ENTSO-E

RDI Roadmap 2024–2034

Innovation Missions to build the power system
for a Carbon-Neutral Europe

entsoe

ENTSO-E Mission Statement

Who we are

ENTSO-E, the European Network of Transmission System Operators for Electricity, is the **association for the cooperation of the European transmission system operators (TSOs)**. The **40 member TSOs**, representing 36 countries, are responsible for the **secure and coordinated operation** of Europe's electricity system, the largest interconnected electrical grid in the world. In addition to its core, historical role in technical cooperation, ENTSO-E is also the common voice of TSOs.

ENTSO-E **brings together the unique expertise of TSOs for the benefit of European citizens** by keeping the lights on, enabling the energy transition, and promoting the completion and optimal functioning of the internal electricity market, including via the fulfilment of the mandates given to ENTSO-E based on EU legislation.

Our mission

ENTSO-E and its members, as the European TSO community, fulfil a common mission: Ensuring the **security of the interconnected power system in all time frames at pan-European level** and the **optimal functioning and development of the European interconnected electricity markets**, while enabling the integration of electricity generated from renewable energy sources and of emerging technologies.

Our vision

ENTSO-E plays a central role in enabling Europe to become the first **climate-neutral continent by 2050** by creating a system that is secure, sustainable and affordable, and that integrates the expected amount of renewable energy, thereby offering an essential contribution to the European Green Deal. This endeavour requires **sector integration** and close cooperation among all actors.

Europe is moving towards a sustainable, digitalised, integrated and electrified energy system with a combination of centralised and distributed resources.

ENTSO-E acts to ensure that this energy system **keeps consumers at its centre** and is operated and developed with **climate objectives** and **social welfare** in mind.

ENTSO-E is committed to using its unique expertise and system-wide view – supported by a responsibility to maintain the system's security – to deliver a comprehensive Roadmap of how a climate-neutral Europe looks.

Our values

ENTSO-E acts in **solidarity** as a community of TSOs united by a shared **responsibility**.

As the professional association of independent and neutral regulated entities acting under a clear legal mandate, ENTSO-E serves the interests of society by **optimising social welfare** in its dimensions of safety, economy, environment and performance.

ENTSO-E is committed to working with the highest technical rigour as well as developing sustainable and **innovative responses to prepare for the future** and overcoming the challenges of keeping the power system secure in a climate-neutral Europe. In all its activities, ENTSO-E acts with **transparency** and in a trustworthy dialogue with legislative and regulatory decision makers and stakeholders.

Our contributions

ENTSO-E supports the cooperation among its members at European and regional levels. Over the past decades, TSOs have undertaken initiatives to increase their cooperation in network planning, operation and market integration, thereby successfully contributing to meeting EU climate and energy targets.

To carry out its **legally mandated tasks**, ENTSO-E's key responsibilities include the following:

- Development and implementation of standards, Network Codes, platforms and tools to ensure secure system and market operation as well as integration of renewable energy;
- Assessment of the adequacy of the system in different timeframes;
- Coordination of the planning and development of infrastructures at the European level (**Ten-Year Network Development Plans, TYNDPs**);
- Coordination of research, development and innovation activities of TSOs;
- Development of platforms to enable the transparent sharing of data with market participants.

ENTSO-E supports its members in the **implementation and monitoring** of the agreed common rules.

ENTSO-E is the common voice of European TSOs and provides expert contributions and a constructive view to energy debates to support policymakers in making informed decisions.

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Executive Summary

The success of the deep transformation of Europe's energy system requires a massive ramp up of research, development and innovation efforts, encompassing activities ranging from new concepts and computer modelling solutions to both small-scale and large-scale demonstrations. The ENTSO-E RDI Roadmap 2024 – 2034 proposes innovation missions and milestones for the core TSO activities in response to the EU climate and energy objectives. It is a Roadmap to accelerate the development of the future power system, a system that needs to be sustainable, flexible, digitalised and at the core of the European energy system of systems.

The RDI Roadmap 2024 – 2034

The world of energy has changed drastically since 2020 as the effect of a global pandemic and the geopolitical turmoil have disrupted the availability of energy sources, materials and equipment crucial for the European energy sector.

In response, the European Commission's REPowerEU action plan sets the tone to accelerate the clean energy transition, improving energy independence while increasing the sustainability of the industrial ecosystem as a whole, towards an affordable, secure and sustainable energy for Europe.

The grand challenges entailed by the energy system decarbonisation and the present international situation call for outstanding solutions to keep the power system reliable and resilient. The ENTSO-E Research Development and Innovation Roadmap 2024 – 2034 (ENTSO-E RDI Roadmap 2024 – 2034) lays down missions for the next 10 years to overcome these challenges and implement the power system for a carbon-neutral Europe.

The ENTSO-E RDI Roadmap is a legally mandated document that outlines key research, development and innovation priorities for modernising the power grid over the next decade. It targets a broad audience, including decision-makers within electricity Transmission System Operators (TSOs), the companies and organisations interacting with the grid, policymakers and anyone else involved in the future evolution of the power grid.

On the premise of European strategy for the clean energy transition and considering the innovation needs of European TSOs, this RDI Roadmap identifies three RDI clusters and six missions with more than 90 milestones to drive the evolution of the energy system. Each milestone represents a key achievement to be reached to keep the power system secure, adequate and cost efficient, while allowing the increasing penetration of variable and distributed energy sources.

This structure enables a clear identification of innovation targets for sustainable and efficient transmission system development, increasing resiliency, securing system operation and enabling an effective European market in response to the EU climate and energy objectives, with the goal of accelerating the realisation of the sustainable, flexible and digitalised power system for a carbon neutral Europe.

The ENTSO-E RDI Roadmap 2024 – 2034 highlights the direct link between the realisation of the innovation milestones in this Roadmap and the supporting technologies in the Technopedia. To effectively use the existing and innovative technologies in favour of the electricity transmission system development to accelerate the clean energy transition, it is estimated that an unprecedented effort from TSOs into RDI activities is required. Although it is known that TSOs' RDI activities have a positive impact on society, from academics to technology providers and to the final energy consumer, TSOs frequently face only partial recognition of their investments in the RDI activities. To bridge the gap with the recognised need for investment in the electricity transmission system development, it is necessary to ensure a better alignment of the outcomes of European funding programmes with the milestones of the ENTSO-E RDI Roadmap, as well as the improvement of forward-looking regulatory frameworks to support the investment from all TSOs in RDI activities.

The RDI Clusters and Missions

ENTSO-E RDI Roadmap 2024–2034

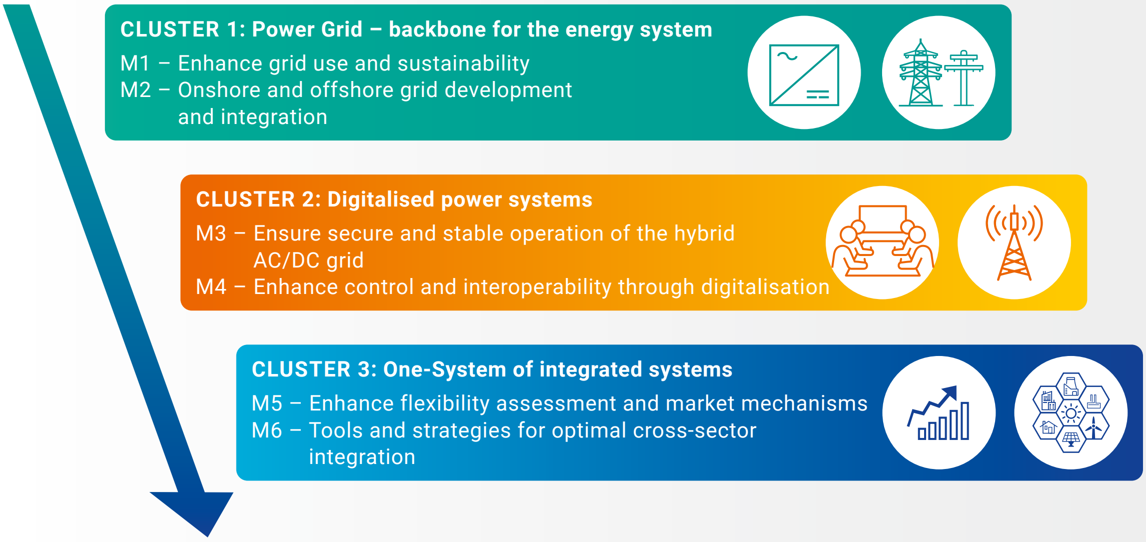

Figure 1: ENTSO-E RDI Roadmap 2024–2034

RDI Cluster 1 – Power Grid: backbone for the energy system

To improve the resilience, efficiency and sustainability of power grids from planning, procurement and construction to utilisation, the following Missions are proposed:

- **M1 – Enhance grid use and sustainability:** optimise existing infrastructure through innovative methods, making the grid more efficient, reliable, secure and sustainable.
- **M2 – Onshore and offshore grid development and integration:** development of HVDC to support the integration of high shares of renewable energy sources and foster the EU green energy transition.

RDI Cluster 2 – Digitalised power systems

To improve the management of hybrid electricity grids with ubiquitous digitalisation, the following Missions are proposed:

- **M3 – Ensure secure and stable operation of the hybrid AC/DC grid:** the high penetration of power electronics interfaced devices calls for the development of innovative models and tools to manage the future system while standards and procedures will be updated.
- **M4 – Enhance control and interoperability through digitalisation:** enhance digitalisation for improved grid monitoring and control, ensuring interoperability. The main focus is the development of innovative tools for control centre operation.

RDI Cluster 3 – One-System of integrated systems

To improve system flexibility and exploit cross-sector integration, valorising resources from the whole energy system, the following Missions are proposed:

- **M5 – Enhance flexibility assessment and market mechanisms**: enhance the flexibility of the energy system by assessing flexibility needs in all timeframes and by developing mechanisms that enable all available flexibility sources to provide flexibility considering both technical and economic aspects.
- **M6 – Tools and strategies for optimal cross-sector integration:** foster the integration of power grids into one-system of integrated systems while ensuring stable and secure operation.

1 The RDI Roadmap

The ENTSO-E RDI Roadmap is a legally mandated strategic document updated every 4 years that outlines the TSOs' long term methodology and main research and innovation for sustainable and efficient transmission system development, increasing resiliency, securing system operation and enabling an effective European market in response to the EU's climate and energy objectives.

ENTSO-E, in accordance with Article 30(1)(i) of the Regulation (EU) 2019/943, is responsible for coordinating the Research, Development and Innovation (RDI) activities of Transmission System Operators (TSOs). The RDI Roadmap, that is periodically updated by ENTSO-E every 4 years, is an instrument that highlights the most promising opportunities, assessing them from different perspectives and providing a selection of recommended innovation pathways.

The main drivers that guided the present RDI Roadmap 2024 – 2034 are the development and implementation of technically viable, reliable and sustainable solutions to develop significant system flexibilities, both short and long duration, timed with the future system needs and the gradual phase-out of fossil fuel generation; to improve the operation of the power system to rise to the challenge of the much more dynamic future power system, that includes the management of a wide portfolio of flexibilities; and to accelerate the achievement of the clean energy transition targets set by EU policies, while keeping the electricity system secure and efficient.

In addition to being a legally mandated task, this RDI Roadmap is primarily intended for TSOs' key decision-makers and related industries, as well as policy specialists and other interested parties. In this view, it aims to identify the most important research and innovation areas for the electricity transmission sector over the next ten years.

The present document, that is based on and in continuation with the RDI Roadmap 2020–2030, outlines selected key milestones aimed at driving the RDI activities of European TSOs, while supporting the attainment of the objective of the European climate and energy goals for 2030 and, on a longer time horizon, the climate neutrality for 2050.

The RDI Roadmap 2024 – 2034 is perfectly aligned with both the EC energy goals in support of the clean energy transition, as well as to the innovation needs stemming from the European TSOs. This approach ensures that TSOs' RDI efforts duly consider the high level agreed-upon top-down and bottom-up drivers and related RDI priorities that have arisen in the past 4 years after the publication of the Roadmap 2020–2030.

Given the primary goal of ensuring a sustainable, affordable and secure electricity system, the RDI Roadmap 2024 – 2034 focuses on topics related to TSO business processes, such as coordinated security of operation, maximising capacity in a secure manner, balancing between generation and demand, dynamic stability, coordinated network planning. The successful implementation of this Roadmap will enhance existing grid use and the utilisation of high-voltage direct current (HVDC) links, the widespread electrification of the energy use, the integration of cutting-edge technologies, the flexibility needs assessment of the electric grids, new methods required for stability management in the presence of widespread power electronic devices, the exploitation of digital solutions and the smart integration of the electricity system with other energy sectors such as transport, heating & cooling and hydrogen.

