ENTSO-E

# Research, Development & Innovation Roadmap 2024-2034

24/5/2024

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# 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, increase resiliency, secure system operation and enabling an effective European market in response to the EU climate and energy objectives.

ENTSO-E, in accordance with Article 30(1)(i) of the Regulation (EU) 2019/943 of the European Parliament and of the Council, 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 the instrument highlighting 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 up to the challenge of the much more dynamic future power system of systems 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.

Apart from 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 to drive 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 strategies for grid development 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 systems, the RDI Roadmap 2024-2034 focuses on topics related to TSO business processes, such as coordinated security of operation, maximising capacity in a secure way, balancing between generation and demand, dynamic stability or coordinated network planning. The successful implementation of this Roadmap will enhance existing grid use and the utilisation of 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 wide spread 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.

The process that led to the update of the RDI Roadmap followed the cycle shown in Figure 1, which is repeated by ENTSO-E on a four-yearly basis. In fact, after the releasing of the RDI roadmap, ENTSO-E proceeds with the development of the RDI implementation plan which represents a bridge between the flagships described in the RDI Roadmap and the real implementation of projects dealing with the identified milestones. The progress of the implemented TSOs projects are then analysed in the RDI Monitoring report which assess the alignment of the current RDI activities with the strategic direction. Then, the Monitoring report serves as a review and provides the crucial inputs for the next RDI Roadmap.


*Figure 1: The ENTSO-E RDI Roadmap cycle*

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

Even though 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 achieve this objective are evolving and key innovation drivers have evolved since the publication of the last ENTSO-E RDI Roadmap 2020-2030. In this chapter a comprehensive analysis of the power system main innovation drivers, from both European institutions and TSOs is provided.

## Key Top-down drivers

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 transports. Beyond that, the EC "**Grids, the missing link - An EU Action Plan for Grids**" and the "**Digitalising the energy system - EU action plan**" recognizes that Europe's power networks are confronted with new grand 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 brings the power grid at the centre of its policy agenda** and promotes deeper electrification of the 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 to develop a fully integrated energy systems increasingly calls for a holistic approach, where the planning and operation of European electricity transmission and distribution networks must be harmonized 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 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 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 EU climate objectives** to reduce greenhouse gas emissions by a minimum of 55% by 2030 and reach net zero emissions by 2050. The EC foresees the large-scale deployment of hydrogen to contribute to climate neutrality, to decarbonize hard to abate energy sectors, to provide long-term large-scale seasonal energy storage thus to help solving the issue of 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 to consider storage assets as being in the overriding public interest, thus to facilitate permitting procedures.

The EU Grid Action Plan put a strong emphasis on correlating planning and operation of Europe's electricity networks with the **planning and operation of the new charging infrastructure for e-mobility.** In addition, the Alternative Fuel Infrastructure Regulation (AFIR) sets mandatory targets for the number and spatial distribution of publicly accessible recharging stations for both EVs and Heavy Duty Electric Vehicles (HDEV). Charging hubs able to serve several trucks at the same time will necessitate connection capacity of more than 10 MW each, thus directly impacting high-voltage grids. The AFIR lays also 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, 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.

As already pointed out in the RDI Roadmap 2020-2030, **huge investments on grids are needed** to achieve the decarbonisation targets maintaining system security and efficiency. While there's 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[1]. This is not only a problem for the future, but one that we are seeing today already, where long lead times for grid upgrades and grid connection acts as a bottleneck for renewables deployment in many places.

This has been also recognised in the EC "State of the Energy Union 2022" where investing in the power grid to enable greater electrification (EUR 29bn) has been listed among other key investment needs.

As the shares of variable renewables such as solar 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 electric vehicles (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 the largest share of that flexibility.

The EU's electricity network has become increasingly digitalised in the last decade, but the speed of transformation needs to increase significantly, **digitalisation of the energy system is now a policy priority**. In fact, digital technologies can help resolve current operational challenges, supporting the integration of renewable and distributed energy resources, and reduce operational costs by optimising system efficiency. In this view, the EC "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. 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 optimize energy systems, including equipment condition-based maintenance to help reducing unplanned downtime and improve energy efficiency, to elaborate accurate weather and renewable power generation forecasts or to support power system operation.

With the deep digitalisation of the energy system, **cybersecurity becomes an increasingly essential requirement**. It plays a key role for the energy

[1] IEA - Electricity Grids and Secure Energy Transitions: https://iea.blob.core.windows.net/assets/ea2ff609-8180-4312-8de9-494bcf21696d/ElectricityGridsandSecureEnergyTransitions.pdf

system to remain secure and robust against cyber incidents and major attacks.

While defining strategic objectives for RDI activities of the coming decade, it must be considered the importance for Europe to **mitigate the risks for the critical materials' supply chain** as declared by the EC in the Critical Raw Materials Act

Finally, it's important to underline the relevance of the Net-Zero Industry Act which aims at promoting investments in the production capacity of products that are key in meeting the EU's climate neutrality goal. In particular, Net-Zero strategic projects, that will benefit from priority status thus shorter timelines, will address resilience of the energy system and cover innovation in PV and renewable technologies, storage and grid technologies among others.

## Key Bottom-Up Drivers

Besides key policy documents, RDI roadmaps and strategies from European TSOs have been analysed to assess the main bottom-up drivers and changes with respect to 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, since innovation, as digitalization 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 by 2050 and acknowledge the relevance of moving towards an **optimised and integrated energy system** by 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 develop and implement solutions with the rapid massive growth of solar and wind power resources connected to the grid by power electronic converters (PEID) that radically change the system characteristics creating a number of significant challenges in terms of system stability. In this view, 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, alongside a surge in intermittent power production from solar and wind energy, lead also 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 like hydrogen, demand-side flexibility, and peak power plants are expected to gain increasing importance and their development is crucial to achieve 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, a major RDI efforts should be dedicated to ensuring **that offshore energy becomes a cornerstone of the EU future energy system** as envisaged by the EC's offshore RES strategy that aims to 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 needed, given that energy fluctuations will become more pronounced. In this view, 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. Today, the availability of huge data processing power and of broad communication bandwidths at significantly lower cost every year, is leading to the mass deployment of digital solutions. 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 drones, robots, and real-time data sensors, will facilitate the adoption of **more efficient, cheaper and safer remote monitoring** and inspection activities in order to maximise the utilization of existing assets. Virtual and augmented reality for remote inspection and maintenance activities will also play a relevant role allowing to save costs by, e.g., minimising the number of physical site visits.

Besides the challenges introduced by the increasing penetration of weather dependent power generation, extreme weather events 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, which are designed to limit the consequences of severe incidents in terms of reduced power outages and recovery times, need to be updated to tap into the new opportunities arising from recent developments in the energy sector. Enhanced resilience analysis methods for identifying grid and system vulnerabilities associated to new risk drivers, in particular related to environmental threats, are needed to offer a different perspective on equipment and electrical engineering operating risks of power systems that are deeply interconnected and depends on one another.

