ENTSO-E Offshore Roadmap

May 2025

Towards a regulatory framework for integrating offshore energy

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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:

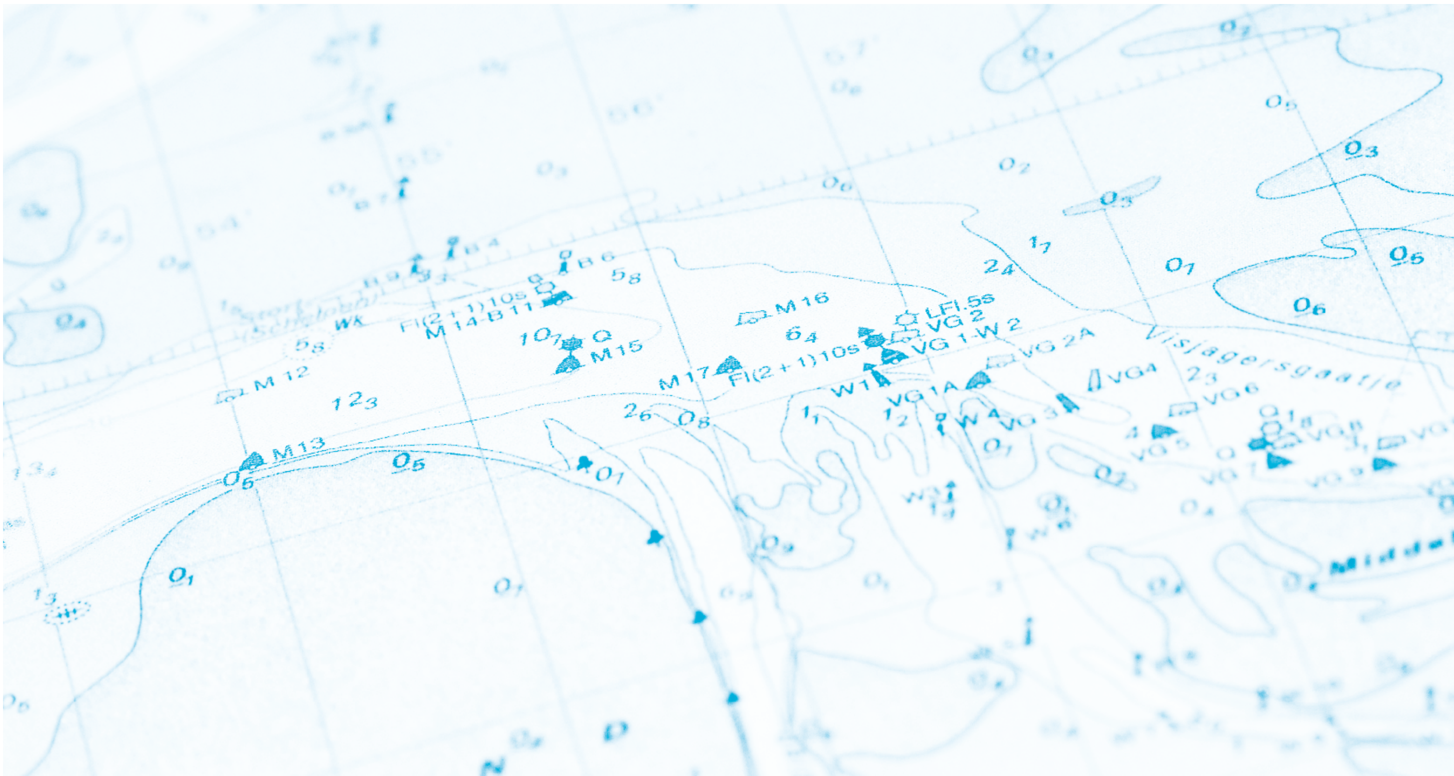
- Development and implementation of standards, Network Codes, platforms and tools to ensure secure system and market operation as well as integration of renewable energy;
- Assessment of the adequacy of the system in different timeframes;
- Coordination of the planning and development of infrastructures 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.

Contents

Acronyms
You will find a link to the Acronyms on each page



EXECUTIVE SUMMARY

The European Union and many European governments have set ambitious targets for renewable electricity generation offshore. This will lead to higher energy volumes and more complex topologies for the additional electricity infrastructure required.

In this Offshore Roadmap we describe ENTSO-E's current work to ensure that the necessary regulatory framework will be ready in time for the development of these new more complex offshore infrastructure.

The focus is on examining six priority areas of the regulatory framework, identified by ENTSO-E and discussed in stakeholder workshops: Geographic Areas/Offshore Bidding Zones, Balancing, Ramping, Frequency Control, Inertia Provision and Grid Forming, and Dynamic Stability. Dedicated subchapters investigate the upcoming challenges and describe the necessary assessments into whether existing regulatory frameworks, guidelines and network codes are sufficient or whether amendments and additional rules are required.

The focus is laid on the regulatory framework as it is the basis for planning the integration of offshore wind not only for TSOs but also project developers. In addition, this document gives an overview of most of the other offshore-related activities of ENTSO-E: grid planning (Offshore Network Development Plans), technical work on cost sharing, research and development, and supply chains.

INTRODUCTION

ENTSO-E's mission is to ensure 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 goal is to deliver on this mission not only for the current transmission infrastructure but also for the future, in which offshore grids will become more commonplace and more complex.

Why an Offshore Roadmap?

The European Union and many European governments have set ambitious targets for the development of offshore renewables, recognising them as a key driver in achieving carbon neutrality, reducing reliance on energy imports, and maintaining the competitiveness of Europe's industry.

Offshore wind, initially developed as a national concern, is increasingly becoming a key area for cross-border cooperation. As wind generation expands across European sea basins, the need for cross-border grid infrastructure will increase. The much higher future volumes of offshore renewable energy and

"Offshore renewables will make a key contribution to reach the EU's ambitious energy and climate targets for 2030 and 2050 and reduce dependency on imported fossil fuels. Offshore renewables are set to become an indispensable part of the energy mix that will be necessary to decarbonise and reach climate neutrality."

EC Communication COM (2023)668 Delivering on the EU offshore renewable energy ambitions

the more complex and interconnected topologies of offshore energy infrastructure will pose new challenges to the safe operation of electricity systems, the functioning of markets, the development and integration of new technologies, and the setting of technical requirements for generation assets and other assets that can be connected and operated in this system.

The question remains as to whether the current regulatory framework (e.g. in network codes and guidelines) will be fit for much higher quantities of renewable generation offshore and more complex offshore network topologies. To develop its "Offshore Roadmap" ENTSO-E has sought to identify possible regulatory gaps that are not covered by today's regulatory framework and to develop strategies and work plans to ensure that a functioning regulatory framework is in place for when more complex offshore infrastructure are developed. The questions of whether and which regulatory tools needs to be adapted, and how, is currently still open. This Roadmap will be updated to reflect the outcome of ENTSO-E's assessment, and to adapt to evolutions of the regulatory and technological landscape.

This Roadmap examines the key regulatory challenges within six priority areas identified by ENTSO-E: Geographic Areas/ Offshore Bidding Zones, Balancing, Ramping, Frequency Control, Inertia Provision and Grid Forming, and Dynamic Stability. In dedicated subchapters we investigate the upcoming challenges and describe the necessary assessments into whether existing regulatory frameworks, guidelines and network codes are sufficient to deliver on European ambitions for offshore wind development.

ENTSO-E focuses on topics which are of a technical nature with regards to the development of the power system, the markets for electricity and system operations. These are the questions where ENTSO-E sees its core competence and which we prioritise in this Roadmap. In addition, this document gives an overview of other offshore-related activities of ENTSO-E: Our work on grid planning (Offshore Network Development Plans), our technical work on cost sharing, on Research and Development and on supply chains.

Guiding principles of ENTSO-E's Offshore Roadmap:

- Rules governing Europe's energy markets, system operations and planning must be written with an efficient onshore-offshore system in mind. **Efficient offshore development and secure operation are integrated into the thinking of all ongoing and future ENTSO-E work.**
- Solutions applied onshore should be utilised offshore when possible. The evolution towards a system integrating high levels of offshore RES capacity should happen organically. TSOs and stakeholders should first use existing frameworks and tools and examine how far they can remain applicable.
- The overall goal of ENTSO-E is to support Europe in building an energy system that is coordinated by markets and operated in an efficient manner – regarding both economic and energy efficiency. This also applies to ENTSO-E's work on offshore topics.
- We need a sea-basin oriented approach: Sea basin specificities may require specific solutions. Some aspects under consideration will benefit from being customised at sea basin level to account for regional differences, such as the share of RES connected via hybrid infrastructure, or the technology used (AC or DC).

