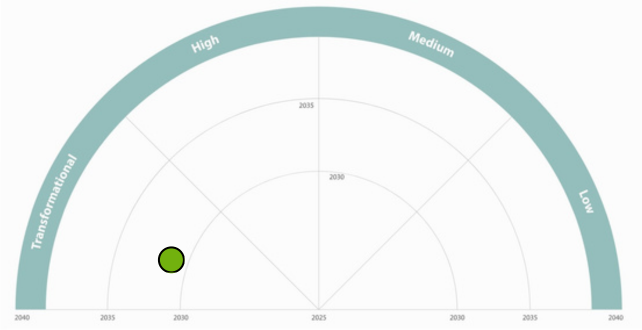
- The installation of **smart meters**, with some countries currently engaged in deploying their second generation, will allow DSOs to understand what is happening on the grid. The use of **Artificial Intelligence (AI) to make predictions and analyses will be necessary for planning LV networks** according to their needs.

Challenges for DSOs

- To ensure proper operation of the network, DSOs need, among others, to **enhance monitoring of LV networks**.
- The **variability of energy flows** makes it necessary to monitor information on **transformers in secondary substations** as well as the **headers of all LV feeders**.
- The presence of new actors, services, and modes of access to the grid, such as **local flexibility markets, flexible connections, and energy communities**, will require DSOs to integrate them into their planning, operation, and maintenance processes. This will also necessitate technological and operational integration.

E.DSO considerations

E.DSO recommends:



E.DSO considerations (continues)

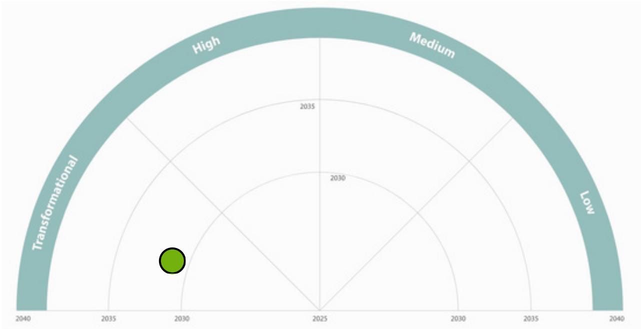
- Strengthening the grid through **investments in MV/LV grids** for **integrating new distributed resources** and **expanding** distribution networks.
- Using **flexible transformer regulation** to adjust voltage dynamically in response to fluctuating demand and distributed energy resource (DER) generation, enhancing grid stability and efficiency.
- Employing **smart transformers, LV balancers and regulators** to maintain voltage within acceptable limits, crucial in high DER penetration areas prone to **voltage fluctuations**.
- Utilising **local flexibility mechanisms** like **demand response** programs and **energy storage** to manage **grid congestion** and ensure **voltage stability** during peak periods and unexpected events.

Potential use cases

- **Real-time Monitoring and Predictive Maintenance**: Implementing advanced monitoring systems on LV networks and secondary substations to increase grid reliability, reduce maintenance costs, and improve response times.
- **Smart Meter Integration and Data Analytics**: Deploying second-generation smart meters to gather detailed consumption and generation data, enhancing energy flow visibility, improving demand forecasting, and optimising distribution.
- **Demand Response and Local Flexibility Markets**: Creating local flexibility markets for demand response programs to improve grid stability, integrate renewable energy sources, and increase energy market participation.
- **Integration of EV Charging Infrastructure**: Coordinating the deployment and operation of EV charging points with existing grid infrastructure to ensure smooth EV integration, reduce network overload risk, and support electric mobility.
- **AI-Driven Network Planning and Optimisation**: Using AI to analyse data for optimising LV network planning and operation, leading to efficient resource allocation, reduced operational costs, and enhanced resilience.
- **Energy Communities and Local Flexibility**: Facilitating the establishment of energy communities to contribute to local flexibility in the grid, increasing energy independence, better utilising renewable energy, and enhancing grid stability.

Ongoing projects

- **Spanish DSOs (i-DE, e-distribución, E-Redes, UFD, …).** In Spain, the deployment of residential smart meters (<15 kW) was completed in 2018. When these smart meters reach 15 years of age, they must be replaced with new ones. This new meter replacement plan is an opportunity for all DSOs, which use power line communications (PLC), to digitise their secondary substations and feeders with



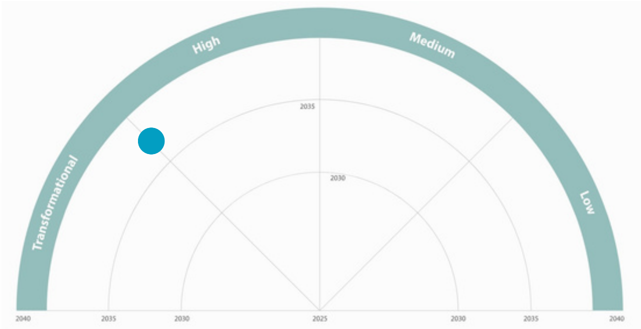
Ongoing projects (continues)

new technologies. The Spanish Government has launched a call for projects with regulatory exemptions (i.e., sandboxes) which was participated by all DSOs. A resolution focused on flexible connections and local flexibility markets is expected in the near future.

- **ORES** has developed a neutral compensator (**Equi-8**) that addresses voltage imbalances in three-phase LV networks, particularly in rural areas with few customers. This redistributes current across phases and between network and compensator neutrals, reducing voltage variation by a factor of 2-3. Voltage regulators are installed to stabilize line voltage in LV networks impacted by new assets like EVs and PV systems. These regulators adjust voltage per phase, with two versions available for different network types. ORES plans to install 20 regulators in 2024 and 50 more in 2025. In addition to this, ORES **Solormax** project uses AI to optimise solar production, preventing grid disconnections by modulating inverters in real-time.

Last update: 4 October 2024

5. Impact of Global Energy Integration



The **integration of various energy sources into the electricity grid** represents a transformative shift toward a more sustainable energy system. By connecting the electricity, heating, cooling, and transportation sectors, a process known as **sector coupling**, the grid becomes more flexible and capable of managing fluctuating demand and supply. This integration enhances efficiency, reduces carbon emissions, and strengthens energy security. However, this also introduces complexities in grid management, requiring new infrastructure, advanced technologies, and regulatory adjustments to maintain grid stability and reliability. As the share of renewable energy in the electricity sector continues to grow, other sectors, such as transport, buildings, and industry, remain heavily dependent on fossil fuels. The decarbonization of these sectors can either happen through electrification or by shifting from fossil fuels to renewable gases like hydrogen or renewable liquid fuels. The conversion between electricity and these gases can further increase storage capacity and add flexibility to the energy system.

Highlights

Sector coupling is crucial for reaching the EU climate targets, including the reduction of greenhouse gas emissions by 55% by 2030. According to the specific goals set by the European Green Deal and REPowerEU, by 2030, 30 million electric vehicles (EVs) should be on the road while 40% of residential heating should be powered by heat pumps. Additionally, district heating and cooling networks are expected to account for 25% of the EU's energy demand by 2030, necessitating robust grid management to handle the increasing and diversified energy load.

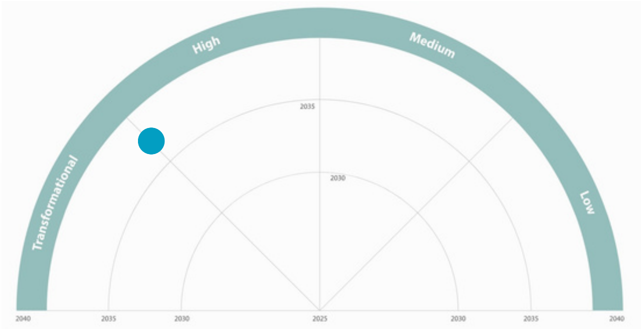
Opportunities for DSOs

- Sector integration enhances grid efficiency, stability, and energy security by diversifying energy sources and optimising the utilization of renewables
- The incorporation of EVs, heat pumps, and district heating systems provides the grid with essential flexibility, facilitating the balance between supply and demand. Furthermore, this integration fosters innovation and creates new business models, contributing to economic growth within the energy sector.

Challenges for DSOs

- The integration of multiple sectors into the electricity grid presents challenges, including the potential emergence of grid congestion and the complexities of managing decentralized and variable energy sources.
- Significant investments in grid modernization are essential, particularly in digital technologies that enable real-time monitoring and dynamic network management.
- Additionally, regulatory frameworks must be updated to support this transition and ensure grid stability and reliability under these new conditions.

5. Impact of Global Energy Integration



E.DSO considerations

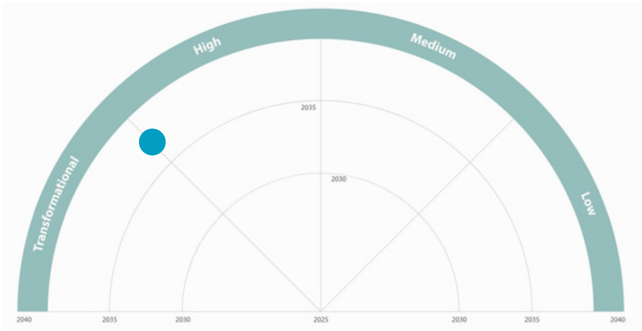
- Distribution System Operators (DSOs) must invest in advanced grid technologies to effectively manage the increased complexity of energy flows resulting from sector coupling. Their application should serve, among others, the development of smart grids, the enhancement of real-time monitoring capabilities, and the incorporation of decentralised energy sources.
- While the necessary technologies are available, integrating all these sources complicates their management.
- DSOs must collaborate closely with regulators to ensure that supportive policies are in place, facilitating the successful integration of EVs, heat pumps, and district heating systems into the grid.

Potential use cases

- **Smart grid management and real-time monitoring**: Use artificial intelligence (AI)and real-time data to balance supply and demand, detect issues promptly, prevent blackouts, and reduce energy losses.
- **Vehicle-to-Grid (V2G) and smart EV charging**: Use EV batteries as grid storage during off-peak hours and coordinate charging schedules to prevent grid overload and enhance flexibility.
- **Heat pump and building load optimisation**: Optimise heat pumps and building-level energy demand to avoid grid congestion during peak times, using predictive data to manage electrification impacts.
- **Renewable energy integration and forecasting**: Enable large-scale integration of solar and wind farms while improving grid planning through accurate generation forecasting.
- **Energy storage and flexibility solutions**: Deploy batteries strategically to enhance resilience, and use Power-to-Gas, Power-to-X, and seasonal gas storage to convert surplus electricity into hydrogen or synthetic fuels, contributing to grid flexibility and seasonal balancing.
- **Promoting Electrification**: Encourage the adoption of electric technologies to reduce carbon emissions and improve energy efficiency across sectors.
- **Cross-sector optimisation**: Harness synergies across energy sectors by using technologies like heat pumps that respond to electricity market signals to efficiently supply district heating networks with storage. Additionally, incorporate insights into the projected growth of district heating and gas networks to adapt long-term electricity investment plans, ensuring aligned infrastructure development and optimised resource allocation.

Ongoing projects

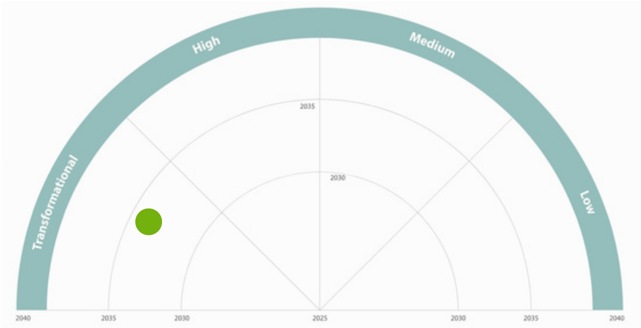
- ORES's FlexmyHeat project combines heat pumps with storage tools to stabilize the power system in Belgium. In response to increasing electricity demand and renewable generation, this project assesses how these technologies can offer flexibility to the grid.
- Stedin is implementing several projects on sector coupling:
  - BEHeaT, combining intelligent buildings, heat storage, heat networks and electricity grids.



Ongoing projects (continues)

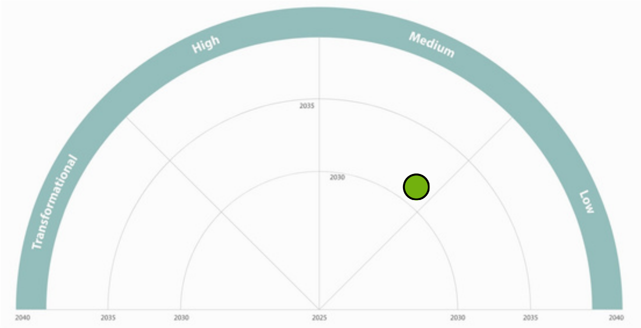
  - **DEMOSES**, developing a coupling methodology for heat, electricity, and green gas distribution grids.
  - **ROBUST**, testing sector coupling at the city and regional levels, including the deployment of large-scale bi-directional V2G.
- Enedis is participating in the European project **ACCU** (Interreg Europe programme). A demonstrator is foreseen in the North of France, in the city of Fourmies, focusing on energy communities and the synergies between power and heat networks.

Last update: 14 February 2025



More information on this technology will be available with the next updates of the Technology Radar.

7. Hydrogen



Hydrogen (H_2) is a key enabler of Europe's energy transition as it is one of the few green sustainable options for seasonal storage at regional level. Next to energy storage it is also an important feedstock for industry. It offers a clean alternative to fossil fuels for heating, power generation and long-haul transportation. The production of green hydrogen with electrolysers also enables a large source of grid flexibility. DSOs are key to transport and supply security of hydrogen, as they can design and operate infrastructure to deliver hydrogen efficiently and cost-effectively. Next to the distribution of hydrogen the location of the high electric power electrolysers and their (flexible) grid connection contracts are of great importance for the planning (expansion) and operation of the electricity grids.

Highlights

Hydrogen demand is projected to grow significantly, with at least half of sectoral demand (mainly industry and transport) supplied via distribution grids by 2040. Depending on the local production surplus of renewable energy, electrolysers can become a significant load factor for the design of the electricity grids. DSOs are recognized as essential players in the EU's hydrogen strategy, with policy frameworks evolving to support their role in both the hydrogen distribution as the optimal support of grid flexibility by the electrolysers.

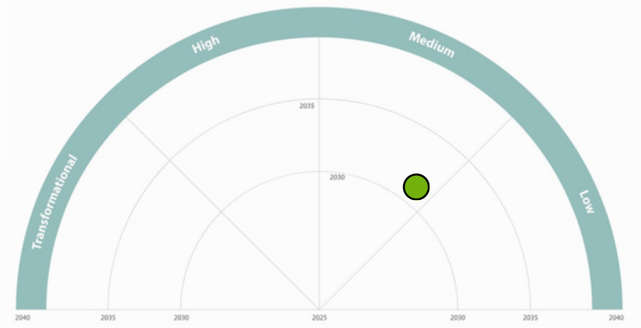
Opportunities for DSOs

- **Decarbonization of industrial consumers** through hybrid or full hydrogen conversion, supporting EU net zero goals.
- **Seasonal energy storage and grid flexibility:** Using power-to-gas technologies with the potential to act as a large scale, dispatchable load that can help electricity grid congestion.
- **System integration:** Allowing for an optimised use of infrastructure and for the integration of higher levels of wind and solar production.
- **Accelerated regional development:** By connecting hydrogen production sites to consumers without investing in high pressure transmission pipelines.
- **Cost effective and safe transport of hydrogen**: using the knowledge of gas distribution system operation.

Challenges for DSOs

- **Regulatory uncertainty:** Who holds exclusive responsibility for hydrogen distribution at the national level?
- **Start up risks:** due to the high capital expenditure and slow ramp-up of production and demand.
- **Managing large electrical loads:** The connection of multi-megawatt electrolysers presents a significant challenge for electricity grid planning and operation. These concentrated, high-power loads can require substantial grid reinforcement and may impact local power quality if not managed correctly.
- **Smart grid integration**: Real-time monitoring and control of hydrogen flows using digital platform and coordinating electrolyser operation with the real-time state of the electricity grid.
- **Public awareness and acceptance** of hydrogen as a viable energy carrier remains limited.

7. Hydrogen



E.DSO considerations

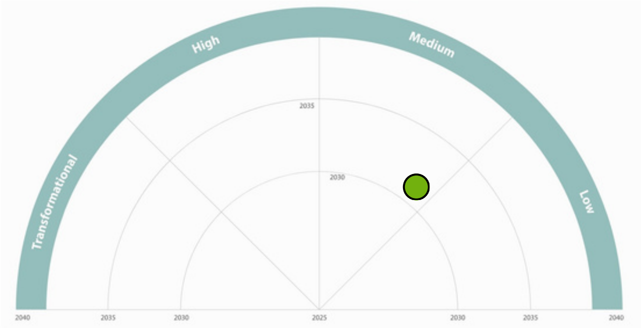
- DSOs have to advocate for clear regulatory frameworks and integrated planning across electricity, gas and heat sectors as they are essential to optimise infrastructure investments.
- E.DSO emphasizes hydrogen's role in industry, sector coupling, grid flexibility, and security of supply.
- E.DSO emphasizes the need for flexible connection agreements for electrolysers as these large additional loads can become dominant in grid planning, operation and system stability. These agreements are essential to unlock the value of electrolysers as a grid balancing tool, allowing DSOs to modulate their consumption to support the network.
- E.DSO encourages DSOs to engage in knowledge sharing, pilot projects, and training to build hydrogen readiness.
- E.DSO recommends coordinated EU support, including funding, innovation programs, and stakeholder engagement to accelerate deployment.

Potential use cases

- **Seasonal storage**: Repurposed gas storage facilities for hydrogen to balance renewable energy supply.
- **Production of green biomethane:** which can be used in the present gas systems enabling a robust and adaptive transition to fully decarbonized gas system.
- **Industrial decarbonization:** Hydrogen for process heat in large and small manufacturing sectors.
- **Power generation:** Hydrogen-fired plants and e-fuel production near carbon capture hubs.
- **Smart grid integration:** Real-time monitoring and control of hydrogen flows using digital platforms.
- **Transport:** Supply to refueling stations and ports and industrials, especially where demand is dispersed.
- **Hydrogen Fuel Cells** provide clean electricity for construction sites, events and temporary power needs.
- Hydrogen can be used in steelmaking processes to replace coal, reducing Iron Ore without emitting CO_2.
- Green hydrogen for ammonia enables carbon-free fertilizer and chemical production.

Ongoing projects

- HyNetherlands (Eemshaven, Netherlands): Large-scale hydrogen production from offshore wind, with distribution via existing gas infrastructure.
- HyNetworks: the construction of a hydrogen backbone in The Netherlands.
- H2L (Lochem, Netherlands): Repurposed existing gas infrastructure for heating houses on 100% hydrogen.
- Underground Sun Storage (Gampern Austria): On site seasonal hydrogen production and storage in repurposed geological gas storage (4,2GWh).
- RAG Energy valley (Kremsmünster Austria): Production of turquoise hydrogen by plasmolysis of natural gas.

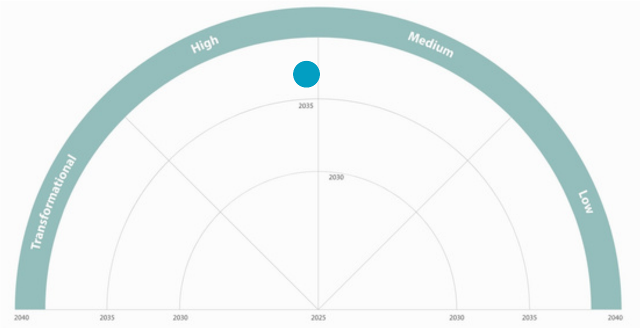


Ongoing Projects (continues)

- **CRAVE H2** (Crete, Greece): The scope of CRAVE H2 is to create a hydrogen valley in the island of Crete, Greece incorporating energy storage applications, aggregation activities to the grid and green mobility applications (fuel-cell buses).
- **Crete Valley** (Crete, Greece): Crete Valley will deliver community-scale demonstrations of green hydrogen production and use, including fuel-cell buses, local electricity and heat supply via hydrogen fuel cells, EV charging with hydrogen-powered fuel cells, and vehicle-to-grid (V2G) integration as part of renewable energy communities in Crete.

Last Update: 30 September 2025

8. Grid-Forming Inverters



In power systems undergoing a transition to net-zero carbon emissions, **inverter-based resources** must provide a new type of service to maintain an adequate level of security and quality of service. For this reason, in recent years, the grid control concept of so-called **grid-forming (GFM)** is regarded as an alternative means to ensure the security of the power system. GFM involves voltage and frequency regulation and the improvement of angular stability in the grid by power electronic converters. The reduced mass inertia of the rotating component of synchronous generators should be replaced by the equivalent behaviour of grid-forming inverters, i.e. the so-called **electrical or (virtual) inertia**.

Highlights

Inverters are characterized by little or no energy storage capacity, on the other hand, they are actuated at much shorter time intervals than synchronous machines, which store kinetic energy depending on the moment of inertia of the rotor. Hence, the optimal control of properly built and configured inverters is considered one of the key challenges in the massive integration of renewable energy sources into existing power grids. The control of inverters can follow two different functions:

- The **grid-forming function**, which maintains a constant internal voltage angle and frequency, controlled to maintain synchronism with other equipment and regulate the active and reactive power of the inverter during the sub-transition interval. The function can additionally provide emergency start-up and continue operation even in the absence of synchronous generators.
- The **grid-following function**, which maintains a constant value of output current to control the reactive and active power injected by the inverter source into the grid during the time interval from sub-transition to transition state. These inverters are inherently dependent on the strength of the grid to which they are connected and cannot operate in island mode or provide emergency start-up.

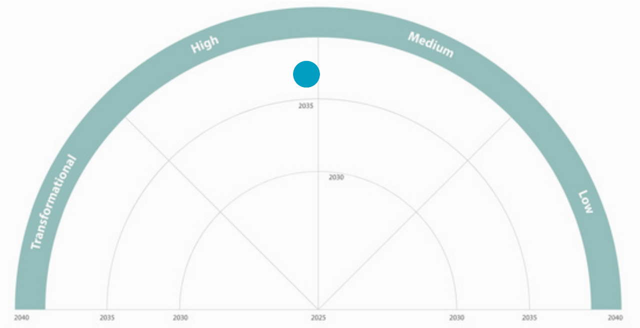
While inverters are currently set on grid-following mode, discussions are underway to introduce obligations relating to GFM in the new Network Code on Requirements for Generators (RfG2).

Challenges and opportunities for DSOs

For an energy supply system that is 100% renewable, GFM solutions are a guarantee of grid quality and stability, as they positively affect the following factors: inertia, system resilience, short-circuit power, system restoration, power system stabilization, and power quality. The use of such functionalities could be an alternative to building new lines, reduce the need for activities of grid reinforcement and redistribution, ensure the stability of an electricity grid fully powered by clean energy, and guarantee the security of the power supply. As one of the goals of this function is frequency system control, the implementation of solutions based on grid-forming should be carried out in close cooperation between TSOs and DSOs.

E.DSO considerations

A potential topic for deeper exploration at the Association level is preparing recommendations for possible future mass application of GFM in distribution grids. Care should be taken to ensure that the provisions of the RfG2 code relating to GFM do not have unjustified costly implications for DSOs.



Potential use cases

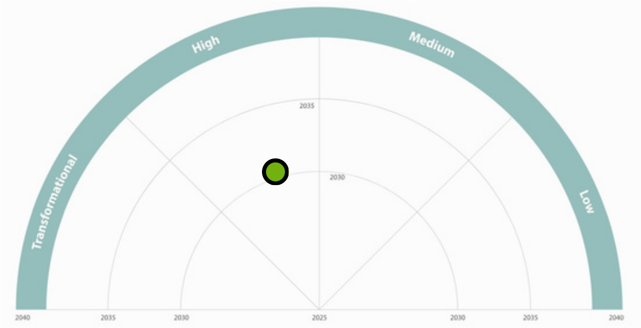
- Creating (forming) system voltage.
- Contributing to fault level (short circuit power).
- Contributing to total system inertia.
- Supporting system survival to enable the effective operation of low-frequency demand disconnection for rare system splits.
- Acting as a sink to counter harmonics and inter-harmonics in system voltage.
- Acting as a sink to counter any unbalance in system voltage.
- Preventing adverse control system interactions.