Moreover, trends include the deployment of innovative materials and solutions towards more **sustainable power systems**, 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 $SF_6$.

**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 need to be assessed and implemented. It is indeed relevant to develop market models, integrate infrastructure planning and operate solutions in electricity and other energy sectors which support 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, need local resources.

To enhance the optimal management of end-users' resources, 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 for participating in energy markets. To empower consumers and promote their engagement, is also needed to set clear rules, make it easy for end-users' devices to cooperate across the system, by means of standardised and modular approaches to customer connections.

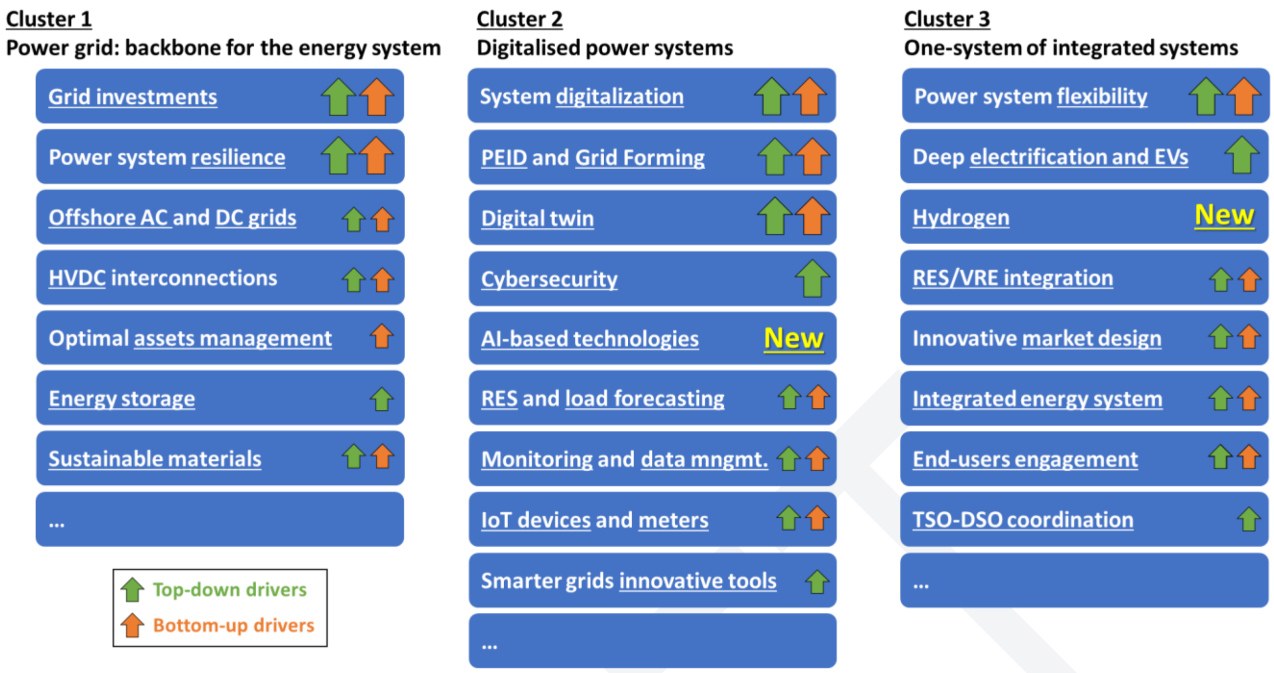



*Figure 2: Main drivers and their relative change in relevance with respect to the former RDI roadmap 2020-2030*

# 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 needed 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 power system for a carbon neutral Europe[2], innovations this Roadmap are aimed to deal with the evolution of the flexibility needs and support 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 TSO business activities in the future energy landscape in Europe that will clearly be a System of interdependent Systems.

RDI efforts must involve integrated and coordinated activities including assets optimization and digitalization to enhance the operation of future power systems, assessment of flexibility needs at all time scales, 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-sectoral 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 towards the power system of the future, see the scheme reported in Figure 3.

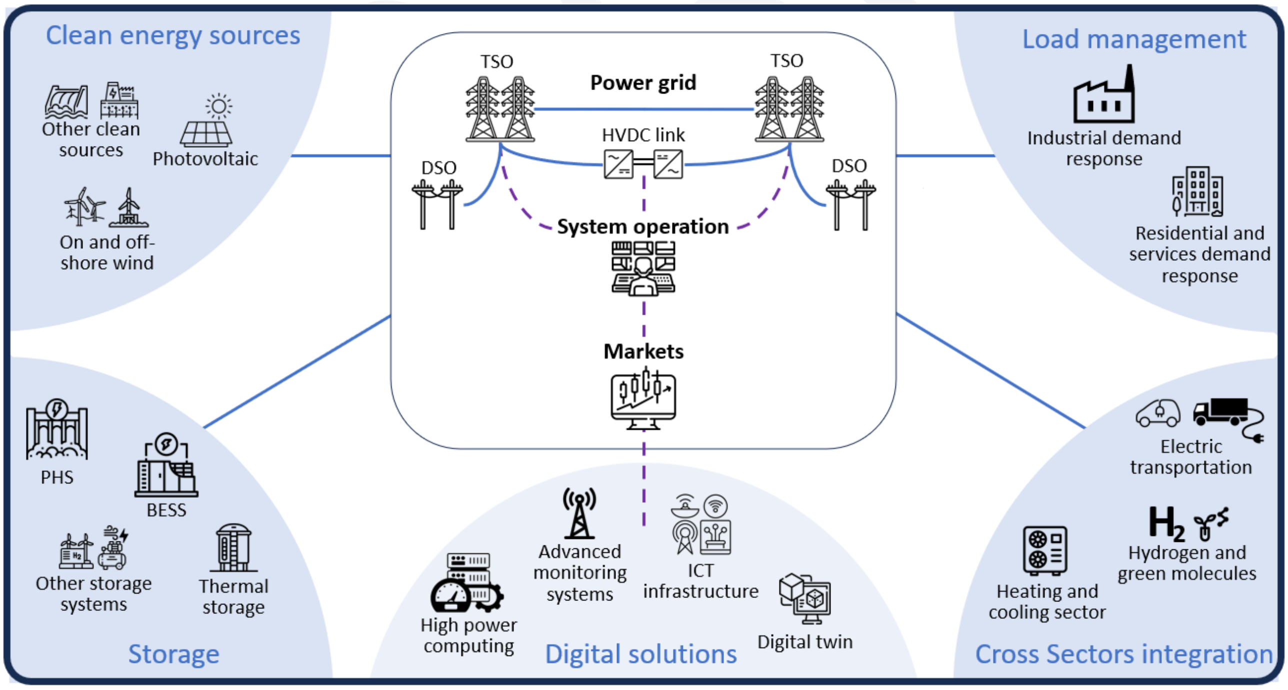



*Figure 3 – The future sustainable, flexible and digital system of systems.*

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 takes into account the outcomes from the ENTSOE RDI Monitoring Report 2022 and

[2] ENTSO-E Vision: A Power System for a Carbon Neutral Europe (entsoe.eu)

related assessment about the ongoing TSOs' RDI activities against the previous RDI Roadmap and the RDI Implementation Plan.