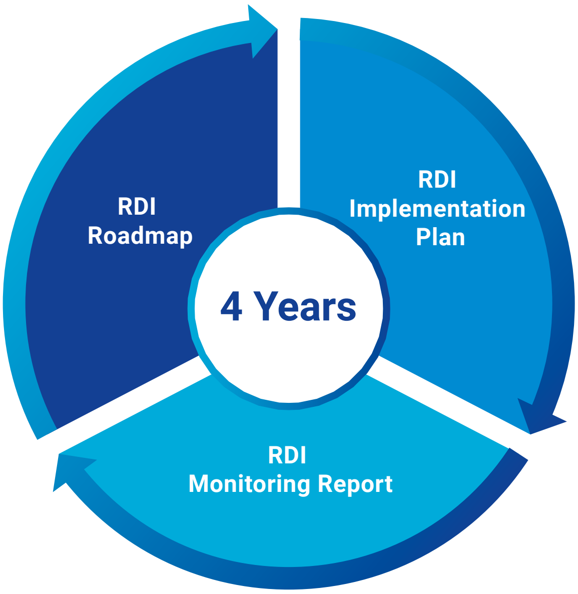

Figure 2: The ENTSO-E RDI Roadmap cycle

The process that led to the update of the RDI Roadmap followed the cycle shown in Figure 2, which is repeated by ENTSO-E on a four-yearly basis. In fact, after the release of the RDI Roadmap, ENTSO-E proceeds with the development of the RDI Implementation Plan, which represents a bridge between the Missions described in the RDI Roadmap and the real implementation of projects addressing the identified milestones. The progress of the implemented TSOs' projects is then analysed in the RDI Monitoring Report, which assesses the alignment of the current RDI activities with the strategic direction. The Monitoring Report then serves as a review and provides the crucial inputs for the next RDI Roadmap.

2 The innovation drivers of a power system for a carbon-neutral Europe

Although the objective at the heart of the European Green Deal to achieve an economy with zero net emissions of greenhouse gases by 2050 is still the main key driver of EU policies, the actual pathways to achieving this objective are evolving and key innovation drivers have evolved since the publication of the last ENTSO-E RDI Roadmap 2020 – 2030. This chapter provides a comprehensive analysis of the power system main innovation drivers, from both European institutions and TSOs.

Key Top-Down Drivers

The European Green Deal aims to make Europe climate-neutral and the REPowerEU Plan is helping to save energy, diversify energy supplies and produce clean energy[1]. Through the **'RePowerEU Plan'**, the EC emphasises the need to diversify European energy supply sources, calling for a massive scaling-up of renewable energy in power generation, industry, buildings and transport. Beyond that, the EC's '**Grids, the missing link – An EU Action Plan for Grids'**[2] and '**Digitalising the energy system – EU action plan'**[3] recognise that Europe's power networks are confronted with new significant challenges, such as the need to serve fast-growing demand linked to the electrification of transport, heating and cooling, industry processes, and the kickstart of low-carbon hydrogen production. Hence, the **EU has brought the power grid to the centre of its policy agenda** and promotes the deeper electrification of energy consumption, underpinned by a strong and integrated energy market, which is also a key part of the European strategy.

Strengthening power grids, together with enhancing their flexibility and establishing links with other energy sectors such as transport, buildings, industry and hydrogen would support the growth of distributed renewable energy sources and shape the energy system of the future.

The aim of developing a fully integrated energy system increasingly calls for a holistic approach, where the planning and operation of European electricity transmission and distribution networks must be harmonised with those of the new hydrogen infrastructure, energy storage and charging infrastructure for e-mobility, as well as the heating and cooling sector.

Strengthening the **coordination between TSOs and Distribution System Operators (DSOs)**, already highlighted as a key topic in the RDI Roadmap 2020 – 2030, is gaining greater importance also considering that relevant shares of variable renewable energy sources are connected at the distribution level.

With respect to four years ago, hydrogen has gained much more attention. In fact, **hydrogen is expected to play an important role in achieving the EU's climate objectives** to reduce greenhouse gas emissions by a minimum of 55 % by 2030 and reach net zero emissions by 2050. The EC foresees that the large-scale deployment of hydrogen will contribute to climate neutrality, decarbonise hard to abate energy sectors, provide long-term large-scale seasonal energy storage, thus helping to solve the issue of the system's long-term flexibility.

Battery storage is also expected to play a crucial role in enhancing the flexibility of the electricity system and, as reported in the REPowerEU Plan, the EC proposes considering storage assets as being in the overriding public interest, thus facilitating permitting procedures.

1 REPowerEU (europa.eu)

2 EUR-Lex – 52023DC0757 – EN – EUR-Lex (europa.eu)

3 EUR-Lex – 52022DC0552 – EN – EUR-Lex (europa.eu)

The EU Grid Action Plan puts a strong emphasis on correlating the planning and operation of Europe's electricity networks with the **planning and operation of the new charging infrastructure for e-mobility**. In addition, Regulation (EU) 2023/1804 on the deployment of alternative fuels infrastructure (AFIR)[4] sets mandatory targets for the number and spatial distribution of publicly accessible recharging stations, for both electric vehicles (EVs) and Heavy Duty Electric Vehicles (HDEVs). Charging hubs, able to serve several trucks simultaneously, will necessitate a connection capacity of more than 10 MW each, thus directly impacting high-voltage grids. The AFIR also lays down targets for shore-side electricity supply in maritime ports, which will require high voltage connections to be directly routed from a HV substation to the port areas. Furthermore, the AFIR states that Member States should assess by end-2024 the **EV potential contribution to the flexibility** of the energy system and this assessment shall be considered by system operators in their network development plans.

Very significant **investments on grids are necessary** to achieve the decarbonisation targets while maintaining system security and efficiency. While there has been a rapid rise in investment for renewable energy sources, nearly doubling since 2010, global investment in grid infrastructures has barely changed, remaining static at around USD 300 billion per year[5]. This is not only a problem for the future but one that we are already seeing today, where long lead times for grid upgrades and grid connection act as a bottleneck for renewables deployment in many places. This has been also recognised in the EC's 'State of the Energy Union 2022', where investing in the power grid to enable greater electrification (EUR 29 bn) has been listed among other key investment needs.

As the shares of variable renewables, such as solar photovoltaic (PV) and wind increase, **making power systems more flexible is an imperative**. In fact, reaching the ambitious targets, set in the EU Solar Energy Strategy for PV installation (385 GW_{DC} by 2025 and 720 GW_{DC} by 2030), will require system operators to further assess system adequacy and security at all time scales. Moreover, the increased flexibility needs should be considered when planning transmission networks and innovative solutions should be deployed, including the use of energy storage systems and demand side management. Enabling smart and bidirectional charging of EVs, the participation of virtual power plants in the energy markets and exploiting the potential of energy communities, smart buildings and smart heating using heat pumps, will contribute to increasing the system flexibility.

Digital technologies can help resolve current operational challenges, supporting the integration of renewable and distributed energy resources, and optimising system efficiency. Therefore, the EU's electricity network has become increasingly digitalised in the last decade. However, the speed of transformation needs to increase significantly and the **digitalisation of the energy system is now a policy priority**. The EC's 'Digitalising the energy system – EU action plan' underlines that the availability of, access to and sharing of energy-related data, based on seamless and secure data transfers among trusted parties, are key enablers for a digitalised energy system. Moreover, it is projected that the deployment of an appropriate data sharing framework for energy could facilitate the participation in the wholesale markets of more than 580 GW of flexible energy resources, making full use of digital solutions by 2050. It is estimated that this would cover over 90 % of the overall flexibility needs in the EU electricity grids. A deep grid digital transformation will also facilitate the deployment of advanced simulations tools, such as digital twins, to allow for a sophisticated virtual model of the European electricity grid.

Artificial Intelligence (AI) is increasingly being used to optimise energy systems, including equipment condition-based maintenance, to help reducing unplanned downtime and improve energy efficiency, to produce accurate weather and renewable power generation forecasts or to support power system operation. The responsible use of AI is considered to support cheaper and more sustainable energy systems.[6]

With the deep digitalisation of the energy system, **cybersecurity has become an increasingly essential requirement**. It plays a key role for the energy system in remaining secure and robust against cyber incidents and major attacks[7].

While defining strategic objectives for RDI activities of the coming decade, Europe must **mitigate the risks for the critical materials' supply chain**, as declared by the EC in the Critical Raw Materials Act[8] Furthermore, it is important to underline the relevance of the Net-Zero Industry Act[9], which aims to promote investments in the production capacity of products, that are key to meeting the EU's climate neutrality goal. In particular, Net-Zero strategic projects, that will benefit from priority status, thus shorter timelines, will address the resilience of the energy system and cover innovation in PV and renewable technologies, storage and grid technologies among others.

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4 **Regulation – 2023/1804 – EN – EUR-Lex (europa.eu)**

5 **Electricity Grids and Secure Energy Transitions – Analysis – IEA**

6 **EU AI Act: first regulation on artificial intelligence | Topics | European Parliament (europa.eu)**

7 **Network Code on Cybersecurity (entsoe.eu)**

8 **EUR-Lex – 52023PC0160 – EN – EUR-Lex (europa.eu)**

9 **EUR-Lex – 52023PC0161 – EN – EUR-Lex (europa.eu)**

Key Bottom-Up Drivers

In addition to key policy documents, RDI Roadmaps and strategies from European TSOs have been analysed to assess the main bottom-up drivers and changes regarding the RDI Roadmap 2020 – 2030, to guide the definition of the main RDI topics of the present Roadmap 2024 – 2034, to efficiently develop the transmission system, to secure system operation and to enable an inclusive and effective European electricity market – as innovation, just as with digitalisation or any investment in the TSO environment, is not a standalone target but should directly contribute to one of the core business targets.

TSOs are aware of the scale of the goal of reaching a net zero energy system[10] and acknowledge the relevance of moving towards an **optimised and integrated energy system** via the development of tools and the creation of cooperation models for holistic energy system planning and management.

TSOs underlines the relevance of RDI activities to coordinate the development and implementation of solutions with the rapid massive growth of solar and wind power resources connected to the grid by power electronic converters (PEID), which radically change the system characteristics, creating significant challenges regarding system stability. Therefore, synthetic inertia and very fast voltage support response are desired PEID functionalities that can be obtained by means of **grid-forming control technology**, enabling PEID to mimic a synchronous generator in response to power system disturbances.

The expected high growth in power demand, in addition to a surge in intermittent power production from solar and wind energy, also lead to an **escalating need for flexibility** within the power system to keep acceptable levels of adequacy and resilience. Hydropower will maintain its significant role in providing flexibility, but emerging sources such as hydrogen, demand-side flexibility and peak power plants are expected to gain increasing importance, and their development is crucial to achieving sufficient system flexibility in future. This should be fostered by careful planning and by the development of tools to assess, monitor and forecast flexibility.

Concerning grid development, major RDI efforts should be dedicated to ensure **that offshore energy becomes a cornerstone of the EU future energy system** as envisaged by the EC's offshore RES strategy, which aims for the integration of 300 GW offshore wind generation capacity by 2050.

In this context, new trends include more emphasis on offshore floating substations and hence on the RDI needs to overcome the present technical challenges and barriers related to the mutual constraints of a floating mechanical structure and an HVDC floating station connected to the land by dynamic cables.

With the increasing share of grid integrated renewables, different approaches to system **real-time management of the grid** are necessary, given that energy fluctuations will become more pronounced. From this perspective, TSOs need to improve the handling of power system stability through control and monitoring-based solutions to assess the system stability margins to withstand disturbances and perform necessary actions. Moreover, system protection schemes have to be developed to improve the stability in certain challenging contingencies.

Digitalisation will play an increasing role in the power system of the future and understanding and maximising its impact on the electricity systems is a key issue. Exploring how to exploit innovative algorithms and emerging digital solutions for the power system management leads to objectives such as the development of digital twins, enhanced monitoring opportunities enabling predictive maintenance and new optimisation opportunities.

Moreover, harnessing other existing and emerging digital technologies, including the use of satellite imagery, drones, robots and real-time data sensors, will facilitate the adoption of **more efficient, cheaper and safer remote monitoring** and inspection activities to maximise the utilisation of existing assets. Virtual and augmented reality for remote inspection and maintenance activities will also play a relevant role enabling costs to be saved by, for example, minimising the number of physical site visits.

In addition to the challenges introduced by the increasing penetration of weather dependent power generation, extreme weather events have become more frequent due to climate change and system operators need to identify and **develop mitigation measures for network and asset resilience**. System defence and restoration plans are designed to limit the consequences of severe incidents by reducing power outages and recovery times and they require updating. Enhanced resilience analysis methods for identifying grid and system vulnerabilities associated with new risk drivers, in particular related to environmental threats, are necessary to offer a different perspective on power systems' equipment and electrical engineering operating risks, that are deeply interconnected and dependent of one another.

Moreover, trends include the deployment of innovative materials and solutions towards more **sustainable power systems** with a life cycle thinking approach, and in particular, the significant **reduction of SF_6** emissions is an important goal. SF_6 alternatives, retro-filling assets with new gases and leaks detection and repair are all part of the possible solution in the phase out process of SF_6.