Ongoing projects

Enedis has funded several research works on the topic of GFM:

- Arshpreet Singh PhD thesis "Stability of electrical distribution grids in the presence of renewable energies" (2023): this thesis provided a study of slow-interaction converter-driven stability in medium-voltage distribution grids with inverter-based resources, assessing the impact of both grid-following and grid-forming operation modes.
- Jane Marchand PhD thesis "Black start and stable operation of a portion of the low voltage grid in islanded mode using local renewable energy production" (2024): this thesis provided a study of solutions to achieve the re-energisation of islanded grids by using the available local renewable power generation. This requires changing the controllers of some of the currently grid-following residential photovoltaic inverters to grid-forming control mode so that they can provide black-start capabilities and impose frequency and voltage.

Last update: 14 February 2025



A **microgrid** is a group of interconnected loads and distributed energy resources with defined electrical boundaries forming a local electric power system at distribution voltage levels, that acts as a single controllable entity and is capable to operate in islanded mode, no matter if it is standalone or grid-connected (IEC 62898).
When operating in islanded mode, microgrids can manage and optimise supply and demand (energy management system) and regulate demand locally. When operating in connected mode, they may also aim to offer new services (provision of flexibilities, congestion management, reactive power management, etc.). Microgrids' major objectives are to improve resilience and decarbonize production. ''Isolated/ remote grids" differ from microgrids in that they are self-sufficient and never connected to the main grid due to geography (islands, rural areas) or chosen design. Microgrids are similar to citizen energy communities in terms of their local focus. Citizen energy communities are based on open and voluntary participation of members, effectively controlled by their members or shareholders with the purpose of environmental, social and economic benefits. Such initiatives can provide grid services, if they are technically capable to do so. Citizen energy communities differ from microgrids, because some customers connected to the grid in the area where the community is located may have chosen not to belong to the community. Furthermore, the legal entities in charge of citizen energy communities are not responsible for the management of the local grid (maintenance and operation of components, identification and management of network congestions, purchase of technical and non-technical losses, etc.).

Highlights

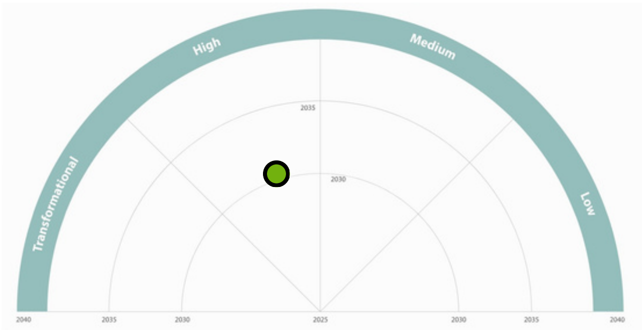
During periods when they are disconnected from the grid, microgrids operate in the same way as islands and isolated sites, which needs to have self-sufficiency of power generation. Today, the strong development of renewable energies represents an opportunity to make these installations less costly and more environmentally-friendly. The global microgrid market is expected to grow at a relatively high annual rate (e.g., estimated at 13.9% in Europe over the period 2025-2032)[1]. Market growth is driven by renewable energy integration, rapid adoption of distributed technologies such as electric vehicles as well as volatile energy prices. Furthermore, the threat of cyber-attacks, climate hazards and geopolitical developments are stimulating the desire for energy independence.

Opportunities for DSOs

- Technical (peak shaving, **resilience**, etc.),
- Environmental (supporting renewable integration),
- Economic (system-level potential cost-savings, reduced grid reinforcement needs, etc.).

[1] KBV Research Europe Microgrid As A Service Market Size Report | 2032

9. Microgrids



Challenges for DSOs

- Operating microgrids requires local energy management systems to deal with supply/demand equilibrium through smart controls of loads and storage.
- Protection systems have to be updated to enable safe operations in islanded mode.
- Appropriate technical provisions are required to enable black start.
- Connection and disconnection of microgrids to the grid can generate local instabilities.
- Technical and contractual conditions for making benefits to be effective yet to be clarified.
- Coordination needs for multiple microgrids among each other and DSO (real-time data exchange, protocols).

E.DSO considerations

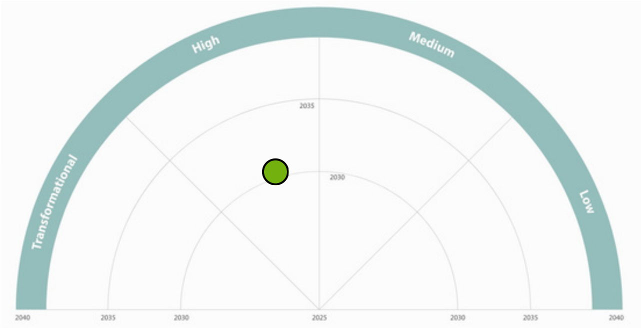
- Microgrids are still complex and expensive solutions to implement and they are not cost-effective if the grid is of good quality.
- The technical and economic competitiveness of the electricity network is therefore not called into question.
- However, in some cases, microgrids are an interesting resilience solution. Microgrids can be promising especially in remote areas or islands.
- Regulatory needs on technical requirements (e.g., islanding, grid reconnection) as well as tariff mechanisms.

Potential Use Cases

- Critical users as a backup power such as hospitals, fire brigades, etc.
- Emergency and as a backup power when natural disasters and for black-start.
- Industrial sites where a local energy management is potentially feasible and cost-effective.

Ongoing projects

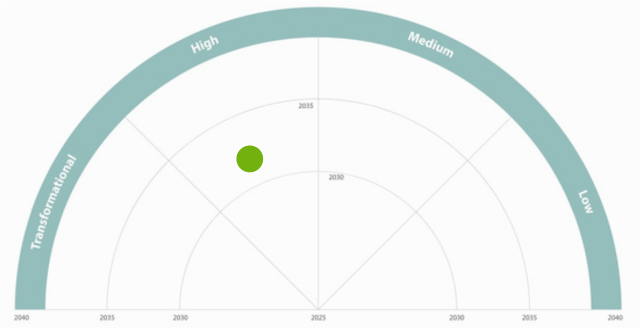
- Scheveningen microgrid project **Stedin/ Smart Beach Grid** with solar PV, EV, battery and heatpumps. Smart, autonomous, self-regulating network where local users share resources. By local balancing, grid congestion is also addressed.
- **Stedin-TU Delft** collaboration student thesis: control of multiple microgrids.
- **Green Village TU Delft pilot on DC microgrids**: Meshed grid with solar PV, battery, street lighting and EV charging. Solid-state protection explored. https://dc-opportunities.com/dcmicrogrids
- **Enedis**
  - Several field demonstration projects (some of which still ongoing) to identify challenges and test solutions for the implementation of microgrids to maintain power supply from local renewable energy installations in the event of climatic events, in various configurations: PV in rural areas (CorezeResilientGrid), wind (RIR), etc. Topics include implementation of an EMS, operation of protections, harmonics, blackstart, control of inverters (Grid Forming / Grid Following).



Ongoing projects (2/2)

- **Enedis**
  - Financed and supervised several PhD theses and research projects on the operation of microgrids, particularly on the control of inverters (Grid Forming / Grid Following). Objective to design innovative solutions to reduce the cost of implementing micro-grids (small systems without rotating machines and, if possible, without batteries, or with only an as small as possible battery).

Last update: 8 December 2025



Efficient energy **storage technology** is needed to overcome fluctuations in renewable energy supply and decrease our reliance on fossil fuels. Storage could provide important system services that range from short-term balancing and operating reserves, and ancillary services for grid stability to long-term energy storage and restoring grid operations following a blackout. Storage can help manage congestion and voltage at different timescales in the distribution network. In some cases, it could defer or even reduce the need to reinforce the network.

Highlights

Pumped-storage hydropower is the most widely used storage technology. Batteries are the most scalable type of grid-scale storage and the market has seen their strong growth in recent years. Other storage technologies include compressed air, gravity storage, superconducting magnetic energy storage, flywheels and hydrogen but these play a comparatively small role in current power systems. Up to date, apart from pumped-storage hydropower, technologies that allow for inter-seasonal or even inter-annual storage are not yet mature. The scarcity and environmental concerns related to raw materials needed to manufacture storage solutions need to be taken into account, particularly for batteries. Article 36 of the Electricity Directive restricts DSOs from owning, developing, managing or operating storage facilities, although some exceptions are possible due to efficient, reliable, safe operations etc.

Challenges and opportunities for DSOs

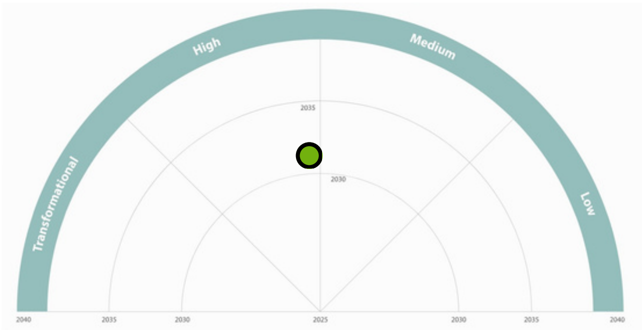
- In addition to the technical and economic performance of storage technologies, their geographical positioning in relation to the distribution grid will be essential for the optimisation of the electricity system.
- The development of storage facilities coupled with renewable facilities can change the management of electricity flows locally.
- The development of storage facilities coupled locally with production can facilitate microgrid emergence.
- Right sizing and location of storage systems in the distribution grid is an important consideration.
- Contractual agreements between DSOs and private parties owning an operating storage are essential to align incentives.

E.DSO considerations

- DSOs must follow the technological advances of the various storage solutions in order to anticipate the possible impact of the development of these on power distribution systems and networks.
- Safety aspects of the various storage technologies, particularly batteries, are important considerations for DSOs.

Last update: 28 September 2023

11. Solid Electrolyte Batteries



Solid-electrolyte batteries (SEBs) represent a next-generation energy storage technology that replaces the liquid electrolyte in conventional lithium-ion batteries with a solid-state material. This innovation promises higher energy density, improved safety (eliminating flammable liquid electrolytes), and longer cycle life. However, SEBs face significant challenges, including high manufacturing costs, limited scalability, and issues with interface stability between electrodes and solid electrolytes. Current developments are primarily at pilot and early commercialization stages, with automotive and stationary storage as key target markets. For DSOs, SEBs are not just an incremental improvement but a potential step-change, enabling new types of grid assets with fundamentally different safety and performance profiles.

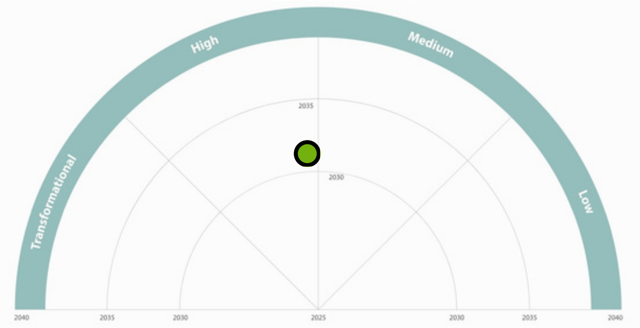
Highlights

- The global solid-state battery market is projected to grow from approximately USD 1.5 billion in 2025 to over USD 8 billion by 2030, driven by EV and stationary storage demand.
- Europe is a key innovation hub, with initiatives under the EU Battery Alliance and Horizon Europe programs.
- Automotive OEMs and energy companies are investing heavily, but commercial deployment for grid-scale applications is expected post-2030.
- This strong investment pipeline signals a maturing supply chain and creates a clear technology roadmap for DSOs to monitor, with the potential for significant cost reductions beyond 2030.

Opportunities for DSOs

- **Unlocking Urban Grid Flexibility & Storage**: SEBs could enable high-capacity, safe storage systems for DSOs to manage renewable integration and peak shaving. Their key advantage is enabling the deployment of large-scale storage in dense urban substations or basements, where fire safety regulations and space constraints make traditional lithium-ion batteries difficult or impossible to permit.
- **Managing the Impact of Ultra-Fast EV Charging**: Faster charging and higher energy density in EVs will impact charging infrastructure planning and load forecasting. More importantly, stationary SEB systems can act as buffer storage at charging hubs. This allows DSOs to offer a lower-capacity grid connection, with the battery handling the extreme peaks of multiple ultra-fast chargers, thereby deferring costly upstream grid reinforcement.
- **De-risking Grid-Scale Storage**: Non-flammable electrolytes reduce fire risk in urban charging hubs and storage facilities. This fundamentally lowers the operational, public, and insurance risk profile of DSO-owned or operated storage, making it a more viable and socially acceptable grid asset.
- **Enhanced Asset Longevity and Reliability**: The promise of a longer cycle life means a lower levelised cost of storage (LCOS) over the asset's lifetime. For DSOs, this improves the business case for using batteries as a long-term alternative to traditional "copper and steel" reinforcement.

11. Solid Electrolyte Batteries



Challenges for DSOs

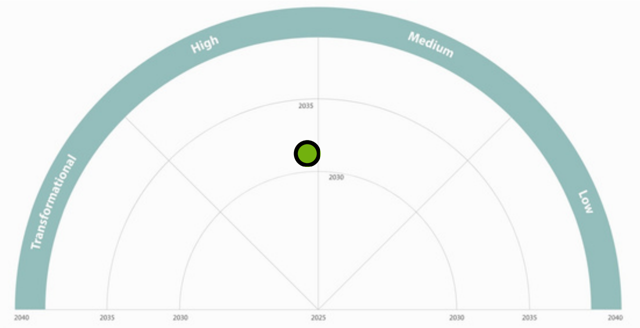
- **High Upfront Cost and Economic Viability**: Despite long-term promise, the initial CAPEX for SEBs will be significantly higher than for mature lithium-ion technologies. DSOs must carefully assess the Total Cost of Ownership (TCO) to identify the specific use cases where the safety and density benefits outweigh the higher upfront cost.
- **Power Electronics and Grid Integration**: The performance of any battery system is dependent on its power conversion system (PCS). DSOs will need to understand the specific grid-forming and grid-following capabilities of the inverters paired with SEBs and how the complete system behaves under network fault conditions.
- **Supply Chain and Manufacturing at Scale**: While investment is high, the supply chain for solid-state electrolytes and components is still in its infancy. DSOs must be aware of the risk of relying on a limited number of suppliers for critical grid infrastructure in the medium term.

E.DSO considerations

- **Develop a Technology Roadmap**: Monitor SEB developments for grid-scale storage pilots and EV charging strategies. DSOs should identify specific locations on their network where the unique safety and density features of SEBs would solve a problem that current technology cannot.
- **Focus on the Business Case**: Assess lifecycle costs and supply chain readiness before large-scale adoption. This analysis must quantify the value of enhanced safety, such as reduced land or infrastructure costs for fire suppression, to properly compare SEBs against incumbent technologies.
- **Drive Standardisation Proactively**: Address standardization and interoperability challenges early (CIRED Policy Briefs). DSOs must engage with manufacturers and standards bodies to ensure that future SEB systems are not proprietary "black boxes," but are interoperable and controllable assets.
- **Leverage Strategic Pilots**: Engage in EU-funded pilots to evaluate real-world performance and safety. Pilots should be targeted to test SEBs in the most challenging and high-value environments, such as densely populated city centres or critical infrastructure sites.

Potential Use Cases

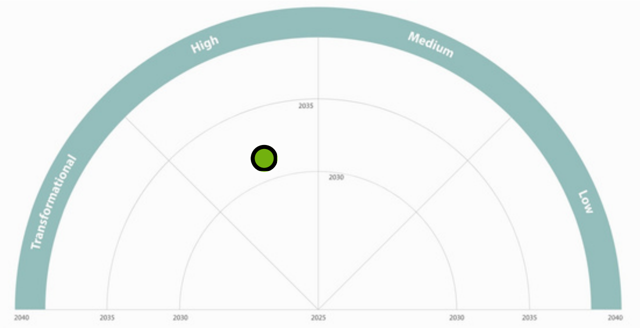
- **Urban Substation Deferral**: Deploy compact, fire-safe SEB storage inside inner-city substations to manage peak load and defer the need for extremely disruptive and expensive transformer and cable upgrades.
- **EV Charging Hub Grid Buffers**: Use SEBs in buffer storage systems to enable ultra-fast charging services with a minimal grid connection footprint, absorbing peak demand locally.
- **High-Resilience Microgrids**: Install SEB systems in critical infrastructure like hospitals or airports, where their enhanced safety and reliability can provide long-duration backup power and black-start capability.
- **Enabling Firm Flexibility Services**: Offer SEB-based storage to industrial customers. Their enhanced reliability and predictable performance make them a superior asset for providing guaranteed, dispatchable flexibility services back to the DSO.



Ongoing Projects

- **SOLVE (2024–2028)**: Develops Generation-4b solid-state batteries with lithium-metal for sustainable mobility. Aims for circular production and high energy density for electric vehicles.
- **SOLiD (2023–2027)**: Pilot manufacturing of solid-state batteries using sustainable materials and recycling concepts. Emphasis on industrial scale-up and digital quality assurance.
- **HELENA (2023–2026)**: Develops halide-based solid-state batteries for electric vehicles and aerospace. Targets high current capability and fast charging for demanding applications.
- **HyLiST (2025–2029)**: Launching in 2025 to create hybrid lithium-metal solid-state batteries. Focus on scalability, industrialization, and strengthening the European value chain.

Last update: 8 December 2025



The concept of **Vehicle-to-Grid (V2G)** is very similar to that of smart charging. Smart charging, also known as V1G, allows for deciding how much capacity/energy to allocate to Electric Vehicle (EV) charging in real-time. V2G solutions go further and add the ability to redirect energy from a battery to the power grid to balance the network, especially when demand suddenly increases. Vehicle-to-Everything (V2X) is not very different from V2G and includes V2H (Vehicle-to-Home), V2B (Vehicle-to-Building), and V2G.

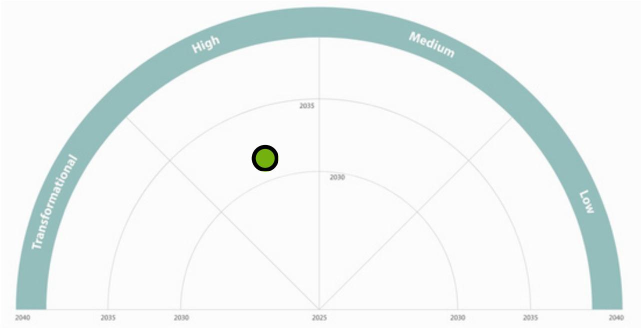
Highlights

The transportation sector is undergoing a revolution that can be seen in the growing number of electric vehicles on our roads. In addition to having a much smaller ecological footprint than combustion vehicles, electric car batteries represent an energy storage option. Globally, 140 to 240 million electric vehicles are expected to be on the road by 2030. That means there will be at least 140 million energy sources on wheels, totalling about 7 TWh of storage capacity. Today, only a few models are compatible with V2G technology. New (distributed) energy sources like V2G are challenged to compete in traditional energy markets that are not fully aligned with their capabilities. Energy regulation is complex and provides an obstacle for emerging technologies like smart car charging and V2G to make an immediate impact.

Challenges and opportunities for DSOs

- The impact of V2G on power quality and voltage control has to be analysed.
- Connection solutions have to be defined for V2G, both in direct current (DC) and alternating current (AC).
- V2G emphasises (sub-)metering (DC or AC) needs.
- The capacity of V2G, on top of smart charging, to meet local congestion and curtailment needs and its implementation must be studied.
- The capacity of V2G to provide reserve and frequency services has to be studied
- An energy aggregator can combine EV batteries and other distributed energy assets, such as solar and home batteries, into virtual power plants (VPPs) that can supply and trade energy on electricity markets. DSOs have to investigate the load profiles of such VPPs.
- DSO’s technical and functional methods for activating V2G have to be defined.
- V2G systems must comply with European grid codes, including requirements for frequency response, voltage control, and autonomous functions such as low voltage ride through (LVRT). Certification processes for EVs and EV supply equipment (EVSEs) are being developed to ensure compliance with these standards.
- According to the Requirements for Generators Network Code (in the process of being updated to RfG 2.0), a V2G electric vehicle is defined as one capable of injecting electricity into the grid, regardless of whether the inverter is onboard or external. This includes both AC and DC charging systems.

12. Vehicle-to-Grid



E.DSO considerations

- The outlook for V2X has yet to be clarified. In particular, the contribution of V2G in addition to smart charging must be specified.
- V2X services for other energy operators must not cause or aggravate congestion on the electricity network.
- V2X are to be incorporated in the Network Code on Requirements for Generators.
- ISO 15118-20 and OCPP 2.1 are essential for ensuring interoperability between EVs, charging stations, and grid operators
- Aggregators play a key role in combining EV batteries into VPPs, but current flexibility markets are not yet fully developed across Europe, limiting the V2G deployment.

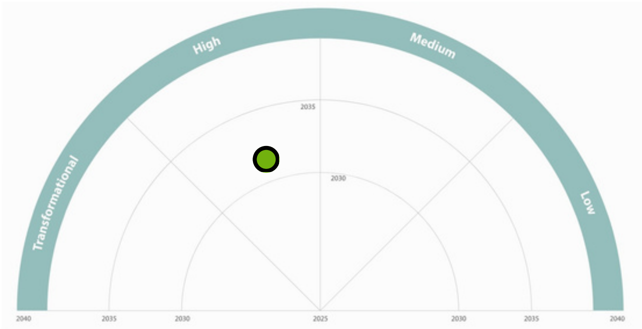
Additional E.DSO considerations can be found in the *E.DSO Technical Paper on V2G Charging Mechanisms*.

Potential use cases

- **Grid congestion mitigation:** V2G enables decentralised energy injection during peak demand periods, thereby alleviating local grid congestion and deferring costly infrastructure upgrades.
- **Renewable energy integration**: Electric vehicles can store surplus energy from renewable sources and discharge it when needed, enhancing the flexibility and reliability of the distribution grid.
- **Provision of flexibility services**: V2G-capable vehicles can act as distributed energy resources, offering ancillary services such as frequency regulation and voltage support to DSOs.
- **Resilience and emergency backup**: In the event of grid disturbances, V2G systems can provide temporary backup power to critical infrastructure, improving overall system resilience.
- **Reduction of technical losses**: Localised energy discharge reduces transmission losses and improves overall system efficiency.
- **Enhanced grid planning and forecasting**: Real-time data from V2G operations can support DSOs in forecasting load patterns and planning future grid reinforcements more accurately.

Ongoing projects

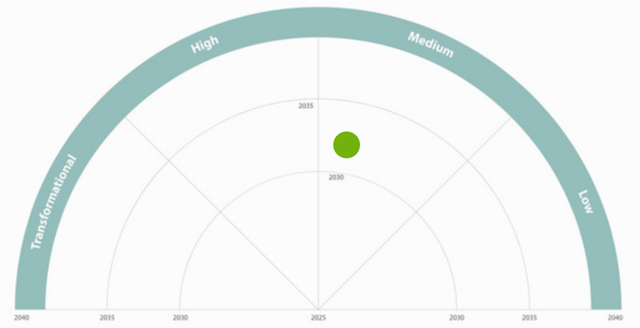
- The **FLOW Project (EU-wide):** Participated by the Enel Group, Areti, E.DSO and partners, this EU-funded initiative explores smart charging and V2G business models. Demonstrations in Menorca and Italy focus on enhancing grid reliability and testing non-firm connection agreements to reduce connection costs and delays.
- **Enedis (France)** is integrating Renault V2G vehicles into the distribution grid using the Linky Meter for settlement purposes.
- **Enel and Frederiksberg Forsyning (Denmark)** are deploying 10 V2G units with Nissan e-NV200 vehicles to provide grid stabilisation services to the Danish TSO Energinet.