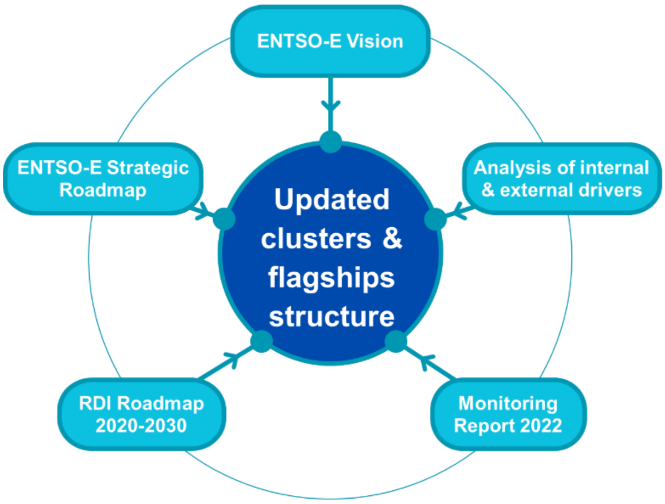



*Figure 4 – Key inputs to the ENTSO-E RDI Roadmap updating process.*

A graphical representation of this process is depicted in Figure 4.

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 to the service of the the TSO objectives, namely

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

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

The Strategic Roadmap is organized 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

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 5. As it can be seen, each pillar is structured into building blocks representing the main thematic areas of interest. As reported in Figure 5, five building blocks are inherent to the future of the power grid (Pillar 1) whereas two of them address the management of the present grid (Pillar 2). All the five building blocks included in Pillar 1 provide inputs to the present Roadmap and in particular, the "Innovation" one embraces all the 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 underpins specific RDI clusters or flagships. In particular, "Infrastructure & Investments" is well represented by the RDI cluster 1 (*Power Grid, the backbone of the energy system*), being centered around the development of the grid infrastructure both onshore and offshore. "Operating future grids", focuses on operating the power system's 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*) that focus on relevant topics such as balancing and operating the integrated energy system, deploying flexible solutions, and implementing proper market mechanisms for energy and flexibility, takes into account 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 flagships 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.

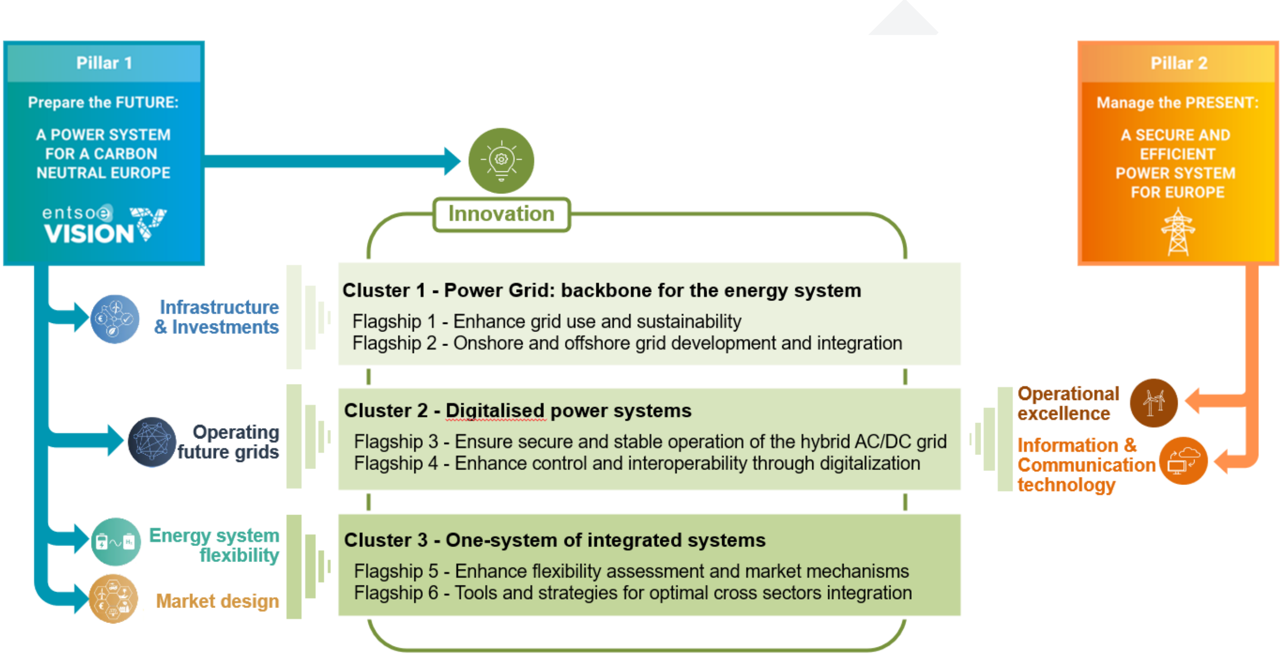



*Figure 5 – ENTSO-E RDI Roadmap 2024-2034 in the framework of the ENTSO-E Strategic Roadmap*

In the following a brief introduction about main motivation, scope and objectives of the three clusters and the related six flagships included in the ENTSOE RDI Roadmap 2024-2023 is reported.

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

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

As electrification and clean energy transition progress, power grids which represent the backbone of the energy system will gain even more relevance for the world economy and our societies. 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.

Maximizing the utilization of the existing grid infrastructure and planning targeted grid reinforcement or new HVDC connections to harvest renewable energy source remotely located from the final consumption is key to guarantee the possibility to reach the ambitious decarbonisation targets while maintaining grids secure and economically efficient.

By applying innovative technologies and further digitalising 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 to support both daily operation and condition-based maintenance.

The RDI Cluster 1 comprises the following two Flagships:

- **F1 – 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.

- **F2 – Onshore and offshore grid development and integration**: To further develop HVDC and offshore grids to support and foster the EU green energy transition. In particular, this flagship addresses the planning of future grids and the entailed foreseen huge investments needed to realize it.

## 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 is highly strategic and hold significant transformative 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 still keeping the wanted high levels of resilience and reliability of the today's power grid.

