Offshore Grids: the next frontier

THIS REPORT WAS A COLLABORATION BETWEEN:

WindEurope is the voice of the wind industry, actively promoting wind power in Europe and worldwide. It has over 500+ members with headquarters in more than 35 countries, including the leading wind turbine manufacturers, component suppliers, research institutes, national wind energy associations, developers, contractors, electricity providers, financial institutions, insurance companies and consultants. This combined strength makes WindEurope Europe's largest and most powerful wind energy network.

Hitachi Energy is a global technology leader championing the urgency of a clean energy transition through innovation and collaboration towards a carbon-neutral future. We are advancing the world's energy system to be more sustainable, flexible and secure. As a pioneering technology leader and the exclusive Knowledge Partner for the WindEurope 2023 event in Copenhagen, Hitachi Energy experts will share their technological know-how and domain knowledge to collaborate with key stakeholders and enable a sustainable energy future – for today's generations and those to come.

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Executive Summary

Europe is on the verge of an offshore wind revolution. The IEA predicts that offshore wind capacity will reach 130-180 GW by 2040[1]. Both the offshore wind and underlying offshore grid technologies are available. Now, the continent must urgently deploy these technologies at speed and scale, while ensuring a coordinated and holistic approach.

Europe's wind energy industry has a legacy of over 40 years, with the first wind farm being commissioned in 1982 on a Greek island. In 1991, almost 10 years later, Europe's first offshore wind farm was commissioned in Denmark consisting of 11 turbines and a total installed capacity of 5 MW.

Meanwhile, following its breakthrough innovation in 1954, high-voltage direct current (HVDC) power transmission, which allows high volumes of power to be transported across large distances, was continuing to expand. In 1997, a new voltage sourced converter (VSC) HVDC power transmission solution was introduced to the global market, enabling the transmission of large amounts of power underground, underwater and through overhead lines. The technology could also be used for applications like city in-feeds, interconnectors and connecting offshore wind farms. Notably, this technology is also an integral building block for hybrid AC-DC transmission systems.

Today, with an EU ambition of 300 GW offshore wind in operation by 2050 and a UK ambition of 50 GW offshore wind in operation by 2030, the offshore wind industry is experiencing a remarkable growth and has been identified as critical in achieving net zero greenhouse gas emissions by 2050. And with that growth, comes the need to evolve the approaches being used to transmit the power from offshore to our industries, businesses, and homes.

Until recently, the development of offshore grid infrastructure has been relatively uncoordinated. That means wind farms have been connected individually to shore, via point-to-point connections, with little coordinated planning for future development. Equally, subsea interconnectors have primarily been used to connect only two separate transmission systems. A more holistic approach is now starting to be adopted, which will result in the development of offshore hybrid projects which connect multiple wind farms to multiple markets combining offshore wind energy generation and transmission assets into one single multi-purpose asset. The natural evolution of these offshore hybrid projects will see them being connected to each other, in a coordinated manner, to form meshed offshore grids in Europe's sea basins.

This report describes the current state of offshore infrastructure development across Europe, the opportunities, and challenges, as well as the enablers associated with delivering this offshore future. Short-to-medium term actions which will drive the offshore industry growth and the creation of meshed offshore grids are identified:

- **To achieve 2030 offshore wind ambitions, countries across Europe must make provisions to ensure a step increase in connecting new offshore wind projects to the grid.** According to WindEurope, in 2022 2.5 GW of offshore wind (306 turbines) were connected to the grid in Europe. This is the lowest capacity connected to the European grid in a single year since 2016 and 30% less than forecasted. Countries across Europe must streamline and accelerate permitting and approval processes, activate the right market signals to boost investments, and shore up their manufacturing bases to achieve Europe's ambitious climate and energy goals.

- **Electricity is becoming the backbone of an evolving energy system and offshore wind energy as part of the energy mix will play a crucial role to keep the target of 1.5 degree warming by 2050 alive.** Unleashing the full potential of offshore wind as a domestic clean energy source requires allocating adequate ocean space for offshore wind and the electricity grid that supports it. Clarity on how to sustainably build large energy infrastructure in our seas and oceans which deliver on societal, economic, environmental, and technical benefits, and how offshore wind infrastructure can co-exist with the marine ecosystem and other sea activities, is needed.