ENTSO-E reaching out to stakeholders:

Cooperation with stakeholders is a key success factor particularly for addressing the six areas identified in this Roadmap. EU offshore energy ambitions will only materialise if the developers of offshore wind farms, technology manufacturers, market participants and others are convinced to invest and cooperate. ENTSO-E has, therefore, involved stakeholders actively in the process of preparing this Offshore Roadmap.

In April 2024 and February 2025 various stakeholders participated in two ENTSO-E stakeholder workshops hosted in Brussels. The quotes of stakeholders in this roadmap document are also an expression of the ongoing dialogue. We will continue to engage with stakeholders in the years to come.

REVIEW AND DEVELOP THE REGULATORY FRAMEWORK ON SIX PRIORITY TOPICS

Beyond infrastructure development, large amounts of offshore RES will profoundly transform Europe's power system, impacting energy markets and how the grid is operated. Some of the challenges ahead are already relevant to the current grid structure, such as dynamic stability, while others are completely new and strictly related to the offshore generation, such as implementing market solutions that ensure efficient competition and use of energy resources across sea and land. In both cases, action is required so that the challenges brought about by offshore expansion, happening in combination with the decommissioning of conventional generation, are efficiently addressed.

From radial connections to hybrid and possibly meshed infrastructure

To use maritime space and resources efficiently it can be beneficial in specific situations to use the same subsea cables both to connect offshore wind to shore and to trade electrical energy between countries. Such systems – in which offshore wind farms are connected to more than one bidding zone or more than one country – are generally referred to as hybrid interconnections. This dual functionality facilitates the integration of offshore renewable electricity whilst allowing for cross-border trade when wind generation is limited.

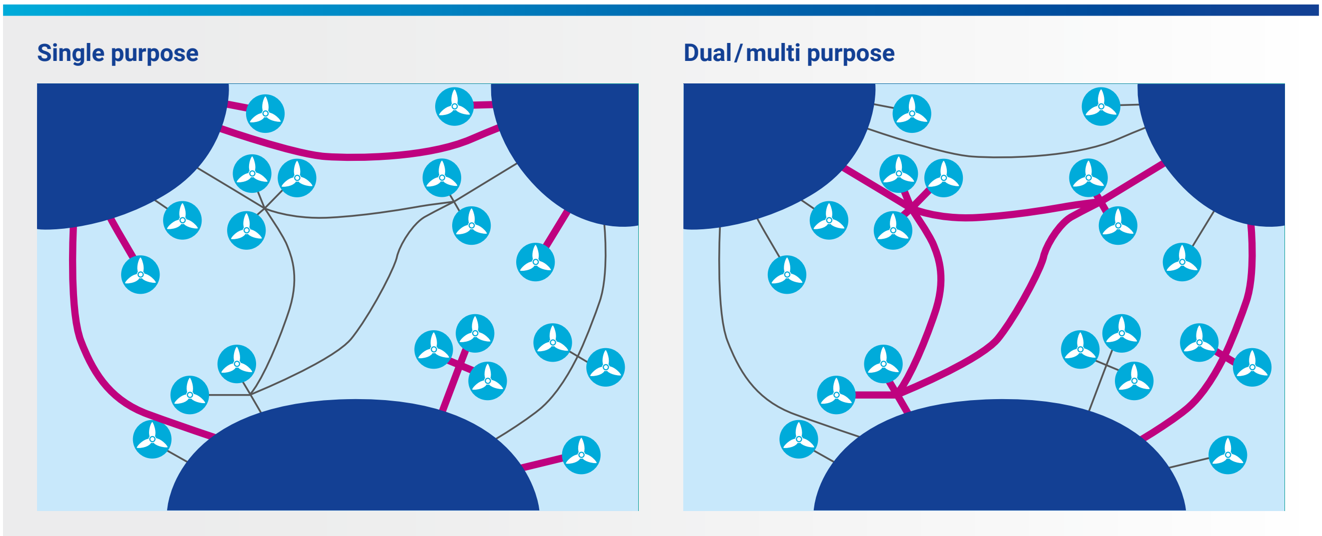


Figure 1. Single purpose and dual/multipurpose offshore configurations

ENTSO-E has identified several regulatory challenges related to efficiently integrating offshore and onshore electricity grids and has selected six priority key topics for further legal and regulatory investigation and discussion. These topics to some extent represent separate challenges, but are also closely interrelated and should be considered holistically.

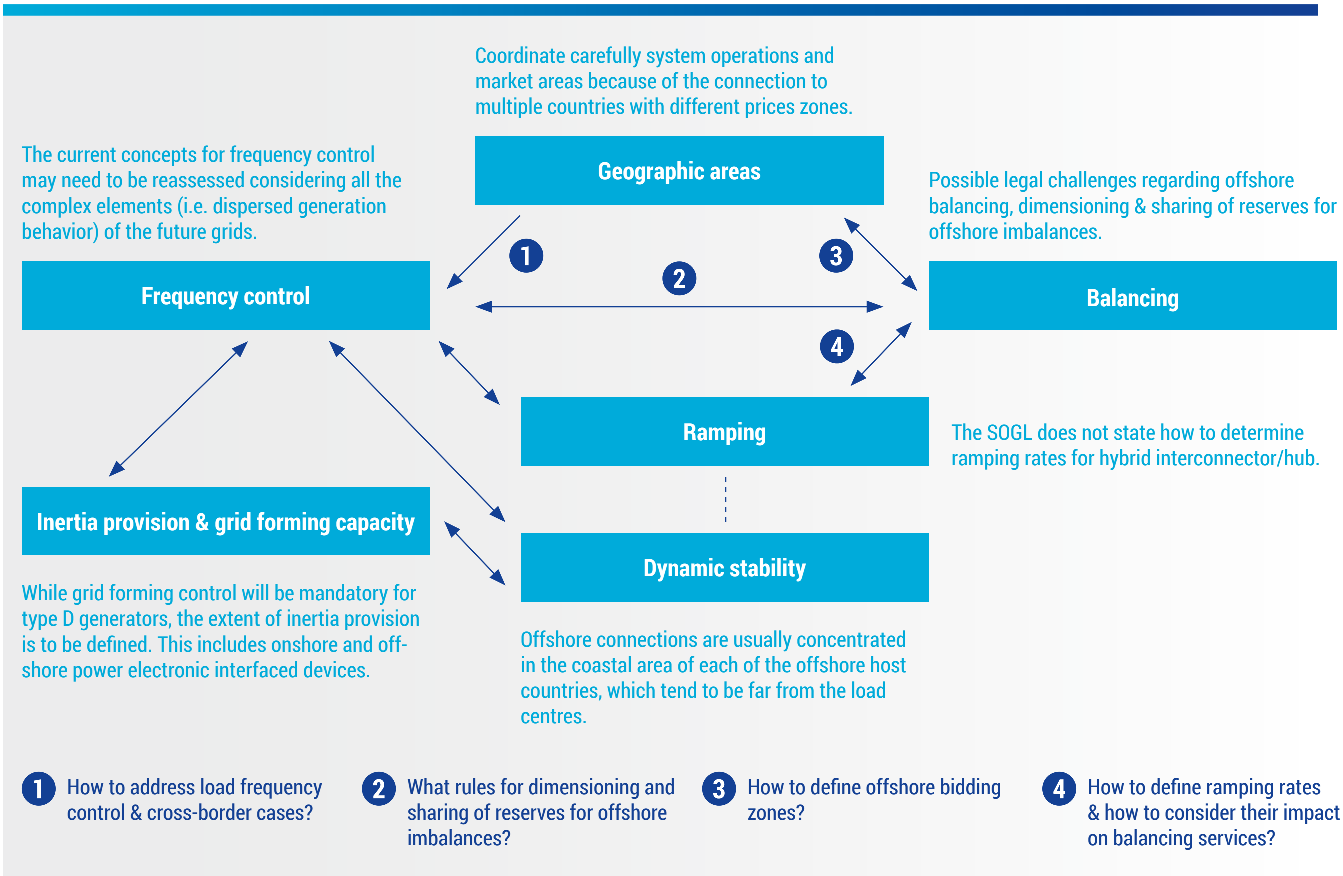
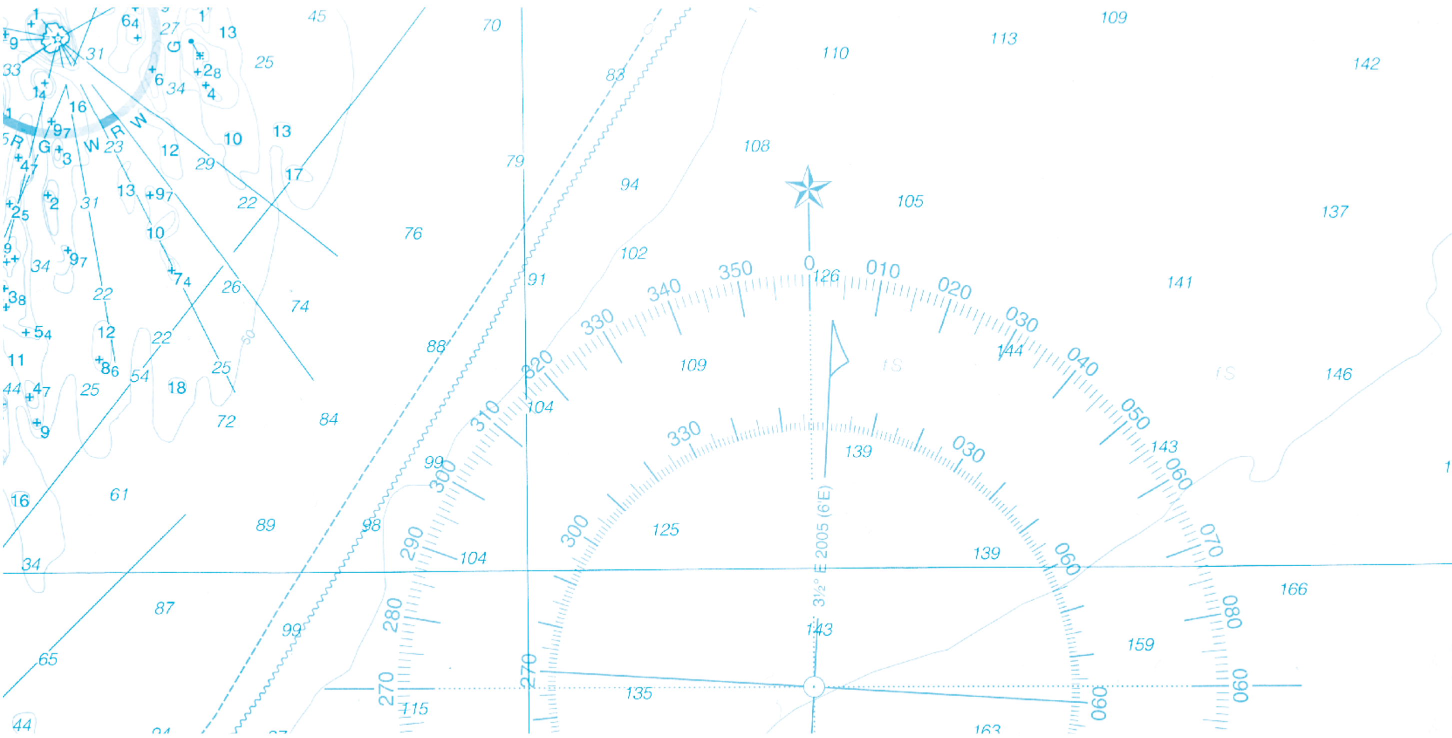