Ongoing projects (continues)

- The **SCALE Project (EU-wide)** foresees a collaboration between WDS, MyWheels, and Renault to deploy bidirectional chargers and compatible EVs, supporting the development of interoperable V2G ecosystems.
- In the case of the DSO **Fluvius (Belgium),** V2G chargers are subject to the same connection requirements as generation units. A structured registration process and a list of certified devices have been established to ensure compliance.
- Through the ‘CARS’ project, **ORES (Belgium)** is exploring two aspects of residential electric vehicle charging: sub-metering using data from the charging point (which can even lead to supply split), and the modulation capabilities of the charging point.

Last update: 26 June 2025



Building-to-Grid (B2G) involves integrating buildings bidirectionally with the electrical grid, allowing them **not only to consume but also to generate** electricity using technologies like **renewable energy** and **storage systems**. Digitalisation facilitates grid and building integration. This approach **creates opportunities for buildings** to generate new value streams through energy services. B2G activities include **participation in demand response**, distributed **energy generation** (e.g., through renewables such as photovoltaics), or **storage** (e.g., thermal storage such as making ice for air conditioning or hot water storage), as well as diagnostics and energy efficiency analysis within the building itself.

Highlights

42% of energy consumed in the EU in 2021 was used in buildings. More or less 80% of the energy consumed in EU households is used for heating, cooling and hot water. 85% of EU buildings were built before 2000 and, amongst those, 75% have a poor energy performance. Acting on the energy efficiency of buildings is therefore key to saving energy and achieving a zero-emission and fully decarbonised building stock by 2050.

Opportunities for DSOs

- Modern buildings utilise **Building Management Systems** (BMS) and Energy Management Systems (EMS) equipped with sensors and actuators to control indoor environments and manage energy consumption.
- Distribution-level **ancillary services** can enhance the reliability and resilience of the grid, especially at the local distribution network level.
- DSOs can significantly contribute to reducing the energy consumption of buildings. **Smart meters** enable them to provide data for assessing the energy performance of buildings and identifying those in need of priority renovation.

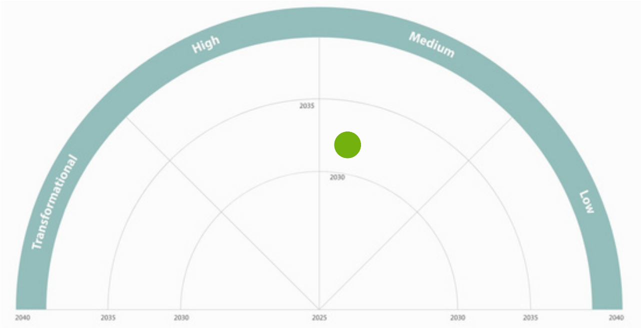
Challenges for DSOs

- Real-time coordination. direct control or through aggregators.
- Cybersecurity. Future B2G interactions will be governed by a set of grid codes covering the electrical and cybersecurity aspects.
- Interoperability. The existing building stock is dominated by legacy systems.
- The standards defining the protocols for data exchange in buildings must allow the integration of the meters operated by DSOs into the system constituted by the intelligent building.

E.DSO considerations

- The objectives of suppliers/retailers and DSOs do not align in the context of B2G integration. For example, suppliers/retailers might aim to balance trading commitments in the energy market using buildings. On the other hand, DSOs may seek to balance local consumption with distribution grid capacity limits.

13. Building-to-Grid



E.DSO considerations (continues)

- E.DSO acknowledges that future grid operations will need to facilitate the integration of **all types of demand-side users, including buildings**, to allow their participation and equitably measure their impact across the power system. The future interactions of building-to-grid should ensure an **efficient financial and functional integration** for a participatory and competitive future electricity market.

Potential use cases

- **Network congestion support.** Turning buildings into already deployed, low-cost storage options for the grid, ready to balance both peaks and valleys of demand in a seamless, automated fashion.
- **Voltage control.** Buildings could assist in voltage control, particularly in networks with significant voltage fluctuations.
- **Demand reduction during scheduled maintenance.** Buildings can contribute to demand reduction during scheduled maintenance work on the network.
- **Resilience and emergency power.** Buildings can serve as sources of emergency power during grid outages, enhancing the resilience of critical infrastructure and supporting community resilience.
- **Electric vehicle (EV) integration**: Buildings can support the charging infrastructure for EVs, optimising energy usage and potentially providing energy back to the grid during times of high demand.

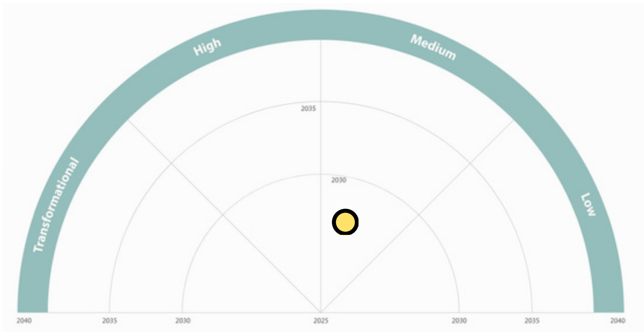
Ongoing projects

- **InterConnect.** Approved by the European Commission under the Horizon 2020 programme, InterConnect gathers 50 European entities to develop and demonstrate advanced solutions for connecting and converging digital homes and buildings with the electricity sector (more info).
- **Platone**, a four-year Horizon 2020 project, focused on enhancing the observability and flexibility of renewable energy resources. The consortium developed advanced management platforms for an open grid market, prioritising user needs. One solution involved installing edge devices at customer sites to collect metering data and receive flexibility activation commands from smart meters (more info).
- **EVELIXIA** unites 36 organisations across 12 EU countries to transform buildings into energy-efficient, connected, smart, and flexible nodes. The project focuses on five Innovation Pathways, deploying solutions in seven countries for B2G and Grid-to-Building (G2B) services (more info).
- **WeForming.** The project seeks to revolutionise energy management in buildings by creating Intelligent Grid-interactive Efficient Buildings (more info).
- **EV4EU.** Funded by the Horizon Europe program, EV4EU aims to implement bottom-up and user-centric Vehicle-to-Everything (V2X) management strategies creating the conditions for electric vehicle mass deployment. It includes V2X in buildings (more info).

Last update: 17 May 2024

14. Smart Distribution Transformers

E.DSO



MV/LV distribution transformers remain one of the most robust and essential assets in distribution networks. Their core function has changed only gradually over time, mainly through improvements in materials, efficiency and loss reduction driven by eco-design requirements. However, the operating context of distribution networks is changing rapidly. The increasing integration of distributed energy resources, photovoltaic generation, heat pumps and electric vehicles is creating more dynamic voltage profiles and more localized power-quality challenges. In this context, Smart Distribution Transformers should not be seen as a single uniform technology, but rather as a family of solutions with different maturity levels and DSO relevance. OLTC-equipped distribution transformers are already a mature and deployable option for targeted voltage management, especially in constrained LV networks or where conventional reinforcement is difficult, slow or hard to permit. By contrast, fully smart or solid-state transformer concepts remain longer-term technologies, with potential future value in areas such as phase-specific control, bidirectional power management, harmonic mitigation and enhanced power-quality support. This section reflects a pragmatic DSO perspective: where these technologies can provide near-term value, where their use remains limited by cost or complexity, and under which network conditions they may complement or defer conventional reinforcement.

Highlights

Power electronics-based smart transformers remain an emerging technology (voltage regulation, phase balancing). Conversely, OLTC-equipped transformers are mature and deployable for local voltage constraints. Regulatory relevance lies in digitalization, flexibility, and optimizing existing grid capacity.

Challenges and opportunities for DSOs

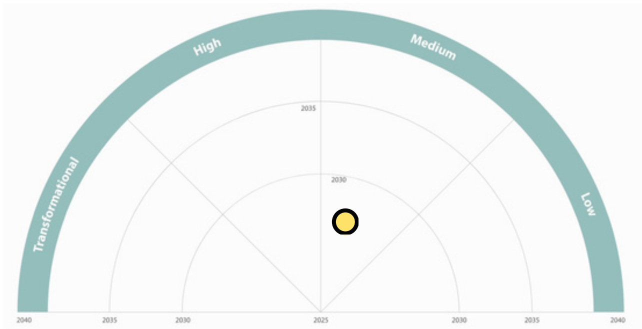
Opportunities

- **Local Voltage Control:** Highly effective in constrained LV grids.
- **CAPEX Deferral:** Increases DER hosting capacity, potentially delaying conventional grid reinforcement.
- **Supply Quality:** Provides faster, more granular voltage regulation compared to manual tap changes.

Challenges

- **Higher Costs:** Significantly more expensive than conventional transformers (around 30% up).
- **Complexity & Reliability:** Requires additional sensing and communication; long-term robustness of solid-state concepts remains unproven.
- **Stranded Assets Risk:** Business case is strictly limited to specific locations with persistent power-quality issues.

14. Smart Distribution Transformers



E.DSO considerations

Near-term value is highly specific: OLTC deployment serves as a non-wire alternative for voltage-constrained areas or where permitting is blocked. Fully smart/solid-state concepts are long-term system assets, not yet ready for mass roll-out.

Potential use cases

- **Voltage management** in LV networks with high PV or other distributed generation, especially where feeders are relatively homogeneous and local regulation can improve compliance without creating new issues elsewhere.
- Under suitable network conditions, **increasing DER hosting capacity** and in some cases **delaying conventional LV reinforcement** in locations with recurring voltage constraints.
- **Providing a practical alternative to grid reinforcement** in constrained areas where conventional grid reinforcement is difficult, slow or hard to permit.
- **Supporting coordinated operation with smart inverters,** LV monitoring and automation systems to improve voltage quality and reduce manual interventions.

In the longer term, solid-state transformer concepts could offer **additional functionalities such as phase-specific control, harmonic mitigation and enhanced power-quality support** in sensitive or highly dynamic networks.

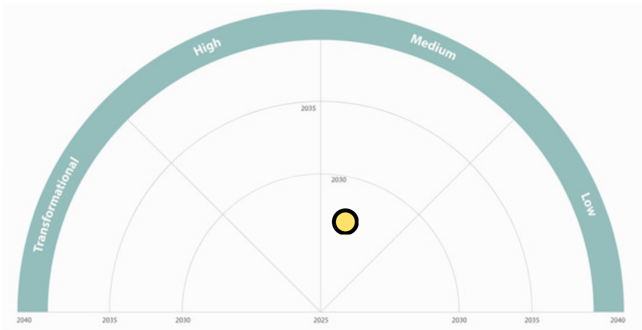
Ongoing projects

- **E.ON / Bayernwerk (Germany):** Following extensive pilots, regulated distribution transformers (RONT/OLTC) have been integrated into standard asset management. Deployment is accelerated in areas with dense EV and PV penetration.
- **TIGON EU Project (Spain Demo):** Deploying Solid-State Transformers (SST) within a live hybrid AC/DC microgrid demonstration. The project monitors real-time bidirectional power flow, wide-bandgap semiconductor performance, and efficient integration of localized RES and EV charging.
- **i-DE / Iberdrola (Spain):** SST Focus: Launching dedicated field challenges under the PERSEO initiative to deploy SST. The project targets active harmonic filtering and bidirectional power control in areas with high industrial EV loads.
- **ČEZ Distribuce (Czechia):** ČEZ Distribuce is evaluating OLTC distribution transformers for specific cases where conventional reinforcement is difficult or too slow to implement. The current focus is on selective deployment, not system-wide rollout.

Link to related E.DSO success cases

Success case number	Title	Company
14.2024	i-TRAFO	i-DE

14. Smart Distribution Transformers



Impact on the energy system

- Improved local voltage management.
- Higly flexible use of existing distribution infrastructure.

Time to scale

OLTC Transformers - 0-5 years (targeted use).
Smart/Solid - state: +10 years (broader relevance).

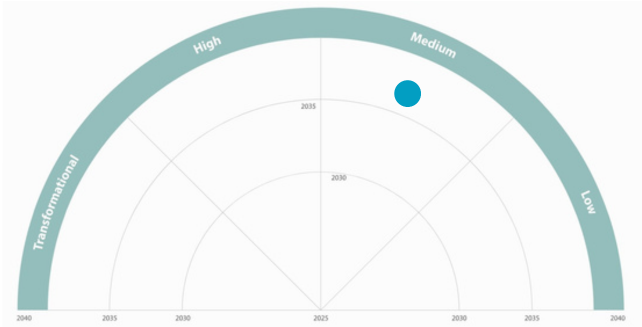
Link to relevant EU policies

- Digitalisation.
- Flexibility.
- Resilience.
- Energy Efficiency.
- Integration of DERs.

Technology deployment across countries with E.DSO members

Last update: 12 September 2026

15. Innovative Charging for Electric Mobility



To overcome the limitations of wired charging, innovative solutions are being researched and tested for electric mobility. Both **static** and **dynamic** wireless charging systems — for urban environments and high-speed operation — are being trialed in Europe, Asia, and the United States.

- **Static induction charging systems** are being developed mainly to charge taxis or buses while waiting at stations.
- Regarding **dynamic charging**, two main technology families stand out: **inductive dynamic systems** and, more specifically for heavy-duty transport, **sliding contact-based systems** using a rail or pantograph. Dynamic charging solutions require significant investment in road infrastructure, which represents a major drawback for large-scale road projects.

Highlights

Dynamic charging will be distributed over long distances and effectively be connected to several points in the grid. Considering inductive charging, the efficiency of the energy flow is comparable to the typical efficiency of fast charging. To limit power losses and facilitate integration with renewable energy sources, inductive solutions are generally DC-based. Over the past few years, there have been **new pilot projects** announced but still **no large-scale rollouts**. For example, France plans to test a **wireless charging highway** by 2025 — a first of its kind in Europe.

Challenges and opportunities for DSOs

- Beyond the general question of **network investments** and **power connection** adapted to support the development of electric mobility, dynamic charging raises the question of **defining connection solutions adapted to linear infrastructures** (AC or DC delivery, etc.).

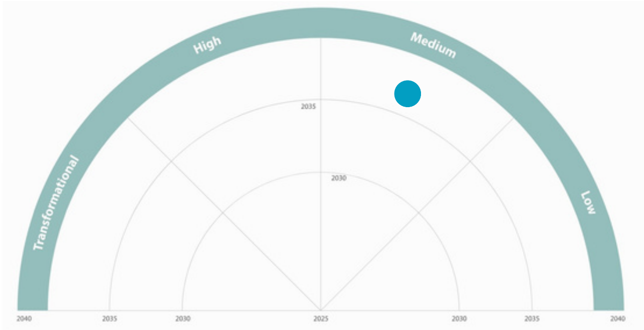
If DC solutions are adopted:

- **DC grids have several challenges to overcome**: protection systems and DC circuit breakers need further development.
- There is a general **lack of standardisation** (especially in terms of voltage levels, other specifications, interoperability, and commissioning procedures), and DC installation **costs are currently high** due to the power converters that are required.
- Power converters are also still not as efficient as AC transformers and have a lower lifespan.

E.DSO considerations

- In collaboration with the stakeholders concerned (car and truck manufacturers, road infrastructure managers, etc.), DSOs should carry out the analyses and implement the demonstrators necessary to identify the relevant solutions and assess the impact of innovative charging options on the distribution network.
- The impact of high-power charging by induction on the grid has to be examined.
- The coupling between storage and charging solutions should be studied.
- Concerning linear charging infrastructures, the DSO perimeter has to be examined and clarified.

15. Innovative Charging for Electric Mobility



Potential Use Cases

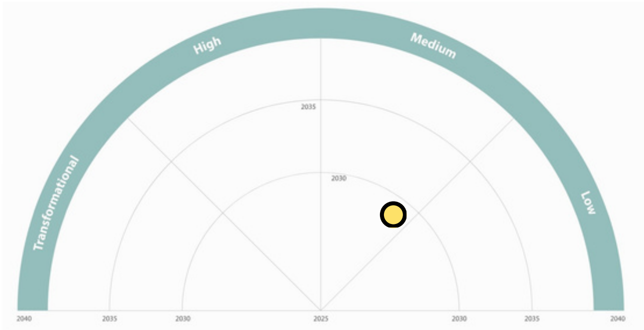
- **Grid flexibility and demand management**: DSOs can modulate wireless charging (especially static) to balance grid demand, reduce peaks, and support local voltage regulation. If compatible, stationary wireless systems could even support bidirectional (V2G) energy exchange to stabilize local networks.
- **Enhanced visibility and monitoring**: Wireless charging systems can be embedded with sensors to provide DSOs with detailed load, voltage, and power quality data. These data can help DSOs predict future energy flows and adapt infrastructure planning.
- **Tariff innovation**: DSOs might design time-of-use or locational tariffs to incentivize charging when grid conditions are favorable.
- **Infrastructure Co-Development**: DSOs can collaborate in deploying electrified roads or bus lines to ensure optimal connection points and power availability.
- **Resilience and emergency applications**: Wireless charging hubs combined with local storage could maintain essential mobility services during grid disruptions. In emergencies, DSOs could leverage connected EVs as mobile energy sources to restore power locally.

Ongoing Projects

- **Enedis**: European project INCIT-EV. This project has resulted in five demonstration sites, including two in France (Paris and Versailles – not managed by Enedis).

Last update: 8 December 2025

16. Onshore Power Supply



Onshore Power Supply (OPS or Cold Ironing/CI) enables ships at berth to connect to onshore electricity instead of running auxiliary engines, reducing CO_2, SO_x, NO_x, and noise pollution. **EU Regulations 2023/1804 (AFIR) and 2023/1805 (FuelEU Maritime) mandate CI adoption by 2030** for container, cruise, and passenger vessels >5,000 GT in **189 TEN-T EU ports.** Estimated investment needs: €7.4bn for port infrastructure, €25bn+ for ship retrofits; up to €80bn for broader port upgrades. While CI technology is relatively mature, **the operational model through which the wide implementation of CI will be sustainable is currently missing.**

Highlights

- **OPS adoption is critical to Fit-for-55 climate neutrality goals**: 10% of maritime transport emissions stem from ports; 19% CO_2 and 22% SO_x emissions from ships at berth.
- As of 2023 only 51 EU ports (309 MW capacity) had OPS; **electricity demand will triple/quadruple by 2030**.
- The OPS technology is relatively mature; some commercial options available.
- IEEE 80005-1-2-3 technical standards ensure interoperability.
- **OPS adoption provides air quality, climate, and noise benefits for ~180 million coastal citizens in EU**.

Challenges for DSOs

- **Electricity grids in ports need to be upgraded to meet the potential demand in the ports**: 100+ MW in large , 10-40 MW in medium and 5-10 MW in small ports.
- The areas of the ports are not the easiest part to supply energy (**weak points of the Grids**)
- **Power quality issues**: Harmonic distortion (frequency converters); Switching transients (equipment of 1-20 MVA)
- **Quality of Earthing and common mode currents/voltages** ➔ accelerated galvanic
- Corrosion.
- **Stability problems**.
- **Power redundancy/resilience problems**.
- **Large nominal capacity of the connections vs low load factor**: cruise ships use the supply typically only less than 14 hours a day).
- **Information asymmetry**: DSOs often lack ship demand data, risking over/under-investment.
- **Monopoly pricing risk**: CI costs may be inflated up to 10–20x actual electricity cost as ports are the sole providers to ships (contrary to EU Directive 2017/352).
- Small/medium ports face **financing barriers; island grids risk blackouts** with large cruise loads
- **CAPEX for off-port upgrades** (substations, lines) often unfunded.

E.DSO Considerations - Business Models*

Standard Intermediary (Helsinki, Oslo, Kiel, Kristiansand, Gothenburg, Copenhagen Hamburg, Livorno)

- Port finances and operates OPS (with public co-funding), reselling electricity to ships.
- Revenue recovered through markups on electricity and/or fixed operational fees.
- Port holds strong pricing power, with limited competition in energy supply.
- Grid operator sets technical supply parameters; coordination remains transactional.
- Suitable for small–medium scale OPS.

Active Intermediary (Ports of Stockholm (Nynäshamn, Kapellskär and Stockholm Norvik)

- Port fully owns and operates OPS as a Closed Distribution Network Operator.
- Investments funded via EU grants plus environmental tariffs applied to all customers.
- Cost recovery through grid connection fees and maintenance charges, not energy markups.
- Close collaboration with frequent customers on investment timing and usage agreements.
- Strong coordination with grid operator via data-sharing and cost-sharing for network upgrades.
- Aligns with sustainability goals but consolidates ports' control over OPS pricing and capacity.

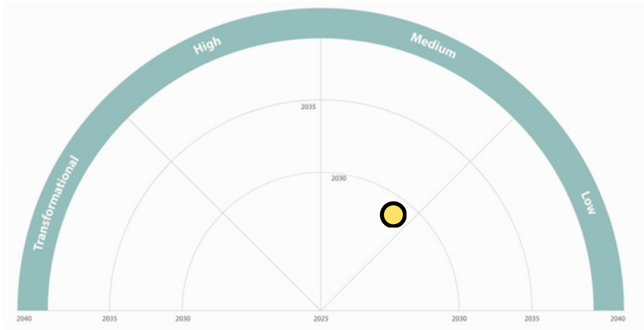
Facilitator (Helsinki, Oslo – certain terminals)

- Port provides OPS infrastructure, but ships contract electricity directly with suppliers.
- Infrastructure funded either by ports (recouped via fixed connection fees) or by shipping companies.
- Opens competition in electricity supply, aligning with 2017/352/EU Directive.
- Reduces port's capital burden, especially when large customers self-finance OPS terminals.
- Ports retain influence through fixed or negotiated fees for use of facilities.
- Enhances transparency and customer bargaining power, but complicates coordination between port, grid, and multiple suppliers.

Extension-to-Grid (Under consideration for Igoumenitsa and Rafina Ports, Greece):

- Treat the infrastructure for OPS as grid extension.
- DSO investing, owning & operating the distribution up to the connection points of the vessels avoids monopoly power over the power supply (on behalf of the port) and enables competitive energy supply for the customers. This is well aligned with the 2017/352/EU Regulation
- Ensure fair, regulated tariffs.
- DSO developing the grid also enables better harmonisation with general grid development plans (reducing coordination asymmetries), delivering the power supply capacity when the need arises.
- Support small/island ports with grid stability measures and targeted funding.
- Provide benefits to all stakeholders.
  - Ports benefit via RES, storage, and complementary services.
  - Ships benefit with free supplier choice and ETS compliance.

*Source: Ennis, S., Mammassis, C., Markellos, R., Prousalidis, J., Manos, A., Loukos, G., & Tracey, N. (2025). Regulatory and Business Innovation in Uncharted Waters: Mandatory Cold-Ironing (Working paper). Centre for Competition Policy, University of East Anglia



Potential use cases - HEDNO (Igoumenitsa Port & Rafina Port)

- **Strengthening local grids**: The rapidly increasing electricity demand from OPS infrastructure drives targeted reinforcement of distribution networks around ports, accelerating grid modernization and capacity upgrades.
- **Accelerating RES integration**: By reinforcing port-adjacent grids to meet OPS demand, ports can host and integrate more renewable energy generation—such as solar, wind, and storage—since the strengthened network can safely absorb and dispatch higher volumes of variable RES.
- **Provision of flexibility services**: Although the technology is not yet mature, in the future OPS infrastructure could enable ship-to-grid flexibility services, allowing berthed vessels to provide balancing and ancillary support once standards, inverters, and regulatory frameworks evolve.