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Innovative market design, able to ensure energy market access and financial incentives for all energy resources to provide adequacy, flexibility and system services, need to be pursued, while the possible integration of offshore solutions into the electricity market requires assessing and implementing. It is relevant to develop market models, integrate infrastructure planning and operate solutions in electricity and other energy sectors, which support the continued electrification of heating and transport. A challenge to consider while developing innovative market schemes is that the mitigation of converter related stability issues, unlike frequency, require local resources.

To enhance the optimal management of end-users' resources, it is key to **support consumers to benefit from the energy transition** and to open up possibilities for end users and consumers to actively interact with the electricity grid. The aim is to establish a system in which consumer consumption and load profiles match with production patterns. The establishment of a consumer-centric system requires a market design that will give consumers the freedom and advantages to participate in energy markets. To empower consumers and promote their engagement, it is necessary to make it easy for end-users' devices to cooperate across the system, by means of standardised and modular approaches to customer connections.

Innovation drivers' summary

The following Figure 3 shows how the main top-down and bottom-up drivers identified in this chapter evolved in the past four years after the publication of the RDI Roadmap 2020 – 2030. As can be observed, several key drivers related to grid infrastructure, digitalisation and enhanced operation increased their relevance. Moreover, AI-based technologies and hydrogen received considerable attention and are duly considered within the different key milestones of the RDI Roadmap 2024 – 2034.

Cluster 1 Power Grid – backbone for the energy system	CLUSTER 2 Digitalised power systems	CLUSTER 3 One-System of integrated systems
Grid investments	System digitalisation	Power system flexibility
Power system resilience	PEID and Grid Forming	Deep electrification and EVs
Offshore AC and DC grids	Digital twin	NEW Hydrogen
HVDC interconnections	Cybersecurity	RES/VRE integration
Energy storage	NEW AI-based technologies	Innovative market design
Optimal assets management	RES and load forecasting	Integrated energy system
Substainable materials	Monitoring and data management	End-users engagement
	IoT devices and meters	TSO – DSO coordination
	Smarter grids innovative tools	

Top-down drivers Bottom-up drivers

Figure 3: Main top-down and bottom-up innovation drivers. The size of the circle represents the relative relevance increase with respect to the RDI Roadmap 2020 – 2030

3 Innovation priorities for the next decade

A secure, clean and affordable supply of electricity is essential for the prosperity of our societies; therefore, power system innovation is crucial for the clean energy transition and the correlated radical transformations to meet carbon-neutral targets. Hence, bold innovation actions are essential to address the present multifaceted challenges. This calls for the integration of TSOs' vision and system needs with the surrounding ecosystem to ensure a sustainable, secure and efficient future power system.

The multifaceted challenges faced by today's power systems call for a strong emphasis on RDI activities to enable the development, demonstration and uptake of the necessary innovative solutions, as we already see the decrease of fossil fuel dispatchable generation, that provides significant flexibility and ancillary services going towards carbon neutrality. Aligned with the ENTSO-E Vision of a power system for a carbon-neutral Europe[11], innovations in this Roadmap are aimed at addressing the evolution of the flexibility needs and supporting the timely deployment of multiple resources of carbon neutral flexibility, including flexible generation, active demand, storage, sector integration and flexible grid use, and overall TSO core business activities in the future energy landscape in Europe that will clearly be a system of interdependent systems.

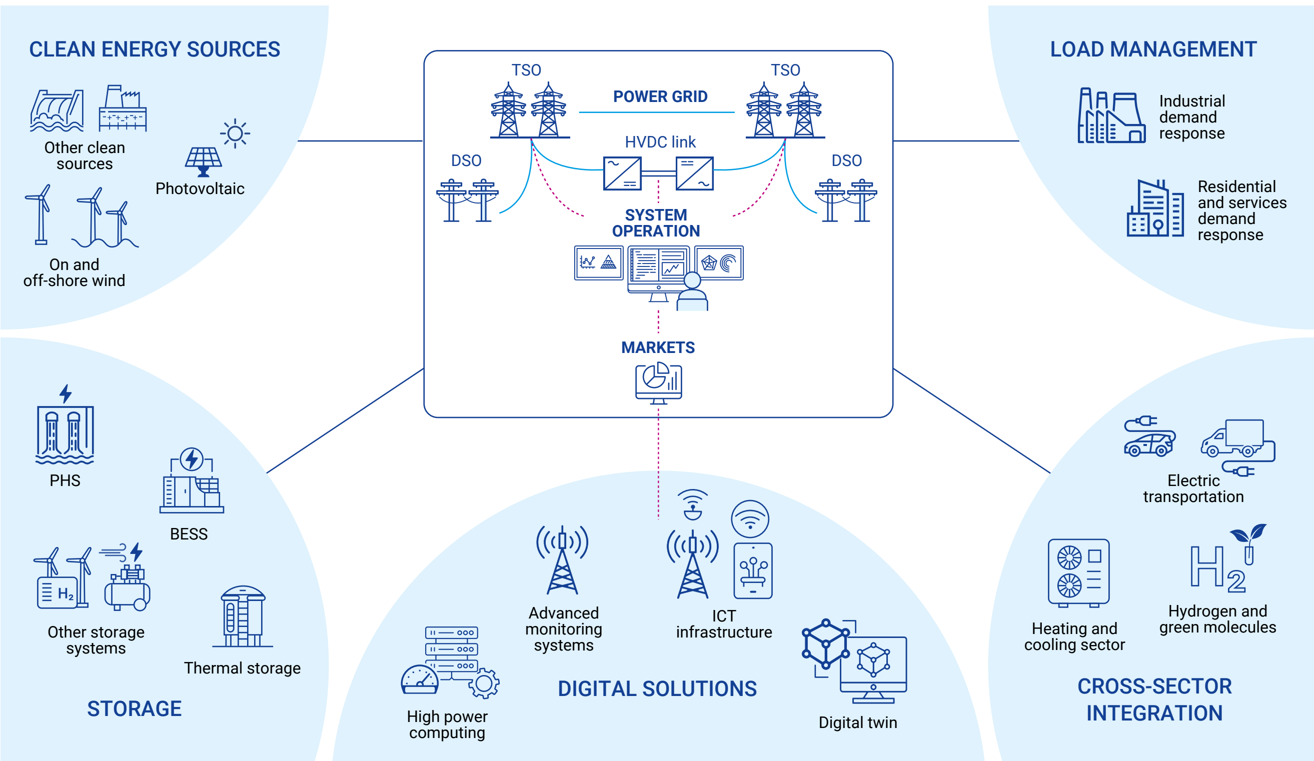

Figure 4: The future power system is sustainable, flexible, digitalised and at the core of the European energy system of systems.

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RDI efforts must involve integrated and coordinated activities, including assets optimisation and digitalisation, to enhance the operation of future power systems, the assessment of flexibility needs at all time scales, the integration and exploitation of new flexibility resources and the gradual transition towards hybrid AC/DC systems, by increasing the number of the HVDC links and inverter-connected devices. Furthermore, cross-sector integration for the planning and development of a holistic energy system, as well as the implementation of market-based interactions, are imperative for addressing the challenges to the power system of the future. The future power system is sustainable, flexible, digitalised and at the core of the European energy system of systems (Figure 4).

The present RDI Roadmap 2024 – 2034 outlines the long-term methodology and TSOs' RDI approach, aligned with the core TSO objectives and in response to the EU climate and energy objectives. Moreover, it considers the outcomes from the ENTSO-E RDI Monitoring Report 2022 and the related assessment regarding the ongoing TSOs' RDI activities against the previous RDI Roadmap and the RDI Implementation Plan.

A graphical representation of this process is depicted in Figure 5.

This ENTSO-E RDI Roadmap 2024 – 2034 is structured around three main Clusters, reflecting an integrated approach that brings together the visions and RDI strategies of the European institutions with those of TSOs.

The three main Clusters of the Roadmap are designed to put innovation at the service of the TSO objectives, namely:

- **Cluster 1 'Power grid: backbone of the energy system'** activities mainly contribute to and improve the sustainable and efficient development of the transmission system;
- **Cluster 2 'Digitalised power systems'** activities mainly contribute to and improve the secure system operation;
- **Cluster 3 'One-System of integrated systems'** activities mainly contribute to and improve flexibility needs assessment and the effective European market for electricity.

ENTSO-E, through the publication of the Strategic Roadmap[12], sets the foundations of the effective strategy for the update of the RDI Roadmap.

The Strategic Roadmap is organised around two interconnected pillars that reflect the dual responsibilities of European TSOs:

- Preparing the power system of the future for a carbon-neutral Europe;
- Managing the present European power system for secure and efficient operation

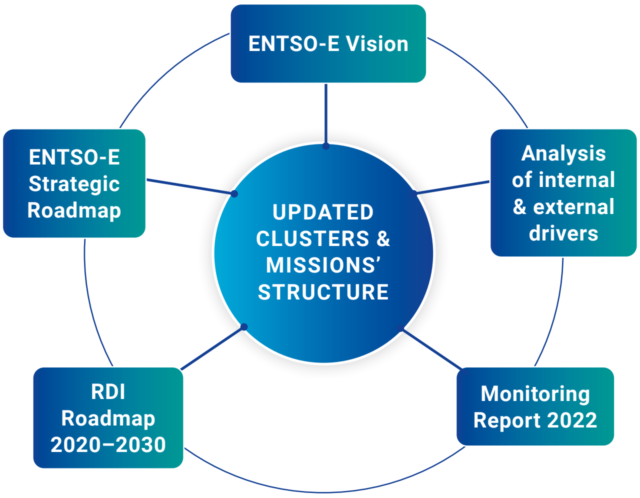

Figure 5: Key inputs to the ENTSO-E RDI Roadmap updating process.

12 ENTSO-E Strategic Roadmap (eepublicdownloads.blob.core.windows.net)

An overview of the innovation plan outlined in the present RDI Roadmap and its alignment with the ENTSO-E Strategic Roadmap is represented in Figure 6. As can be seen, each pillar is structured into building blocks representing the main thematic areas of interest. As reported in Figure 6, five building blocks are inherent to the future of the power grid (Pillar 1), whereas two address the management of the present grid (Pillar 2). All five building blocks included in Pillar 1 provide input to the present Roadmap and, in particular, the 'Innovation' one embraces all three RDI clusters of the Roadmap 2024–2034. In fact, its primary goal of providing the necessary tools and methods to accelerate the energy transition is exactly the purpose on which the RDI Roadmap is based on. The other building blocks of Pillar 1 underpin specific RDI clusters or missions. In particular, 'Infrastructure & Investments' is well represented by the RDI Cluster 1 (Power Grid – the backbone of the energy system), being centred around the development of the grid infrastructure, both onshore and offshore. 'Operating future grids', focuses on operating the power systems securely and efficiently based on innovative approaches and best practices as it is underlined by the milestones under the RDI Cluster 2 (Digitalised Power systems). Finally, the third RDI Cluster (One-System of integrated systems), which focuses on relevant topics, such as balancing and operating the integrated energy system, deploying flexible solutions and implementing proper market mechanisms for energy and flexibility, considers all inputs from the Strategic Roadmap building blocks 'Energy system flexibility' and 'Market design'.

Differently from the first pillar which envisages the development of research and innovation activities, Pillar 2 reflects TSOs commitment to continue to provide a secure and efficient European power system for the whole of Europe. This responsibility and related commitment is very well aligned with the topics addressed by the second RDI Cluster (Digitalised power systems). Indeed, the Strategic Roadmap areas related to 'Operational excellence' and 'Information & Communication technology' serve as catalysts to Cluster 2 missions being well aligned with the main goals of developing effective innovative solutions and improving the ICT infrastructure, in order to support the interconnected power system and to ensure secure operation.