- **A shift away from point-to-point offshore connections towards offshore hybrid projects and ultimately offshore grids will deliver on multiple socio-economic benefits.** Offshore hybrid projects and offshore grids in Europe's sea basins will provide benefits such as optimizing infrastructure build-out and on-land beach crossings, increasing infrastructure utilization rates and improving the ability of the power system to match supply and demand. More clarity is needed at the European level however to mitigate investment risks and to accelerate the deployment of such offshore projects.

- **The technologies are available to meet our near- and medium-term goals – now we must deploy them at speed and scale.** These clean energy technologies, including enabling technologies for the evolution from point-to-point connections to offshore hybrid projects and ultimately to meshed offshore grids, already exist. While the industry must innovate to improve efficiency and reduce cost, coordinated deployment of these technologies at 'speed' and 'scale' will now be critical. A full-scale offshore grid project deployment, combined with amending the existing network codes to make them fit-for-purpose for such deployments, is now necessary to respectively enable and highlight the benefits of meshed offshore grids. In addition, the continued efficient development and modernization of Europe's onshore grids will also be crucial to ensure that the power generated and transported offshore can reach its final destination – homes, industries, and businesses.

- **While the technologies are available, work is still needed to develop the frameworks and specifications needed to plan, build, operate and maintain meshed offshore grids.** New functional specifications, and amendments to the existing network codes will be necessary. Procurement and contractual frameworks will need to be designed and agreed amongst stakeholders. Business model innovation will be essential to develop viable projects. Interoperability, which is not only a technical matter, will also be required at a regional level across these frameworks and specifications.

- **The potential for interoperability of the critical HVDC components of meshed offshore grids has been demonstrated through innovation projects – immediate next step needed is a full-scale offshore grid project deployment.** The possibility to manage the interoperability of multi-terminal HVDC transmission network development has been demonstrated through projects such as the EU Horizon 2020 funded project PROMOTioN. The next step needed is to implement a meshed offshore grid in a full-scale high-voltage project. The EU funded InterOPERA project and UK funded Aquila project both aim to deliver on full-scale HVDC multi-terminal, multi-vendor, multi-purpose real-life applications by 2030.

- **Even as we strengthen local footprints, leveraging global supply chains will continue to be important.** Recent policy announcements globally point to a reshoring of manufacturing. Nonetheless, resilient global supply chains are of paramount importance when trying to ensure energy transition momentum. Supply chain disruptions impacting project timelines and costs are a reminder that a healthy global supply chain and open and fair trade, enabling manufacturers to leverage resources across the world, will be needed to ensure a speedy build-out of the renewables and grids to take our energy systems to the next level. This will also require Europe diversifying sources of imports and managing its raw materials more effectively.

- **Enhanced management and development of resilient supply chains is possible if technology providers have visibility of project development across a longer time frame. New policy and regulatory approaches, as well as new and innovative business models will be essential enablers for this holistic forward-looking planning.** Recent supply chain disruptions highlight the importance of policy makers and regulators moving away from single project approvals towards multi-project approvals and developing holistic forward looking and integrated approaches when it comes to on and offshore grid development, but also refurbishment and modernization of existing grids. Furthermore, a long-term approach also needs to be reflected in procurement practices from project developers. Project developers must embrace new business models based on long term integrated plans, including replicability. This long-term planning can provide manufacturers with the long-term visibility needed to secure the supply chain, including justifying investments in additional capacity and can provide justification for anticipatory investments into additional installed capacity or offshore grid technology enhancements.

- **We must maintain a healthy supply chain of skills/talent as we continue to build out the infrastructure which the energy transition is depending upon.** One of the most complex and enduring supply chain disruptors is the talent challenge. To plan, build, operate and maintain meshed offshore grids, the power sector will need to attract and retain skilled workers, while also managing changing demographics and employee expectations. Starting at the grass roots and even incorporating 'energy transition' as part of academic curricula will be important, while also promoting more dedicated programs in universities and vocational institutes.