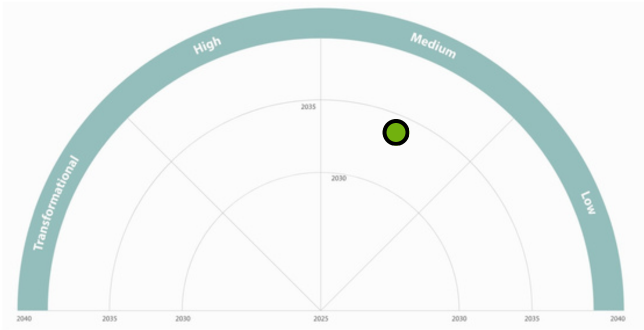
Ongoing Projects

- **Enedis (Seine Docks, Paris, Bordeaux Port, Marseille Port)** :
  - Responds to a connection request made by the port operator. The voltage threshold (low voltage or medium voltage) is decided based on the requested power. The cost of this connection is the same as any other connection of the same power, regardless of its use.
  - Potential network extensions are included.
  - The connection point and the metering point are located at the boundary between public and private property.
  - Downstream from this metering point, the installation belongs to the client, who is typically the port operator.
  - It is the port operator who makes the connection to the quay, and it is also them who integrates the frequency adaptation system (50/60 Hz).
  - The energy supply contract is requested by the port operator, who offers a complete service to the shipowner in need of a berth.
  - The occasion of electrifying energy supply in ports can be also used to consider electrification of other industrial assets located in the port area.

Last update: 8 December 2025

Suistainable Development

17. SF_6 Free Equipment



Technologies containing **SF_6** are widely used in electricity networks, mostly at Medium Voltage (MV) and Low Voltage (LV) levels. These technologies are used in switchgear to isolate and protect different sections of the grid such as switchboards, circuit breakers, metal-enclosed switchgear, and gas-isolated switchgear, amongst others. SF_6, according to the USA Intergovernmental Panel on Climate Change, has the highest global warming potential (GWP), 23000-25000 times higher than CO_2. The gas also has an atmospheric lifetime of 3200 years. According to Schneider Electric, over 30 million units worldwide of MV switchgear use SF_6, and 10 million of these units are in the EU Member States, containing in total more than 8600 tons of SF_6.

Highlights

The electricity distribution and transmission systems are responsible for 80% of SF_6 emissions. According to the LIFE SF6-FREE HV BREAKER project, considering only HV lines, 33 tons of SF_6 are released across Europe every year. The new F-Gas Regulation will introduce a full ban for MV switchgear relying on F-gases, with a gradual phase-out by 2030, and a ban for HV switchgear by 2032.

Opportunities for DSOs

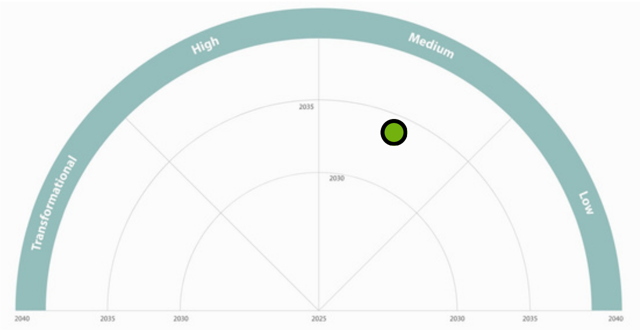
- Contributing to the **reduction of greenhouse gas emissions**.
- Potential to develop **innovative solutions**.

Challenges for DSOs

- Market Availability. Not enough switchgear manufacturers with SF_6-free solutions are available on the market compliant with the F-gas Regulation. Hence, insufficient production capacities will lead to delays in grid expansion.
- Potential cost increase on new technology purchasing, existing infrastructure upgrading, installation, maintenance and training.
- Finding current SF_6 equipment replacements with similar performance characteristics.
- Maintenance of existing SF_6-based installations until the end of their lifetime.

E.DSO considerations

- DSOs are committed to the transition to an SF_6-free grid.
- It is necessary to have a close interaction with the equipment manufacturers so that the development and deployment of SF_6-free solutions can be accelerated and addressed in an effective way.
- All technical grid equipment, including switchgear and circuit breakers, must meet strong reliability criteria throughout their entire life cycle. With this, any future SF_6 solution must be proven to be as reliable, cost-effective, and safe as currently deployed SF_6-based technology.
- Research and experimentation between transmission and distribution equipment manufacturers and end-users on SF_6-free solutions should be enhanced.

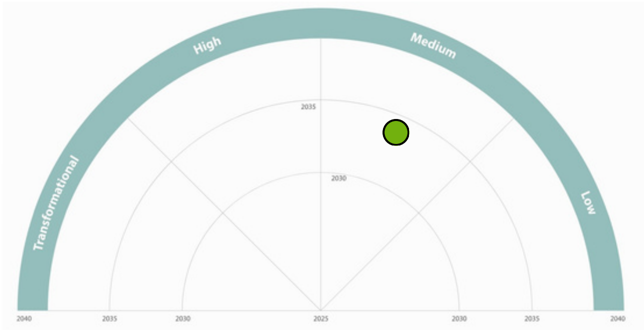


Potential use cases

- **Air-insulated Switchgear (AIS).** Usage of air as insulation medium instead of SF_6 in circuit breakers, disconnect switches, and busbars, amongst others.
- **Gas-insulated Switchgear (GIS).** Alternative gases such N_2 and a mixture of dry air and synthetic gases are being used as insulation gases instead of SF_6.
- **Solid-insulated Systems (SIS).** Solid insulation materials can replace SF_6 in some applications due to their electric insulation properties.
- **Vacuum-insulated Switchgear (VIS).** Usage of a vacuum environment as an insulation medium instead of SF_6. As an example, on circuit breakers, the arc extinction and current interruption are done in a vacuum environment. VIS is a viable option since it offers good insulation properties.

Ongoing projects

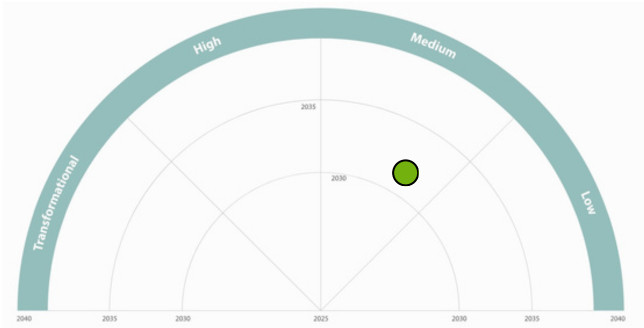
- **LIFE SF6-Free** is deploying SF_6-free MV switchgear pilot installations and developing innovative MV SF technology with Shunt Vacuum Interruption (SVI) (more info).
- **LIFE SF6-Free HV Breaker** aims at combining a viable gas alternative to SF_6 with an improved interrupting unit technology suitable for an outdoor high voltage live tank circuit breaker (HVLTCB) operating from 245 kV/50 kA to 550 kV/50 kA (more info).
- Enedis is carrying out experimentation works on SF_6-free alternative solutions. These works allow the qualification of alternative solutions to SF_6, such as **AIS for higher voltage primary substations with vacuum interruption**. Furthermore, Enedis no longer installs new electrical 24 kV switchboards with SF_6 in its primary substations since 2021.
- E-REDES has been testing various SF_6-free solutions together with manufacturers and technology providers since 2021.
  - A new type of **SF_6-free MV switchgear with vacuum switching and solid insulation media** (up to 24kV) is being tested in the framework of the NextStep project, serving as the test bed for E-REDES' first SF_6-free MV secondary substation switchgear integrated with Internet of Things (diagnosis of insulation condition and MV condition).
  - An **SF_6-free secondary substation protection** is being tested in three 15/10kV secondary substations to validate the technological performance of a secondary distribution cell without SF_6 with remote control and integrated network protection.
  - Another pilot is being performed on a 15/10kV secondary substation to validate the technological performance of an **SF_6-free secondary distribution cell with integrated remote control**.
  - The technological performance of a **primary distribution cell without SF_6** as an alternative to the current AIS is being validated in a 60/30kV substation and a 15/10kV secondary substation.
  - E-REDES is also evaluating HV alternative solutions to comply with regulatory provisions for the technological phase-out of SF_6 solutions.



Ongoing projects (continues)

- E-REDES Spain is testing various SF_6-free solutions:
  - **Remote-controlled modular cells with vacuum cut-off technology** integrated into the MV distribution network.
  - **SF_6-free modular line cells** sewn to an SF_6 protection cubicle in a transformer substation.
  - **SF_6-free modular protection cabinets**.
  - Automated secondary distribution **MV switchgear with dry air insulation and vacuum cut-off technology.**
- Enel is currently trialling, mainly in Spain and Italy, SF_6-free equipment both at the MV (up to 24KV) and HV levels (up to 145KV). During 2019 and 2020, thanks to an open innovation approach, Enel involved two of the main suppliers of MV and HV equipment in developing SF_6-free projects in compliance with their current technical requirements. The installation of twenty **MV Ring Main Units** (RMU) at 24 kV **with alternative gas insulation** was conducted in Italy and Spain, while five **HV circuit breakers** at 145 kV **with dry air insulation** were installed in Spain.
- E.ON grid operators are currently running different pilot projects at MV and HV levels using dry air and vacuum for insulation and braking respectively.
  - At the MV level, a complete primary substation has been installed with **'AirPlus' technology** and an existing primary substation has been enlarged with two **dry air insulated switch panels** (both operating at 24 kV).
  - On higher voltage levels (i.e. at 110 kV), two **SF_6-free switch panels** have been installed with a 145 kV **dry insulation with a vacuum circuit breaker** respectively, complemented by **dry air instrument transformer sets** enabling remote online performance monitoring.
- i-DE is currently testing SF_6-free equipment at MV (on secondary substations at 24 kV) and HV (on primary substations at 132 kV) in collaboration with different manufacturers with the purpose of developing and reaching market maturity for these products.
  - MV trials use **dry air with vacuum breaking**, while HV trials use an **alternative fluorine gas**.
  - Available SF_6-free technologies are being analysed, but none of them have been found ready for a successful implementation on the network yet.
  - i-DE has been committing to the verified end-of-life management of SF_6 switchgear since the mid-90s, providing recycled SF_6 for maintenance.

Last update: 17 May 2024



Circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible.
DSOs wish to reduce the environmental footprint of their activity: this includes the carbon footprint, but also the impact of other products (lead, single-use plastic, etc.) and more generally the consumption of natural resources. Resource consumption takes place during network operation but also during the construction of new structures. An effective way to reduce this footprint is to re-use existing equipment as much as possible. Many innovations must be developed to progress in the desired direction.

Highlights

The European Commission adopted the new circular economy action plan (CEAP) in March 2020. This is one of the main building blocks of the European Green Deal, Europe's new agenda for sustainable growth. The EU transition to a circular economy will reduce pressure on natural resources and will create sustainable growth and jobs. It is also a prerequisite to achieve the EU 2050 climate neutrality target and to halt biodiversity loss and the majority of regulations foreseen in the plan, have been implemented.

Challenges and opportunities for DSOs

Opportunities

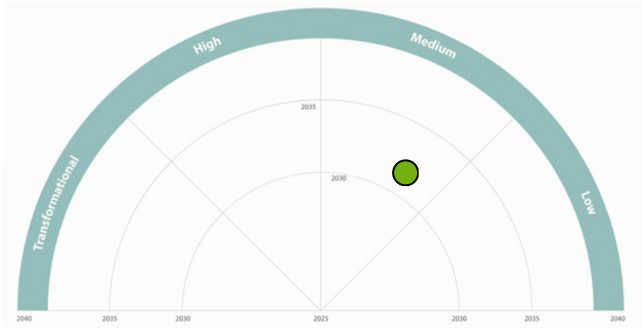
- Reduction of carbon emissions.
- Reduction of the consumption of rare resources.
- Improvement of corporate image through commitment to the ecological transition.
- Positive impact at long term on rare resources costs.

Challenges

- Possible increase in costs at short/middle term.
- Impact on OPEX/CAPEX balance.
- Control of component reliability and warranty management.
- Creation of the industrial sector necessary to support these objectives.
- Sovereignty of this industrial sector.
- End-of-life management: improving end-of-life management and preparing for re-use, through: the disassembly of the product (disassembly time, number of parts, absence of gluing, etc.) and increasing its recyclability and separability (effective recyclability rate after dismantling).

E.DSO considerations

- DSOs must aim to reuse materials as much as technically and economically possible: incorporation of **recycled materials** in the manufacturing of equipment, **repair of components** (including old ones) when possible, etc.
- The **network tariff provisions**, and in particular those relating to the remuneration of investments, must encourage DSOs to take action in the fields of recycling and circular economy.
- DSOs must undertake, in conjunction with component suppliers, research and development work to find solutions allowing **components to be reused** as much as possible.

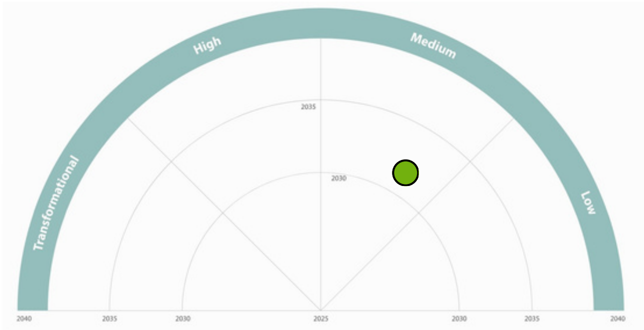


Potential use cases

- Use of cables made partly from recycled materials.
- Refurbishment of end-of-life transformers.
- Repair of equipment in primary and secondary substations, even old ones.
- Reuse of some of the components (metallic cable support, etc.) during the renovation of old overhead lines.

Ongoing projects

- **Enedis** is carrying out the following projects related to recycling and circular economy:
  - Retrofit of the mobile part of certain medium voltage (MV) circuit breakers (the fixed part is retained, even beyond 20 years).
  - Transition from cutting in SF to cutting in vacuum while retaining the fixed part of the initial MV circuit breaker.
  - Repair of MV/LV transformers.
  - Scheduled renovation of HV/MV transformers (lifespan extended by 15 years).
  - Scheduled renovation of MV overhead lines (lifespan extended by 25 years).
  - For the new equipment that is purchased, integration into calls for tenders of better-distance criteria concerning the principles of the circular economy (eco-design, end-of-life management).
- **Stedin** focuses on the “front-end” of their processes where they can identify several opportunities for increasing sustainability. Examples include adjusting specifications to avoid undesirable materials, adopting designs that require fewer materials, including sustainability as a criterion in the selection of products, and challenging suppliers to develop sustainable alternatives. Plenty of attention is being paid to cables and buildings, as these are areas in which a huge impact can be achieved.
- The **EDP networks platform**, which is currently operating in Portugal (E-REDES), Spain and Brazil, is developing a 2-year Iberian project on circular economy, based on the EDP group policy, with seven axes of action: efficiency in the use of resources and materials, product longevity, digitalisation, resource valorisation, new business models, circular supplies and influence/awareness. The main goal is to achieve an 85% operational waste valorization by 2026 and an 85% increase in the total waste recycled from operations by 2025. In this project, the circularity and carbon footprint of the network assets were assessed, and an implementation roadmap was designed, and is currently being implemented.
- **E.ON** is carrying out several activities related to recycling and circular economy: using circular wooden poles for overhead lines, refurbishing old transformers, reusing transformer oil, introducing an internal platform to reuse components and repairing high voltage (HV) transformers, introducing sustainability targets on circularity in planning.
- **ORES** is reconditioning (i.e., replacing insulators with plugs to avoid direct HV contact) transformers that have reached a certain age but which are not at the end of their life yet.



Link to the relevant E.DSO success cases

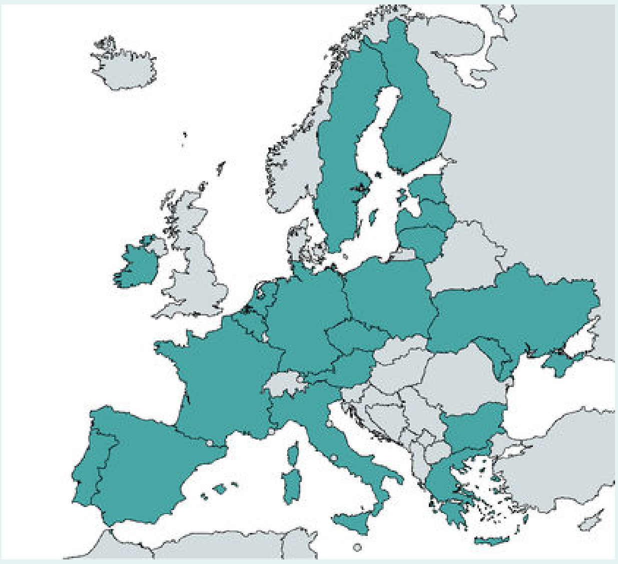
Success case number	Title	Company
20.2025	Cartoline	Enedis
4.2024	DeepGourboGen	Enedis

Impact on the energy syestem: Recycling and circular economy does not necessarily change how grid is operated, but they change how the grid is built, maintained, renewed and expanded. Recycling and circular economy extend the lifetime of grid assets, reduce material use and waste, and lower the environmental footprint of electricity infrastructure. By reducing the need for full replacement and promoting more sustainable procurement, they can also defer investment needs and free up resources for grid modernisation and electrification.

Link to relevant EU policies

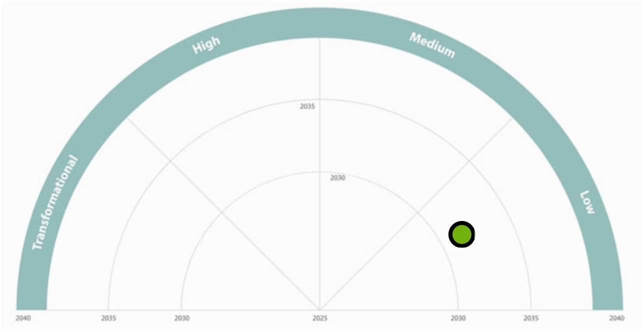
- In general, policies in the domain of Sustainability/biodiversity protection and Circular economy.
- In particular, Circular Economy Act, Competitiveness Compass, Clean Industrial Deal, Circular Economy Action Plan, Regulation on Packaging Waste & Directive on Waste Electrical and Electronic Equipment.

Technology deployment across countries with E.DSO members



Last update: 12 September 2026

19. Line Corridors that Support Biodiversity



Line corridors that support biodiversity refer to the cleared areas beneath and around **overhead power lines** that, when managed sustainably, can become valuable habitats for various species and contribute to biodiversity conservation. These strips of land, typically maintained to prevent vegetation from interfering with power lines, have the potential to serve as **ecological corridors**, connecting fragmented ecosystems and supporting the movement of wildlife and the growth of native plants. In the context of electrical distribution networks, these areas can be managed through practices such as **selective vegetation maintenance, the introduction of native species, and the creation of specific habitats**, turning utility corridors into spaces that enhance both environmental sustainability and operational safety.

Highlights

The **EU's Biodiversity Strategy for 2030** aims to reverse biodiversity loss by enhancing protected areas, restoring ecosystems, and introducing binding restoration targets through the Nature Restoration Law. The strategy focuses on **expanding the Natura 2000 network**, improving agricultural and forestry practices, and integrating nature-based solutions like carbon-capturing ecosystems. It supports green investments and ensures legal frameworks for habitat restoration. This initiative aligns with the European Green Deal and other sustainability policies and will receive substantial funding.

Opportunities for DSOs

- **Sustainability goals**: Supporting biodiversity helps DSOs meet environmental regulations.
- **Connectivity**: These line corridors can connect ecosystems, aiding wildlife movement and promoting a healthier environment.

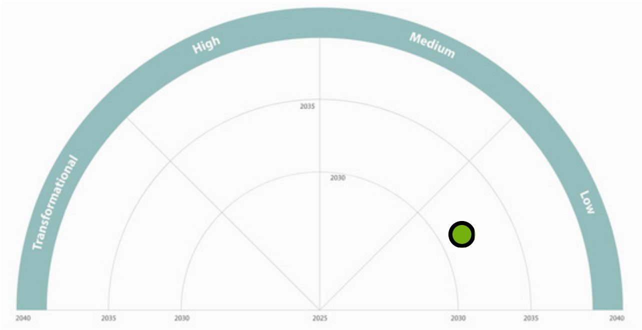
Challenges for DSOs

- **Balancing safety and biodiversity**: DSOs need to ensure the corridors don't interfere with grid safety.
- **Increased costs**: Implementing biodiversity initiatives may require additional investment.
- **Regulatory complexity**: Keeping up with changing regulations can add complexity.
- **Continuous management**: Managing these areas requires continuous monitoring and resources.
- **Need for coordination** with other environmental protection authorities.

E.DSO considerations

- E.DSO wishes to promote the development of exchanges of experience and the sharing of good practices between E.DSO members on these solutions.
- A balance must be found to promote biodiversity without affecting the security of the electricity distribution system and while remaining attentive to costs and therefore to the level of distribution fees paid by network users.

19. Line Corridors that Support Biodiversity



Potential use cases

- Installation of nests or other animal facilities on top of power poles.
- Coordination with other public/private environmental protection authorities.
- Use of ecologically-friendly equipment (e.g. pesticide-free).
- Taking biodiversity into account in public lighting projects (light pollution, etc.).
- Promoting efficiency in vegetation management, potentially through the use of artificial intelligence (AI).
- Promoting network security-related projects to prevent natural hazards.

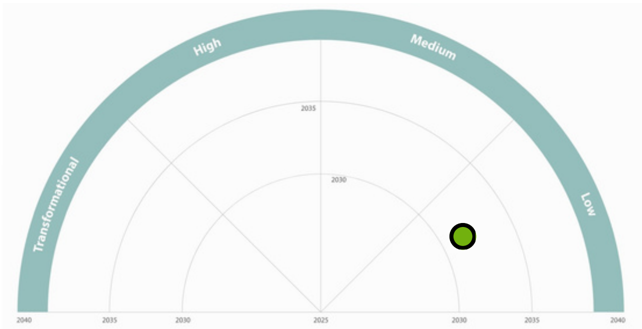
Ongoing projects

- ORES promoted the following initiatives:
  - A **ban** (admittedly, in application of the law) **of the use of pesticides** in third-party contracts for the management/maintenance of the surroundings of their facilities, sites and posts and the application of a late mowing policy in some of these locations.
  - The **installation of two stork nests** at the top of electricity poles on their network in collaboration with local wildlife protection associations and the Royal Ornithological League. The aim was to ensure the safety of Ores's installations and the birds in places where they could nest "erratically", potentially causing power failures and bird mortality. The initiative was crowned with success, with the birth of two stork chicks in one of the two nests in 2023.
  - A number of initiatives have also been undertaken in the field of **smart lighting**:
    - The production of a 'Vade-mecum for taking biodiversity into account in public lighting projects', which was put online and published for local authorities by the Walloon public service.
    - The promotion of the 'black grid' to local authorities to reduce light pollution.

- UFD has committed to environmental protection through several innovative projects. These include **advanced vegetation management** with drones, AI, and LiDAR, **fire and smoke detection** for early incident response, and the **reduction of electrocution risks** for raptors by replacing insulators with anti-perching devices, all in alignment with regional environmental plans.

- Netz Niederösterreich has been consulting ecologists, biologists and planners to find a line corridor that respects nature and its biodiversity in sensitive areas. In terms of bird protection, the DSO has been:
  - Marking the wires of 110-kV-power lines with **bird protection flags** to prevent collisions in sensitive and/or highly frequented habitats.
  - Installing new 20-kV-power lines underground to **prevent bird collisions**.
  - Financially supporting research programmes, to ensure the **cross-border bird protection** of endangered species. For example, the DSO co-finances the **LIFE EUROKITE** project (2017-2027) that researches the mortality of red kites by using telemetry.