Figure 2. Six priority topics of ENTSO-E's Offshore Roadmap and interdependencies between them



Priority Topic 1: Geographic Areas and integration of Offshore Bidding Zones

Larger and more interconnected offshore systems will have to be integrated efficiently into the existing framework for system operations and markets. The installation of numerous High-Voltage-Direct Current (HVDC) grid components will create new system characteristics: Currently the operational rules (the System Operation Guideline) is generally based on synchronous areas, but offshore systems will consist partly of non-synchronous-areas. Examination is needed into whether the existing framework is also sufficient for such systems (i.e. the coordination of non-synchronous areas) or whether the framework requires improvement.

With operating and coordinating system operations and market areas the Transmission System Operators are providing the groundwork for functioning electricity grids onshore and offshore. On the system operations side a clear process has to be set up to assign offshore systems to Load Frequency Control (LFC) Blocks, LFC Areas, Monitoring Areas, Scheduling Areas and System Operation Regions and to ensure smooth coordination between onshore and offshore systems. On the market side offshore bidding zones have to be assigned to capacity calculation regions, imbalance regions and imbalance price regions via a clear process. Clear responsibilities for the different areas for specific TSOs will be key. Hybrid interconnections connect offshore wind farms (OWFs) to onshore grids while also serving as interconnectors between countries. The offshore bidding zone (OBZ) model is the target framework for integrating hybrid projects into European electricity markets. This model allows for efficient coordination of cross-zonal electricity flows and wind injection from the OWFs.

It must be noted that simultaneous cross-border exchanges and wind injection are limited by the maximum physical (thermal) capacity of the infrastructure offshore. OBZs will be integrated in the European electricity markets via market coupling across all timeframes. ENTSO-E is working to ensure processes and methodologies are in place to set up offshore bidding zones and assign such offshore bidding zones and their new borders to system operations and market areas with the relevant responsible TSOs.

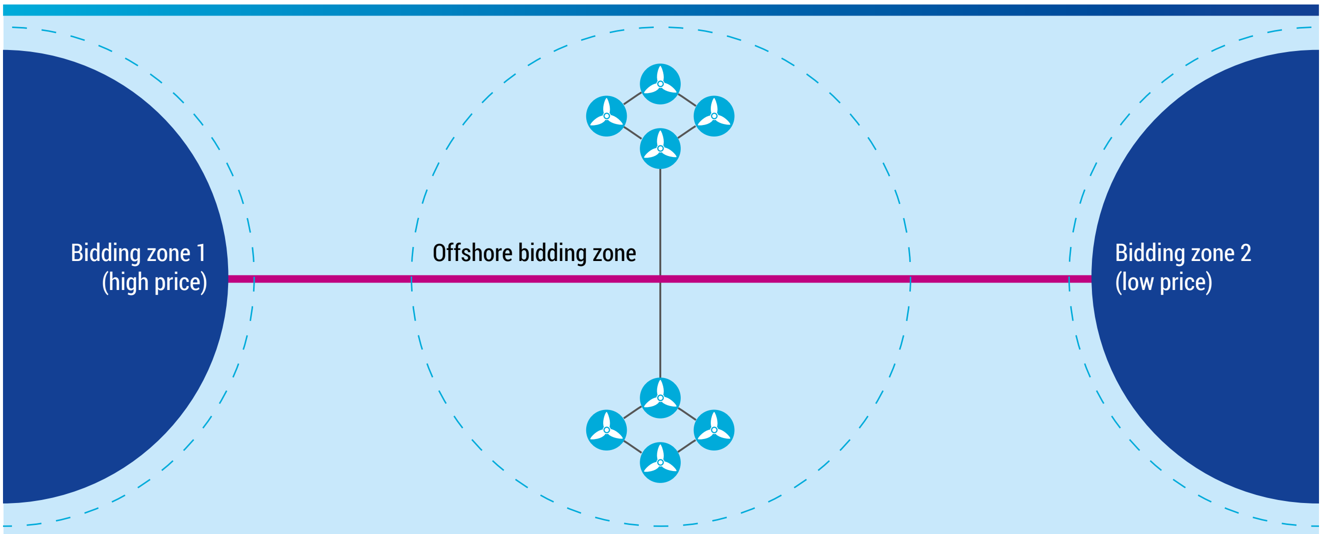


Figure 3. Example of Offshore Bidding Zone configuration

Additionally, offshore hybrid projects have unique characteristics such as minimal load and limited frequency variation compared to onshore grids. Real-time fluctuations in the output from connected OWFs add further complexity. This might create additional tasks to integrate them into existing operational and market areas and processes.

As a result, system operations and market areas for OBZs and hybrid systems need to be carefully coordinated due to their cross-zonal nature. To address these challenges, frameworks for operations and markets must be in place to ensure the safe and secure operation of both offshore and onshore grids while minimising the risk of unplanned infrastructure outages.

Clarity on the setup of operational areas and market areas can also inform how new grid assets and generation assets offshore should be designed to ensure resilience, interoperability, automatised communication and operational concepts, e.g. how to deal with the operational loss of system elements.