- **Energy islands will be some of the largest energy infrastructure ever constructed and will be a key steppingstone for meshed offshore grids.** Not only will energy islands serve as hubs, gathering electricity from surrounding offshore wind farms and transmitting it to neighboring grids, but they will also position wind power as a beacon of regional cooperation. Completion, and operation, of these energy islands as planned e.g., North Sea Island, Princess Elisabeth Island, will be essential to meet Europe's climate and energy goals.

- **The challenge of developing meshed offshore grids will require the next generation of ambitious multi-stakeholder collaborations.** Stakeholders will need to collaborate within and across geographies and sectors, and across different stakeholder groups. Cross-border and cross-sector coordination and cooperation will be pivotal to capture the full societal, environmental, economic, and technical value of meshed offshore grids. Initiatives such as the North Seas Energy Cooperation agreement between governments will be key to promote and cultivate the type of collaboration needed to ensure effective coordination from planning to operation stages. This collaboration will be essential to ensure that Europe's meshed offshore grids result from a holistic European grid planning exercise, as opposed to a coordinated planning of different national grids as is the case today.

- **Across all areas, from policy and regulation, financing, sustainability, design, construction, operation and maintenance, a clear governance framework will be an essential enabler.** While the current point-to-point connection approach is relatively clear, the shift to meshed offshore grids, with multiple terminals and multiple vendors and connecting clusters of wind farms as well as multiple markets, will introduce significant complexity. One example is the shift from dedicated to shared infrastructure e.g., multiple windfarms or interconnectors will now rely on common infrastructure, introducing benefit- and cost-sharing issues. An effective governance framework should clearly outline the roles and responsibilities (as well as the limit of those responsibilities), of all involved stakeholders. While new protocols may be required, the existing onshore grid frameworks and approaches should be reutilized to the greatest extent possible, but with the necessary amendments to reflect offshore grid specificities.

2.

Setting the Scene

Europe's power systems are facing a period of unprecedented changes as electricity accelerates its path to becoming the backbone of the evolving energy system[2]. This paper focusses on the expected offshore developments, particularly offshore grids, where two key drivers will be: (1) an increasing level of renewable energy resources, especially offshore wind projects needing to connect to our power grids, (2) the build out of an increasing number of subsea interconnectors enabling countries to trade electricity, leverage the complementarity of renewable resources and increase the security, resilience and flexibility of Europe's power supply.

2.1 Ambitious European Offshore Wind Targets

With a UK ambition of 50 GW offshore wind in operation by 2030 and an EU ambition of 111 GW of offshore renewable generation capacity by 2030 and 317 GW[3] in operation by 2050, the future challenges for offshore wind development include transporting this amount of offshore wind power to shore and integrating it into transmission systems. The current challenges will be how to get it built and operational within relatively short timeframes.

Significant offshore wind targets were announced in Europe during 2022:

The Esbjerg Offshore Wind Declaration: In May 2022, European Commission President Ursula von der Leyen participated in an Offshore Wind Summit in the Port of Esbjerg (Denmark) with German Chancellor Olaf Scholz, Belgian Prime Minister Alexander De Croo, Danish Prime Minister Mette Frederiksen and Dutch Prime Minister Mark Rutte. In a joint declaration, they highlighted the role of North Sea offshore wind in strengthening the EU's energy security and pledged to expand their North Sea offshore wind capacity to 65 GW by 2030 and 150 GW by 2050. In 2023, Belgium hosted the second 'North Sea Summit'. The original five leaders were joined in Ostend by heads of state and government from France, Ireland, Luxembourg, Norway, and the UK. The objectives agreed in Esbjerg were extended to incorporate the potential of the new participating countries.

The Marienborg Declaration: At the Baltic Sea Energy Security Summit, in August 2022, leaders from Denmark, Sweden, Finland, Germany, Poland, Latvia, Lithuania and Estonia signed the Marienborg Declaration. The Eight Baltic Sea countries agreed to increase the offshore wind capacity currently installed in the Baltic Sea by 2030 and will also cooperate on grid interconnections. The countries have committed to a combined ambition for offshore wind in the Baltic Sea region of at least 19.6 GW by 2030 – a significant increase compared to the previous 2.8 GW.