19. Line Corridors that Support Biodiversity



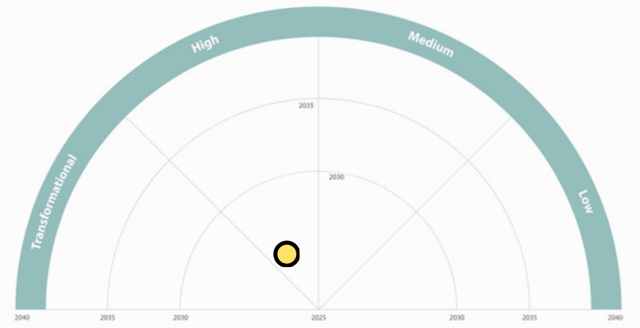
Ongoing projects (continues)

- Performing forestry maintenance such as tree felling outside of the breeding season.
- Reforestation of native, site-adapted species in case the line corridor runs through forest areas.

- Enedis is a partner in two projects financed by the LIFE Programme of the European Union that support biodiversity:
  - **SafeLife4birds**, which goal is to reduce the mortality of 13 bird species against power lines by tackling bird collision, electrocution and disturbance during the breeding season as well as improve and share knowledge across Europe.
  - **LIFE GYPACT**, which goal is to restore and conserve bearded vultures and improve the viability of bird populations.

Last update: 14 February 2025

Information Technology and Telecommunications



Generative AI refers to a category of artificial intelligence systems designed to create new content rather than simply analyse existing data. These systems can generate text, images, code, or insights based on patterns learned from large datasets. In the context of electricity distribution network management, Generative AI primarily supports content creation, knowledge work, documentation, and decision support for human experts. It can help synthesize information, assist with reporting, training, and operational analysis, and improve overall productivity. However, Generative AI is not intended for autonomous grid control or for making high-impact decisions independently.

Highlights

According to Bloomberg Intelligence, the generative AI market is expected to reach around $1.3 trillion by 2032, accounting for 10–12% of global technology spending. Valued at about $40 billion in 2022, the market rose to roughly $64 billion in 2023, driven by rapid adoption across software, infrastructure, and enterprise use cases. This acceleration is best illustrated by ChatGPT. Launched in November 2022, it reached one million users in five days, becoming the fastest-growing consumer application ever. Adoption has continued at scale, with several hundred million weekly active users globally by 2025–2026, signaling the mainstream uptake of generative AI. On the regulatory side, the EU AI Act, adopted in 2024, is the world's first comprehensive AI regulation. It introduces specific transparency and risk-management obligations for generative and general-purpose AI models, with key provisions beginning to apply in 2025 and full enforcement extending into 2026. (EU AI Act: first regulation on artificial intelligence).

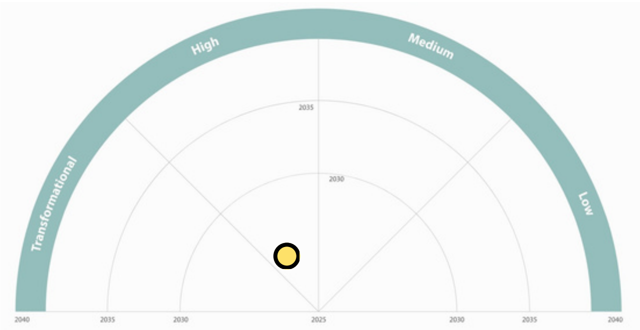
Challenges and opportunities for DSOs

Opportunities

- **Enhance employee productivity** across DSO processes as Generative AI has the potential of automating routine, repetitive content related tasks and augmenting work activities that require problem-solving and abstract reasoning skills.
- **Support personal experiences:** generative AI can tailor content, products, and services to individual preferences for DSO customers, partners and employees.
- **Automate human-like content creation,** support informed decision making and augment human creativity across DSO processes.
- **Augment software development.**
- **Ability to support DSO decision-making** by synthesizing information across data sources, domains, and perspectives, helping experts explore options, assess implications, and align stakeholders in complex planning and operational contexts.

Challenges

- The use of generative AI will require **specialised resources and adapted validation processes** (bias/accuracy monitoring, privacy and security management) before establishing confidence in processes critical to the distributor.



Challenges (continues)

- **Data quality:** Generative AI relies on high quality training and input data (e.g. grid data)
- **Intellectual property:** information entered in Generative AI services can become part of its training set, determining ownership of content created by GenAI is complex.
- The adoption of Generative AI introduces **governance challenges** that go beyond technology, including the need for robust validation arrangements, clear accountability for AI outputs, and explicit policies on data usage and intellectual property. Without such governance in place, Generative AI cannot be safely applied in DSO-critical processes.

E.DSO considerations

- This type of artificial intelligence was popularised later than predictive AI and has therefore experienced more recent adoption and success. As a result, Generative AI can be considered a fast-emerging technology, currently in the pilot or early-adoption phase, with significant impact expected in the short to mid term.
- Generative AI solutions performances are directly based on data availibility and quality and emphasize data privacy concerns.
- Generative AI algorithm performance control requires special attention and dedicated monitoring tools.
- Generative AI technologies require specific skills and companies will have to develop specific training programs.
- Development and implementation of Generative AI solutions must be carried out with the aim of reducing their carbon footprint.
- Particular attention must be paid to the ethical aspect of Generative AI (potential concerns about justice, fairness, accountability etc...).
- It will be necessary to ensure that the results of generative AI are always identified as being generated by a machine.
- For decisions with high operational or safety impact, Generative AI should be used strictly as a supporting tool, with human oversight as a mandatory requirement rather than an optional control.
- Even when final decisions remain with humans, Generative AI can significantly influence how problems are framed and options are assessed, which makes consistent governance and transparency across DSO processes essential.

Potential use cases

- **Improve knowledge management:** retrieve stored internal knowledge for better-informed decisions across DSO processes, clarify complex regulations etc.
- **Boost grid management and operations by automating & augmenting tasks:** incident planning & response, network development studies, grid engineering, asset performance & planning, demand load forecasting, network control, etc.
- **Enhance customer experience** by generating personalised content, recommendations, and automating responses to customer requests.
- **Faster product- and software engineering:** creating novel designs, prototypes, code and testing these.

Ongoing projects

Stedin:

- Stedin is advancing Generative AI capabilities through scalable, responsible, and high-impact adoption, including the development of capabilities to safely operationalise advanced AI systems such as monitoring, evaluation, and compliance. In parallel, Stedin enables organisation-wide adoption via shared building blocks like a standardized RAG (Retrieval-Augmented Generation) template and a GenAI Gateway, ensuring consistent, secure, and governed integration of LLMs. At the same time, Stedin focuses on high-impact use cases, such as AI-driven validation of contractor quotations to detect inconsistencies or unjustified costs, improving the quality and reliability of agreements between Stedin and its partners.

ČEZ Distribuce:

- Proof of Concept including dedicated implementation of OpenAI based generative AI model as a chatbot for connection requirements information prepared for customers and tested by internal employees. Next steps would be to integrate chatbot in public website, analytics of Customer's feedback, internal chatbot for corporate documentation, HR onboarding etc.

UFD:

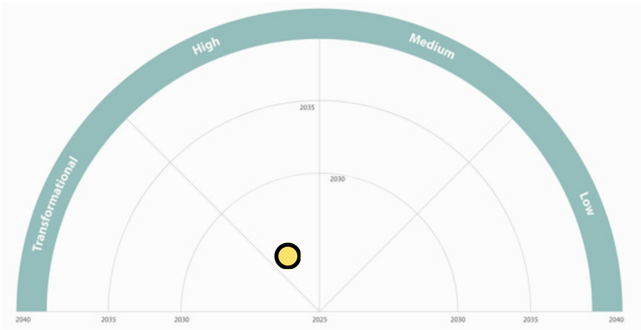
- UFD, its working on two projects to leverage generative artificial intelligence. Both projects are similar and aim to provide our Call Center and Control Room Operators a co-pilot to support their activity and personalise responses to customer calls and incidents, respectively.
- Additionally, it is planned to use AI as a simple manager for advanced queries to the repository of information available in the cloud, offering a unique and straightforward result.

ORES:

- As part of a pilot project, generative AI will be used to optimally estimate the baseline calculation model to be assigned to a network user in order to assess flexibility services. For each specific case, the output will specify the formula to be applied to achieve both technical and economic efficiency, while also preventing fraudulent behaviors (such as "gaming" across multiple markets simultaneously).

Link to relevant E.DSO success cases

Success case number	Title	Company
20.2025	Cartoline	Enedis
4.2024	DeepGourboGen	Enedis

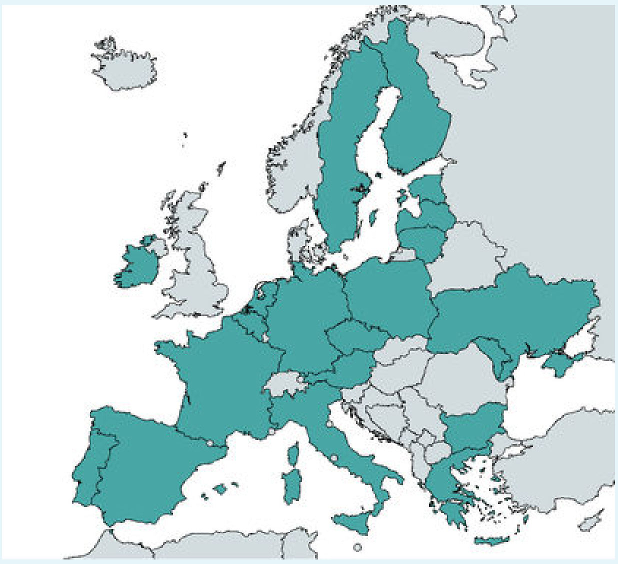


Impact on the energy system
Improved decision making support and coordination.

Time to scale
- 0-5 years.

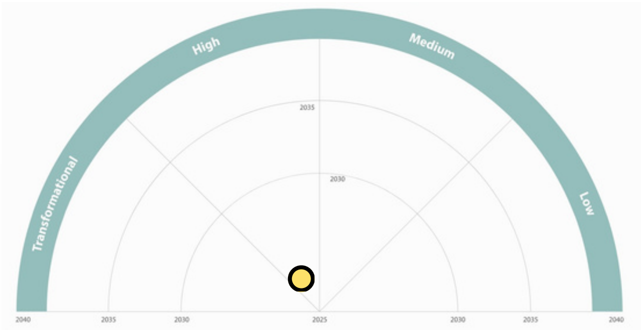
Link to relevant EU policies
Digitalisation, Data sharing, Cybersecurity (NIS2), Flexibility,, EU AI act.

Technology deployment across countries with E.DSO members.



Last update: 12 September 2026

21. Predictive AI



Predictive AI is a type of artificial intelligence that focuses on forecasting, prediction and decision support based on historical and real-time data. The main subcategories of predictive AI models are supervised and unsupervised learning, time-series models, reinforcement learning, and mathematical optimisation. In practice, it is often implemented through hybrid models that combine several approaches to improve robustness, performance, and decision-making quality. AI performance is based on the combination of the availability of a large amount of data, large computing capacity, and machine learning algorithms. As distribution networks are generating a growing amount of data, due to the deployment of smart meters and increased measurement and communication capabilities, DSOs have early on considered AI solutions.

Highlights

For the European Parliament, artificial intelligence represents any tool used by a machine to "reproduce human-related behaviours, such as reasoning, planning and creativity". The AI Act is a proposed European law on artificial intelligence – the first law on AI by a major regulator anywhere. The law assigns applications of AI to three risk categories. First, applications and systems that create an unacceptable risk are banned. Second, high-risk applications are subject to specific legal requirements. Lastly, applications not explicitly banned or listed as high-risk are largely left unregulated.

Challenges and opportunities for DSOs

Opportunities

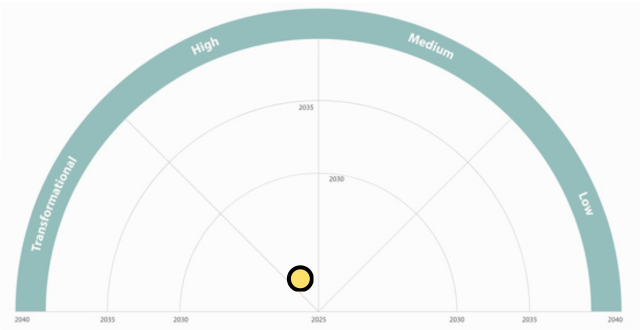
- **Enhance demand/supply forecasting** and decision making adjust distribution, increasing flexibility and minimising the risk of blackouts.
- Supports DSOs to **integrate (distributed) renewable energy sources** into the grid.
- **Reduce the risk of grid failures** by performing timely maintenance by using intelligent, predictive algorithms detecting anomalies in the grid.
- **Enhance productivity** of employees by automating & augmenting repetitive and data intensive tasks.

Challenges

- **Data Privacy**. Handling sensitive grid data while maintaining privacy is essential.
- **Cybersecurity**. Protecting AI systems from cyber threats is critical to ensure grid reliability.
- **Data quality**. AI relies on high-quality training and input data (e.g. grid data).
- Integrating AI into distribution grids involves managing distributed energy resources (DERs), **ensuring seamless coordination and optimisation is a challenge for DSOs.**

E.DSO considerations

- Although it is integrated into this technology radar, predictive AI is considered a mature tool that is already delivering value for DSOs and therefore represents a “here and now” priority rather than an emerging technology.
- The performance of AI solutions is directly based on data availability and quality and emphasized data privacy concerns.



E.DSO considerations (continues)

- Facilitating and accelerating the industrialisation of AI solutions into core information systems has now become one of the major challenges of industrial AI.
- AI algorithm performance control requires special attention and dedicated monitoring tools.
- AI technologies require specific skills and companies that integrate them have to develop specific training programs.
- Development and implementation of AI solutions must be carried out with the aim of reducing carbon footprint.
- Particular attention must be paid to the ethical aspect of AI (potential concerns about justice, fairness, accountability etc. ...).
- European legal texts under preparation must account for the specificities of DSOs.

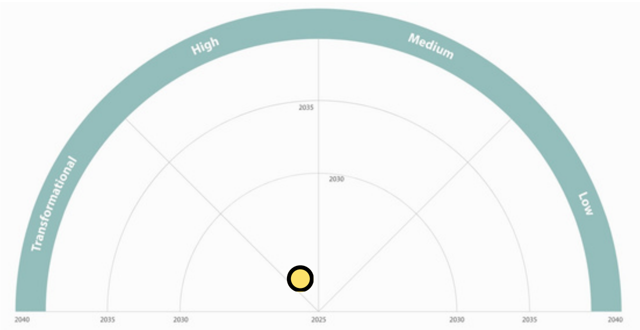
Potential use cases

- Production and Demand forecast: AI combined with classical solutions may improve forecast quality.
- Congestion management prediction: determining how much flexibility is needed in the future.
- Distributed Energy Resources (DER)/Flexibility: AI allows to handle 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 realisation of network development studies accounting for technical constraints, and technological and sociological hypotheses.
- Asset management: AI performances in image processing allow automatic diagnosis to enhance programmed renovation. The learning capacity of AI allows, in some cases, to perform predictive maintenance.
- Image recognition: e.g. electricity energy meter & components recognition from meter photos, detecting assets on technical drawings.
- 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.

Ongoing projects

UFD:

- UFD is leveraging artificial intelligence to transform the inspection of overhead high- and medium-voltage lines through its DALI project. The initiative combines high-productivity drone operations, including BVLOS flights, with advanced AI-based image analysis to digitalise and automate the inspection process. DALI enables large-scale and systematic monitoring of the network, already reaching 5,000 km inspected in 2023 and 11,000 km in 2024. The solution processes large volumes of data, supported by AI models trained with over 20,000 km of inspection images, allowing automated detection, classification and prioritisation of defects.



Ongoing projects (continues)

This approach replaces manual and heterogeneous inspections with a standardised, scalable and cost-efficient model, significantly improving data quality, asset visibility and operational efficiency, while supporting vegetation management and regulatory inspections. Beyond inspection, DALI provides a key digital foundation for advanced capabilities such as digital twins, predictive asset management and risk-based maintenance, positioning UFD at the forefront of data-driven grid operation.

ESO:

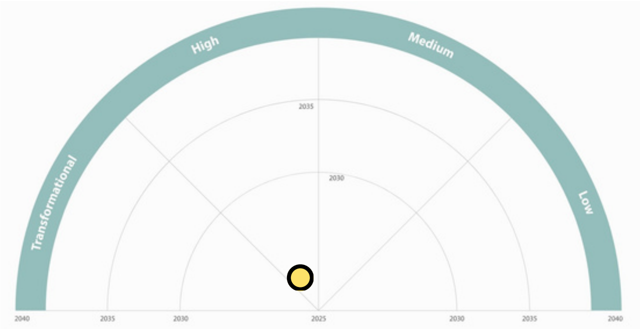
- Mass outage prediction tool - A machine learning-based system was created to provide alerts (predicts number of outages per region) for potential large-scale mass power outages in the 10 kV overhead line (OHL) networks. The tool considers weather forecasts, historical ESO outage data, and technical network parameters to enhance its predictive capabilities.
- Contractor documentation quality assessment tool - A machine learning-driven model has been developed for assessing the quality of network documentation. This model categorises contractor-provided documentation as either “acceptable” or “not acceptable”, pinpointing the specific document page and identifying the type of error present. These errors may include inaccuracies in electrical addresses, rates, lengths, diagrams, or overall document composition. The system then takes corrective actions, such as updating the records or notifying relevant employees, as needed.
- DMS grid fault classification tool – The tool utilises Natural Language Processing (NLP) models to classify the nature of grid element faults based on engineer-provided fault description text. The outcomes generated by these models are employed for cross-referencing with the failure causes inputted by engineers to identify potential human errors in the process.

Link to relevant E.DSO success cases

Success case number	Title	Company
17.2025	AI powered Fraud Detection	UFD
18.2025	ARIIA	Enedis
22.2025	Detection of Non-Technical Losses	Enedis
25.2025	Feeder Load Estimation	ČEZ Distribuce
36.2025	PRoDiGE	Enedis
2.2024	Analytics4Vegetation	E-REDES
7.2024	DORA	Enedis
10.2024	GridWise	E-REDES
21.2024	PQsmart	Netz Niederösterreich
23.2024	Smart Cable Guard	Alliander

Impact on the energy system

High impacts on forecasts (network planning, congestion management, demand forecasting) leading to improved energy efficiency and DER integration).



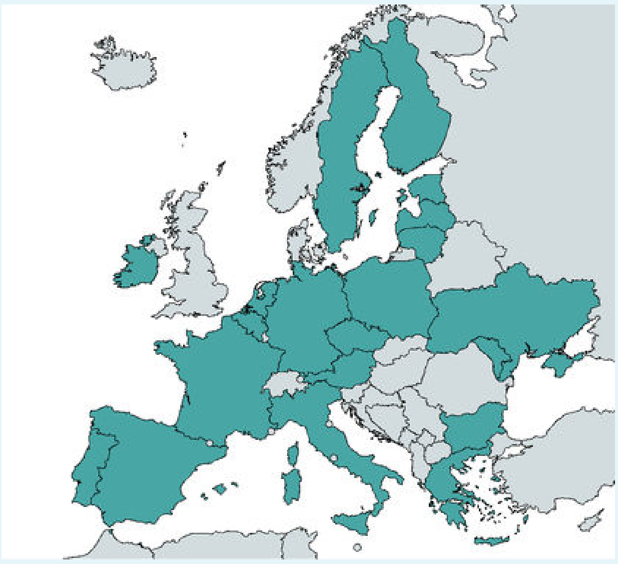
Time to scale

- 0-5 years.

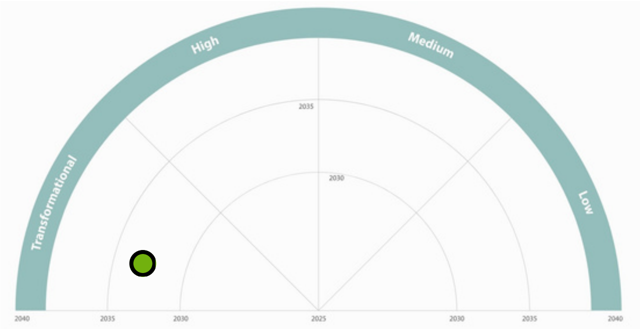
Link to relevant EU policies

Digitalisation, Data sharing, Cybersecurity (NIS2), Flexibility,, EU AI act.

Technology deployment across countries with E.DSO members.



Last update: 12 September 2026



Agentic AI is emerging as a paradigm for next-generation smart grids, enabling autonomous decision-making, adaptive coordination and resilient control in complex energy systems. Agentic AI refers to AI systems composed of one or more AI agents – (semi-)autonomous software entities that apply AI techniques to perceive, decide, and act in pursuit of defined goals across digital or physical environments such as intelligent assets and advanced robots. While agentic AI often builds on predictive and generative models, it is fundamentally distinguished by its ability to independently execute actions rather than only providing recommendations or content. AI Agents represent a fundamentally new software paradigm — one that holds the promise of automation in ways not always possible earlier. As electricity distribution systems become more dynamic due to electrification, DER integration, EV charging, bidirectional flows and increasing operational complexity, Agentic AI has the potential to shift the electricity system from predominantly human-orchestrated to (semi-)autonomous operation, reshaping how control, coordination and resilience are organised, while introducing new challenges around governance, security and safe grid operation.

Highlights

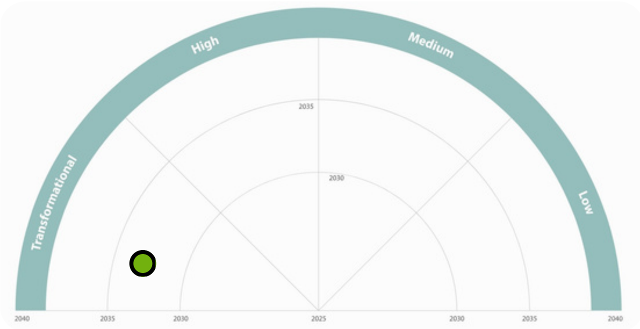
- Gartner forecasts that by 2028, 15% of day-to-day work decisions will be made autonomously through agentic AI and 33% of enterprise software applications will include agentic AI, up from less than 1% in 2024. At the same time, most organisations are still in the pilot or early scaling phase[2].
- For DSOs, the regulatory relevance is high: under the EU AI Act, AI systems used in the management and operation of the supply of electricity can qualify as high-risk AI systems.
- Agentic AI is emerging as both a critical driver of increased power grid demand and a key technological solution to manage that very surge.

Challenges and opportunities for DSOs

Opportunities

- **Enhance workforce productivity** and move from task automation to workflow orchestration. Agentic AI can help DSOs automate repetitive tasks and support employees with better context enabling faster end-to-end execution, especially in dynamic processes where traditional automation fails to handle exceptions and variability.
- **Transform how DSOs organise work and allocate decision rights.** As agentic AI matures, it can support a shift from human-led task execution to human-supervised, AI-orchestrated execution, changing how work is distributed between people and AI across the organisation.
- **Improve decision velocity and operational responsiveness**. In increasingly dynamic distribution systems, agentic AI can shorten the path from signal to action by linking data, reasoning and workflow execution across functions.
- **Enable new forms of value creation for DSOs.** Beyond productivity gains, agentic AI may help DSOs deliver more proactive, resilient and scalable services, for example through better coordination of outage response, maintenance, compliance, engineering support and customer interaction.

22. Agentic AI



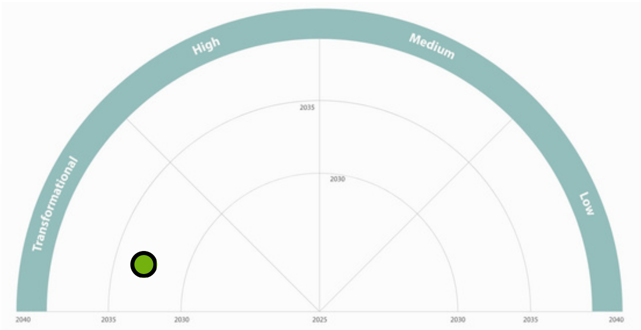
Challenges

- **Governance and accountability:** The increasing autonomy of Agentic AI introduces fundamental governance and accountability challenges, where ensuring that humans remain accountable for outcomes in line with regulatory and safety obligations is crucial.
- **Trust, safety and reliability:** Ensuring predictable and safe behaviour becomes critical as agentic AI may influence operational decisions or interact with systems of record and control.
- **Data, security and access control:** Agentic AI relies on trusted, interoperable data across IT and OT environments, while cybersecurity, identity and access management become more complex when AI systems can initiate actions autonomously.
- **Operational readiness:** scaling agentic AI requires redesigned workflows, monitoring and clear human-agent operating models.
- **System-level impacts of AI growth**: The rapid expansion of AI infrastructure, especially data centres, can increase local network constraints, planning uncertainty and pressure on grid reliability.