Objective: ENTSO-E's objective is to establish and develop a viable operational framework that meets the technical and operational requirements of OBZs while ensuring system security is maintained.

NOTE: Effects of Offshore Bidding Zones on the business case of Offshore Wind Farms

The allocation of the cross-border transmission capacity as well as the electricity price of the Offshore Bidding Zone is the result of market coupling. The price for generated power in the OBZ, in the absence of significant local demand, is likely to converge to the price of the onshore bidding zone to which the OWF's power can be delivered without congestion. Although this topic is not one of the topics that are mandatory for ENTSO-E, we acknowledge from the intensive stakeholder dialogues that this is a key concern for wind park developers.

While promoting overall market efficiency and managing congestions, the introduction of OBZs with flow-based market coupling or advanced hybrid coupling could impact offshore wind farms' future revenues and their ability to hedge risks, such as increased price and volume risks due to the offshore wind competition for the interconnector capacity with the import and exports from other bidding zones. Additionally, the first examples of OBZs that will be developed will be characterized mainly by (wind) generation, as they will likely have limited or no demand. This high dependence on interconnectors for exporting electricity influences OWFs and overall OBZ's system operations and will have impacts on prices.

Priority Topic 2: Offshore Balancing

The first OBZs (e.g. projects like LionLink, Bornholm Energy Island, Princess Elisabeth Island) are expected to primarily connect offshore wind and have no or very limited amounts of demand and, hence, no or minimal inertia. How offshore power imbalances are dealt with, therefore, needs to be considered. Most likely the imbalances from the OBZ need to be transported immediately e.g. by the respective HVDC systems to the neighbouring onshore areas.

First of all for this a technical concept (e.g. power flow configuration), allocation criteria and a mechanism to integrate the OBZ into the frequency containment process (FCP) of one or several connected onshore synchronous areas, would need to be developed.

If balancing of OBZs is reliant on onshore reserves, imbalances will need to be considered in the dimensioning of onshore reserves.

The OBZ will be equal to an imbalance price area and the OWFs will be assigned to balance responsible parties (BRPs) which will be financially responsible for their imbalances. BRPs in OBZs will be exposed to their own imbalance price based on the value of balancing energy following the activation of balancing energy through the EU balancing platforms. The European balancing platforms will ensure the most efficient activation of balancing energy bids to solve the OBZ imbalances. The offshore imbalance price shall ensure that offshore imbalances are settled in an efficient way whilst providing incentives to offshore BRPs to minimise their imbalances. Offering balancing products (e.g., downward flexibility) to balancing markets might be an opportunity for wind park operators to add to their business case.

In a next step also the participation of offshore generators in the FRR process will be considered. For this the parks will have to be qualified as ancillary service providers.

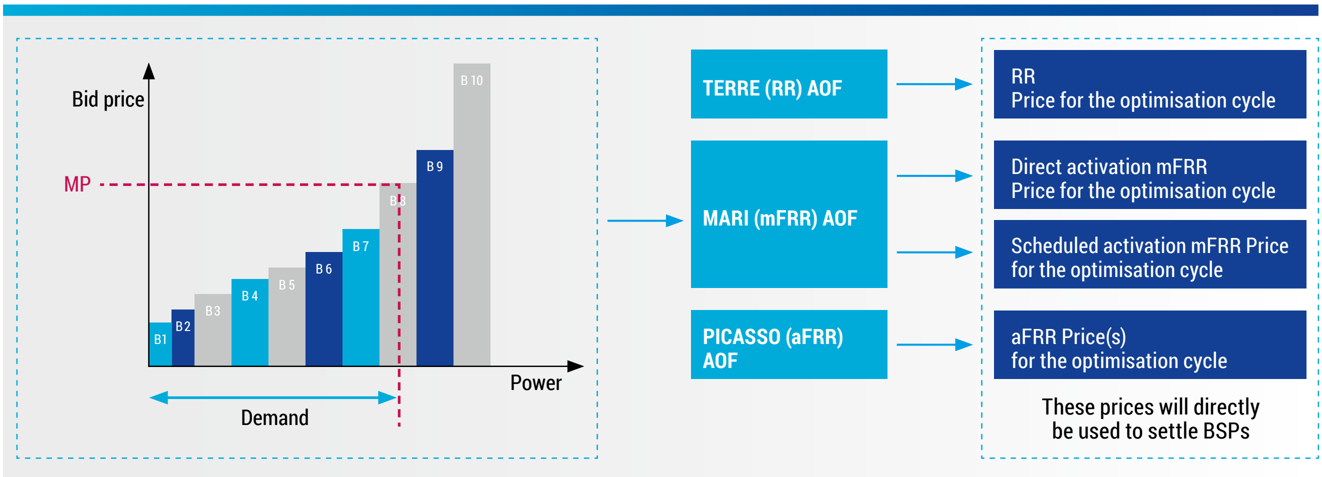


Figure 4: Marginal price forming and balancing energy pricing for different processes

Specifically, the following challenges will be investigated/addressed:

- Management of instantaneous imbalances via the HVDC system;
- Integration of OBZs into the EU balancing platforms
- Creating an adequate imbalance price;
- Potential impact on dimensioning and sharing of reserves for offshore imbalances;
- Cost allocation for procurement and activation of reserves;
- Role of market parties in the balancing of the OBZ.

Objective: ENTSO-E is working on an Offshore Balancing concept that is aligned with the European regulation and allows for the integration of OBZs (with only generation and no or limited demand) and OWFs in the European balancing markets. Thereby we will identify possible aspects and issues which cannot be solved with existing regulation and, thus, need to be addressed at European level.

Priority Topic 3: Frequency control

Without preventative measures, concentrated areas of offshore wind generation along with the connection of hybrid interconnections and more complex offshore grids will lead to a higher risk of large sudden losses of power. Weather-related phenomena like lightning or violent storms can also influence the stability of operation of offshore wind parks. Radial connections with cables close to each other could have a larger loss of infeed due to (for example) a common mode fault. Also, hybrid or possibly meshed structures are exposed to the risk of singular fault scenarios. Such scenarios of larger faults could disconnect many GWs from the power system, exceeding the current reference incident case, and become even more challenging when considering the varying sizes of synchronous areas. Additionally, frequency stability depends on five key factors—generator inertia, load inertia, load damping, contingency size, and frequency response speed—which become more critical in low-inertia systems featuring extensive offshore wind and multi-terminal HVDC links.

ENTSO-E considers frequency control to be a pan-European topic, mainly organised at the level of the synchronous areas of Continental Europe, the Nordics and Ireland/Northern Ireland Synchronous Areas. Increased interdependencies between the synchronous areas are expected, both as a result of increased interconnectivity through HVDC systems, and due to the cross-synchronous area impact of generation losses such as resulting from weather related phenomena.

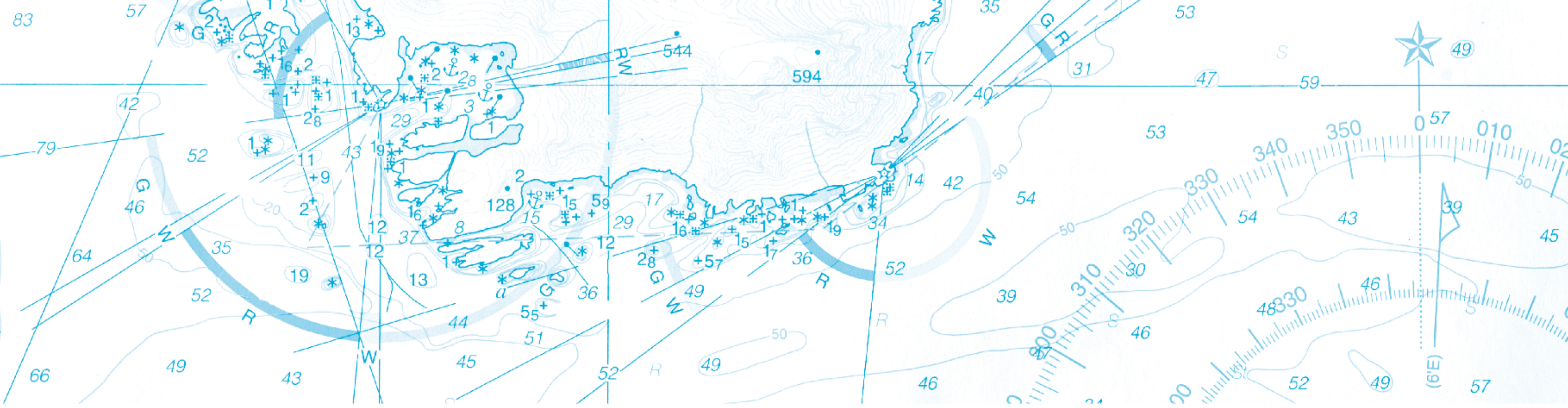
The current concepts for frequency control (including the criteria of reference incidents) should be reassessed considering all the complex elements (e.g. dispersed generation behaviours) of the future grids. In this sense, it may be appropriate to evaluate a reference incident criterion suitable for each synchronous area considering also the mutual interactions due to HVDC links:

> *A key question is what will, in the future, be the technical maximum of an instantaneous power imbalance on the ENTSO-E grids (with respect to the System Operations Guidelines dimensioning criteria based on the highest expected single imbalance to be covered) both overall and specifically for each synchronous area?*

Large scale offshore renewable generation means additional research and solutions are needed to estimate provisional inertia and establish on-line monitoring for the different onshore synchronous areas. New emerging technologies and systems will help manage frequency stability better in the future, e.g., Wide Area Monitoring Systems (WAMS), Energy Storage Systems (such as batteries), grid forming capabilities, advanced functionalities on wind farms like grid forming or synchronous condensers with additional flywheels. Offshore generation will be required to support onshore frequency quality and it should be investigated how to integrate this in frequency stability processes in the different synchronous areas. In particular, strategies such as advanced under-frequency load shedding, synthetic inertia provision, and fast primary frequency response can be critical for mitigating large frequency excursions when sudden power imbalances occur.

It needs to be ensured that different synchronous areas do not influence each other negatively via the offshore grid. We should aim for a future system with synchronous areas that will mutually cooperate and help each other in maintaining frequency stability. Coordinated frequency management across these areas is essential to avoid unintended cross-border effects and ensure that frequency support in one region does not exacerbate disturbances in another.

Objective: ENTSO-E aims at addressing frequency control in a coordinated manner between the relevant synchronous areas, prepare commonly for the additional challenges posed by offshore wind and increased interconnectivity between the separate areas to ensure a stable system frequency in the future system.



Priority Topic 4: Ramping Rates for DC links and wind farms

The development of significant volumes of offshore generation and the expansion of offshore networks poses some challenges to system balancing, voltage stability and dynamic stability in terms of the ramping rates of this infrastructure/generation and the impact on the onshore grids. The ramping rate describes the rate of change of active power by a power generating module, demand facility or HVDC system.

Offshore generation is expected to have similar forecast errors as existing renewable generation today. However, the size of the OWFs can be much larger causing larger uncertainties. These uncertainties are delivered at a single point onshore also creating challenges for TSOs onshore as they can lead to steep changes in active and reactive power.

Synchronous area	IE–GB	CE–GB	CE–Nordic	GB–Nordic
Ramping rate (MW/min)	15	100	30	30
Ramping period (min)	–	10	10	10
Type of ramping	Constant	Constant	Constant	Constant
Number of links	3	6	9	1
Comment	Ramping rate can be lower based on security analysis. The ramp rate limit is apportioned equally among the interconnectors.		NorNed: the 10 minutes is used until the step is more than 300 MW. In that case the ramping period is extended and ramp max speed is 30MW/min.	

Table 1: Current ramping arrangements between synchronous areas. The rates are applied on a per-link basis. The ramping period refers to the time during which the ramping between two market time units takes place.

For point-to-point interconnectors, the operational framework defines a ramping period which is common to all TSOs and a ramping rate defined by the TSO responsible for balancing the interconnector flows. With offshore windfarms, there is a question as to whether the existing ramping framework can be applied or needs to be adapted.

Currently there is no common TSO assessment on the impact of significant offshore RES feeding into the onshore system. The System Operations Guidelines defines the responsibilities for TSOs, with the Synchronous Areas and LFC Blocks having policies and agreements in place which define ramping requirements and set related parameters.

ENTSO-E's goal in 2025 and 2026 is to analyse ramping requirements among TSOs to ensure ramping limits that:

- are compatible with existing regulatory frameworks and expected offshore developments;
- guarantee adequate system balancing, operational resilience and good operational practices;
- are compliant with the System Operations Guideline and cognisant of national regulatory frameworks (notwithstanding proposals to change regulation may be necessary); and
- recognise technical capabilities of generation and load in an offshore bidding zone.

Objective: ENTSO-E will investigate the potential need for harmonised ramping requirements in the context of the planned expansion of offshore RES and offshore grids, to ensure efficient and secure system operation.

Priority Topic 5: Inertia Provision and Grid Forming Capability

Inertia in today's power systems mainly refers to the kinetic energy stored in large rotating generators and some industrial motors, which gives them the tendency to remain rotating. If there's a sudden drop in the power balance of the system (i.e. sudden loss of a major generator) the frequency would drop as well. This drop will be damped depending on the available stored energy or inertia of the system. This stability support traditionally granted by synchronous generators will no longer be available in an almost exclusively RES-dominated system. Therefore, in case of imbalances, the power system is exposed to larger and faster frequency deviations and the risk of being unable to withstand events that were previously manageable (e.g. like out-of-range system splits in Continental Europe).

To deal with incidents and imbalances in the European transmission system largely dominated by inverter-connected generation and HVDC systems grid forming capabilities of power generating modules and HVDC systems will be essential. AC and DC connected offshore power plant modules (mainly wind power plants) need to contribute together with onshore power generating modules, HVDC systems and energy storage systems with grid forming capability during normal as well as disturbed grid conditions.

To manage imbalances and incidents an ensemble of grid forming solutions needed to be implemented in the EU power system. Gird forming capabilities can be implanted by:

- Synchronous condensers
- Static synchronous compensators (STATCOMs) with grid-forming capability and storage
- Power park modules with grid-forming capability
- Energy Storage systems with grid forming capability

Solutions need to be distributed throughout the system which reduces the active power effort on each unit. The decision on the best mix of solutions should be made at the national level including grid connection requirements for system users.

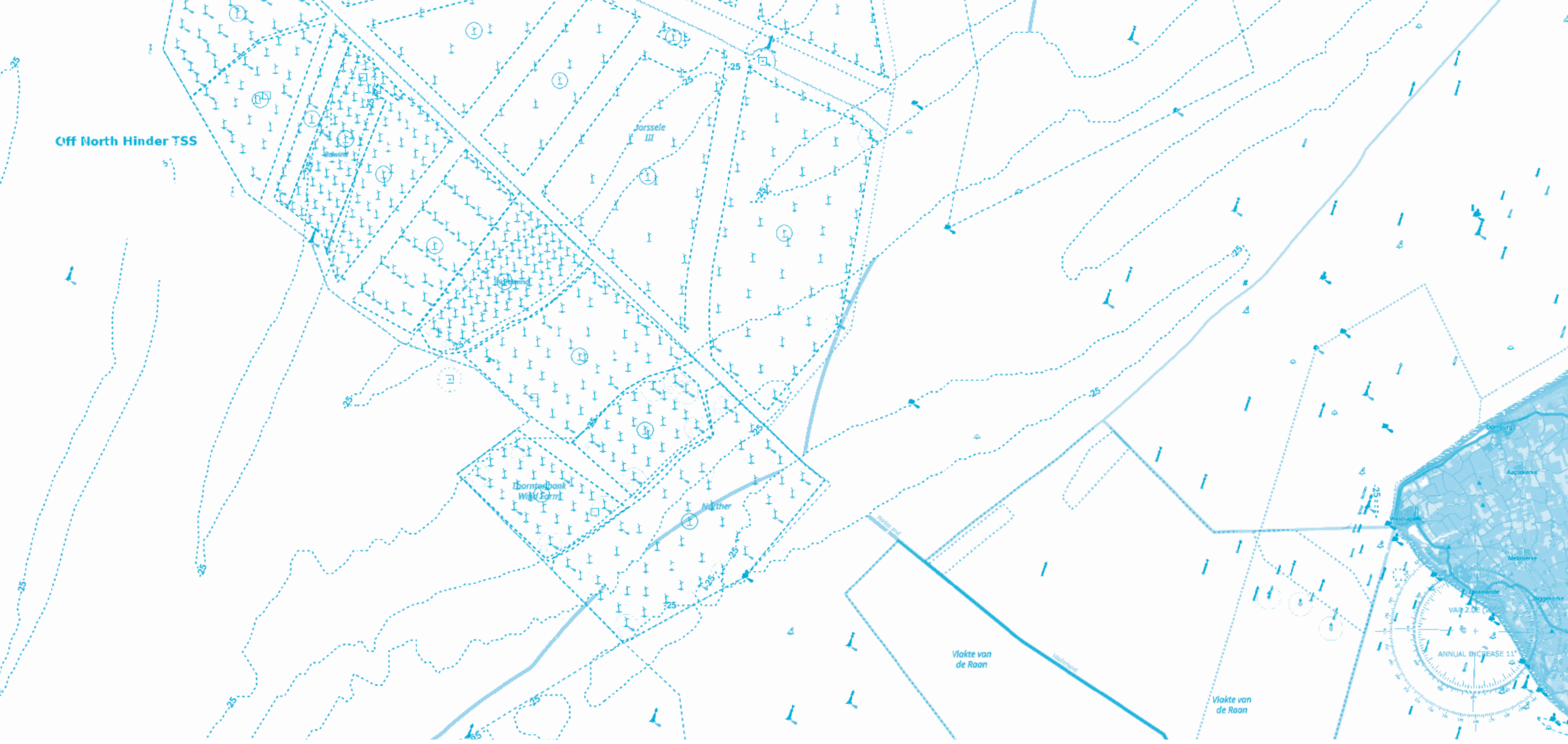
The grid connection regulations for generators in the RfG 2.0 and the HVDC 2.0 are currently being finalised for publication and will also further support the integration of offshore generation, with the implementation of new technical requirements related to grid forming and inertia provision. However, these requirements will by default not enter into force immediately due to the implementation period of the EU connection network codes to national regulations (which is expected by 2029 across Europe). ENTSO-E recommends to accelerate the implementation period on the national level grid forming requirement with the support of regulators and member states. On the latter ENTSO-E has recently released a technical report on detailed grid forming requirements for national level implementation, which is meant to be published by Q3 2025 resonated with the support of European stakeholders . Quick progress is, therefore, needed.