North Seas Energy Cooperation: In September 2022, energy ministers from the nine members of the North Seas Energy Cooperation (NSEC) agreed to reach at least 260 GW of offshore wind capacity by 2050. This will represent more than 85 per cent of the EU-wide ambition of reaching 300 GW of offshore wind capacity by 2050. The members of NSEC are Belgium, Denmark, France, Germany, Ireland, Luxembourg, the Netherlands, Norway, Sweden, and the European Commission. The members have also agreed on expansion targets for the North Sea region of 76 GW of offshore wind by 2030, and 193 GW by 2040. In addition, NSEC has agreed on developing more hybrid offshore projects combining wind farms and interconnectors and connecting to several member states. As of December 2022, the NSEC and the United Kingdom also established a cooperation framework to facilitate the development of cost-effective and sustainable offshore renewable energy.

What is clear, is that the delivery of these targets will require high levels of interconnection between states, combined with a significant build out of offshore wind infrastructure. However, despite these announcements, WindEurope reported in February 2023 that turbine orders in Europe were down by nearly half in 2022, and no new investment decisions were made in offshore wind. Also, in 2022, only 2.5 GW of offshore wind (306 turbines) were connected to the grid in Europe. This is the lowest capacity connected to the European grid in a single year since 2016 and 30% less than forecasted. Europe must make provisions to ensure a step increase in connecting new offshore wind projects. Urgent action to streamline and accelerate permitting and approval processes, activate the right market signals to boost investments, and shore up manufacturing bases across Europe is needed.

2.2 More Interconnections

The EU has set an electricity interconnection target of at least 15% by 2030[4] to encourage EU countries to interconnect their installed electricity production capacity. This increase in interconnection will be essential to integrate the large volumes of renewables being developed. Figure 1 below illustrates the possible development of cross border interconnector capacities from 2020 to 2040.

Cross border electricity interconnectors run via subsea cables, underground cables or via overhead lines, to connect the electricity systems of two neighboring countries, markets, or zones. The number of subsea interconnectors has been growing. In particular, thanks to technological innovations such as VSC (voltage source converter) HVDC (high voltage direct current) which enables the transmission of large amounts of electricity with minimal losses through XLPE cables[5] and offering reduced physical and environmental footprint and increased grid resilience.

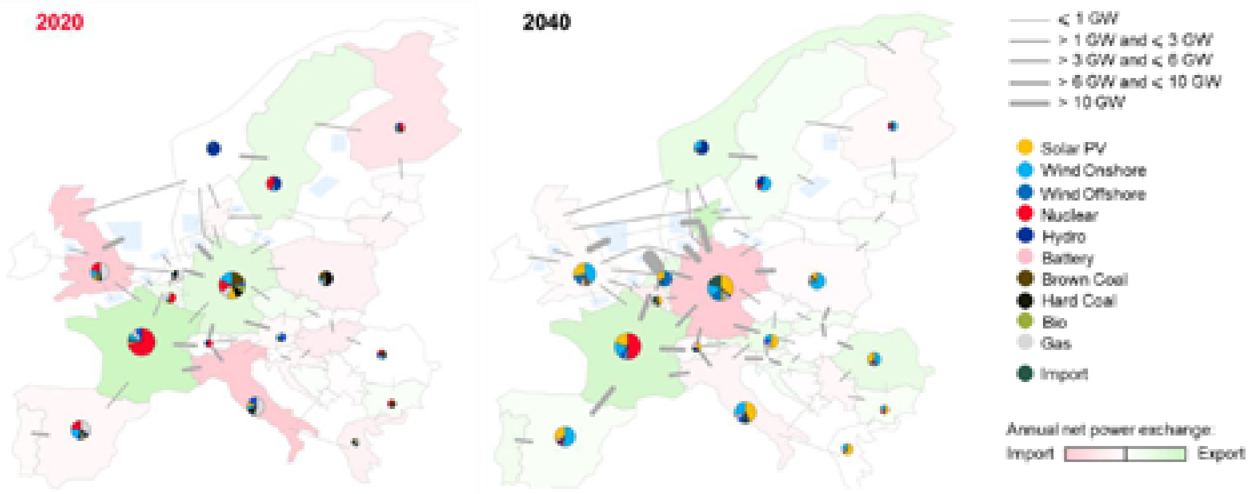
As an example, the 720 km North Sea Link recently commissioned between UK and Norway[6] is, at time of writing, the longest subsea interconnector in the world. It enables the two countries to share renewable energy, offering consumers at both ends access to cleaner and more secure energy supply.