E.DSO considerations

- DSOs should recognise that agentic AI is still at an early and experimental maturity stage. While the technology shows strong potential, most solutions are not yet sufficiently mature, reliable and robust for complex, critical enterprise use cases or decision-making.
- In the near term, the focus should be on experimentation and supervised deployment in low-risk domains, rather than large-scale or mission-critical deployment.
- DSOs should evaluate where agentic AI over time has the potential to enable a broader shift towards more autonomous operations and business models.
- For any agentic AI use case - especially when connected to the management and operation of the electricity system - DSOs should evaluate whether the solution may fall under high-risk AI obligations, and should design for human oversight, robustness, cybersecurity, and traceability from the start.
- DSOs should prioritise the creation of a trusted data foundation across IT and OT, with clear governance, role-based access and traceability.
- Agentic AI requires DSOs to build the skills, governance and organisational capabilities needed to redesign processes, manage human-agent collaboration, and maintain clear accountability as digital workers become part of execution.
- DSOs should define clear boundaries for agent decision-making through graduated autonomy levels, with appropriate human oversight triggers.
- DSOs should consider the energy use, carbon footprint and wider grid impacts associated with agentic AI.

22. Agentic AI



Potential use cases

- **Cybersecurity automation and response coordination:** Continuously correlate security signals across IT and OT environments and autonomously initiate pre-authorised containment or investigation actions.
- **Semi-autonomous grid operation and control:** AI agents continuously coordinate grid configuration and operational measures across the network, operating autonomously within system-level policies and safety constraints.
- **Self-healing grid orchestration:** Distributed AI agents detect disturbances, coordinate corrective actions across grid zones and stabilise the system autonomously, with humans supervising exceptions.
- **Flexibility orchestration at system level:** AI agents independently identify, negotiate, activate and release flexibility across assets, customers and markets to maintain system balance in near real time.
- **Market coordination:** AI agents act on behalf of DSOs in real-time interactions with markets, aggregators and other system actors to align grid constraints and market behaviour.
- **Incident and outage management:** Autonomously detect incidents, assess grid impact and coordinate predefined response actions across grid operations.
- **Field service and maintenance orchestration**: Autonomously prioritise and coordinate maintenance actions using asset condition, history, work management data and crew availability.
- **Internal operations and corporate workflows**: Act as autonomous digital workers for internal, non-grid-critical processes such as HR onboarding, procurement coordination, finance reconciliation, regulatory and compliance workflows
- **Software engineering:** Act as autonomous participants that plan, code, test and debug software across the development lifecycle, while human engineers supervise, review decisions and handle exceptions.
- **Grid development:** AI agents continuously evaluate and adjust long-term grid development strategies by autonomously balancing reinforcement, flexibility and operational measures.

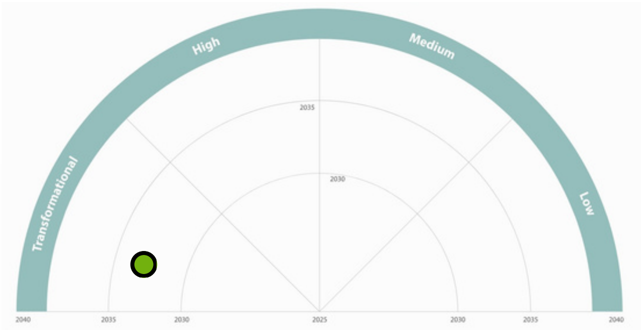
Ongoing projects

At the time of writing, the Technology Radar Task Force is not aware of any ongoing project on Agentic AI.

Link to relevant E.DSO success cases

Success case number	Title	Company
39.2025	Self Healing Systems	Avacon

22. Agentic AI



Impact on the energy system

Potentially shifts the electricity system from human orchestrated to (semi-)autonomous operation, increasing adaptiveness and resilience while introducing new challenges around control, security and safe grid operation.

Time to scale.

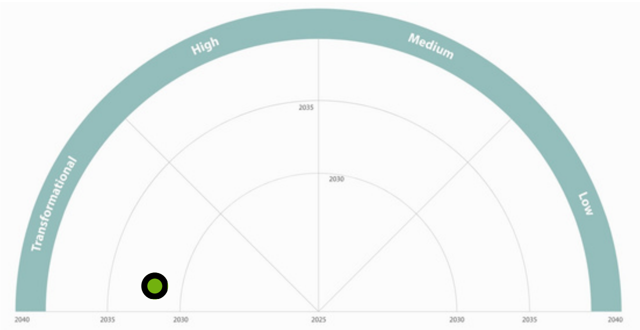
- 5 - 10+ years (depending on use case criticality).

Link to relevant EU policies

Digitalisation, Data sharing, Cybersecurity, Flexibility, Resilience, EU AI act.

Technology deployment across countries with E.DSO members

Last update: 12 September 2026



Edge computing refers to a distributed computing architecture characterised by decentralised processing power. Specifically, it enables data to be processed directly by the device that generates it or by a local computer. In this scenario, there is no longer a need to transmit large volumes of data to a remote data centre for analysis. Edge computing facilitates real-time processing of data in large quantities, as close as possible to its source, leading to reduced bandwidth usage, lower latency, and the necessary security layer for handling sensitive data. This technology is primarily prevalent in the Internet of Things (IoT) domain, where it competes with cloud computing.

Highlights

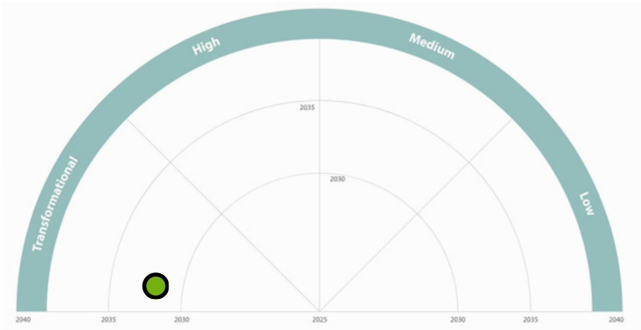
Edge computing is evolving as new technologies such as artificial intelligence and machine learning bring new data analysis capabilities to the table, and emerging business models such as IoT as a service enable solution providers to deliver innovative offerings in new ways. With an average increase of 16% per year, spending on edge computing totalled $40 billion in 2022 in Europe and should reach $64 billion in 2025. Service providers, editors and manufacturers are sharpening their offers to meet the growing demand from companies.

Opportunities for DSOs

- **Enhanced Grid Visibility and Control at the Grid Edge:** The enhancement of computing capabilities enables the rapid execution of complex distributed analyses, especially in primary and secondary substations. This allows DSOs to move from reactive to proactive network management, for example by using local data to predict transformer overloads or proactively manage voltage fluctuations caused by high solar PV penetration.
- **Improved Network Resilience and Reliability:** This provides flexibility to the network and minimizes reaction times by enabling local decision-making and automation of grid operations (e.g., FLISR – Fault Location, Isolation, and Service Restoration). Directly translates to improved SAIDI/SAIFI reliability metrics, a key performance indicator for DSOs, by significantly reducing outage durations..
- **Foundation for a Self-Healing, Autonomous Grid:** Facilitates the autonomous operation of the medium and low-voltage network, [reducing the need for manual intervention and creating a pathway towards a more resilient, self-optimising electrical system.
- **Efficient Data Management and Reduced Telecoms Costs:** Optimizes data storage by processing raw data locally and only transmitting valuable insights or alarms back to central systems. This drastically reduces the cost and complexity of scaling communications networks to thousands of secondary substations.

Challenges for DSOs

- **Lifecycle Management and Scalability:** Equipment Lifecycle. Deploying, managing, patching, and updating the software and firmware on thousands or tens of thousands of distributed edge devices presents a significant operational challenge. DSOs must consider the total cost of ownership, including remote management and end-of-life replacement.



Challenges for DSOs (continues)

- **Interoperability and vendor Lock-In:** Increased likelihood of failure and difficulty in settling responsibilities. This is attributed to the integration of currently independent devices, resulting from the integration of various use cases. Without a commitment to open standards, DSOs risk being locked into proprietary, single-vendor ecosystems, which limits innovation and increases long-term costs. This makes industry initiatives like the E4S Alliance critical.
- **Cybersecurity at the edge:** While edge computing can enhance security in some ways, each intelligent device also represents a new potential entry point for cyber-attacks. Securing a massively expanded attack surface requires a robust, end-to-end security architecture from the device to the control room.
- **Data governance and algorithm ownership:** As critical functions like fault detection are run on edge devices, clear governance is needed. DSOs must address questions of who owns the data, who is responsible for the algorithms, and how to ensure their performance and reliability over time, especially when using third-party solutions.
- **Skills and organisational change:** Successfully leveraging edge computing requires converging traditional Operational Technology (OT) and Information Technology (IT) skills. DSOs will need to invest in training and potentially restructure teams to manage these new, software-defined grid assets effectively.

E.DSO considerations

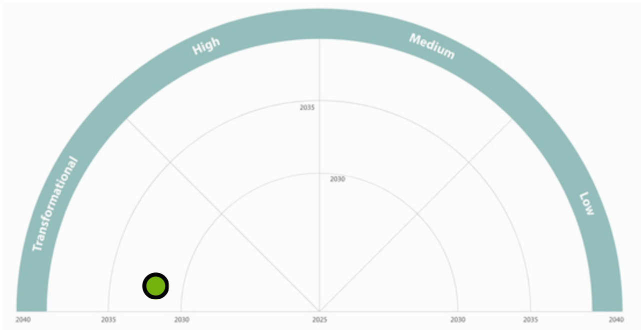
- DSOs should conduct analyses and implement demonstrators to identify relevant use cases for edge computing.
- The technical benefits of edge computing solutions are evident for secondary substations. It is necessary to be monetised.
- DSOs should also recognize the contribution of such solutions at primary substations and throughout the network.
- Active participation in ongoing industry discussions is crucial for DSOs. These discussions should encompass governance and standards, including aspects such as cybersecurity, software solutions, and the definition of future standards.
- Participation is vital to advocate for the specific requirements of DSOs.
- DSOs need to develop a comprehensive security strategy for edge computing.

Potential use cases

Enhanced Grid Visibility & Operations

- **LV Grid Visibility:** Turns the low-voltage network from a "black box" into a fully visible asset, enabling proactive voltage management (e.g., for solar PV) and rapid fault location.
- **Intelligent Data Gateway:** Aggregates and pre-processes local data from smart meters and sensors, reducing the load on central systems and cutting communication costs.
- **Predictive Analytics:** Uses local AI/ML to forecast transformer load and capacity issues, allowing for pre-emptive action before an overload occurs.

23. Edge Computing



Potential use cases (continues)

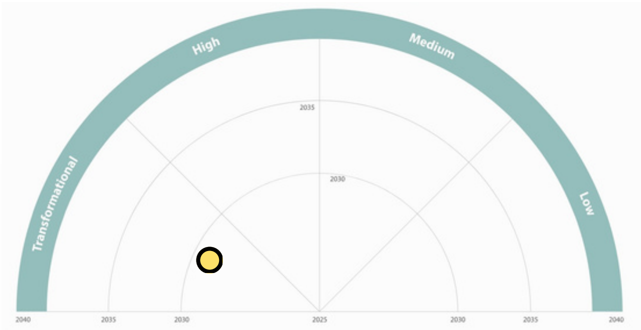
Optimised Asset & Energy Management

- **Condition-Based Asset Management:** Continuously monitors transformer health (temperature, load, gases) to prevent catastrophic failures, reduce maintenance costs, and extend asset life.
- **Local Flexibility Orchestration:** Manages local Distributed Energy Resources (DERs) like batteries and EV chargers as a "non-wires alternative" to defer or avoid costly network upgrades.
- **AI-Powered Inspections:** Uses cameras and AI to automatically detect equipment hotspots, physical damage, or vegetation encroachment, reducing the need for manual site visits.

Ongoing projects

- **Special mention deserves the E4S Alliance (Edge for Smart Secondary Substation)**, where a standards-based, open, interoperable, and secure architecture is being defined to enhance the automation, scalability, security, and manageability of secondary substations worldwide. Involved DSOs : i-DE, E-Redes, Enedis, UFD, Helen, Unareti/A2A (more info).
- **i-DE and Iberdrola Group:**
  - **E4S** (acting as DSO) - pending demonstration pilot during the first half of 2026.
  - **VIRTGRID** (acting as external DSO validator).
  - **IA4TES** (acting as promoter), testing Artificial Intelligence (AI) use cases and software applicable to the edge.
  - **SEC2GRID** (acting as external DSO validator), testing cybersecurity in distributed environments and virtualisation of cyber use cases.
  - **Virtual Data Concentrator** (internal development pilot at i-DE).
  - **DPP solution** (2023). RFI analysis and evaluation of state-of-the-art edge computing solutions to adapt to the DSO environment.
  - **MiDE4S** (2021). Demonstrative piloting of Minsait solution in i-DE's environment.
- **UFD and Naturgy Group:**
  - **E4S** (role DSO) - pending demonstration pilot during the first half of 2026
  - **VIRTGRID** (acting as external validator DSO)
- **Stedin:**
  - **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. Visualisation of aggregated load via anonymized smart meter data, providing insights into grid performance.
  - **Piloting modular architectures on edge computers** to test security risks and flexibility benefits
- **HEDNO**
  - Participates in HEDGE-IoT and ODEON HE projects.
- **ENEDIS**
  - In addition to its participation in E4S as DSO, **Enedis** is working on Edge Computing through academic partnerships and has been financing PhD works: "Analysis of new IT architectures for managing distribution networks implementing centralized and distributed smart functions" (PhD, INPG 2025-2027)

24. Internet of Things



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 artificial intelligence (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 is transferable over a network without requiring human-to-human or human-to-computer interactions.

Highlights

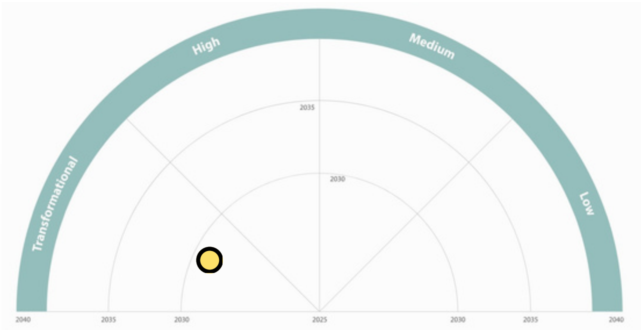
According to Gartner's Utilities 2024 CIO Agenda Insights and Data, 56% of utility respondents indicate increasing investment in IoT, with enterprises varying widely on their IoT maturity. Larger utilities have ongoing IoT-enabled initiatives for use cases, ranging from incremental benefits (for example, asset optimization or regulatory reporting) to transformative benefits (for example, dynamic operations of renewable assets). Factors such as falling costs of technology, a large number of vendors, and relative ease of deployment for new use cases and experimentation are accelerating IoT adoption. Due to a larger addressable market and R&D funding, the price/performance of IoT solutions is improving faster than utility vertical solutions, such as advanced metering infrastructure (AMI) or (supervisory control and data acquisition) SCADA. IoT applications could sharply increase in the future with the development of edge computing and 5G.

Opportunities and challenges for DSOs

- IoT could bring benefits with voltage quality analyses in different nodes and voltage loss per phase and Last Gasp.
- IoT facilitates real-time monitoring (power quality, asset characteristics, etc.).
- IoT enables powerful asset management solutions (power transformers, overhead lines, partial discharges, etc.).
- IoT could be used in the future for the implementation of decentralised flexibilities (including V1G/V2G).
- IoT facilitates the integration of power and utility OT, IT, consumer technology (CT), and engineering/energy technology (ET).
- The lifetime of IoT devices is assumed to be shorter than the lifetime of usual equipment.

E.DSO considerations

- IoT is an already available and widely used technology. Its applications could sharply increase in the future with the development of smart secondary substations and smart Low Voltage (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.



E.DSO considerations (continues)

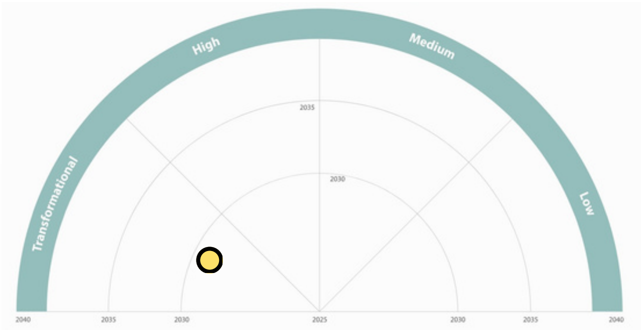
- The successful implementation of IoT needs to bridge the cultural differences between IT and OT operations.
- As IoT devices make new and different cyberattacks possible, cybersecurity is a major issue.

Potential use cases

- **Grid monitoring**: IoT sensors monitor the health of the grid infrastructure (e.g. power quality, monitoring transformers), detecting faults and predicting maintenance needs to prevent outages.
- **Predictive maintenance**: IoT devices can predict equipment failures before they happen by analysing data from sensors. This reduces downtime and maintenance costs.
- **Renewable energy integration**: IoT helps in managing the variability of renewable energy sources like solar and wind by optimising their integration into the grid.
- **Electric vehicle (EV) charging**: IoT can manage EV charging by monitoring charge levels, optimising charging times, and integrating with the grid to balance demand and supply.
- **Energy theft prevention**: IoT-enabled smart grids can detect and prevent energy theft, saving significant costs
- In combination with IoT, **smart meters** provide real-time data on energy consumption, allowing for better demand management and dynamic pricing. The separate *smart meters and dedicated metering devices* factsheet, to be available in the upcoming Radar editions, will provide further detail on this.

Ongoing projects

- Enedis developed **SmartConnect**, an IoT platform for the management of more than 100'000 connected objects. The main IoT solutions that are industrialised by Enedis include the monitoring of primary station transformers, surge arresters, fault localisation indicators, flood detectors and mobile generators.
- The **GridWise project** integrates information and operational technology to effectively monitor E-REDES's transformer substations. By employing advanced technologies such as AI, IoT, big data analytics, and edge computing, GridWise performs continuous monitoring of LV circuits to guarantee power quality parameters, detect faults, and identify non-technical losses such as theft or fraud.
- E-REDES has also launched the **Distribution Network Webcams project** aimed at developing a dashboard for detecting, classifying and managing substation alarms.
- Stedin is running several innovation projects that leverage IoT (sensors) for grid monitoring and predictive maintenance. Use cases include climate monitoring, underground temperature monitoring and monitoring transformers.
- Netz Niederösterreich's **PQsmart project** leverages 10-minute voltage profiles from smart meters to detect voltage limit violations, perform predictive maintenance, identify defective components, and optimise LV switch states.

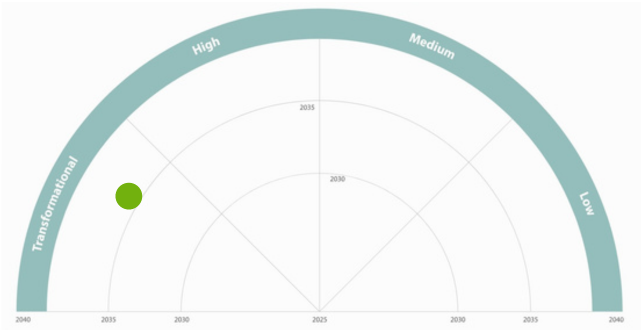


Ongoing projects (continues)

- UFD is implementing the **Fire Detection** solution, a system leveraging AI and IoT to safeguard large forested areas from wildfires. The system utilises electrical towers and power lines as monitoring platforms. The initial deployment phase covers approximately 430 km² in Ourense, Galicia.

Last update: 14 February 2025

25. Quantum Computing



Quantum computing (QC) uses the quantum properties of matter (superposition states, interference and entanglement) to perform calculations with qubits. To this end, four technologies are competing: superconduction qubits, silicon qubits, trapped ion qubits and photonic qubits. Although a universal quantum computer, able to solve any problem through quantum algorithms, is not yet available, progress is being made and the industry is working with researchers to create quantum computers adapted to solve useful problems and thus benefit from a real quantum advantage. While QC technologies are not yet mature and their development may entail uncertainties, it is anticipated that within the next 10 years, QC will revolutionise a number of fields: simulation, optimisation, machine learning and cryptography.

Highlights

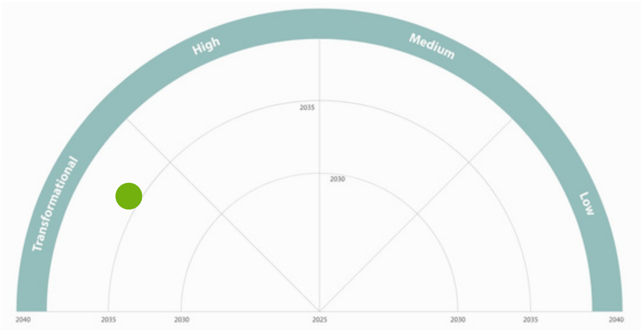
As of 2023, GAFAM and numerous start-ups are offering Quantum Computing-as-a-Service to demystify quantum computing. The quantum advantage should be indisputable within 5 years and this explains the interest shown by governments and the funds raised in start-ups. By way of example, start-ups Pasqal (France) and IQM (Finland) raised respectively €100 million and €128 million in 2022. QC can bring opportunities to DSOs for real-time operations and control of the grid. Yet, the risks it poses in the cybersecurity domain necessitate DSOs to take an interest in these technologies.

Opportunities for DSOs

- **Enhancing scalability and efficiency for detailed power system simulations**, e.g., optimal power flow.
- **Facilitating real-time system operations, protection and control** (power flow, voltage control, coordination for advanced relays and protection devices, etc.).
- **Facilitating local energy optimisation** by aggregation of large-scale distributed energy resources (DERs), and detailed modelling of battery energy storage systems.
- **Enhancing machine-learning-based models and forecasting**.
- **Enhancing data security by quantum encryption and potential integration with blockchain**.

Challenges for DSOs

- **Integration with existing ICT systems,** i.e., integration of QC with classical computing-based existing systems. Hybrid quantum-classical systems are being developed in the transition phase.
- **Cybersecurity**: Existing cryptographic protocols are based on classical encryption. Development of quantum-proof (or post-quantum) cryptography (PQC) could be needed.
- **Interpretability and complexity**: The complexity of algorithms and their probabilistic nature make it challenging to interpret results and track/ solve encountered problems. Explainable artificial intelligence for QC can address some of these challenges.



E.DSO considerations

Data security is an integral part of the DSO business. DSOs need to keep a close eye on the development of quantum algorithms, which could render conventional methods of encrypting and protecting data obsolete. Therefore, DSOs may need to invest resources in developing PQC.