What ENTSO-E is doing to date on the topic:

Project Inertia Phase II: The resilience of the system in case of a split with the Continental Europe Synchronous Area is being assessed, to draw conclusions on the need to address declining system resilience and propose necessary solutions and mitigation measures in a step-by-step, no-regret approach to ensure secure and efficient operation for a future-ready decarbonised system.

- TYNDP: Description of system challenges and associated solutions, including specific offshore generation aspects.
- Amendment of Connection network codes (RfG 2.0, NC HVDC 2.0) and publication of implementation guidance documents:
  - ENTSO-E proposes specific provisions for technical requirements and compliance schemes for grid forming aimed at relevant grid users.
  - The entry into force of such amendments is deemed necessary and urgent.
  - ENTSO-E recommends to implement as soon as possible grid forming capabilities for battery storage systems.

Objective: ENTSO-E's goal is to assess the need to address declining system resilience and propose necessary solutions and mitigation measures in a step-by-step, no-regret approach to ensure secure and efficient operation for a future-ready decarbonised system.



Priority Topic 6: Dynamic stability

Sea basin grid solutions will necessitate a concentration of power converters. Generation, demand, storage, Flexible AC Transmission System (FACTS) will be connected to AC or DC networks that will interconnect with each other.

These offshore networks are likely to be weak networks in terms of system strength (voltage control capacity and short circuit power) and inertia, which might pose a challenge to system stability, especially related to converter driven stability and resonance stability. This might lead to control interactions, that could affect several generation plants, HVDC converters, storage, demand, etc. Yet, there are no clear or coordinated criteria to enforce and ensure a certain level of system strength in access and connection to the network and during operation.

There is a growing need for common stability assessment methodologies for offshore grids with a high penetration of power electronics (see Figure 5). While existing practices for onshore grid stability assessment rely on well-established models, offshore meshed HVDC networks require new approaches that account for dynamic interactions between multiple converters, their control systems, and their interactions with onshore AC grids. For effective system strength management, new coordinated approaches must be developed (i) harmonised system strength requirements for offshore and onshore grid access and operation (ii) definition of minimum grid-forming capabilities for offshore converters, ensuring sufficient inertia-like response and robust voltage control and (iii) advanced testing and validation procedures to evaluate the resonance risk and converter-driven stability across different vendors and grid configurations.

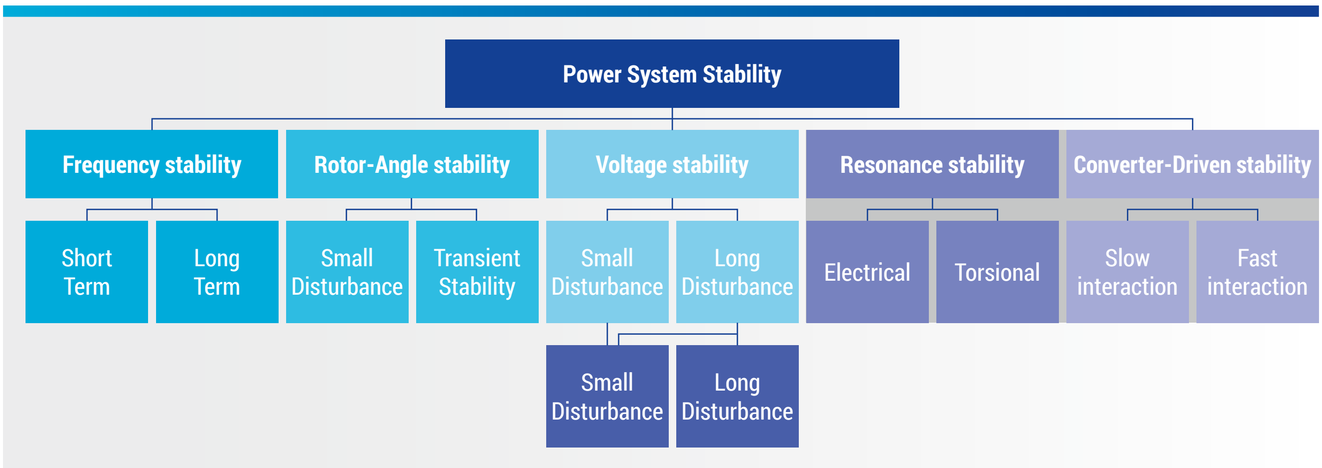


Figure 5: Resonance and converter stability framework

Power electronics in different assets from different suppliers controlled by different operators could show unpredicted interactions and loop reactions. For instance, depending on the control scheme, voltage controls may be a destabilizing cause of electromechanical oscillations (e.g. interarea modes) in the grid, which would trigger the need for complementary power oscillation damping control. In the same way, short circuits in these areas could affect several offshore assets, causing disconnections. The synchronous machines (generators and synchronous condensers) with onshore connection but located close to the converter terminals of the offshore grid, could suffer from sub synchronous resonance risk, which can damage the synchronous machine components and, in general, worsen the stability of the network.

Additionally, system-wide stability studies should incorporate the effects of fast control actions from multiple HVDC links, FACTS devices, and renewable generation units to avoid large-scale cascading disconnections. Improved coordination between HVDC grid control centers and onshore TSOs will be essential for mitigating such risks.

Onshore areas connecting offshore fluctuating wind generation, will experience additional stress and more challenges related to voltage control, fault detection (if area has low short circuit ratio) and power quality issues (mainly involving harmonics). Given the rapid deployment of offshore wind energy, there is a need for enhanced real-time stability monitoring tools and coordinated protection schemes to prevent cascading failures.

At present, the challenge of forced oscillations coming, for example, from offshore wind farms has already been detected and is currently addressed within ACER's recommendation on the Network Code Requirement for Generators[2] (NC RfG) to the European Commission. Recording devices (e.g. PMUs) should be installed at the park coupling point for enhancing an accurate monitoring of the park dynamic behavior.

Predicting and recognising such phenomena with the needed level of accuracy and reliability in advance is very complex, expensive and time-consuming, and, therefore, reasonable hypotheses have to be made in order to handle this complexity. Moreover, making all these models interoperable and assessable is a considerable challenge.

Objective: Prepare a strategy to ensure dynamic stability for more advanced grids dominated by power electronics onshore and offshore, and establish more knowledge (ongoing projects, studies, etc.) about resonance and converter driven stability, assessing the need for regulatory and technical developments and disseminating best practices.