2.3 Evolving from point-to-point connections to meshed offshore grids

Currently, almost all offshore windfarms are connected to shore via ‘radial’ or ‘point-to-point’ connections. Equally, almost all subsea electricity interconnectors are shared between only two markets. Two types of offshore transmission systems exist, based on either alternating or direct currents (HVAC or HVDC). For wind farms close to the shore, HVAC will often be the preferred solution. However, HVDC technology can become cost competitive currently for connections beyond 50 km[8] from shore, depending on a number of factors including loss evaluation and power level.

One drawback of these point-to-point connections is that transmission equipment is designed and installed to transmit 100% of the output from the windfarms but remains unused in low or no wind conditions. This underutilization is significant when one considers a typical offshore wind generator load factor of 40%. Another concern, relating to reliability, is that each wind farm depends on one cable for power transmission. These point-to-point connections offer no redundancy and represent a risk to wind farm projects depending on revenues from sales of wind power delivered to connected grids.

FIGURE 1. Possible development of cross border interconnector capacities from 2020 to 2040[7]



Source: WindEurope and Hitachi Energy

While the current approach has worked for the first wave of offshore wind farm installations, given the ambitious plans across Europe for offshore wind deployment, a more holistic and coordinated offshore infrastructure plan is required to connect the large volumes of 'distant from shore' offshore wind development expected. These ambitious plans coincide with the availability of enabling technology, such as pre-engineered high-power voltage-source based offshore HVDC solutions with multi-terminal capability.

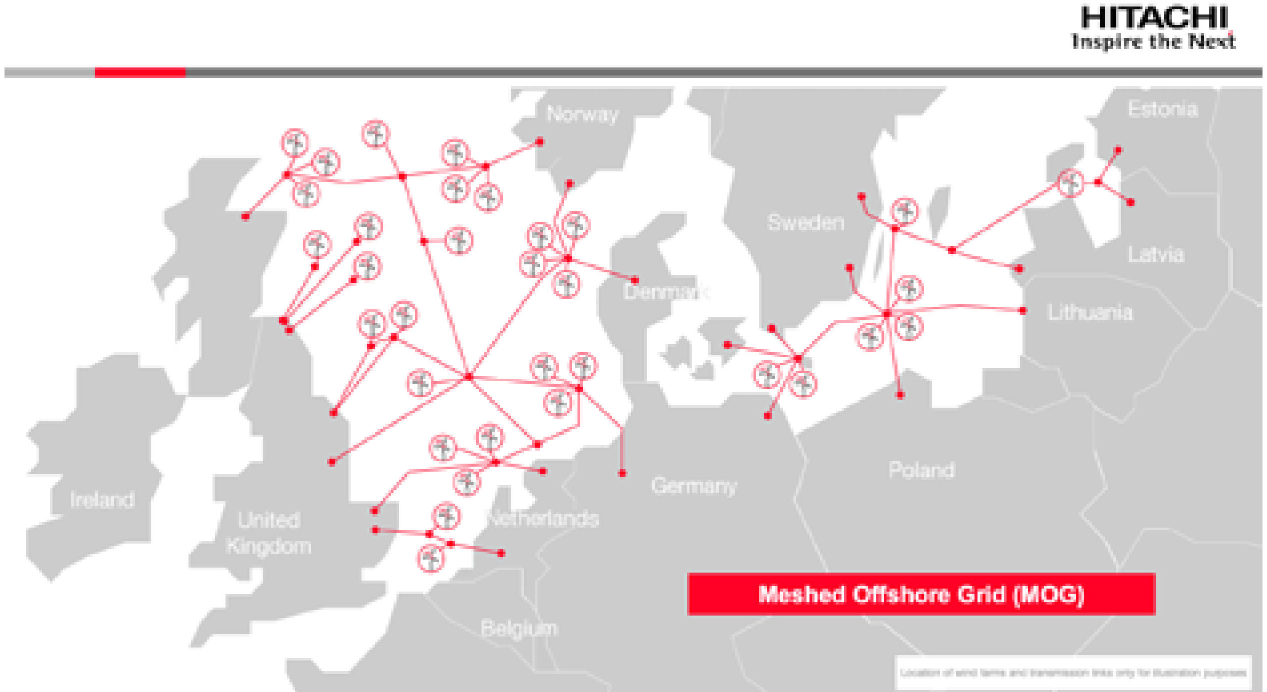
The UK Government, through its Holistic Network Design for Great Britain, sets out a single, integrated design that supports the large-scale delivery of electricity generated from offshore wind, taking power to where it's needed across Great Britain. The delivery of the Caithness-Moray-Shetland link, due for completion in 2024[9], will be the first multi-terminal HVDC system in Europe using voltage-sourced converter technology and a key enabler for this plan.