As we move towards real-time power grid monitoring and management, standardisation of new technologies is becoming crucial. Moreover, the large penetration of Power Electronics Interfaced Devices (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 made available radically innovative solutions to make power system operation more efficient and secure.

The RDI Cluster 2 comprises the following two Flagships:

- **F3 – Ensure secure and stable operation of the hybrid AC/DC grid**: This flagship spans multiple concepts, such as to demonstrate stable operations of PEID dominated power systems by leveraging converters' grid forming capabilities, to develop models and simulation tools and to update restoration plans.
- **F4 – Enhance control and interoperability through digitalisation**: This flagship 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 electrification of demands call for a shift towards a unified, interconnected one-system of integrated systems, where seamless cooperation of actors across different sectors is prioritized. To fully exploit the potential of cross sector integration and specially to unlock electric system flexibility, all available resources have to be properly considered and valorised. In this view, innovative solutions to exploit the electrification potential from residential, business services, industry, heating & cooling and transport sectors must be deployed. To function smoothly and efficiently, the interconnected and integrated system require 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 harmonized planning and activities.

The RDI Cluster 3 comprises the following two Flagships:

- **F5 – Enhance flexibility assessment and market mechanisms**: With the goal of enhancing the flexibility of the energy system, this flagship focuses on the flexibility needs and requirements assessment and on innovative solutions to leverage all available flexibility sources considering both technical and economic aspects.
- **F6 – Tools and strategies for optimal cross sectors integration**: The main aim of this flagship is to assess the potential of integrating power grids into 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 Flagships

The electricity grid is facing major transformations and TSOs are frontrunners in the innovation process needed to maintain power systems reliable and affordable 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 need to be implemented, including fresh approaches to expanding and realizing 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, and security against threats, while also reducing carbon footprint. Thus, by embracing innovation, we can build an energy system that is flexible and efficient making electric grids able to deal with the pace needed to decarbonise the entire energy system rapidly and effectively.

Six Flagships, organised in three clusters representing key areas for future power systems, are presented in this chapter. Within each flagship, specific milestones indicate the objectives to reach in order to deploy the envisaged innovation. Power systems are a very complex ecosystem and Flagships 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 need to be ensured. In this way all the necessary skills and resources to achieve the different milestones will be guaranteed.

Cluster 1 - Power Grid: backbone for the energy system

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

- Flagship 1 – Enhanced grid use and sustainability.
- Flagship 2 – Onshore and offshore grid development and integration.

Cluster 2 - Digitalised power systems

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

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

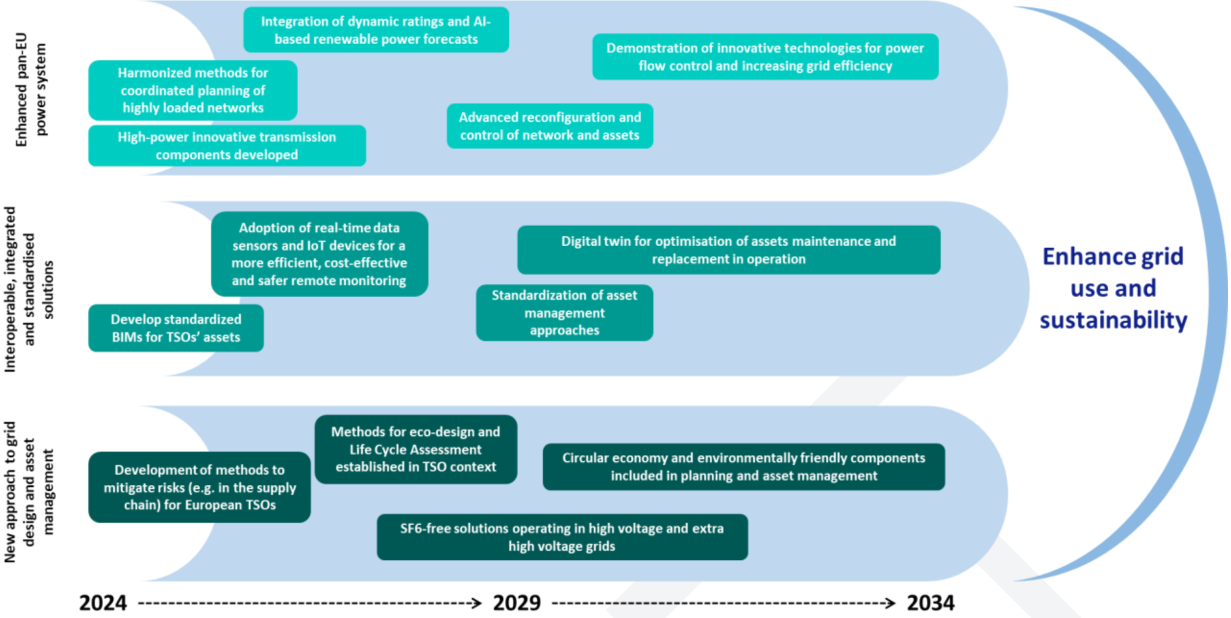
Cluster 3 - One-System of integrated systems

To improve system flexibility and exploit cross sector integration valorizing resources from the whole energy system.

- Flagship 5 – Enhance flexibility assessment and market mechanisms.
- Flagship 6 – Tools and strategies for optimal cross sectors integration.

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

## Flagship 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 IEA[3] they currently receive too little investments. To support and guarantee the acceleration of renewable energy deployment while ensuring secure and reliable power system operation, major innovation is needed to enhance transmission grids use and sustainability.

This flagship covers key milestones related to the improved exploitation of the EU power system as a whole. Innovative grid technologies and digital solutions need to be implemented in the short term, and 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. On a longer perspective, the developed innovative technologies such as **power flow control applications** aiming at increasing grid efficiency need to be **demonstrated in real environment**.

In the coming years, **AI-based methods** for 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** and the **adoption of real-time data sensors and IoT devices** will make possible to operate grids close to their physical limits.