WHAT ELSE IS ENTSO-E DOING TO MAKE THE FUTURE OFFSHORE GRID A REALITY

Coordinating the planning of Europe's offshore network: the TYNDP's Offshore Network Development Plans

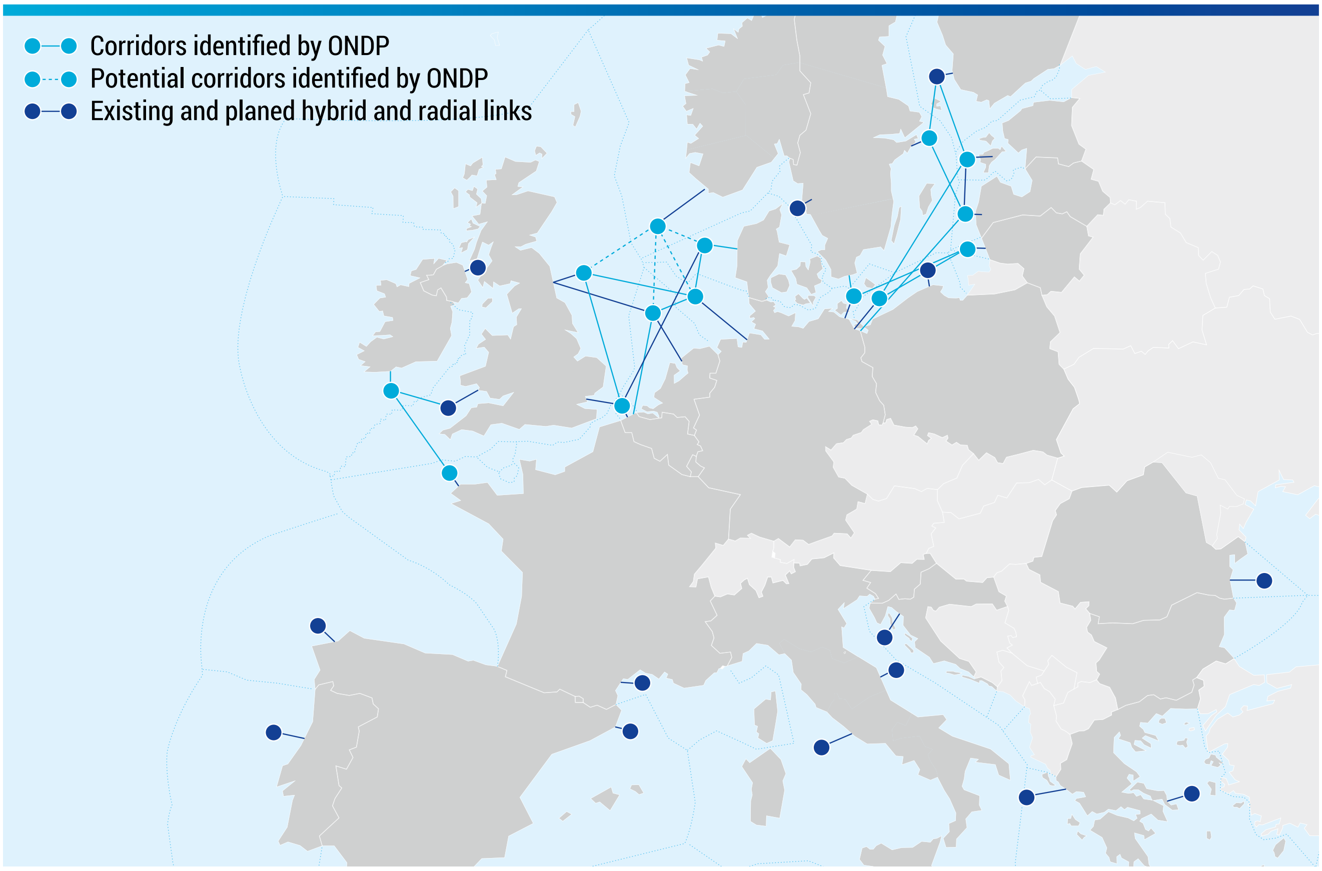


Figure 6. Offshore corridors identified in the ONDP 2024

"Balancing the rapid deployment of offshore grid infrastructure with the need to preserve and restore our marine environment is paramount. The health of our seas and the wellbeing of fragile marine ecosystems are vital for human life and economy. Therefore, while energy infrastructure development requires acceleration to meet the EU's climate goals, nature must be considered in the process."

Antonella Battaglini,
CEO, Renewables Grid Initiative

In January 2023 EU Member States agreed to increase their efforts to integrate up to 354 GW of offshore RES generation capacities by 2050 in European energy systems. In updated targets of December 2024 this number reached 365 GW. The energy potential of European waters needs a strong transmission system in order to connect to consumption. ENTSO-E's Offshore Network Development Plans (ONDP) per sea basin translates EU Member States' non-binding agreements on offshore goals into offshore transmission corridors, transmission equipment needs and related costs. ONDPs are parts of ENTSO-E's Ten-Year Network Development Plan and are mandated by the TEN-E Regulation (2022/869 EU Reg Art 14.2).

Direct connection of offshore generation to shore will continue to be the most common connection solution throughout Europe. However, hybrid infrastructure – which connects offshore generation and onshore bidding zones also interconnecting energy markets - will play an important role in efficiently integrating the energy produced, especially in the Northern Seas and Baltic Sea. The ONDP 2024 finds that hybrid corridors will progressively grow to connect 14% of offshore RES in 2050.

Supporting EU Member States and the European Commission with technical guidance on offshore cost-sharing

Up to now, countries and the hosting TSOs that invested in joined infrastructure projects onshore or stand-alone interconnectors across borders typically agreed on a 50:50 cost sharing key or territorial principle for the investment. In the future, solutions for cost sharing might become more complex in specific cases, with costs and benefits potentially distributed between the hosting parties via other sharing keys. Beyond that it is possible that benefits of offshore infrastructure – in the same way as for onshore projects - occur for non-hosting countries that do not directly connect offshore RES to their systems. This is why EU Member States and the European Commission search for fair, transparent and politically acceptable solutions for sharing the costs of offshore infrastructure.

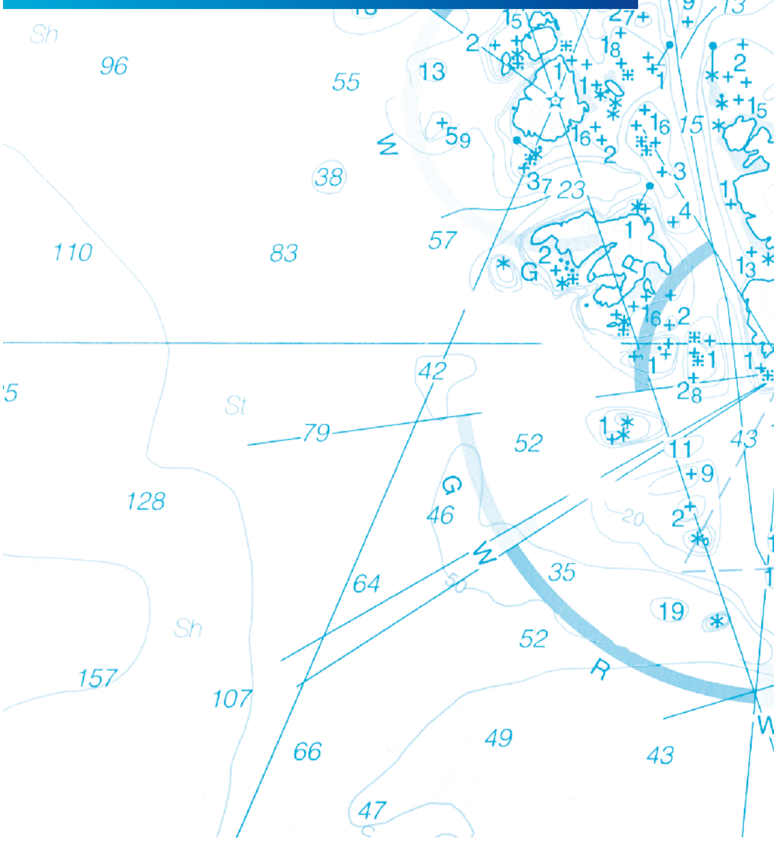
Today, agreements and decisions on cost sharing usually rely on a joint project assessment by the TSOs promoting the project, in coordination with their ministries and NRAs. Where there is a political will to balance benefits between hosting countries and possibly also non-hosting countries, concrete approaches are needed. The decision on what such approaches should entail must be made at political level. ENTSO-E's role is to assess potential options and propose design evolutions from a neutral perspective and provide technical guidance to support political and regulatory decision makers.