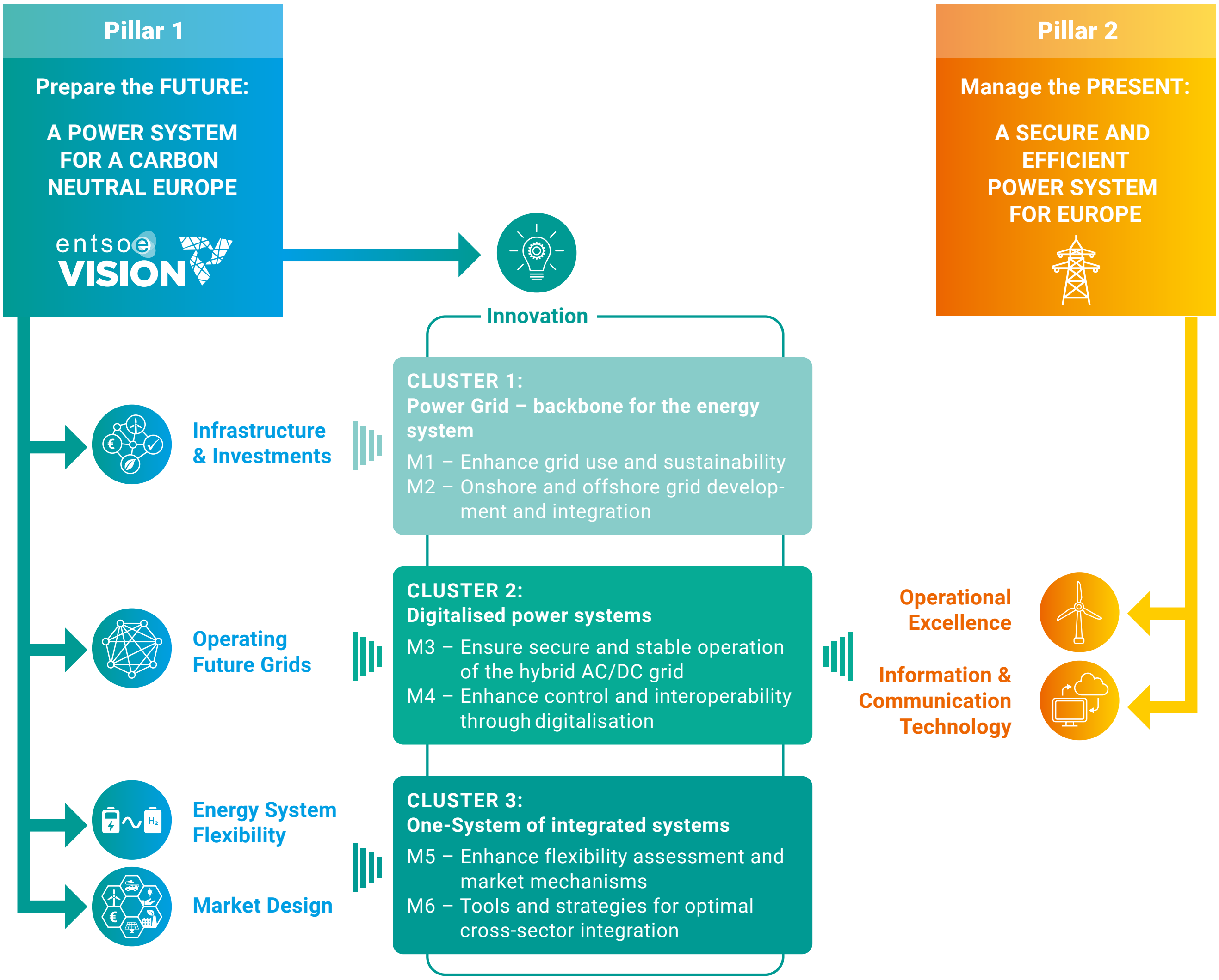

Figure 6: ENTSO-E RDI Roadmap 2024–2034 in the framework of the ENTSO-E Strategic Roadmap

In the following, a brief introduction about the main motivation, scope and objectives of the three Clusters and the related six Missions included in the ENTSO-E RDI Roadmap 2024 – 2023 is provided.

RDI Cluster 1 – Power Grid: backbone for the energy system

To improve the resilience, efficiency and sustainability of power grids from planning, procurement, construction to utilisation.

As electrification and clean energy transition progress, power grids are recognised as the backbone for the energy system. To deliver electricity from bulk, as well as from an increasing number of distributed renewable generators, to homes, factories and businesses, while improving sustainability through the whole power system value chain, calls for strong RDI efforts and the implementation of both incremental innovation and also radically innovative solutions.

Maximising the utilisation of the existing grid infrastructure and planning targeted grid reinforcement or new HVDC connections to harvest renewable energy sources remotely located from the final consumption is the key to achieving the ambitious decarbonisation targets, while maintaining grids more securely and economically efficiently.

By applying innovative technologies and the further digitalisation of the existing assets, it will be possible to enhance system operation, also thanks to the development of digital twins, for power grids able to exploit real-time data, thus supporting both daily operation and condition-based maintenance.

The RDI Cluster 1 comprises the following two Missions:

- **M1 – Enhance grid use and sustainability:** To enhance the optimal use of the existing grid infrastructure and to make it more resilient, reliable, secure and sustainable, thanks to the implementation and deployment of innovative components and methods.
- **M2 – Onshore and offshore grid development and integration:** To further develop HVDC and offshore grids to support and foster the EU clean energy transition. In particular, this missions addresses the planning of future grids and the entailed foreseen investments necessary to realise them.

RDI Cluster 2 – Digitalised power systems

To improve the management of hybrid electricity grids with ubiquitous digitalisation.

The widespread application of digital technologies and the exploitation of the resulting data streams and data spaces are highly strategic and have the potential to expedite the clean energy transition throughout the entire energy sector. Within the domain of electrical systems specifically, these advancements can facilitate the seamless integration of progressively increasing amounts of variable renewable energy sources, while maintaining the desired high levels of resilience and reliability of today's power grid.

As we move towards real-time power grid monitoring and management, the standardisation of new technologies is becoming crucial. Moreover, the large penetration of PEID requires stepping up efforts to guarantee the smooth operation of cyber-physical systems, while ensuring grid security, stability and ability to recover from outages.

Digitalisation and enhanced computation capacity will also make available radically innovative solutions to support the secure and efficient operation of the power system with increased overall complexity and weather dependency.

The RDI Cluster 2 comprises the following two Missions:

- **M3 – Ensure the secure and stable operation of the hybrid AC/DC grid:** This Mission spans multiple concepts, such as demonstrating the stable operations of PEID-dominated power systems, by leveraging converters' grid forming capabilities, especially in distributed systems, developing models and simulation tools, and updating restoration plans.
- **M4 – Enhance control and interoperability through digitalisation:** This Mission focuses on the enhancement of control and monitoring operations by system digitalisation. Particular emphasis is given to control centres' innovation, especially concerning the development of innovative tools and the optimisation of secure grid operations.

RDI Cluster 3 – One-System of integrated systems

To improve system flexibility and exploit cross-sector integration, valorising resources from the whole energy system.

To ensure future-proof power systems, TSOs need to expand their focus beyond their traditional tasks. The rise of distributed generation and the increasing electrification of energy demand call for a shift towards a unified, interconnected one-system of integrated systems, where the seamless cooperation of actors across different sectors is prioritised. To fully exploit the potential of cross-sector integration and especially to unlock the flexibility to handle the increased complexity of the system and to balance what will become a weather-dependent system, all available resources have to be properly considered and valorised. From this perspective, innovative solutions to exploit the electrification potential from residential, business services, industry, heating & cooling and transport sectors must be deployed. To function smoothly and effectively, the interconnected and integrated system requires markets platforms and ICT tools to be operated. Moreover, to ensure a reliable and efficient cross-sector integration, TSOs, DSOs, market players and other key actors need to design harmonised planning and activities.

The RDI Cluster 3 comprises the following two Missions:

- **M5 – Enhance flexibility assessment and market mechanisms:** With the goal of enhancing the flexibility of the energy system, this Mission focuses on the flexibility needs and requirements assessment and on innovative solutions to leverage all available flexibility sources, considering both technical and economic aspects.
- **M6 – Tools and strategies for optimal cross-sector integration:** The main aim of this Mission is to facilitate the integration of power grids into a one-system of integrated systems and to develop innovative tools, models and solutions to foster this evolution while ensuring stable and secure operation.

4 RDI Roadmap Missions

The electricity grid is facing major transformations and TSOs are frontrunners in the innovation process needed to maintain power systems' reliability and affordability, while integrating high shares of renewables. This requires a significant increase in innovation efforts, consisting in a mix of articulated projects, ranging from theoretical models and simulations to small-scale tests and large-scale demonstrations.

To drive significant improvements towards the ultimate goal of power system decarbonisation, successful innovative ideas require implementation, including fresh approaches to expanding and realising new practices, processes and technologies. This will enhance power systems' capabilities, resilience in the face of severe events, reliability for consistent operation, safety for personnel and equipment, security against threats, while also reducing the carbon footprint. Thus, by embracing innovation, we can build an energy system that is flexible and efficient, ensuring that electric grids are able to deal with the pace needed to decarbonise the entire energy system rapidly and effectively.

Six Missions, organised in three Clusters representing key areas for future power systems, are presented in this chapter. Within each Mission, specific milestones indicate the objectives to reach in order to deploy the envisaged innovation. Power systems are an extremely complex ecosystem and Missions cover a wide range of innovation needs, thus, to achieve sensible and tangible results, a collaborative and cooperative approach, convening all the stakeholders across the energy system, needs to be ensured. In this manner, all the necessary skills and resources to achieve the different milestones will be guaranteed.

RDI Cluster 1 – Power Grid: backbone for the energy system

Achieving the milestones in this Cluster will improve the resilience, efficiency and sustainability of power grids from planning, procurement and construction to utilisation. The milestones are organised into two Missions:

- **Mission 1 – Enhanced grid use and sustainability;**
- **Mission 2 – Onshore and offshore grid development and integration.**

Mission 1 – Enhance grid use and sustainability

Electricity grids, the backbone of today's energy systems, are set to become increasingly important as clean energy transitions progress. However, according to the International Energy Agency (IEA)[13], they currently receive too little investment. To support and guarantee the acceleration of renewable energy deployment, while ensuring a secure and reliable power system operation, major innovation is needed to enhance transmission grids' use and sustainability.

This Mission covers the key milestones related to the improved exploitation of the EU power system as a whole. Innovative grid technologies and digital solutions require implementation in the short term, in particular **high-power innovative transmission components**, methods for the **coordinated planning of high-loaded grids**, and in the medium term, **advanced network reconfiguration** and novel control strategies. From a longer term perspective, the developed innovative technologies, such as power flow control applications, aiming to increase grid efficiency need to be **demonstrated in a real environment**.

In the coming years, **AI-based methods** for the real-time monitoring of the grid status and to **forecast renewable generation and electric consumption**, as well as the implementation of solutions such as **dynamic line rating, dynamic transformer rating** and the **adoption of real-time data sensors and IoT devices**, will make it possible to operate grids close to their physical limits.

In addition to monitoring and control, to develop innovative solutions that are **interoperable, integrated and standardised** will, in the medium term, pave the way towards further improving the management of the transmission grid assets. To achieve this, suitable pathways, including the **development of assets' Building Information Modelling (BIM)**, standardised approaches for assets management and innovative technologies such as **digital twin**, for example, to optimise assets maintenance, utilisation and refurbishment, require identification and implementation.

To enhance and ensure the environmental sustainability of the transmission grid and of the entire power system, new approaches to grid design and asset management need to be developed and applied. In the short term – also considering global supply chain disruptions and the resulting supply bottlenecks in recent years – **approaches to mitigate risks (e.g. in the supply chain) for European TSOs** need to be developed and adopted. On a longer-term horizon, methods to enhance **sustainable grid planning and asset management**, such as grid components' circular **economy, life cycle assessment** and **eco-design,** have to be considered and implemented. For example, the deployment of **SF_6-free solutions** is a relevant step to enhance the sustainability of transmission power systems and in line with the EC commitment to phasing down fluorinated greenhouse gases.