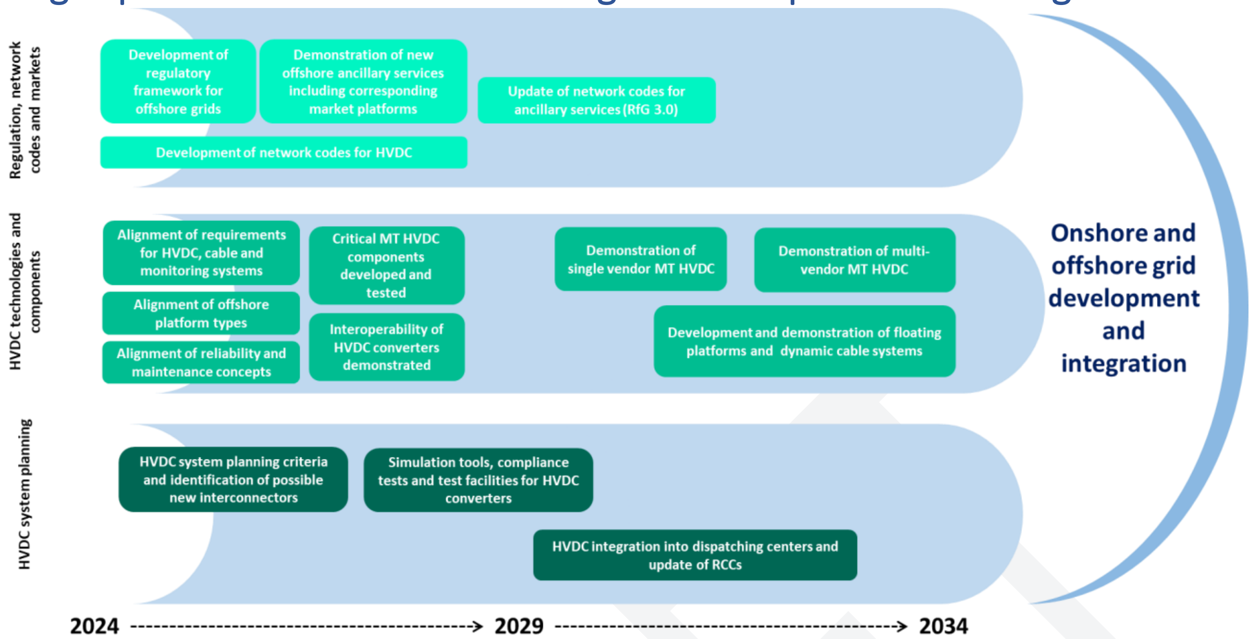
Besides monitoring and control, to develop innovative solutions that are **interoperable, integrated and standardised** will, in the medium term, pave the way towards further improving the management of the transmission grid assets. To achieve this, suitable pathways to include the **development of assets' BIMs**, standardized approaches for assets management and innovative technologies such as **digital twin**, for example, to optimise assets maintenance and refurbishment, need to be identified and implemented.

In order to enhance and ensure the environmental sustainability of the transmission grid and the entire power system, new approaches to grid design and asset management need to be develop 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. As an example, the deployment of **SF6-free solutions** is a relevant step to enhance the sustainability of transmission power systems, and in line with the

[3] IEA - Electricity Grids and Secure Energy Transitions: https://iea.blob.core.windows.net/assets/ea2ff609-8180-4312-8de9-494bcf21696d/ElectricityGridsandSecureEnergyTransitions.pdf

EC commitment to phasing down fluorinated greenhouse gases.

## Flagship 2 – Onshore and offshore grid development and integration




High-voltage direct current (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. In this view, 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 to carry more clean electricity 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 high-voltage direct current (HVDC) connections must be utilised instead. As a result, a major part of the integration of large-scale offshore renewables into the European energy systems will be made by means of HVDC connections.

Therefore, the development and implementation of a new **EU regulatory frameworks 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 needs to be demonstrated** in real operation and the corresponding **market platforms** has to be developed, taking into consideration the needed evolution of **network codes for HVDC**.

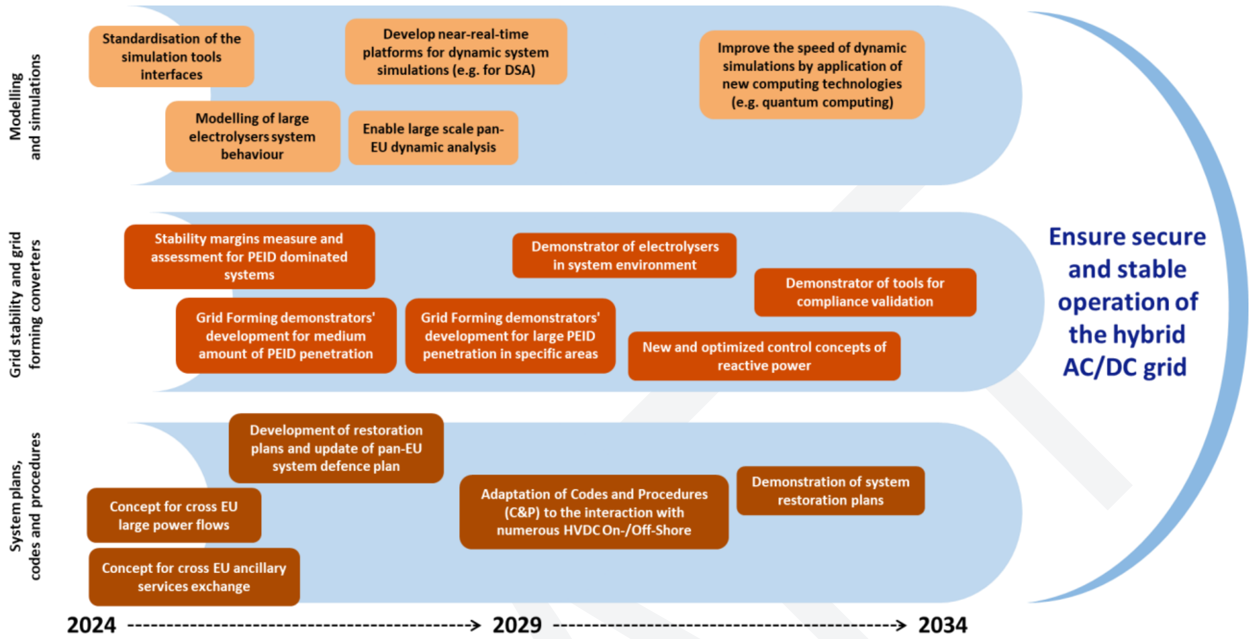
Besides regulatory and market platforms innovation, significant standardisation work is still required to enable multi-vendor HVDC network integration. To achieve this, **requirements for HVDC, cables and monitoring systems**, as well as **offshore platform types** and **reliability and maintenance concepts** need to be aligned. Moreover, to foster the deployment of offshore and onshore HVDC links, in the short term, **critical Multi Terminal (MT) HVDC components** need to be further developed and field tested, considering **interoperability of HVDC converter** as a key aspect in order to achieve the **demonstration of Multi Terminal HVDC** first considering **single vendor** then multi-vendor configurations. In this view, the **development of simulation tools, compliance tests and corresponding test facilities** will be key.

On 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 extended offshore HVDC grids.

The further development of HVDC connections represents a key opportunity for the modernisation of EU power systems, thus **HVDC planning criteria** need to be carefully developed, paying particular attention to the identification of **possible new interconnections** able to harvest renewable energy generated far from consumption sites and to enhance EU internal market integration. Finally, on 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 (RCC)**.