The assessments executed by ENTSO-E in the context of offshore cost sharing are twofold:

1. **Quantitative Analysis:** ENTSO-E has the mandate to translate the EC Guidance on Cross-Border Cost Sharing (CBCS) into a calculation methodology, which can be applied on ONDP and TYNDP data. The SB-CBCS is a transparency dedicated tool to assess the benefits and implications of developing the projects addressing transmission needs identified in the ONDP. In addition, the calculation tool SB-CBCS will support Member States in future revisions of their regional offshore renewable goals and facilitate discussions and negotiations on possible options or schemes for cost sharing of the offshore grid, firstly at the regional level. ENTSO-E's assessments are based on voluntary data input and have only an informative character. It is up to each Member State to determine the use of its energy resources, choose between different decarbonised energy sources, and the general structure of its energy supply. ENTSO-E will finalise the assessment in June 2025.
2. **Assessing policy options:** Discussing potential schemes of sharing keys, enabling instruments and sources of financing with some ideas stemming from EC guidance and others from TSOs themselves with a broad circle of stakeholders for actual cost sharing along with their advantages and disadvantages to allow for fair, transparent, sustainable and efficient cost sharing and/or effective investment support. ENTSO-E intends to present the considerations of a set of policy options in June 2025.

"We will need to get more multi-lateral cooperations among Member States. It can be coordinated at EU level and solutions can be developed at a regional level. To create effective solutions, offshore wind and grids need this regional perspective."

Leonardo Meeus,
Director Florence School of Regulation



Ensuring the needed technology becomes available in time: Research, Development and Innovation

TSOs are contributing to the development of the HVDC transmission technology, which is necessary for power transmission from the offshore asynchronously connected power park modules to the onshore AC networks. ENTSO-E and TSOs are involved in a multitude of projects which address the challenges in all phases from basic ideas, through interoperability and markets towards operation of the HVDC Systems taking into consideration not only point-to-point connections, but also multi-terminal DC networks. Projects include for example HVDC-WISE, InterOPERA, PROSECCO, InterSCADA, DEADALOS and THEUS.

Projects are umbrellas for relevant stakeholders, manufacturers, utilities, vendors and universities for open exchange of ideas. They enable building more complex and more efficient HVDC systems. Although their scope is broad, there is still further research needed, e.g. on asynchronously connected demand (e.g. Power-to-Gas, Electricity Storage Modules, Demand Units) to offshore AC hubs. These and further research needs are presented in ENTSO-E's Innovation Roadmap 2024–2034 and will be developed more in depth in an RDI Implementation Plan in 2026.

Tackling the supply chains challenge jointly with manufacturers

To go from today's offshore wind installed capacity to 2050 objectives, the average speed of installation will need to increase 9-fold (in comparison to the last 10 years). This is a considerable challenge for the overall value chain, including the manufacturing capacity of both generation and transmission equipment, supporting manufacturing capacity such as ships, yards, ports and harbours to assemble and deploy the equipment in the sea, and human resources to design, build and operate offshore systems.

ENTSO-E, T&D Europe, Europacable and the EU DSO Entity have been working together on the implementation of Action 13 of the European Commission's Grid Action Plan, addressing supply chain and procurement challenges to advance Europe's grid infrastructure. The collaboration aims to align practices for equipment testing, streamline factory acceptance processes, and develop functional specifications for critical grid components. It also supports revisions to EU procurement rules to promote flexibility and efficiency while fostering workforce development and innovation.

> *"After the first year of the Grid Action Plan, we can look back on one year of very constructive and forward-looking collaboration with the organizations of the network operators. Together, we are committed to seizing the opportunity of the energy transition to strengthen the European grid technology sector while simultaneously delivering the expectations raised by an accelerated transformation of Europe's energy systems towards a sustainable, reliable, and affordable future. High expectations have been placed on the electricity value chain, but we are confident that together we will cope with them."*
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> ***Jochen Kreusel, President, T&D Europe***

NEXT STEPS

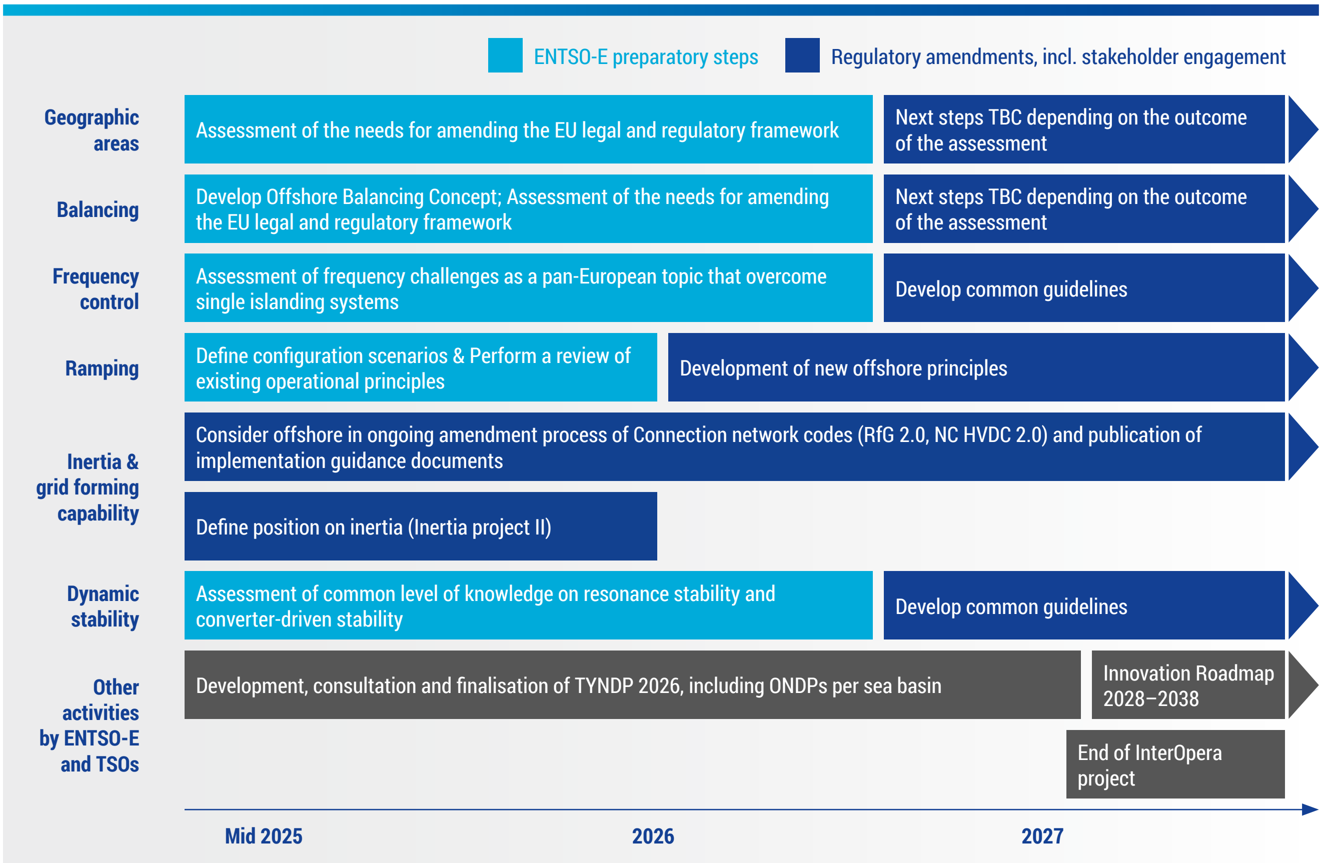

Figure 7. Timeline of ENTSO-E's main ongoing and upcoming activities under the Offshore Roadmap

Figure 7 provides an overview of ENTSO-E's main ongoing and upcoming activities, on the six topics previously described and on other activities including Offshore Network Development Plans of TYNDP 2026 and R&D. The Roadmap will be regularly updated to reflect regulatory and technical evolutions and progress on ENTSO-E's ongoing work and discussions with stakeholders.

ENTSO-E will follow up on the two workshops that took place in April 2024 and February 2025 by continuing the discussion with a broad circle of stakeholders, in two separate work-streams: one focused on market-related issues and another investigating the more technical issues.

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