13 **IEA – Electricity Grids and Secure Energy Transitions**

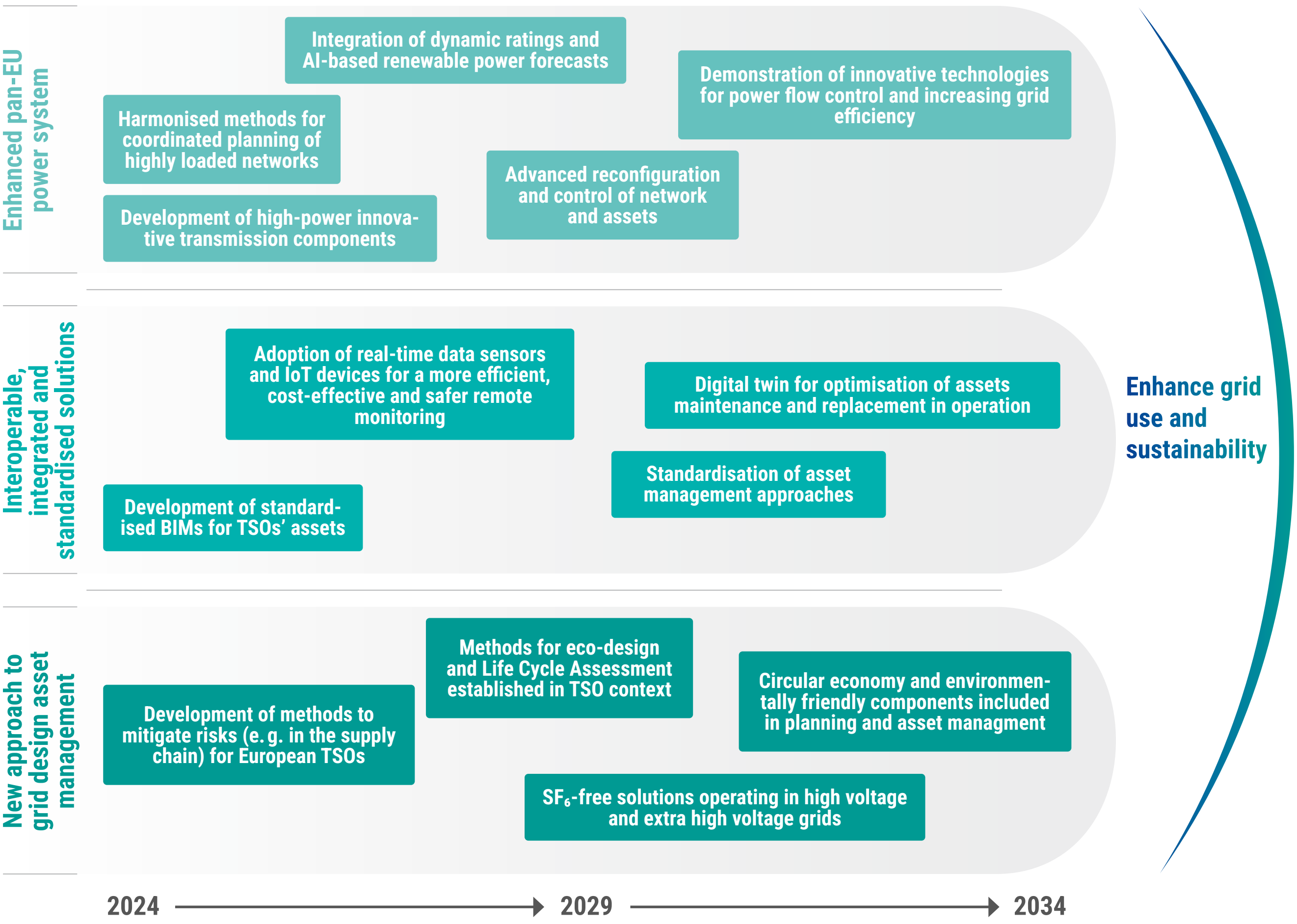

Figure 7: Mission 1 – Enhance grid use and sustainability

Mission 2 – Onshore and offshore grid development and integration

HVDC is an increasingly important technology, as very large amounts of electricity need to be transmitted across Europe and new HVDC interconnections will play a key role in future development plans for the European transmission grid. From this perspective, the use of the advanced functionalities of HVDC links in system operations is essential for the secure and efficient operation of the grid.

Electrical grids able to harvest offshore wind energy by connecting wind farms to national electricity systems, thus carrying more clean energy to communities in every part of Europe, are a key priority. Due to the remote locations of offshore wind farms and their increasingly large distances to the shore, traditional high-voltage alternating current (AC) transmission technology is no longer viable and HVDC connections must be utilised instead. Consequently, a major part of the integration of large-scale offshore renewables into the European energy systems will be made via HVDC connections.

Therefore, the development and implementation of a new **EU regulatory framework for offshore grids**, both in accordance with the EU wide energy policy objectives and those of the Member States, and to increase the economic viability of meshed HVDC projects, by providing a suitable financial framework, are of paramount importance. Moreover, **new offshore ancillary services require demonstrating** in real operation and the corresponding **market platforms** have to be developed, taking into consideration the necessary evolution of **network codes for HVDC**.

In addition to regulatory and market platforms innovation, significant standardisation work is still required to enable large-scale HVDC grid integration. To achieve this, **requirements for HVDC, cables and monitoring systems**, as well as **offshore platform types** and **reliability and maintenance concepts**, need to be aligned. Moreover, to foster the deployment of the offshore and onshore HVDC grid in the short term, **critical Multi Terminal (MT) HVDC components** require further development and field testing. **The interoperability of HVDC converters** is a key aspect to achieve the **demonstration of Multi Terminal HVDC**, first as a **single vendor**, then as a multi-vendor configuration. From this perspective, the **development of simulation tools, compliance tests and corresponding test facilities** will be key.

From a longer-term perspective, the development of reliable **dynamic cables and the demonstration of floating offshore platforms** represent key innovation steps for the development of deep-water offshore grids.

The further development of HVDC connections represents a key opportunity for the modernisation of EU power systems. Therefore, **HVDC planning criteria** require careful developing, paying particular attention to the identification of **possible new interconnections,** able to harvest clean energy generated far from consumption sites and to enhance EU internal market integration. Finally, from a longer-term perspective, the progressive deployment of HVDC links with enhanced functionalities calls for the integration of HVDC links into TSO's dispatching centres and for the update of Regional Coordination Centres (RCCs).

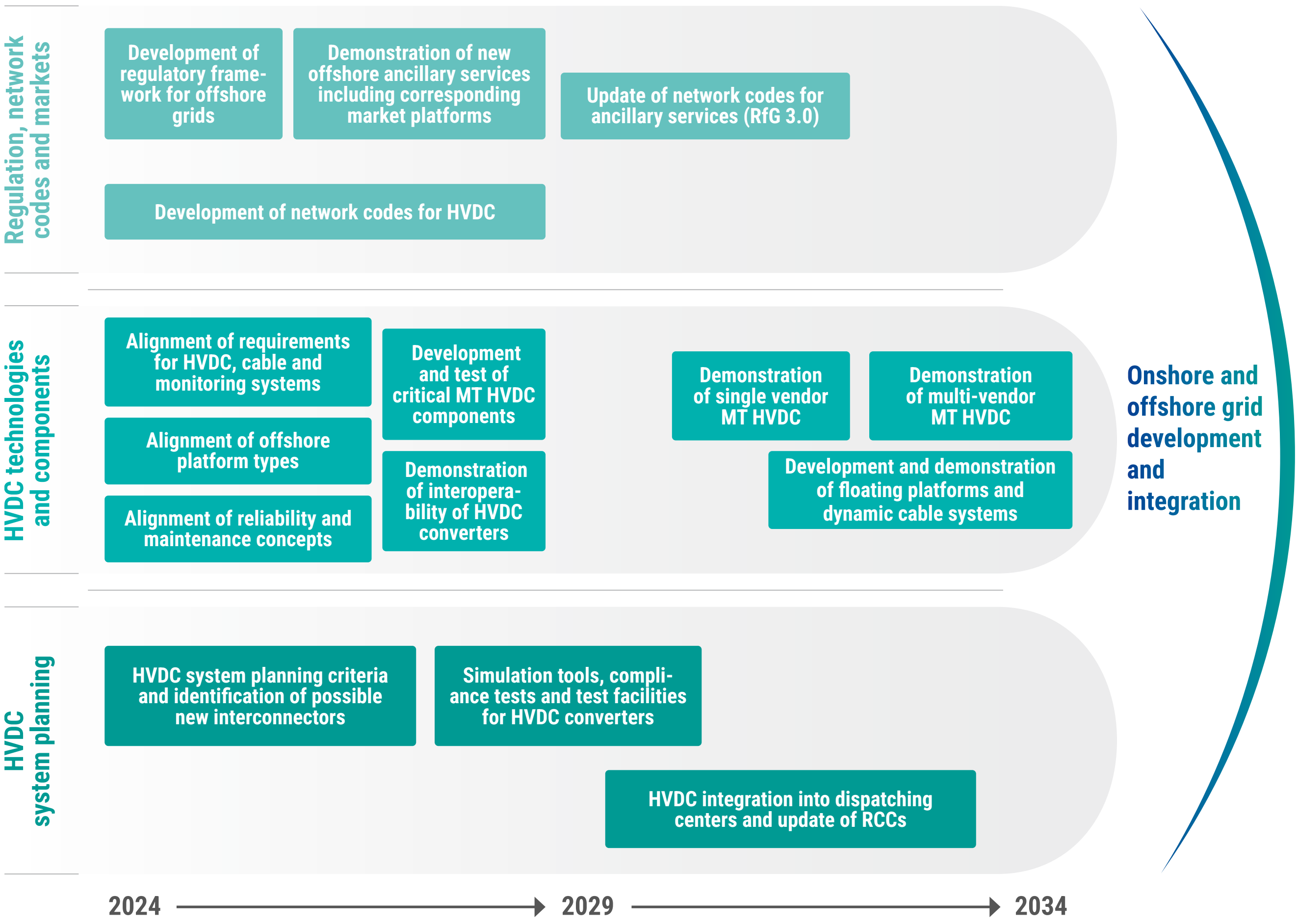

Figure 8: Mission 2 – Onshore and offshore grid development and integration

RDI Cluster 2 – Digitalised power systems

Achieving the milestones in this Cluster will improve the management of hybrid electricity grids with ubiquitous digitalisation. The milestones are organised into two Missions:

- **Mission 3 – Ensure secure and stable operation of the hybrid AC/DC grid.**
- **Mission 4 – Enhance control and interoperability through digitalisation.**

Mission 3 – Ensure secure and stable operation of the hybrid AC/DC grid

With the increasing electrification of end-use consumption, ensuring a secure and reliable electricity supply is paramount. However, the large shares of variable renewable energy sources, such as solar and wind, replacing conventional sources in the generation mix, are posing additional challenges to the power system and introducing new control complexities. Moreover, the growing presence of DC links in transmission grids is leading to the transition towards hybrid AC/DC systems, which require prioritising actions to guarantee stable power grid operation. To cope with this, **standardised interfaces** for **models and simulation tools,** able to facilitate the interaction among different software tools to simulate the behaviour of hybrid AC/DC grids and their components under different operating conditions, are needed. Moreover, models to simulate the impact of specific new power system components, such as the **large electrolysers system behaviour**, must be developed. In the medium-term, innovative tools and solutions will allow for **large-scale pan-EU dynamic analysis** and the development of **near-real-time platforms for dynamic system simulations**. From a longer-term perspective, the deployment of innovative AI-based tools will be possible thanks to the expected huge leap in computing power and the **availability of new technologies such as quantum computing**.

In the short-term, **stability margins of future PEID-dominated systems** need to be carefully assessed to guarantee stable system operations and a key opportunity arises from exploiting **grid forming** capabilities from power converters both onshore and offshore. The ability of inverter-based resources to perform grid forming, thus supporting system stability, requires **demonstrating** in power systems through a step-by-step approach, starting from systems with **medium to high penetration of PEID**. From this perspective, the integration of electrolysers in the **power system also** requires demonstrating.

The increased power electronics penetration into power grids and the high share of generation from renewable sources are leading to more challenging voltage control; thus, common approaches for the **secure delivery of reactive power** require developing and agreement among system operators. The proper monitoring of the compliant behaviour of grid-connected resources and HVDC links under the different operating conditions, thanks to enhanced and suitable tools **for compliance validation**, is another technical aspect to be considered to ensure secure and stable grid operation.

Furthermore, to ensure the AC/DC grid stability, TSOs need to develop control strategies and tools to **manage large power flows across Europe** as well as platforms and approaches to **improve cross-EU ancillary services exchange**. Finally, it is of particular importance to **demonstrate restoration plans** and **pan-EU system defence plans,** as well as to **adapt codes and procedures considering numerous HVDC and offshore plants**. This will be the key to properly operating the AC/DC power system in all different scenarios, ranging from normal operation to unplanned situations, emergencies and faults.