# RDI Cluster 2 – Digital power systems

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



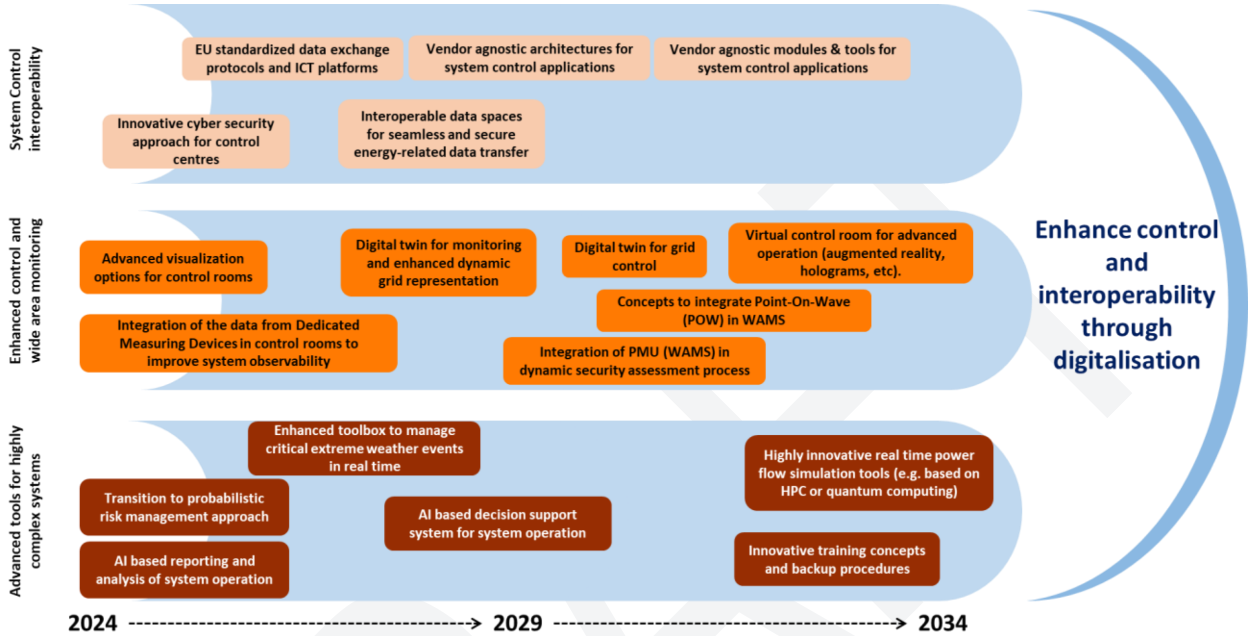

With the increasing electrification of end-use consumption, ensuring a secure and reliable electricity supply is paramount. However, the large shares of variable renewable energy sources, like solar and wind, replacing conventional sources in the generation mix are posing additional challenges to the power system and introducing new control complexities. Moreover, the growing presence of DC links in transmission grids leads to the transition towards hybrid AC/DC systems that require prioritizing 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**. On a longer-term perspective, the deployment of innovative AI-based tools will be possible thanks to the expected huge leap in computing power and by the **availability of new technologies like quantum computing**.

In the short term, **stability margins of future Power Electronic Interfaced Devices (PEID) dominated systems** needs 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, needs to be **demonstrated** in real power systems through a step-by-step approach, starting from systems with **medium to high penetration of PEID.** In this view, the integration of **electrolysers in the power system** needs to be **demonstrated** as well.

The increased power electronics penetration into power grids and the high share of generation from renewable sources are leading to a more challenging voltage control, thus common approaches for the **secure delivery of reactive power** need to be developed and agreed upon 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 in order 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 key to properly operate the AC/DC power system in all different scenarios ranging from normal operation to unplanned situations, emergencies and faults.

## Flagship 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 advantages from 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 **standardization 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 to the increasing system digitalisation. Moreover, pursuing **vendor agnostic architectures** and developing **vendor agnostic modules & tools for system control applications** will enhance the options to manage the increasing grid complexity and will allow for more coordinated and efficient system operations.

In the short term TSOs need to implement **advanced visualization options** for control centres in order to support control room operators' daily activities with more effective visualization 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 performing their daily tasks and training activities. Paramount to control room operations it is also the deployment of a monitoring infrastructure enabling close to real-time grid observability. In this view, in the coming years, the **integration of the data from Dedicated Measuring Devices (DMD) in control rooms** will be crucial **to improve system observability**.

**Digital twins** of the electrical grid will play a key role, in the medium to long term, in providing grid **dynamic representation** and eventually aid to **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 open the way to further enhance grid observability.

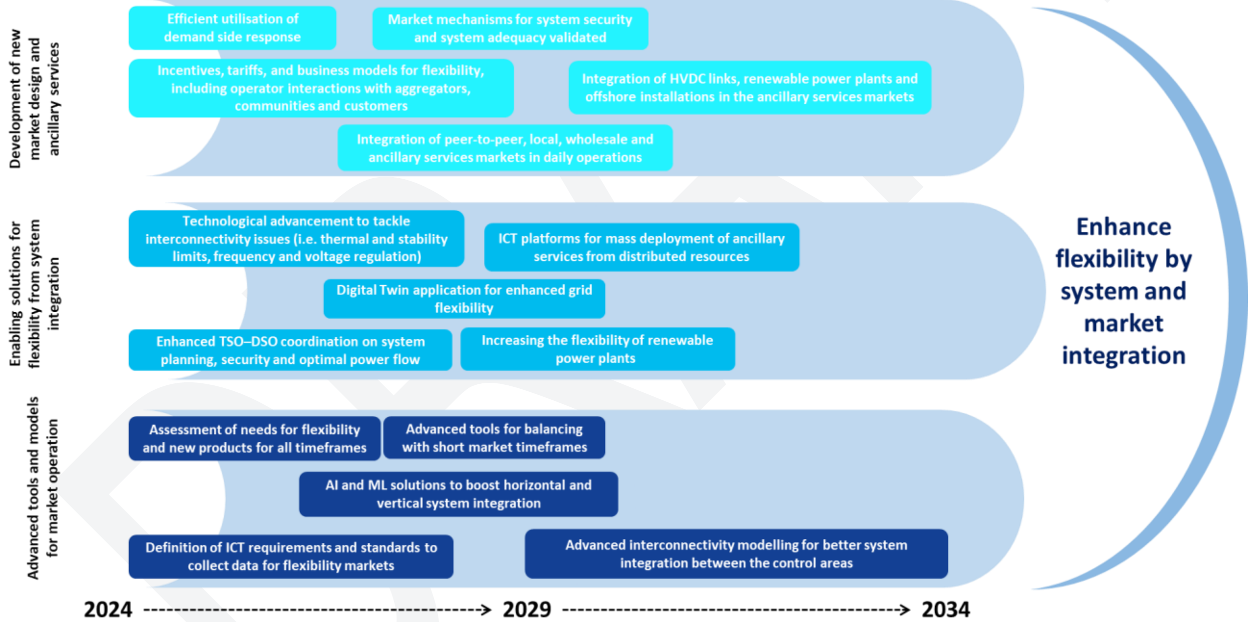
**AI-based technologies** are expected to provide breakthrough innovation and will be leveraged to make control room operations more efficient, starting from routine activities such as **producing continuous and periodic reports** as well as allowing detailed analysis of network status. Moreover, on a longer time 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. In this view, enhanced **tools must be implemented to manage criticalities and emergencies** in real time, thus improving the so called as 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 call also for a **transition towards probabilistic risk management** approaches with respect to the traditional deterministic ones. On 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, **continuous training** of control room personnel for the efficient and effective use of the implemented solutions will be key to fully exploit all the newly introduced digital tools features.