Potential use cases

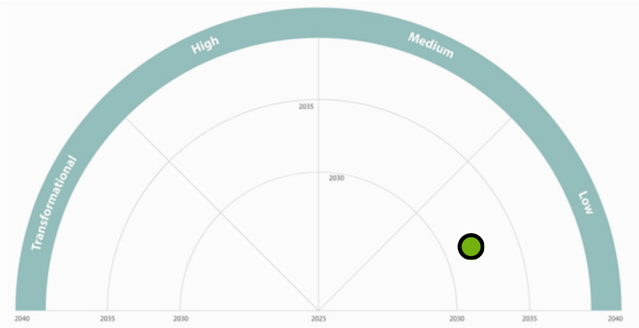
- **Cryptography**: cybersecurity of assets and encrypted communications for the essential service operator and quantum-based encryption to secure large quantities of data.
- **Simulations**, e.g., stochastic studies of large and interconnected systems and their detailed modelling involving network constraints and potential reconfigurations of network constraint situations.
- **Local energy optimisation**: local power flow and voltage management with large-scale aggregation of distributed energy resources and detailed modelling of battery storage systems.
- **Machine learning**: improving the assessment of equipment condition based on image processing, predictive maintenance, Fault Location, Isolation, and Service Restoration (FLISR) algorithms, load forecasting - especially enhanced weather forecasting - and hence, wind, and solar generation, improving chatbots for the relations with customers, etc.
- **Real-time optimisation capability for network operation, protection and control,** e.g., minimal technical losses, system costs or maximal usage of sustainable resources, voltage/ load control, coordination for advanced protection devices and controls Advanced FLISR Algorithms, etc.).

Ongoing projects

Several DSOs are carrying out technological monitoring activities, but none have mentioned any ongoing projects in the field of QC.

Last update: 14 February 2025

26. Blockchain



Blockchain is a technology for storing and transmitting information, based on a distributed ledger secured by cryptography and validated through consensus mechanisms. It maintains a transparent and tamper-resistant history of transactions. Depending on the design, a blockchain can be public (open to anyone) or private (restricted to specific participants). Beyond cryptocurrencies, its applications span supply chain management, healthcare, digital identity, asset transfer and tokenization, the Internet of Things, smart contracts, decentralized finance, etc. Blockchain can enable new ways to manage and trace energy flows, facilitate peer-to-peer energy trading, improve transparency in billing and settlement processes, support the integration of distributed renewable resources, and help build decentralized energy marketplaces.

Highlights

The whole blockchain market—encompassing technology platforms, services, and infrastructure—is estimated at around **US $31–33 bn in 2025**, and is expected to explode to **US $393 bn by 2030–2032**, depending on the source. A 2017 McKinsey study found implementing blockchain could boost industrial productivity by up to **9 %** and deliver **7 % cost savings**, through enhanced progress tracking and improved cost and schedule estimates. In 2025, Zhou demonstrated, through an experimental blockchain-based energy market, substantial enhancements in transaction efficiency, characterized by higher transaction volumes and frequencies, shorter settlement times, reduced costs, and improved transparency.

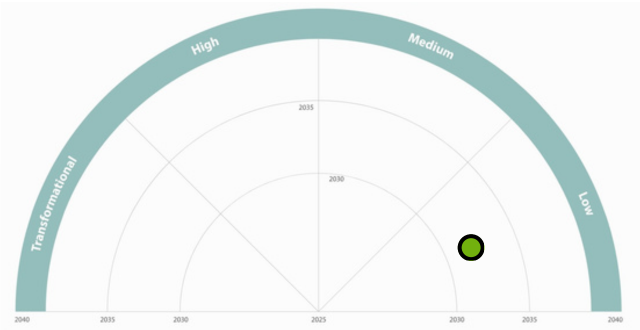
Challenges for DSOs

- **Scalability & performance:** Public blockchains can be slow and energy-intensive, while private/permissioned blockchains raise governance questions
- **Interoperability:** Integrating with existing grid systems and smart meters can be complex and lead to high migration costs
- **Regulation & governance:** must be compliant with energy regulations and legal frameworks. Who decides the rules of the ledger?
- **Market adoption:** Prosumers, aggregators, suppliers, and regulators must adopt and trust the technology. Otherwise, we face the risk of fragmented solutions (incompatible blockchains).

Opportunities for DSOs

- **Transparency & traceability:** Immutable records of energy flows and green certificates which can increase trust among prosumers.
- **Integration of distributed resources:** Better management of solar, wind, batteries, EVs by enabling automated mechanisms to remunerate flexibility (demand response)
- **Operational efficiency:** Reduced administrative costs and faster settlements/billing processes.
- **Trust and cybersecurity:** A decentralized infrastructure makes data more resilient to manipulation or fraud which is useful for protecting sensitive consumption and transaction data
- **New services & innovation:** Aggregation of resources, tokenization, and local market facilitation.

26. Blockchain



E.DSO considerations

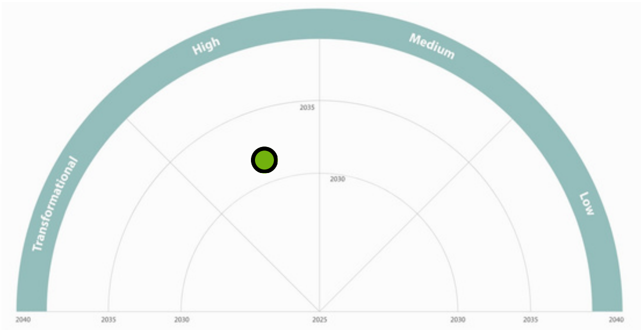
- DSOs must follow technological and regulatory developments related to blockchain in order to make the most of these advances to improve their operational performance.
- Blockchain technology consumes a lot of energy. In the context of global warming, this point needs to be improved to make this technology compatible with the ecological transition.
- Blockchain cybersecurity raises new problems that have to be addressed.
- DSOs, which are responsible for metering data, could take advantage of blockchain to carry out this task more effectively.

Potential use cases

- **Peer-to-Peer (P2P)** energy trading in local microgrids.
- **Decentralized energy marketplaces and new macro business models** (this can include for example, energy-backed tokens).
- **Automated settlement and billing** via smart contracts.
- **Integration, monitoring and coordination** of distributed energy resources (DERs), including demand response programs.
- **Immutable tracking of energy flows** and renewable certificates for transparency and compliance.

Last update: 30 September 2025

27. Digital Twins



Digital twins (DTs) are data-driven virtual representations of physical assets, processes and systems across the electricity network, from individual components up to system-level views. By combining real-time and historical data with simulation models and advanced analytics, they enable monitoring, diagnosis, forecasting and scenario evaluation across planning, operation and maintenance activities. Rather than a single unified model, Digital Twins for DSOs typically evolve as a federation of purpose-specific twins, supporting different decision horizons (exploratory, planning-grade and operational) and responsibilities. They rely on four core technological enablers: **grid sensing and IoT, simulation and system models, AI-based analytics, and scalable cloud–edge computing infrastructures.**

Highlights

Digital Twins are becoming a foundational enabler of the digitalisation of European electricity distribution networks. They significantly improve situational awareness, decision quality and resilience across planning and operational timeframes. European initiatives and pilots are progressively validating Digital Twin approaches aligned with the EU Digitalisation of Energy Systems and Grid Action Plan. Their value depends not only on data availability, but also on organisational readiness, governance structures and trust in model outputs.

Challenges and opportunities for DSOs

Opportunities

- **Improved decision quality** and confidence in planning and operations.
- Faster and more robust **scenario analysis** under uncertainty.
- Enhanced **resilience** through predictive insights and anticipation of grid constraints.
- Over time, enabling semi-automated and adaptive **decision support** in core DSO processes.

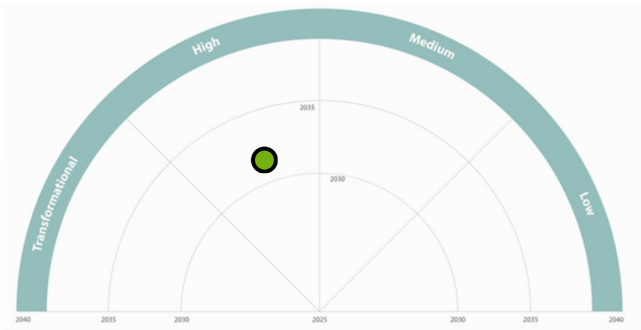
Challenges

- Ensuring sufficient **data availability, quality, integration and scalability** across heterogeneous systems.
- Managing **model validation**, change management and organisational adoption.
- **Aligning Digital Twin outputs** with operational responsibilities and regulatory requirements.

E.DSO considerations

- Digital Twins should be understood as modular, use-case oriented capabilities, rather than a single monolithic system.
- Clear ownership, validation processes and accountability for decisions are essential to ensure trust and sustained value creation.
- Interoperability, standard interfaces and alignment with existing DSO systems (e.g. ADMS, DERMS, GIS) are critical.
- Adoption should follow a progressive approach, matching maturity levels to operational criticality and regulatory constraints.
- Coordinated knowledge sharing across DSOs can accelerate learning, scalability and replicability.

27. Digital Twins



Potential use cases

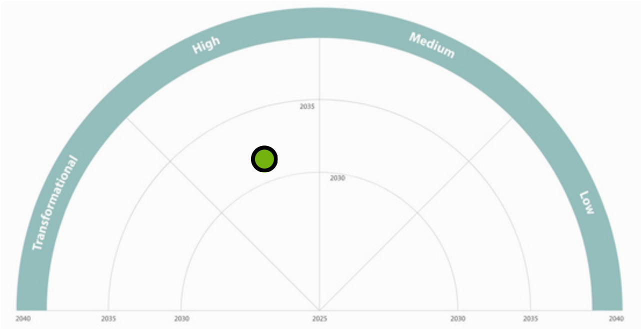
- Network planning and hosting capacity assessment.
- Active system management and flexibility assessment.
- Asset health monitoring and predictive maintenance.
- Cyber-physical grid resilience and security analysis.
- TSO–DSO coordination and system-wide simulations.
- Operator training and preparedness.
- Disaster response and restoration planning.
- Energy efficiency and optimisation studies.

Ongoing projects

- **TwinEU** – Horizon Europe project developing interoperable Digital Twin concepts, data and model exchange frameworks.
- **Enedis** – Digital Twin applications supporting asset management, grid operation and planning through advanced simulations and analytics.
- **E-REDES** – Digital Twin and analytics solutions for network optimisation, power flows, asset health and real-time visualisation.
- **EDP** – AI-based Digital Twin initiatives for short-term forecasting to support operational and planning decisions.
- **ORES** – Deployment of Digital Twin-related tools for LV grid analysis, DER integration and operational planning.
- **UFD (Naturgy)** – Deployment of Digital Twins for MV and LV networks supporting planning, operation and DER integration.

Link to relevant E.DSO success cases

Success case number	Title	Company
31.2025	LV Advanced Planning	UFD
42.2025	SOLORMAX	ORES



Impact on the energy system

Digital twins improve observability and resilience by enabling predictive, data-driven decisions, better risk anticipation and more efficient integration of distributed energy resources.

Time to scale

- 0–5 years (Progressive scaling already underway for planning-grade and selected operational use cases, with broader deployment expected within this timeframe.)

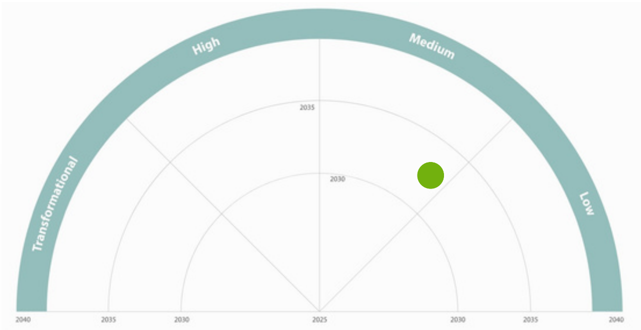
Link to relevant EU policies

- Digitalisation & Data - Digitalising the Energy System – EU Action Plan (COM/2022/552)
- Flexibility - Increasing Flexibility in the EU Energy System – European Parliament (2025)
- Decarbonisation & System Integration- Energy System Integration Strategy – European Commission

Technology deployment across countries with E.DSO members

Last update: 12 September 2026

28. Building Information Modeling



Building Information Modeling (BIM) is a digital form of construction and asset operations. It brings together technology, process improvements and digital information to radically improve client and project outcomes and asset operations. BIM is a strategic enabler for improving decision making for both buildings and public infrastructure assets across the whole lifecycle. It applies to new build projects; and crucially, BIM supports the renovation, refurbishment and maintenance of the built environment – the largest share of the sector. In the context of energy infrastructure, BIM offers substantial value to electricity transmission and distribution networks. By enabling better planning, visualization, and data integration throughout the asset lifecycle, BIM supports grid operators in managing complex infrastructures, improving reliability, and optimizing maintenance and investment decisions. For transmission and distribution system operators, BIM contributes to a more resilient, efficient, and digitally integrated grid — essential for meeting the evolving demands of the energy transition.

Highlights

The European Commission estimates that €584 billion will be needed by 2030 to upgrade EU electricity grids (EC, 2023). Digital solutions like BIM and digital twins are key to this transformation, enabling smarter planning and maintenance. According to the IEA, such tools can reduce maintenance costs by 10–15% and improve system reliability (IEA, 2022). The ENTSO-E & EU DSO Entity joint report (2024) highlights that deploying digital asset models will be critical for integrating distributed energy resources (DER) and ensuring grid stability as electrification and decentralization progress.

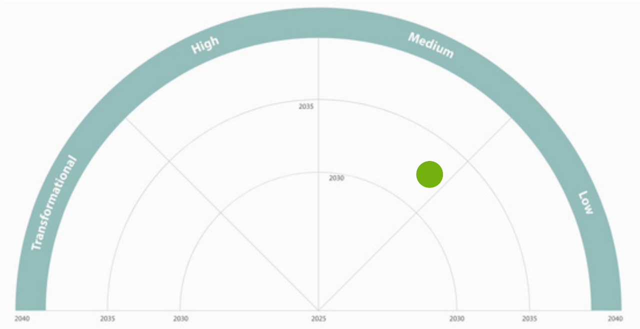
Challenges for DSOs

BIM offers great potential for **improving planning, construction and asset management** for electricity distribution. For DSOs, it offers clear benefits but also requires addressing key challenges.

- Tool and data interoperability.
- Integration with legacy systems.
- Upfront investment and training needs.
- Resistance to organisational change.
- Cybersecurity and data governance.

Opportunities for DSOs

- Better collaboration in project design and planning.
- Early detection of technical constraints.
- Improved asset data (3D models, digital records).
- Enabler for digital twins and smarter maintenance.



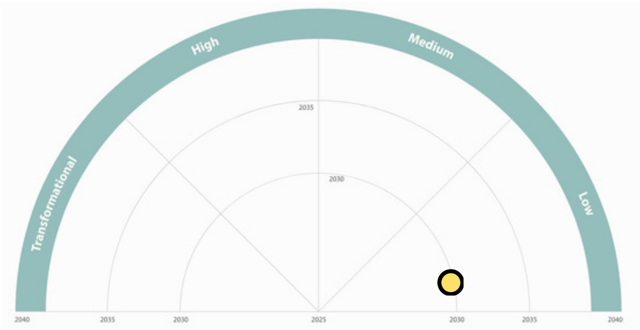
E.DSO considerations

- **Strategic Value for Grid Digitalisation**: BIM supports the digital transformation of DSOs by improving asset planning, construction, and maintenance. It aligns with EU goals for smarter, more resilient grids.
- **Enhanced Collaboration with External Stakeholders**: BIM facilitates data exchange with municipalities, telecoms, and other infrastructure developers, improving coordination on projects impacting the grid.
- **Need for Common Standards**: Promoting European-wide BIM standards and interoperability (aligned with CEN/CENELEC) is essential to ensure consistency across DSOs and member states.
- **Enabler for Digital Twins**: BIM can serve as a foundation for digital twins, enabling real-time simulation, monitoring, and smarter asset management.
- **Implementation Challenges**: Includes high initial investment, training needs, integration with legacy systems, and cybersecurity risks.

Potential Use Cases

1. **Asset Management:** Centralize and update detailed information about all network components for better maintenance planning and asset lifecycle management.
2. **Network Planning and Design:** Use 3D models to detect design clashes early, improve accuracy, and optimize resource allocation before construction.
3. **Real-time Monitoring and Simulation:** Integrate BIM with sensor data to simulate network behavior, detect faults, and optimize load management dynamically.
4. **Outage Management:** Visualize faults and network status to speed up diagnosis, crew deployment, and outage restoration.
5. **Safety and Risk Assessment:** Simulate hazardous scenarios and plan safe work procedures to protect crews and infrastructure.
6. **Regulatory Compliance and Reporting:** Automate generation of reports and documentation for regulatory authorities with up-to-date network data.
7. **Integration of Distributed Energy Resources:** Model the impact of renewables, storage, and EVs on the network to support flexibility and stability.
8. **Stakeholder Collaboration:** Share BIM models among DSOs, contractors, and regulators to improve communication and coordination.
9. **Training and Development:** Use BIM-based virtual environments to train staff in realistic operational and emergency scenarios.

Last update: 30 September 2025



New **virtual reality (VR)** & **augmented reality (AR)** technologies provide considerable untapped potential for business use. This stack of visual technologies ranges from fully immersive environments where the real world is completely replaced by a digital variant (virtual reality) to an environment where the digital world blends with the surroundings of the observer (augmented reality). In most cases, it is possible to use hand tracking or speech to interact with virtual or holographic content (extended reality), further supporting the case for specific business-oriented applications for field work, training, data insights and business processes.

Highlights

Investment in augmented and virtual reality continues to be high, with Meta, Google and Apple currently pushing development in the realm of extended reality. The market for consumer devices is moving towards smaller smart glasses, mostly aimed at streaming content or gaming. Upcoming devices are expected to be more light-weight, faster and more versatile. However, a business-ready alternative for the recently decommissioned HoloLens has yet to emerge.

Opportunities for DSOs

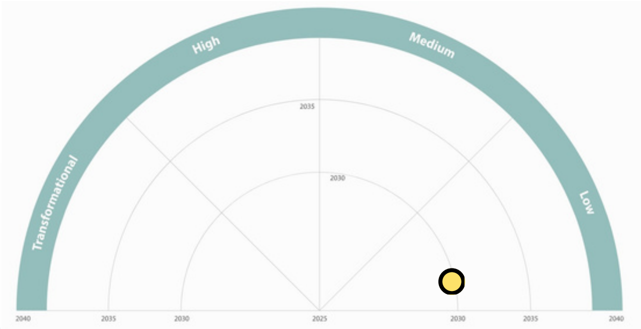
- Employing augmented and virtual reality in training processes can result in accelerated education of technical staff, thus providing one solution for the shortages in the technical work force.
- Increased insight in the location and situation of underground networks can help with localizing existing assets and placement of new assets.
- New types of user interfaces can be deployed for the display of location-bound sensor data of overground and underground assets.
- Overlaying the real world with digital information allows for hands-free interaction with digital systems.

Challenges for DSOs

- The current market in augmented reality devices ("smart glasses") requires a catalyst device to propel the market forward, to create a wider range of business-ready hardware.
- Maintenance of the associated software is not yet mainstream.
- Finding a device which complies with the necessary safety regulations may be a challenge.
- Adoption of this fundamentally different way of working may pose a challenge for the work force.

E.DSO considerations

- To fully leverage the business potential, DSOs should synergize their efforts in this field, as well as cooperate with universities, research organizations and start-ups to develop generic applications and standards that can be deployed across all DSOs.
- Devices should be selected which offer versatility in the development of apps, a clear business development strategy, long-term customer support and which comply with safety regulations.



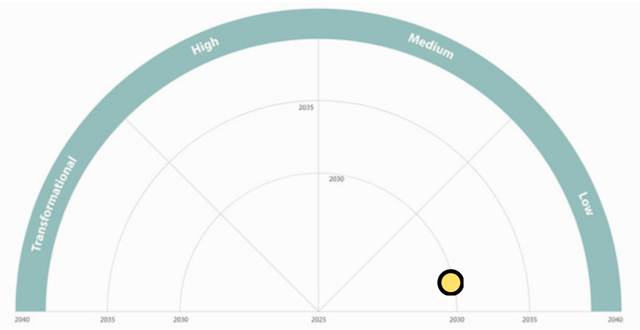
Potential Use Cases

- VR can be employed in training to practice certain acts (such as the construction of assets or parts of our networks) in a safe work environment, allowing time and an immersive, guiding environment to absorb new knowledge more effectively.
- AR can be employed in training to provide step-by-step guides for acts with strict guidelines, such as switching. This allows the operator to train with hands-on experience while learning the guidelines, and requires less supervision.
- Similarly, guides or document libraries in AR may be used for context in the field, e.g. operator libraries for switchgear.
- AR spatial planning tools for planning large overground assets can be used to speed up stakeholder processes, specifically where conflicting interests are in play.
- AR spatial planning tools displaying the existing or planned underground network situation at the correct location using GNSS, may help engineers planning upcoming large-scale field work.
- The same tools may be beneficial to field technicians, providing an instant overview of the underground situation. This may help to locate underground assets and aid with the situational registration of new underground assets.
- Virtual reality can be employed for practicing crisis situations, when it is difficult to gather the crisis managers in a physical location for training. VR can offer life-like scenarios and circumstances which makes the training feel more like a real-life situation.
- Sensordata may be overlaid on overground assets, allowing for quick insights in time-based data during operation malfunctions.

Ongoing projects

- The **TS360 solution** was put into operation by PREdistribuce to enhance their asset management system functionalities for transformer stations. By capturing 360° panoramic views of the stations and enhancing this data with documentation on the stored devices and access information, TST360 allows technicians to virtually visit the stations and obtain device information remotely. The system also facilitates record keeping of previous modifications and assessment of the feasibility of new installations.

- With the support of the Poznań University of Economics and Technology, **Enea Operator** has developed a flexible and innovative VR training system for technical service employees on connection activities and live-line working technology in HV/MV and MV/LV power stations. The training combines free movement around power stations, exercises and exams under different scenarios.

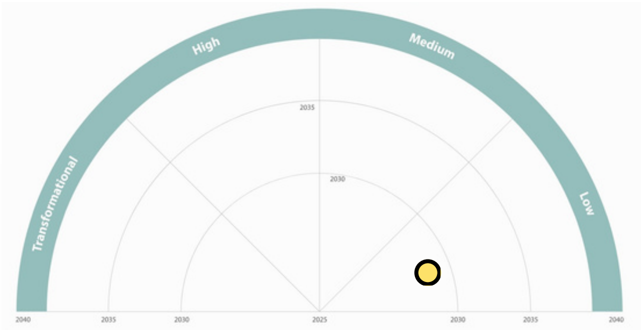


Ongoing projects (continues)

- **HEDNO** is involved in the EU funded project Motivate XR, which aims to contribute to a novel generation of XR collaborative authoring, publishing, and experiencing tool suite for training and assistance to industrial operations Motivatexr. HEDNO leads a pilot use case utilizing AR glasses, GIS and digital twin tools in remote training or assistance of technicians that perform on-site maintenance on wooden poles of the distribution network. More information here and here.
- In **Alliander** technical training school, trainers use Guides 365 on the HoloLens to train new technical staff in a variety of technical acts, such as switching a Magnefix device.
- Alliander build a full-scale electrical substation using VR, allowing new staff to practice field work at the substation in a safe but immersive environment. Alliander engineers, who plan new construction work on our networks, use a custom app for surveying sites, comparing the real-life situation with their plan drawings, by overlaying the plans on reality with AR.
- **Alliander** uses AR in the discussions between the DSO and municipalities, for placing an overground mid-voltage substation. This method helps in settling disputes about the location, as both parties represent different interests.
- **Alliander** investigates new and smaller smart glasses and evaluate their business potential.
- **Enedis** uses virtual and augmented reality in many training courses and is currently continuing its gradual migration to these educational support technologies. These solutions are used for core business topics, such as training for lockout agents, but also for certain general topics related to the business world, such as raising awareness of harassment.

Last update: 30 September 2025

30. Advanced Communication



Disclaimer: In future versions of the Technology Radar, Task Force 6 will consider the creation of separate factsheets for different advanced communication technologies to reflect the differences in their application, impact and timelines.