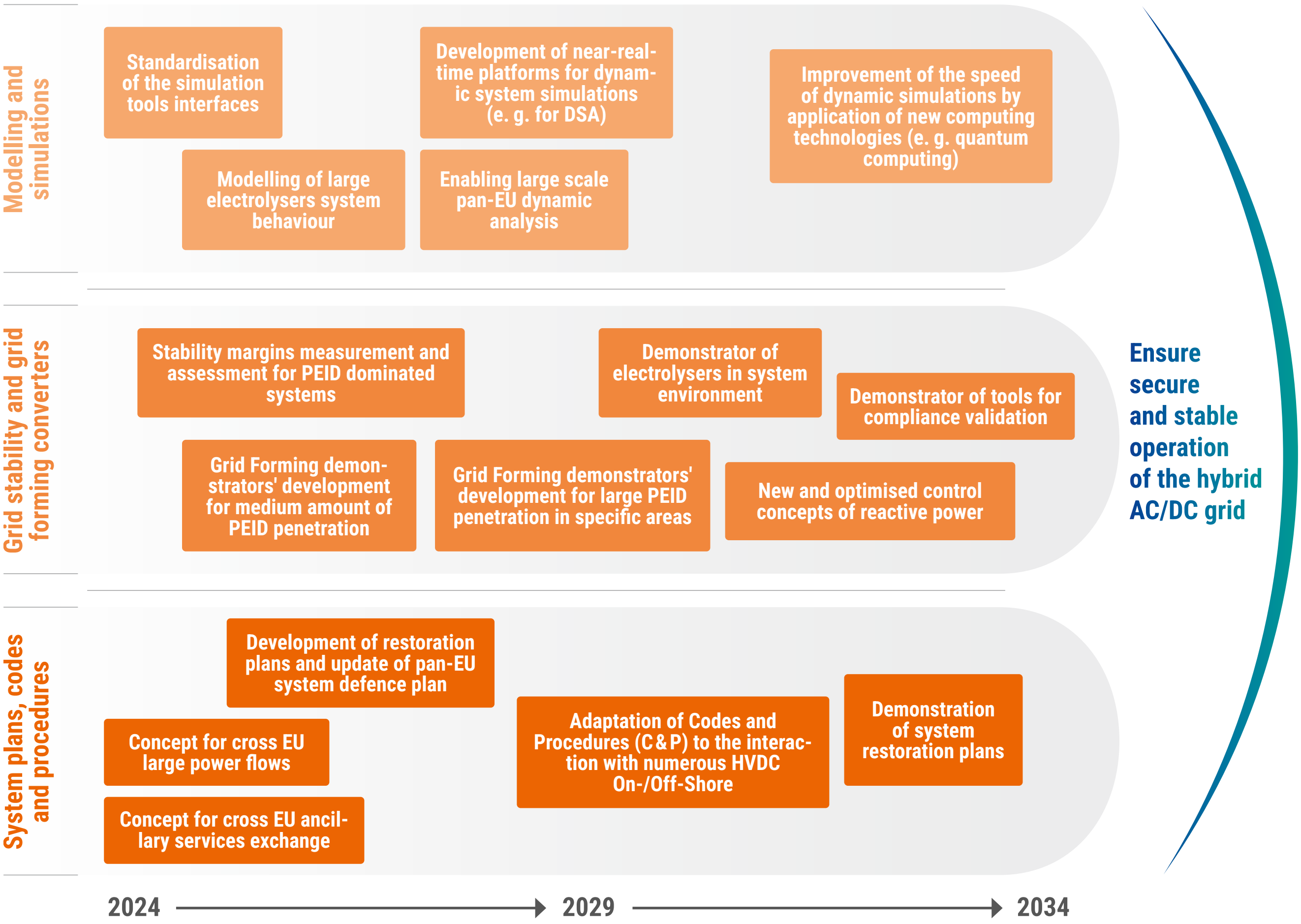

Figure 9: Mission 3 – Ensure secure and stable operation of the hybrid AC/DC grid

Mission 4 –
Enhance control and interoperability through digitalisation

The increasing complexity of the energy system and the growing number of distributed resources call for the development of smarter and more resilient power grids. System operators are challenged to manage transmission systems more flexibly and to accelerate the ongoing digitalisation, while ensuring protection against cybersecurity threats. This translates into a change of paradigm for the management of the electric system. Control centres operation needs to be improved by leveraging innovative methods and approaches, while taking advantage of the deployment of a pervasive monitoring infrastructure.

In the short-term, TSOs must ensure the interoperability of different control centres at both national and European level, thanks to the **standardisation of data exchange protocols** and the deployment of **interoperable data spaces for seamless data transfer,** while developing and implementing innovative **cyber security approaches** to minimise the risk associated with the increasing system digitalisation. Moreover, pursuing **vendor agnostic architectures** and developing **vendor agnostic modules & tools for system control applications** will enhance the options for managing the increasing grid complexity and will allow for more coordinated and efficient system operations.

In the short-term, TSOs need to implement **advanced visualisation options** for control centres to support control room operators' daily activities with more effective visualisation interfaces and by making alert signals clearer. On a longer time horizon, it is expected that control room operators will be supported by even more innovative tools, such as **augmented reality or holograms**, in the performance of their daily tasks and training activities. Paramount to control room operations is also the deployment of a monitoring infrastructure enabling close-to-real-time grid observability. From this perspective, in the coming years, the **integration of the data from Dedicated Measuring Devices (DMDs) in control rooms** will be crucial to improving system observability and situational awareness.

Digital twins of the electrical grid will play a key role, in the medium to long term, in providing grid **dynamic representation** and eventually aiding **grid control**, while the development of **new concepts for Wide Area Monitoring Systems (WAMS)** will open new possibilities for **dynamic security assessment** in the years to come. Moreover, the development of **concepts for the integration of Point-On-Wave (POW) measurement technology in WAMS** will pave the way to further enhancing grid observability.

AI-based technologies are expected to provide breakthrough innovation and will be leveraged to make control room operations more efficient, starting from routine activities, such as **producing continuous and periodic reports** in addition to enabling a detailed analysis of network status. Moreover, from a longer-term perspective, AI will also be introduced in decision support systems, thus providing a direct support to the on-line system operation.

Climate is changing and extreme weather events are becoming increasingly frequent. From this perspective, enhanced **tools must be implemented to manage criticalities and emergencies** in real time, thus improving the so-called operative resilience and supporting the operators in assessing possible multiple failures of both the physical and the digital infrastructures. Moreover, the increasing weather-related risks also call for a **transition towards probabilistic risk management** approaches with respect to the traditional deterministic ones. In the long term, real-time operation will be enhanced by the exploitation of **highly innovative power flow simulation tools,** that will leverage the foreseen innovation in computing technologies (e.g. high power computer or even to exploit quantum computing).

Finally, the **continuous training** of control room personnel for the efficient and effective use of the implemented solutions will be key to fully exploiting all the newly introduced digital tools features.

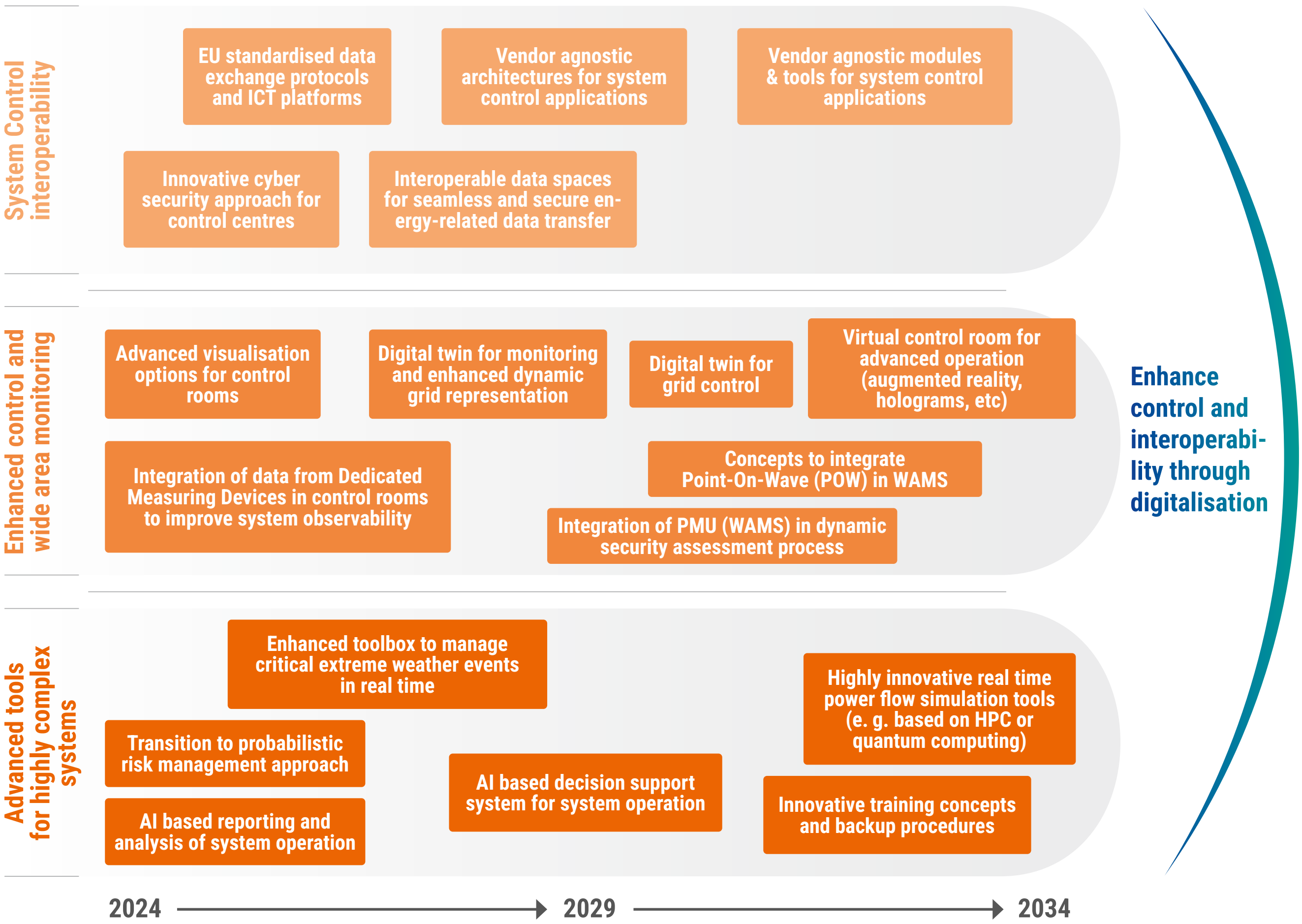

Figure 10: Mission 4 – Enhance control and interoperability through digitalisation

RDI Cluster 3 – One-System of integrated systems

Achieving the milestones in this Cluster will improve system flexibility and exploit cross-sector integration, valorising resources from the whole energy system. The milestones are organised into two Missions:

- **Mission 5 – Enhance flexibility assessment and market mechanisms.**
- **Mission 6 – Tools and strategies for optimal cross-sector integration.**

Mission 5 – Enhance flexibility assessment and market mechanisms

As the shares of variable renewables and distributed energy resources increase, power systems need to become more flexible to facilitate their integration. To meet climate goals, it has been estimated that the need for system flexibility has to sharply increase in the coming years and therefore grids have to be operated to leverage all possible sources of flexibility. To achieve this, grid-enhancing technologies should be deployed, digitalisation need to be exploited to allow demand response and energy storage integration and any kind of flexibility solutions, also from other interfaced sectors, should be leveraged.

To enhance the coordinated utilisation of resources, **peer-to-peer, local, wholesale and ancillary services markets** should be integrated in daily power system operation. Moreover, from a longer-term perspective, **market mechanisms for system security and system adequacy** require implementation and validation.

To continuously expand the portfolio of suitable flexibility sources, TSOs will have to implement solutions for the **efficient utilisation of demand side response** and, in the longer term, for the **integration of HVDC links, renewable power plants and offshore installations in the ancillary services markets**. It is also crucial to establish proper incentive mechanisms to foster flexibility services provision. Different approaches need to be pursued, ranging from the development of new **market mechanisms** to the application of **tariffs** and **incentives**, and the implementation of innovative **business models**, while also considering **operator interactions with aggregators, communities and customers**.

In the short term, **TSO–DSO coordination** will be reinforced, especially concerning system planning, thus making possible to optimise resource allocation and the efficient exploitation of distributed flexibility sources. TSOs will also foster **technological advancement that tackles interconnectivity issues,** such as thermal and stability limits, as well as frequency and voltage regulation to enhance the connection among different systems.

Digitalisation and in particular the adoption of **digital twins** and advanced algorithms, will make it possible, in the long term, to **increase** the exploitation of **flexibility from renewable power plants**. From this perspective, suitable **ICT platforms for the mass deployment of ancillary services from distributed resources** (generation, controllable loads and storage systems, etc.) will also be developed and implemented.

Following the ENTSO-E Vision of a power system for a carbon-neutral Europe, TSOs will produce, with relevant stakeholders, a pan-European assessment of flexibility needs for the whole timespan of the energy transition, to guide a cost-efficient deployment of flexibility resources. Hence, the continuous **assessment of the grid's needs regarding flexibility** will guide TSOs in deploying targeted and effective solutions for enhancing power system flexibility. Moreover, with the aim of enhancing the transactions of flexibility, TSOs will have to define **ICT requirements and standards to collect market data**. Innovative solutions, enabled by **AI and machine learning techniques,** and block chain will also facilitate the unlocking and exploitation of system flexibility, for example by enabling the development of solutions **boosting horizontal and vertical system integration**.

Moreover, advanced tools need to be developed for balancing the grid with short market timeframes, while in the longer term other important concepts, such as the development of advanced interconnectivity modelling for better system integration, need to be implemented to achieve the desired high level of system integration.