# RDI Cluster 3 – One-System of integrated systems

## Flagship 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. In order 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 in order to leveraging all possible sources of flexibility. To achieve this, grid-enhancing technologies should be deployed, digitalisation need to be exploited to allow demand response, energy storage integration and any kind of flexibility solutions also from other interfaced sectors should be leveraged.

To enhance the coordinated utilization of resources, **peer-to-peer, local, wholesale and ancillary services markets** should be integrated in daily power system operation. Moreover, on a longer-term perspective, **market mechanisms for system security and system adequacy** need to be implemented and validated.

To continuously expand the portfolio of suitable flexibility sources, TSOs will have to implement solutions for the **efficient utilization of demand side response** and, on a 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.**

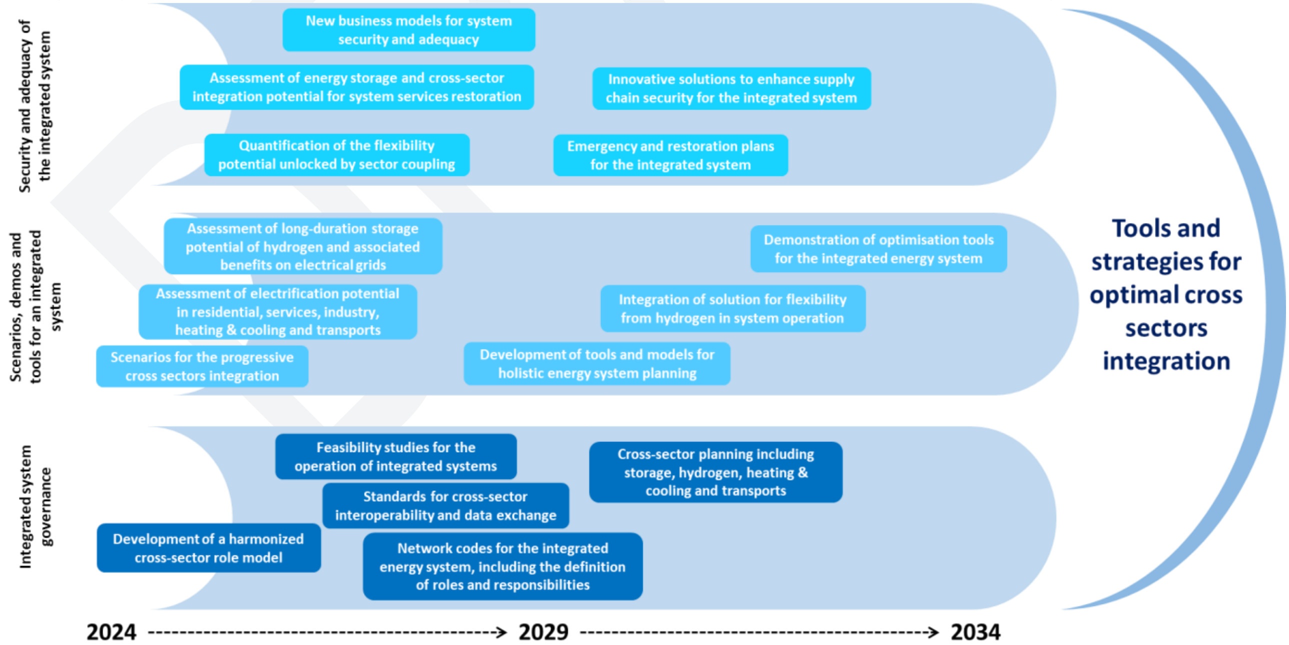
In the short term, **TSO-DSO coordination** will be reinforced, especially concerning system planning, thus making possible to optimize resources allocation and efficient exploitation of distributed flexibility sources. TSOs will also foster **technological advancement that tackle interconnectivity issues** 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 possible, in the long term, to **increase** the exploitation of **flexibility from renewable power plants**. In this view, suitable **ICT platforms for mass deployment of ancillary services from distributed resources** will be also 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 in terms of flexibility** will guide TSOs in deploying targeted and effective solutions for enhancing power system flexibility. Moreover, with the purpose 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 making possible 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 terms other important concepts, such as the development of advanced interconnectivity modelling for better system integration, need be implemented in order to achieve the desired high level of system integration.

## Flagship 6: Tools and strategies for optimal cross sectors 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. In this view, a series of new functionalities that will enable the operation of a holistic system has to be provided by European system operators.

To guarantee 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 need to be quantified and monitored. On the other hand, in the medium term, to ensure the security of the electricity supply, new business models for system security and adequacy need to be implemented and emergency and restoration plans for the EU integrated system have to be developed. Moreover, considering the increasing interdependence among different energy vectors, innovative solutions to enhance supply chain security for the integrated system, need to be developed in order 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 sectors integration**. Since the electricity vector 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 needed additional system flexibility, therefore, amongst other solutions, **long-duration storage potential of hydrogen** and other resources will be carefully assessed. In this view and in a longer-term perspective, the **integration of flexibility from hydrogen in system operation** need to be carefully evaluated.

TSOs will be able to promote and achieve efficient and optimized 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 need to be demonstrated** 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 that 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 harmonized 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-sectoral integration and management. These approaches will finally lead on the longer term to a holistic **cross-sector planning** that will embrace all the different sectors and technologies.

# 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. In this view, ENTSO-E 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 Flagships. This chapter also highlights the link between this Roadmap and the ENTSO-E Technopedia as an important way to foster key innovative solutions spreading and uptake, 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 on the most promising ones, will be fundamental to improve core business targets, such as the coordinated security of operation, maximising capacity in a secure way, 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 to underline the technologies that could be adopted for addressing the identified RDI flagships and milestones. A mutual link is established since the RDI objectives set by this roadmap also serve as an input to Technopedia, thus enhancing a better understanding on 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 6 and Figure 7.