Advanced communication refers to the use of emerging data communication technologies to enhance the efficient, reliable, and secure exchange of information between devices, systems, and users connected to the electricity grid. Beyond 5G and Internet of Things (IoT), which are separately tracked on this Technology Radar, advanced communication includes technologies such as:

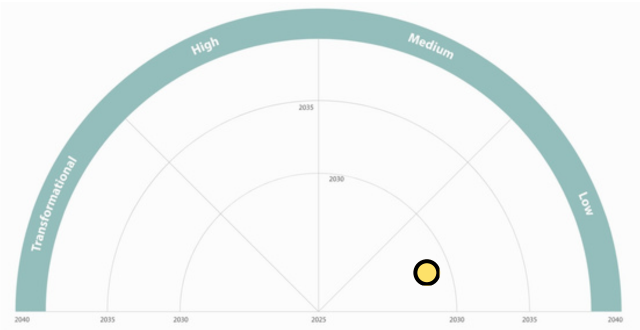
- **6G**, which will potentially provide ultra-low latency and massive connectivity for real-time grid management. 6G will succeed 5G and is expected to become available around 2030, offering 10 times faster connectivity, better reliability and lower latency compared to 5G.
- **(Low Earth orbit) satellite communication**, which ensures wide coverage and communication resilience, especially in remote areas or during disasters.
- **Low-power wide-area networks (LPWAN)**, such as LoRa, NB-IoT or LTE-M over 450Mhz, providing long-range IoT connectivity for applications that require low bandwidth and long battery life.
- **Power Line Communication (PLC)**, divided into narrowband and broadband PLC, which uses existing electrical power conductors as physical communication media. PLC does not require the deployment of new infrastructure, is highly reliable and enables DSOs to have full control over their communications.
- **Quantum communication/networking**, which leverages the principles of quantum mechanics to transmit information in an ultra-secure and efficient way.

Highlights

As more distributed energy resources (DERs) are integrated into the grid and as climate change causes more frequent severe weather events, maintaining a resilient and reliable energy infrastructure will require robust secure data communication systems designed to meet performance requirements. Today, DSOs depend upon a wide variety of communication technologies to support existing operations (including metering, substation monitoring/automation, protection systems, and generation dispatch) each with its unique communication system needs. Advancing grid operations and service paradigms, such as generation and demand coordination of large numbers of DERswith different ownership, will challenge and alter existing operational processes as more data will be exchanged. This will drive the deployment of new communication technologies with different performance and security characteristics (source: US Department of Energy, Office of Electricity).

Challenges and opportunities for DSOs

- Advancements in communication technologies can significantly enhance the efficiency, security, and reliability of electricity distribution systems, paving the way for smarter and more resilient grids.



Challenges and opportunities for DSOs (continues)

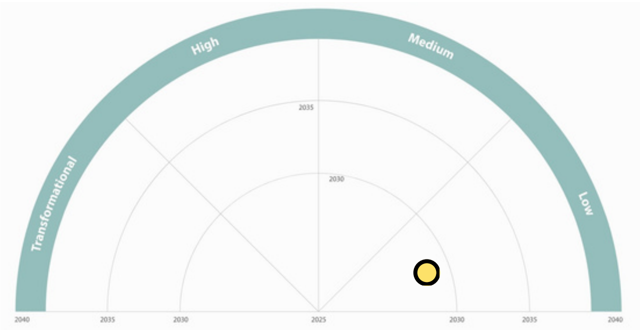
- Some solutions will be relatively straightforward and can be achieved by using standard products from a third-party communications provider. However, if more control by the DSO is desired, or the products being offered do not meet their requirements, the implementation of new solutions will become more complex.
- Several communication technologies, such as low-orbit earth satellite communications, are mainly provided by non-EU parties. This might result in an increasing dependence on foreign parties for the operation of critical infrastructure. The potential sovereignty risk is that DSOs lose control and autonomy over their data, operations and technology.

E.DSO considerations

- As many of these emerging communication technologies are not yet available, DSOs must follow technological and regulatory developments in the field.
- No single "silver bullet" exists for communications technology for grid operations. It is recommended to apply the appropriate communication technology to support grid requirements by (source: US Department of Energy, Office of Electricity):
    - Understanding the strengths and weaknesses of different communication technologies. This will be increasingly important as the grid evolves to support and rely upon distributed generation.
    - Identifying the grid services or processes (e.g. SCADA, protection, metering) that need communication support and determining associated communication requirements (such as latency, throughput, bandwidth, availability, and security)
    - Determining the current state of communication technologies at the DSO.

Potential use cases

- **Real-Time Monitoring**: Provide high-speed, secure, low-latency communication for real-time monitoring and control of grid operations. (e.g. 6G, quantum communication, broadband power line communication)
- **DER Management**: Support the integration and management of distributed energy resources, such as solar panels, battery storage systems and electric vehicles (e.g. with 6Gand broadband PLC).
- **Advanced Metering Infrastructure (AMI)**: Enhance the capabilities of AMI with faster collection and processing of data from smart meters and sensors. (e.g. with 6G, broadband PLC, LPWAN).
- **Cybersecurity**: Protect sensitive data from cyberattacks (e.g., with quantum communication/networking).
- **Remote Monitoring and Control**: Satellite communication provides reliable connectivity for remote substations and power generation plants, enabling real-time monitoring and control. This is crucial for areas where terrestrial communication infrastructure is lacking.



Potential use cases (continues)

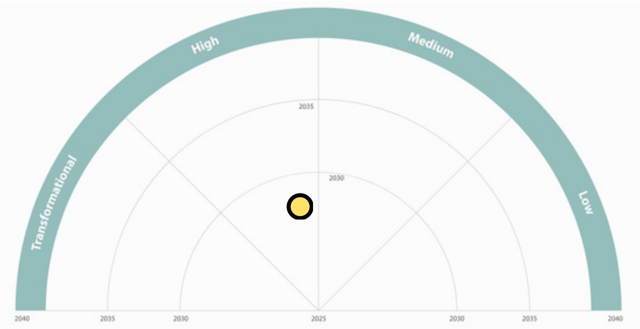
- **Disaster Recovery and Resilience**: In the event of natural disasters or other emergencies, satellite communication can serve as a backup to terrestrial networks, ensuring continuous operation and quick recovery of the grid.

Ongoing projects

- Enedis is testing the use of 5G to replace wired technologies and ensure low-latency connectivity with decentralised generation for anti-islanding systems.

Last update: 28 September 2023

Other Technologies



Originally developed for military applications, **drones** have found their way into many fields due to the improved levels of safety and efficiency they bring. These robotic unmanned aerial vehicles (UAVs) operate without a pilot on board and with different levels of autonomy. Initially focused on image capture, their uses are set to expand thanks to the expected progress in drone systems (ability to fly longer distances), Artificial Intelligence (image processing, guidance, etc.), sensors (miniaturisation of lidar, etc.), telecommunication (5G, etc.), and technical action capabilities (manipulator arms, etc.). The development of the use of drones is highly dependent on regulations, which lay down strict rules that vary considerably depending on whether or not the operator is flying within sight of the UAV.

Highlights

The European Drone Strategy 2.0 sets out a vision for the further development of the European drone market. The new Strategy builds on the EU's safety framework for operating and setting the technical requirements of drones and lays down how Europe can pursue large-scale commercial drone operations while offering new opportunities in the sector. The Strategy envisions the following drone services becoming part of European life by 2030: emergency services, mapping, imaging, inspection and surveillance within the applicable legal frameworks by civil drones, as well as the urgent delivery of small consignments, such as biological samples or medicines.

Opportunities for DSOs

- Lightweight drones open up the prospect of improved pruning monitoring, post-storm and post-failure diagnostics, and automated infrastructure monitoring and diagnostics.
- Drones offer (important) benefits to utility field operations, and can acquire larger volumes of data more reliably and rapidly in inaccessible or hazardous locations than on-site humans.
- Drones can increase the quality and response time in infrastructure monitoring while minimising material and human resources and monitoring costs.

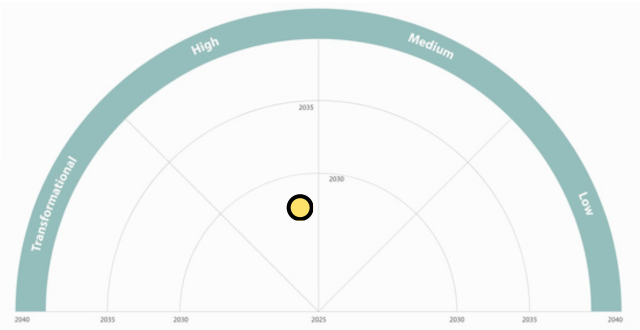
Challenges for DSOs

- The usage of drones for vegetation and infrastructure monitoring still poses regulatory challenges.
- Drones have limited power and useful flight time.

E.DSO considerations

- DSOs must follow technological and regulatory developments relating to drones, making the most of these advances to improve their operational performance.
- DSOs must understand the evolving requirements for data aggregation, analysis and integration with other IT systems and provide the necessary tools in line with security and governance guidelines.
- DSOs should work together to promote regulatory changes throughout the European Union that would facilitate the use of drones.
- DSOs should present recommendations regarding insourcing or outsourcing drone usage (e.g. Drones as a standard tool vs. drones as a service based on service-level agreements).

31. Drones



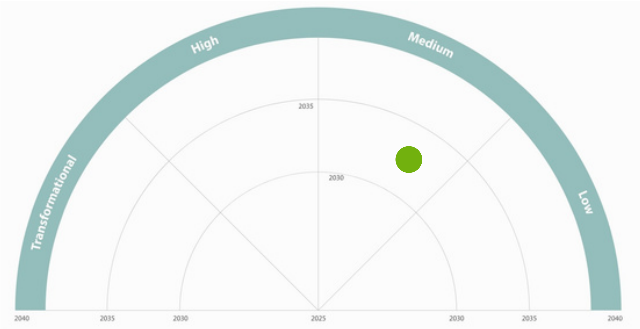
Potential use cases

- Aerial network inspection, both visual and thermal.
- Remote asset monitoring, including in areas with limited access.
- Vegetation management.
- Unmanned tree pruning using drones.
- Digital network mapping and Geographic Information System (GIS) applications.
- Supervision of maintenance and development works.
- Emergency response and damage assessment.
- Insulator cleaning by drones in inaccessible areas.

Ongoing projects

- **ALTITUDE project,** automatic aerial network inspection using drones and machine learning. In ALTITUDE, HEDNO serves as the pilot user. Other project partners are Renel (project promoter), Innora and SciDrones (more info).
- E-REDES **GridDrone project.** E-REDES decided to carry out a pilot project with an Estonian company, Hepta Airborne, where it inspected 1000 km of HV and MV network in the districts of Viseu and Coimbra (PT). The results of this project were evaluated internally, with the help of members of the Vegetation Management Department (DGV) of E-REDES and EDP Labelec, with the service currently provided always at quality standards (more info).
- E-REDES **E-Drone project,** carrying out inspections of network assets using commercial drones. For this project, it was necessary to complete the process of acquiring the drones, taking out civil liability insurance, training the pilots, obtaining the respective licences, registering E-REDES as a drone operator with the National Civil Aviation Authority (ANAC) and the National Aeronautical Authority (AAN) and, finally, appointing an operational manager. The use of this technology allowed for carrying out a detailed inspection of the network and visualising all the asset components. At the forefront of innovation, E-REDES uses and adapts innovative solutions for the inspection of its technical assets (more info).
- UFD, through its **GALA** (Advanced Overhead Lines Management) and **DALI** (Drone & AI Line Inspection) projects, carries out vegetation management and oversees inspections, preventive maintenance, and predictive maintenance based on risk management using drones Beyond Visual Line of Sight (BVLOS). This is achieved through the construction of the digital twin of its entire high and medium voltage network, as well as the utilisation of various recognition algorithms employing AI (more info).
- ČEZ Distribuce conducts **aerial LiDAR inspections of lines and substations and scans for pruning planning**. Currently, this is partially used as a business-as-usual solution, generating cost savings thanks to higher precision on what vegetation needs to be cut.

Last update: 17 May 2024



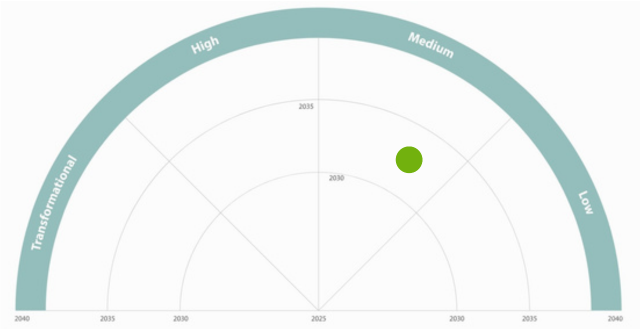
Robotics is used in multiple fields (industrial, agricultural, domestic, scientific, educational, medical, military, leisure, service, transport robotics, etc.) and is a science of technological integration at the crossroads of mechanics, electronics, computer science and networks, in particular communication. The desire to relocate production to Western countries, the ageing of the population and the increasing demand for automation are drivers of the revival of robotics, especially since the key technologies of robotics are experiencing spectacular advances: the rise of artificial intelligence, the sophistication of sensors, improved battery efficiency, internet of things (IoT), 5G, etc. As a result of these advances, single-function robots are being replaced with polyfunctional robots (including humanoids) that can take on a multitude of tasks and are also designed to operate in a world with humans. Polyfunctional robots can seamlessly switch between tasks as required, improving efficiency and providing a faster return on investment, resulting in accelerated adoption across industries and use cases.

Highlights

- The global industrial robots market was valued at USD 41.9 billion in 2023 and is set to surpass USD 192 billion by 2033. Asia-Pacific leads the market, capturing 62.9% of the global share, with China as the largest contributor. Europe follows with Germany at the forefront, while North America sees strong adoption, particularly in the U.S., driven by the automotive and electronics sectors.
- Leading companies, including FANUC, ABB, and Yaskawa, control a significant portion of the market, driving innovation with AI integration, enhanced programming, and sustainability-focused solutions (here).
- On the proposal of the Chinese National Committee, which will act as its secretariat, the IEC has created a new technical committee on robotic systems for the electrical industry, including distribution networks.
- Gartner predicts that by 2030, 80% of humans will engage with smart robots on a daily basis, up from less than 10% today.

Challenges and opportunities for DSOs

- Industrial robots are able to operate in high-risk environments (live work), support heavy loads, perform arduous tasks and be available 24 hours a day, 7 days a week. Driven by an operator or autonomous and capable of adapting to their environment, they should **enable DSOs to improve health, safety and productivity**.
- To date, robots are generally used in controlled and restricted areas. **DSO operation fields are various and usually not completely controlled**. Under these circumstances, adaptation and security are major challenges.



E.DSO considerations

- DSOs must **identify tasks that can be robotised** in their businesses in order to test available solutions, develop new ones and assess the associated gains and performance.
- Opportunities for increased automation should be expanded by measuring each process against the abilities of existing and planned polyfunctional robots.
- The main usages for distribution networks are potentially related to maintenance and inspection.

Potential use cases

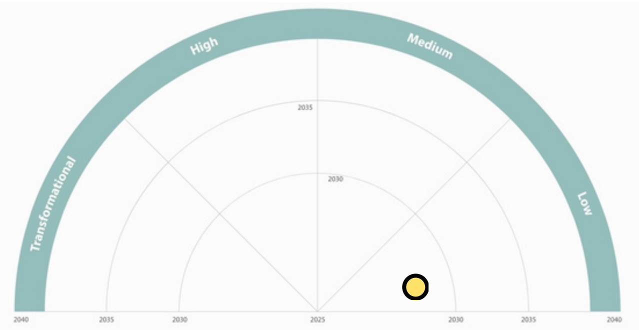
- **Inspections**: Robots can perform routine inspections of substations, underground cables, and other infrastructure. *Please note that this Radar contains a dedicated factsheet for Drones that also covers potential use cases for the inspection of infrastructure such as overhead power lines.*
- **Infrastructure installation:** Robots can assist in upgrading and installing new infrastructure, such as installing smart meters, cables or digging trenches.
- **Logistics**: Robots can deliver parts to field workers.

Ongoing projects

- The Dutch DSOs (Alliander, Enexis and Stedin) together with Gasunie (gas TSO) have signed a letter of intent for a **joint Robotics Lab**. In the lab, robotic solutions are developed for tasks where human intervention is not necessary. By automating repetitive and dangerous tasks, robots increase efficiency, safety, and effectiveness for the Dutch DSOs.
- Enedis has developed **TST-Bot**, which is a remotely operated robot designed to perform live work on medium-voltage networks using an insulated platform with robotic arms. It enhances operator safety and reduces environmental impact. The TST-Bot will be tested on the MV network by four Enedis live working teams throughout 2025.

Last update: 26 June 2025

33. Additive Manufacturing (3D Printers)



Additive Manufacturing or **3D printing** enables the production of complex designs and shapes. Initial limits of 3D printing have been pushed back, both in the size of the objects to be produced and in the materials used (stainless steel, plastic, glass, metal, concrete, eco-materials, etc.). However, despite these advancements, the technology still faces significant challenges, including high costs, low printing speed, limited part sizes, and strength. For DSOs, the primary value lies in addressing critical supply chain and asset management challenges for aging grid infrastructure.

Highlights

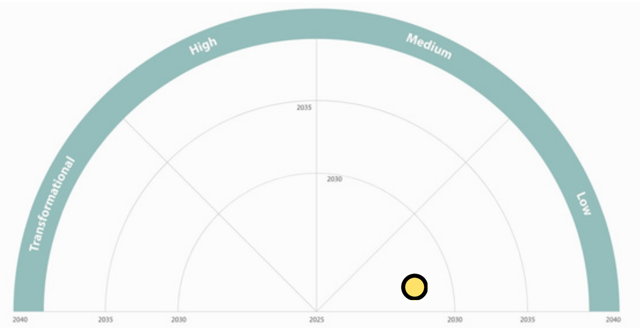
The European Additive Manufacturing Market was valued at USD 6.84 billion in 2025 and is expected to reach USD 13.17 billion by 2030. The highest demand in Europe comes from small and medium-sized businesses that are in need of high-speed, reliable and low-cost prototypes. This concerns numerous sectors, particularly automotive, healthcare, aerospace and defence. For the energy sector, this market growth is crucial as it drives down the cost of industrial-grade printers and expands the range of robust, certified materials suitable for operational use in demanding grid environments.

Opportunities for DSOs

- **Solving the Legacy Equipment Challenge:** Additive Manufacturing enables the production of small batches of discontinued components to extend the operational life of equipment—starting with simple parts such as hinges or cabinet doors and progressing to more complex elements like medium-voltage breaker components.
- **Enhancing Supply Chain Resilience & Reducing Inventory:** By enabling on-demand printing, AM reduces dependence on long and often fragile supply chains. This allows DSOs to drastically cut physical inventory costs and warehousing space, while simultaneously reducing lead times for critical, hard-to-source parts from months to days.
- **Improving Field Crew Safety and Efficiency:** AM allows for the rapid creation of specialised, custom tools, jigs, and fixtures for field crews. These bespoke tools can make complex installation or repair tasks safer, faster, and more ergonomic, leading to direct operational efficiency gains.
- **Accelerating Innovation and Prototyping:** AM would allow, among other things, the creation of several prototypes of equipment prior to their mass production. This de-risks innovation by allowing engineers to physically test and refine new component designs quickly and cheaply before committing to expensive tooling for mass manufacturing.

Challenges for DSOs

- **Material Qualification and Certification:** The single biggest hurdle is ensuring that a printed part meets or exceeds the mechanical, thermal, and electrical specifications of the original. A rigorous testing and certification process is essential before any component can be safely deployed on the live network.



Challenges for DSOs (continues)

- **Intellectual Property (IP) and Design Rights:** Scanning and reproducing a part may infringe on the OEM's intellectual property. DSOs must establish a clear legal framework for reverse-engineering components or work with OEMs to acquire digital designs.
- **Scalability and Economics:** AM is currently most cost-effective for one-off parts or very small batches. It is not a replacement for traditional mass manufacturing, and the business case must be evaluated on a part-by-part basis against the cost of sourcing or conventional fabrication.
- **Advanced Applications:** Advanced AM of IoT devices and embedded sensors would entail the creation of parts and products with embedded electronics. This remains a future-facing opportunity that requires significant R&D to prove its reliability and value for grid applications.

E.DSO considerations

- **Adopt a Phased, Risk-Based Approach:** DSOs should actively monitor advancements in Additive Manufacturing to leverage these innovations and enhance operational performance. The recommended starting point is with low-risk, non-critical applications such as custom tools, enclosures, or non-energised mechanical parts to build skills and confidence.
- **Develop a Digital Inventory Strategy:** The long-term value is not the physical printer but the creation of a certified library of digital part designs. DSOs should focus on building this "digital warehouse" of tested and approved components, ready for printing when needed.
- **Address the Skills Gap:** Key challenges include high setup costs, limited material compatibility, intellectual property concerns, and workforce skill gaps. Successful adoption requires investment in upskilling the workforce with capabilities in 3D CAD modelling, material science, and printer operation.
- **Collaborate to Accelerate:** Additive Manufacturing offers solutions that can support DSOs in reducing their environmental footprint by enabling repair and reuse strategies. Collaboration between DSOs to share learnings, best practices, and even digital designs for common components can significantly reduce costs and accelerate the safe adoption of the technology across the industry.

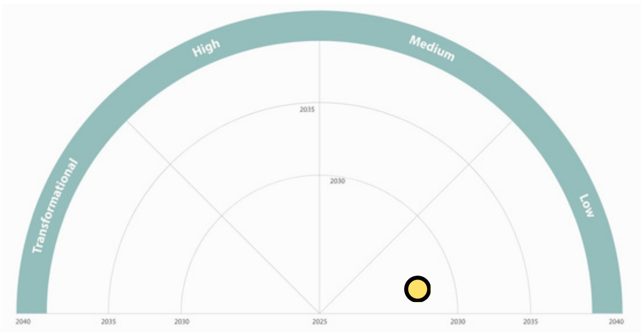
Potential use cases

Leveraging 3D printing to enhance asset management, improve operational efficiency, and accelerate grid modernisation.

Asset Management & Resilience

- **Legacy Equipment Support**: On-demand printing of obsolete and discontinued parts to extend the life of aging, critical infrastructure and avoid costly replacements.
- **Digital Inventory:** Shifting from physical warehouses to a "digital warehouse" of certified designs, cutting storage costs and eliminating supply chain delays.
- **Storm Restoration**: Rapidly printing custom components for emergency repairs to accelerate network recovery and improve reliability metrics (SAIDI/SAIFI).

33. Additive Manufacturing (3D Printers)



Potential Use Cases (continues)

Operational Efficiency & Safety

- **Custom Tooling & Jigs:** Producing specialised, ergonomic tools for field crews to make complex tasks safer, faster, and more efficient.
- **Bespoke Asset Protection:** Printing custom guards (e.g., for wildlife protection) to prevent outages and reduce preventative maintenance costs.
- **Training & Simulation Models:** Creating detailed scale models of substations and equipment for safer, more effective workforce training and planning.

Grid Modernisation & Innovation

- **Rapid Prototyping:** Quickly and cheaply creating and testing new component designs before committing to mass production.
- **Custom Sensor Mounts:** Printing bespoke brackets and housings to easily retrofit modern IoT sensors onto legacy grid assets.

Ongoing Projects

- Enedis has approximately 300 trained employees capable of manufacturing 3D printed parts and more than 100 3D printers located throughout France. The company has a collaborative library of over 400 objects, some of general interest and others more specific to our business, accessible to all employees. The library's use is mainly divided between two use cases:
  - Designing prototypes before transferring them to mass production
  - Producing small batches, particularly to maintain the lifespan of devices that no longer have spare parts.
- The number of pieces manufactured is estimated at around 5,000 pieces per year."
- This initiative by a major European DSO serves as a powerful proof-of-concept, demonstrating that a distributed, at-scale AM capability is not just theoretical but is being successfully operationalised today.

Last update: 30 september 2025

E.DSO - European Distribution System Operators
Rue de la Loi 82, 1040 Brussels, Belgium
+32 (0) 2 737 1340
info@edsoforsmartgrids.eu

www.edsoforsmartgrids.eu

Follow us on