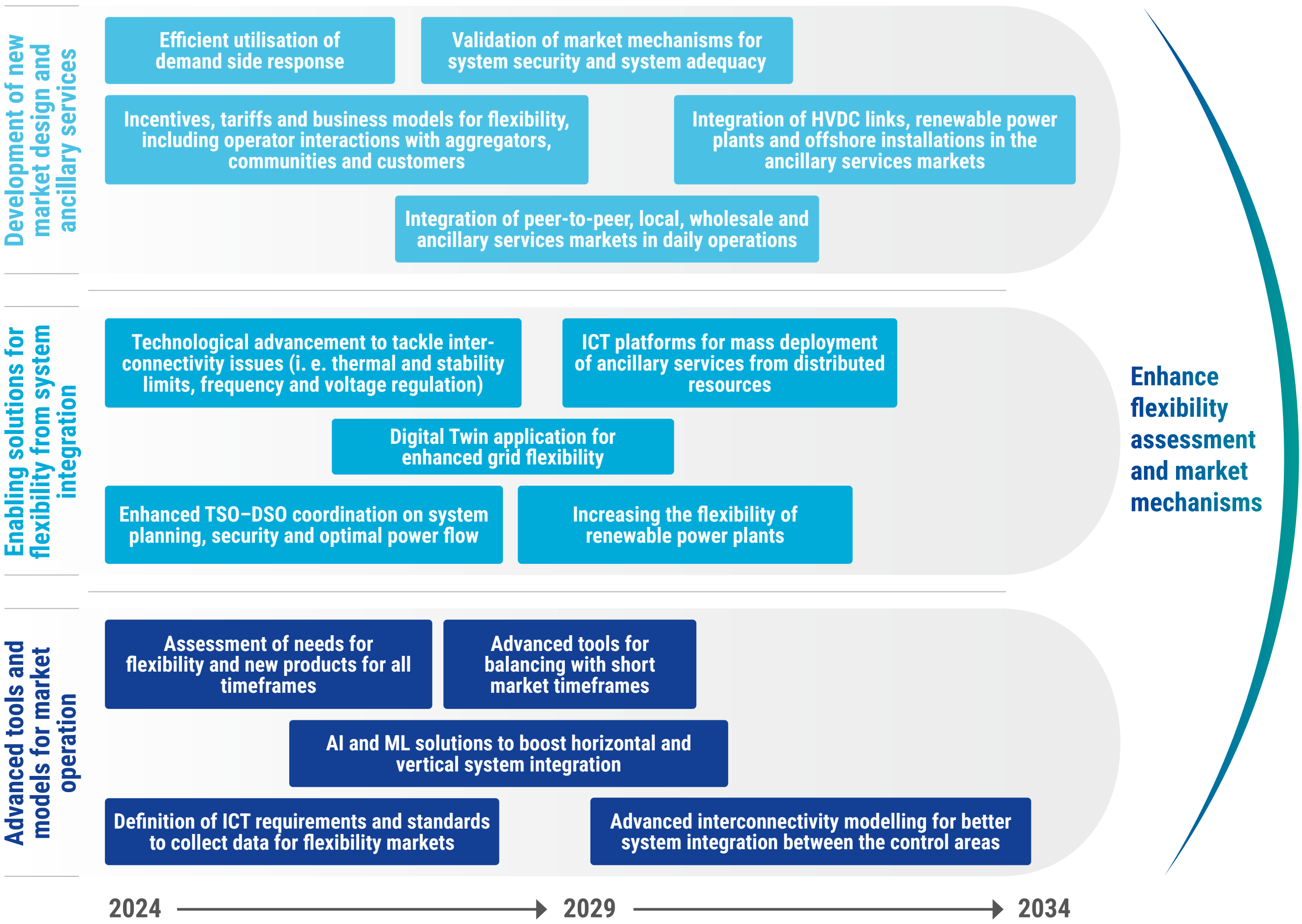

Figure 11: Mission 5: Enhance flexibility assessment and market mechanisms

Mission 6 –
Tools and strategies for optimal cross-sector integration

The current electricity system is evolving towards a network of interconnected energy systems. This demands a well-defined architecture and a clear identification of responsibilities and cooperation across all the involved actors and stakeholders in the different sectors. From this perspective, a series of new functionalities, that will enable the operation of a holistic system, has to be provided by European system operators.

To guarantee the stable operation of the future integrated system, the flexibility potential unlocked by sector coupling, as well as the potential of energy storage and cross-sector integration to support system restoration, require quantifying and monitoring. On the other hand, in the medium-term, to ensure the security of the electricity supply, new business models for system security and adequacy require implementation, and emergency and restoration plans for the EU integrated system require developing. Moreover, considering the increasing interdependence among different energy vectors, innovative solutions to enhance supply chain security for the integrated system require developing to maintain the overall security of the integrated system of systems.

The holistic planning of the transition towards a system of integrated systems requires the assessment of the potential benefits unlocked by the coupling of the different energy systems by leveraging the results made available by the **scenarios for the progressive cross-sector integration**. As electricity will be the key enabler for system integration, in the short-term, the **electrification potential** for all different energy sectors (i.e. residential, services, industry, heating & cooling and transport) must be properly assessed and monitored. Energy storage is expected to cover a significant portion of the necessary additional system flexibility; therefore, among other solutions, the **long-duration storage potential of hydrogen** and other resources will be carefully assessed. From this perspective and from a longer-term perspective, the **integration of flexibility from hydrogen in system operation** requires careful evaluation.

TSOs will be able to promote and achieve efficient and optimised system integration by developing **tools and models for holistic energy system planning**. For example, in the long-term, **optimisation tools for the integrated energy system require demonstrating** within the power system operation to achieve full integration among different energy sectors. It is important to underline that the developed new tools have to encompass the entire energy system, thus allowing for the most efficient use of flexibility resources across all sectors.

The definition of **network codes, which include the definition of roles and responsibilities**, represents a key milestone towards a well-functioning system of integrated systems. In this regard, the top priority is to **develop a harmonised cross-sector role model** to formally identify the roles and the responsibilities of the various involved actors and stakeholders. Moreover, to allow and facilitate the interconnections between the various integrated energy sectors, **standards for cross-sector interoperability and data exchange** must be developed.

Moreover, specific **feasibility studies that explore the operation of the integrated system** will pave the way for optimal cross-sector integration and management. These approaches will finally lead in the longer term to holistic **cross-sector planning,** that will embrace all the different sectors and technologies.

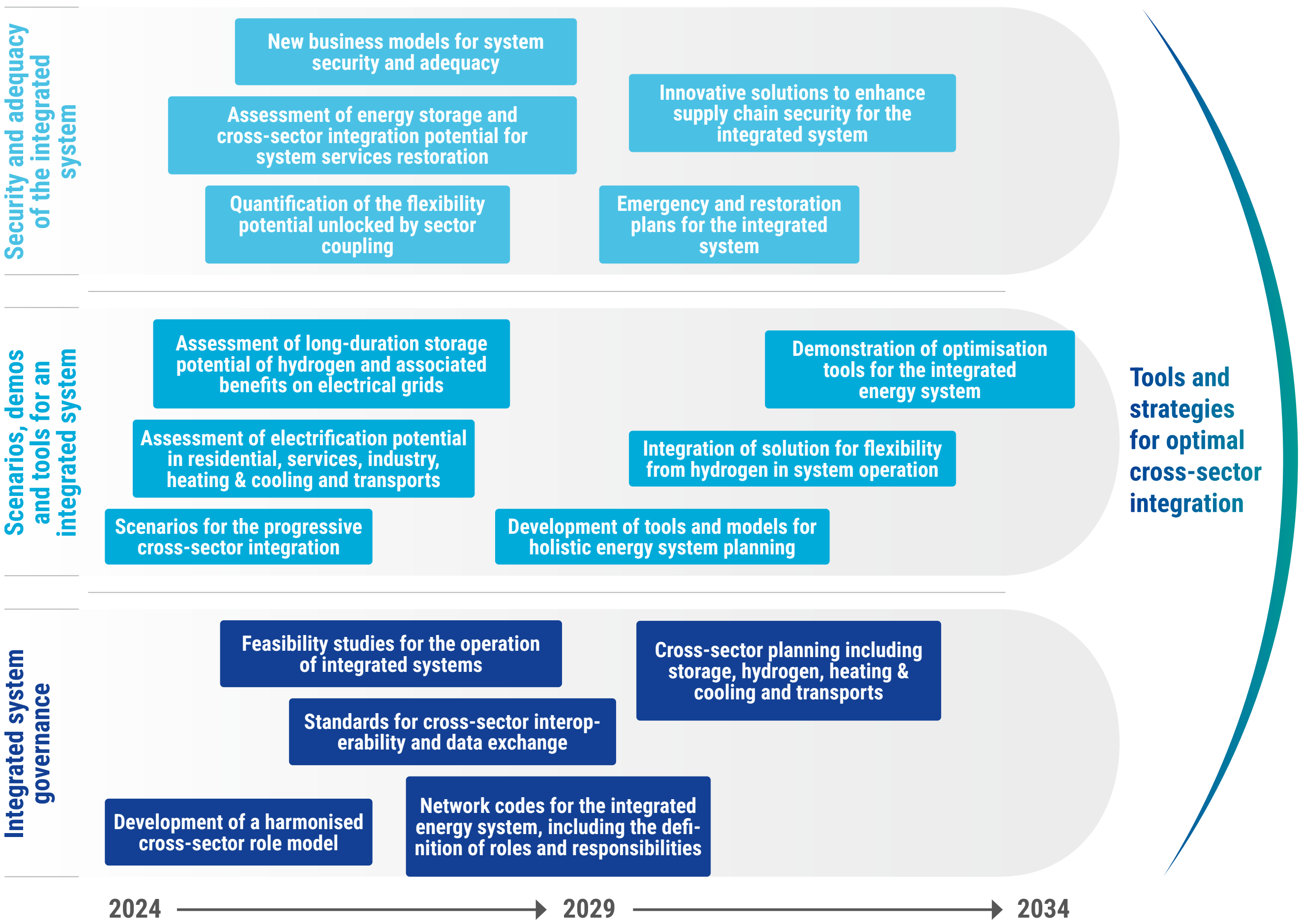

Figure 12: Mission 6: Tools and strategies for optimal cross-sector integration

5 Pathways towards high impact on the European energy system

Achieving the milestones highlighted in this RDI Roadmap 2024 – 2034 requires strong RDI efforts and funding instruments adequate to the scale of the challenges. From this perspective, ENTSO-E has performed a preliminary analysis of the Full Time Equivalent (FTE) engineers required to develop RDI activities to duly address all the innovation comprised in this Roadmap's six Missions. This chapter also highlights the link between this Roadmap and the ENTSO-E Technopedia as an important way to foster the spread and uptake of key innovative solutions, building credible pathways towards high impact on the European energy system.

To address the RDI priorities set by this RDI Roadmap for the next decade, the implementation of mature technologies and solutions, as well as enhancing the research into the most promising ones, will be fundamental to improving core business targets, such as the coordinated security of operation, maximising capacity in a secure manner, balancing between generation and demand, dynamic stability or coordinated network planning.

A tool which will be key for the uptake of innovative and state-of-the-art technologies is the ENTSO-E Technopedia, which collects factsheets of technologies covering the fields of transmission assets, digital and flexibility solutions. The up-to-date information gathered by Technopedia will help involved actors to assess the available technologies, their advantages and readiness level. Establishing a strong and direct link between Technopedia and the RDI Roadmap allows the technologies to be underlined that could be adopted for addressing the identified RDI Missions and milestones. A mutual link is established as the RDI objectives set by this Roadmap also serve as an input to Technopedia, thus enhancing a better understanding of the available technologies and their field of application.

The connections between the ENTSO-E Technopedia technology types, namely 'Asset', 'Digital' and 'Flexibility', and the Clusters of the present RDI Roadmap 2024 – 2034 are manyfold and depicted in Figure 13 and Figure 14.

In more detail, **Asset technologies** listed in Technopedia are linked to milestones of both Cluster 1 and Cluster 2. For example, 'Voltage source converter' relates to different milestones of Mission 2 and 3, while 'Phase shifting transformers' are relevant to Mission 1 and 'STATCOM' to both Mission 3 and Mission 1. Other technologies categorised as 'Asset' in Technopedia, such as 'Dynamic Line Rating (DLR)', as well as 'HVDC Circuit Breakers' and 'Hybrid AC/DC OHL', will be key to enhancing the grid use (Mission 1) and to ensuring stable grid operation (Mission 3).

Digital technologies listed in Technopedia are instead tied to all three Clusters, as digitalisation is not a target in itself but it will directly improve the core business processes. From this perspective, we can note that 'Artificial Intelligence' is linked to many topics addressed by the RDI Roadmap and that nearly all the clusters have specific milestones dedicated to different aspects of 'Digital Twin' technologies, for example 'Digital twin for optimisation of assets maintenance and replacement in operation' (Mission 1), 'Digital twin for monitoring and enhanced dynamic grid representation' and 'Digital twin for grid control' (Mission 4) and 'Digital twin application for enhanced grid flexibility' (Mission 5).

Flexibility technologies are involved in all clusters as, heading towards carbon neutrality, the flexibility needs identified by TSOs and DSOs will be translated into services and market-based mechanisms, developed to provide the related flexibility services for planning and managing the system, and this will require the deployment of multiple resources of carbon-neutral flexibility, including flexible generation, active demand, storage, sector integration and flexible grid use. More specific examples can be found, e.g. 'Virtual Power Plants' is connected to some Mission 5 milestones, while several other specific technologies listed in Technopedia, such as 'Demand response', 'Battery technology', 'Market Coordination Platforms' or hydrogen-related technologies, are linked to several topics of the RDI Roadmap.