More in details, **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 Flagship 2 and 3 while "Phase shifting transformers" are relevant to Flagship 1, and "STATCOM" to both Flagship 3 and Flagship 1. Other technologies categorized 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 (Flagship 1) and to ensure stable grid operation (Flagship 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. In this view, we can notice 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 optimization of assets maintenance and replacement in operation" (Flagship 1), "Digital twin for monitoring and enhanced dynamic grid representation" and "Digital twin for grid control" (Flagship 4), and "Digital twin application for enhanced grid flexibility" (Flagship 5).

**Flexibility technologies** are involved in all clusters as, going 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 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 seen, e.g "Virtual Power Plants" is connected to some flagship 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.

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 grid as its backbone. .

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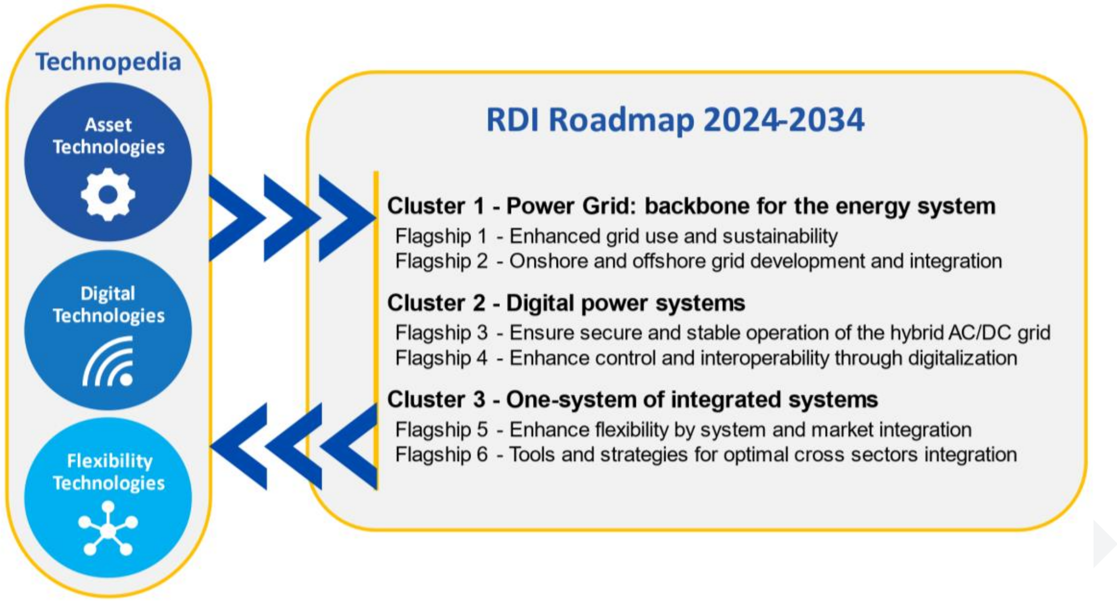


*Figure 6 – Interaction between ENTSO-E Technopedia and the RDI Roadmap 2024-2034*

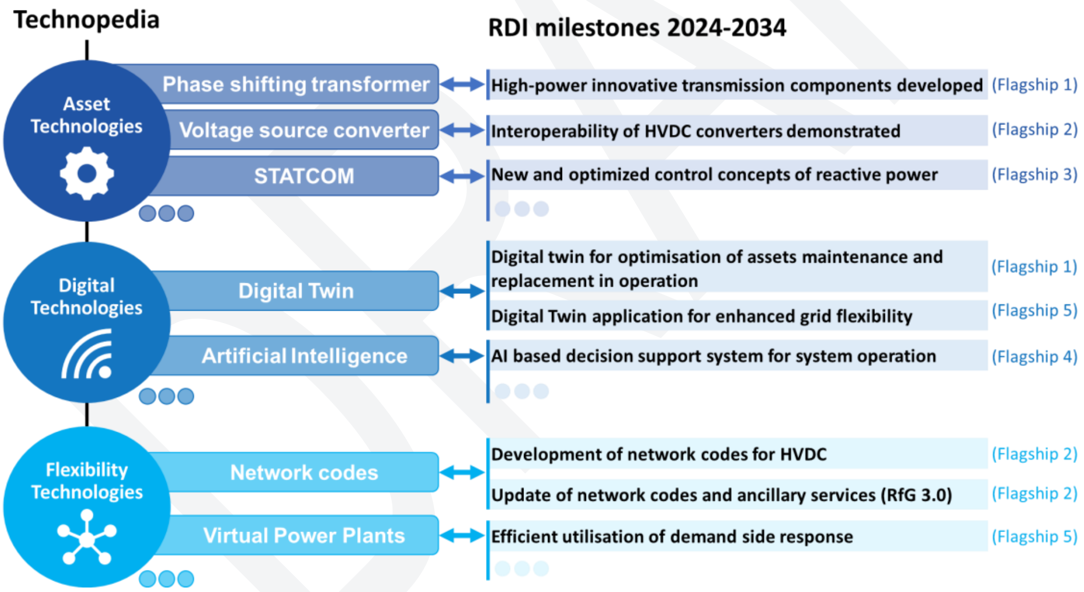


*Figure 7 – Example of specific interactions between the Technopedia technologies and the RDI Roadmap milestones*

## 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 a 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 harmonizing 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, six Flagships and outlines 90+ key milestones, with the concern of translating innovations into improvements of the 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 need major RDI efforts to be reached.

Following previous observations from ACER concerning the estimation of resources needed to fulfil the RDI activities, TSOs did a first estimation on 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 all TSO RDI activities, it is estimated that, in each year, each of the 40 members of the ENTSO-E need an average of 5.6 Full Time Equivalents (FTE)[4] 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 to define the proper financing framework for the evolution of the pan-European electricity system.

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 view underline the relevance of an evolution of the incentivising framework to allow for 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, conducing to the realization of the milestones in this Roadmap. Therefore, appropriate incentive frameworks for TSOs' RDI activities spread across the ENTSO-E control areas would enable to tap into a wider pool of knowledge and to foster synergy between different fields, which is crucial for tackling the complex and often multi-disciplinary challenges that modern power systems are facing.

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

It would be most effective to utilize both methods in parallel, extracting benefits from each approach to accelerate the energy transition towards ensuring energy security and promoting energy independence in a carbon neutral Europe, which requires forward-looking regulatory frameworks to support the investment from all TSOs in RDI activities[5].

# 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. 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 of systems ensuring energy security and promoting energy independence in a carbon neutral Europe.

Towards 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

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

[5] Innovation Uptake through Regulation (entsoe.eu)

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 to drive European TSOs research, development and innovation activities over the period 2024-2034. Organised in six Flagships, 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 addressing selected priorities for the upcoming years.

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