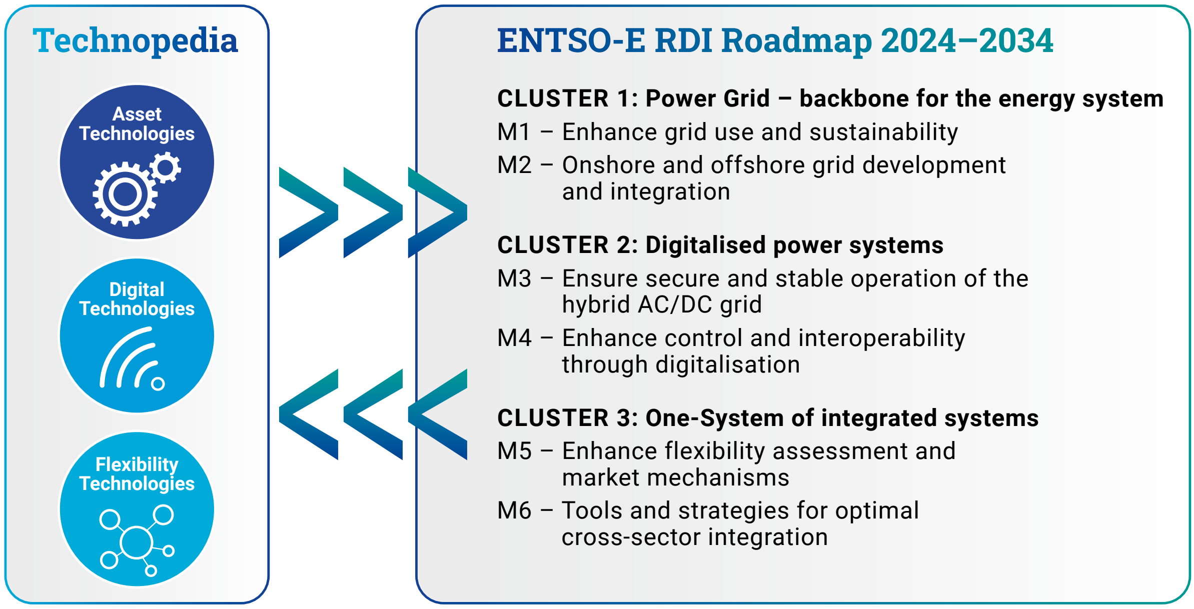

Figure 13: Interaction between ENTSO-E Technopedia and the RDI Roadmap 2024 – 2034

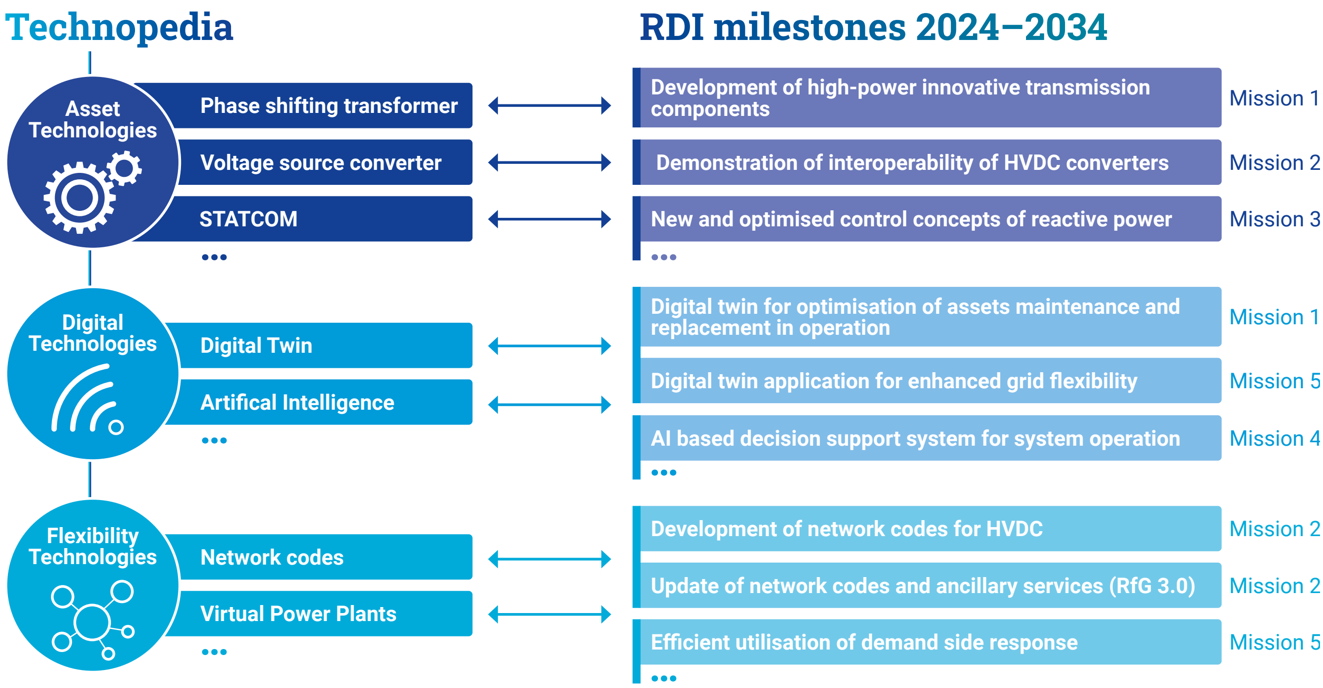

Figure 14: Example of specific interactions between the Technopedia technologies and the RDI Roadmap milestones

This strong link between the RDI Roadmap and Technopedia enables the creation of pathways towards high impact on the European energy systems. Furthermore, as the power system technologies support the achievement of the milestones in this Roadmap, achieving the milestones in this Roadmap promotes the technology readiness level of the power systems technologies. Hence, the targeted RDI efforts of the TSOs in delivering the milestones are necessary to exploit and develop the technologies to build a carbon-neutral energy system that is a sustainable, flexible and digital system of systems, with the power system at its core.

Making it happen

It is important to mention the relevance of de-risking grid investments by setting up strategies to highlight the strategic importance of grid infrastructures and, hence, the importance of continuous political support. This approach will be seen by investors as a reliable signal, thus enhancing their willingness to invest in clean energy transition-related projects.

In fact, by harmonising the ENTSO-E RDI inputs with internal RDI requirements, the TSOs' RDI efforts will enhance the system performance and security, while simultaneously contributing to the collective goal of achieving the EU's broader energy objectives. Hence, this RDI Roadmap is structured around three Clusters and six Missions and outlines 90+ key milestones, with the aim of translating innovations into improvements of the TSOs objectives, such as efficient transmission system development, secure system operation and enabling an effective European market, as well as with the overarching energy targets established by the European Commission that require major RDI efforts to be reached.

Following previous observations from ACER, concerning the estimation of the resources required to fulfil the RDI activities, TSOs performed an initial estimation of the effort required to achieve the milestones. Building upon data from previous RDI projects collected to support the ENTSO-E RDI Monitoring Report 2022 and other TSO RDI activities, it is estimated that, in each year, each of the 40 members of ENTSO-E require an average of 5.6 Full Time Equivalents (FTE)[14] to achieve the successful implementation of projects and activities addressing the identified RDI milestones. This effort estimation is a projection of the effort that all TSOs alone need to devote to research and innovation actions and it does not reflect the efforts from other stakeholders in the collaborative activities necessary to successfully achieve the milestones. Hence, the projection of the effort of TSOs alone can be seen as a lower bound of the overall effort required to successfully deliver the milestones, and it aims to inform public authorities and policy makers responsible for defining the proper financing framework for the evolution of the pan-European electricity system.

The Energy Council acknowledges the role of electricity grid infrastructure development as a critical enabler of the energy transition, security of supply and EU climate objectives[15].To accelerate the energy transition and achieve carbon neutrality with energy security and independence, it is necessary for TSOs to boost their own RDI capabilities and, in this way, underline the relevance of the evolution of the incentivising framework to enable TSOs' direct investments to properly address relevant RDI activities and topics. This will steer collaborative innovation activities between TSOs, as well as with research centres, universities and technology developers, leading to the realisation of the milestones in this Roadmap. Therefore, appropriate incentive frameworks for TSOs' RDI activities spread across the ENTSO-E control areas would make it possible to tap into a wider pool of knowledge and to foster synergy between different fields, which is crucial for tackling the complex and frequently multi-disciplinary challenges that modern power systems are facing.

Regarding external research ecosystems, suitable calls for projects, addressing the milestones reported for each of the six Missions of the present ENTSO-E RDI Roadmap, would provide support to European TSOs in developing and leveraging such research ecosystems towards common objectives. As TSOs are committed to accelerating the energy transition[16], presently, TSOs are largely following this second path of RDI support by using the different funding programmes available, often without full recognition of the investments in the RDI activities.

It would be most effective to utilise both methods in parallel, extracting benefits from each approach to accelerate the energy transition. Including the milestones of this Roadmap as outcomes of the topics in the European Commission innovation programmes and improving forward-looking regulatory frameworks to support the investment from all TSOs in RDI activities[17] are two of the measures that can be taken to accelerate the development of the sustainable, flexible and digitalised power system for a carbon-neutral Europe.

14 Here it is used the guideline 1 FTE = 215 working days (**Guideline-unit-costs.pdf (europa.eu)**)

15 Advancing Sustainable Electricity Grid Infrastructure – Council conclusions (30 May 2024) (europa.eu)

16 RDI Monitoring Report: Screening 117 research & innovation projects of the TSOs (entsoe.eu)

17 **Innovation Uptake through Regulation (entsoe.eu)**

6 Next steps towards implementation

Building on the ENTSO-E Vision of a power system for a carbon-neutral Europe and on the ENTSO-E Strategic Roadmap, this ENTSO-E RDI Roadmap outlines the key RDI milestones to guide the research and innovation agenda of European TSOs over the next decade. Six Innovation Missions and 90+ milestones have been identified thanks to a comprehensive and collaborative approach that includes the analysis of the power system main innovation drivers, from both European institutions and TSOs. The effective achievement of these milestones will build a sustainable, flexible and digitalised power system, ensuring energy security and promoting energy independence in a carbon-neutral Europe.

To achieve a carbon-neutral Europe with energy security and energy independence, the European electricity system needs to keep high levels of reliability and cost-efficiency while integrating an increasing amount of onshore and offshore renewable technologies, as well as an increasing amount of distributed energy sources.

To accelerate the energy transition, this Roadmap identifies 90+ key milestones, with the aim of driving European TSOs' research, development and innovation activities over the period 2024 – 2034. Organised into six Missions, the selected milestones are fully aligned with both EC strategies for the clean energy transition and the innovation needs by European TSOs.

The effective achievement of the identified milestones will ensure that the power system facilitates the energy security and energy independence in the European space with global net zero emissions. Building on this Roadmap 2024 – 2034, ENTSO-E will develop the RDI Implementation Plan, outlining project concepts which address the selected priorities for the upcoming years.

Given the grand innovation challenges outlined in this RDI Roadmap, which focuses on the power system, but embraces the whole energy system value chain, enhanced cooperation among TSOs and all stakeholders is paramount. In fact, to develop the necessary demonstration projects, different experiences and skills need to be combined in a joint and coordinated effort, as well as RDI funding instruments adequate to the scale of the challenges.

Contributors

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List of Abbreviations

BIM	Building Information Modelling
DMD	Dedicated Measuring Devices
DLR	Dynamic Line Rating
DSO	Distribution System Operator
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
EV	Electric Vehicles
FTE	Full Time Equivalents
HDEV	Heavy Duty Electric Vehicle
HVDC	High-Voltage Direct Current
ICT	Information Communication Technology
POW	Point-On-Wave
PV	Photovoltaic
RES	Renewable Energy Source
RDI	Research, Development and Innovation
TRL	Technology Readiness Level
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
WAMS	Wide Area Monitoring Systems

Drafting Team

RDI Planning convener:
Nuno Pinho da Silva . . . . REN | Working Group

Anastasiia Synytsia . . . . Ukrenergo
Anders Nørgaard . . . . Energinet
Kevin Lunge . . . . Amprion
Lóránt Dékány . . . . ENTSO-E
Luca Orrú . . . . Terna
Maksymilian Przygrodzki . . . . PSE
Mihai Marcolt . . . . Transelectrica
Valentinas Dubickas . . . . Svenska Kraftnät

Luciano Martini . . . . RSE
Mattia Cabiati . . . . RSE
Omar Pasqualotto . . . . RSE

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ENTSO-E AISBL
8 Rue de Spa | 1000 Brussels | Belgium
www.entsoe.eu | info@ entsoe.eu

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