One step further in terms of ambition, and still relying on multi-terminal interconnectors, will be the development of offshore hybrid projects (also sometimes referred to as multi-purpose interconnectors). As defined by WindEurope, offshore hybrid projects connect multiple wind farms to multiple markets combining offshore wind energy generation and transmission assets into one single multi-purpose asset. These offshore hybrid projects optimize infrastructure build-out, increase infrastructure utilization rates and improve the ability of the power system to match supply and demand. They are expected to represent one third of all offshore wind capacity by 2050. Examples include the Triton Link, which will link the artificial energy islands of Denmark and Belgium and will transmit 2,000 MW over 773 km with HVDC technology. Another example is the Nautilus interconnector between Belgium's artificial island and the United Kingdom. The link is expected to transmit 1400 MW over a 140 km distance.

While offshore hybrid projects offer significant advantages, including socio-economic welfare benefits, investments in offshore hybrid projects today are riskier than connecting wind farms to individual countries and building separate interconnectors. Such risks will need to be mitigated to enable their accelerated development.

The natural evolution beyond offshore hybrid projects will be the creation of meshed offshore grids in Europe's sea basins, likely through the connection of multiple offshore hybrid projects. A simplified illustration of this is included in Figure 2. Countries from around the North Sea and Baltic Sea have already started to work on regional initiatives to jointly plan the development of offshore grids and the European Network of Transmission System Operators for Electricity (ENTSO-E) has been mandated to develop regional Offshore Network Development Plans by January 2024[10].

FIGURE 2. Simplified Illustration of a Future Meshed Offshore Grid. Credit: Hitachi Energy



Source: Hitachi Energy

3.

Offshore Grids – Perspectives

With the first offshore grids come a host of opportunities, but also challenges. This chapter explores the policy, financing, environmental, and technical perspectives to consider when developing offshore grids.

3.1 A Policy Perspective

3.1.1 Trans-European Networks for Energy (TEN-E) Regulation

In June 2022, the revised Trans-European Networks for Energy (TEN-E) Regulation[11] laying down new EU rules for cross-border energy infrastructure entered into force. The TEN-E Regulation aims to enhance connections between the energy infrastructure of EU countries and accelerate financing and permitting for new energy infrastructure projects that are crucial for the EU energy system.

The TEN-E Regulation includes a focus on offshore grids with provisions to support the scale-up of EU offshore grid development. The regulation focuses on a sea-basin level. ENTSO-E has been mandated to propose strategic Offshore Network Development Plans, giving visibility to grid promoters, investors and the supply chain on what offshore grids to expect by 2050, with intermediate steps in 2030 and 2040. This exercise will be essential to ensure that Europe's meshed offshore grids result from a holistic European grid planning exercise (as opposed to a coordinated planning of different national grids as is the case today).

The TEN-E regulation will also help with timely delivery of cross-border infrastructure by proposing ways to simplify and accelerate permitting and authorization procedures, when it comes to Projects of Common Interest (PCIs) and Projects of Mutual Interest (PMIs). PCIs are infrastructure projects (mainly transmission and storage) which have a significant impact on the EU electrical system and help the EU achieving its energy policy and climate objectives: ensuring affordable, secure, and sustainable energy for all citizens. PMIs are projects between EU Member States and third countries, that contribute to the EU and the third country's overall energy and climate objectives.

Nonetheless, further work is required at the policy maker level including addressing potential conflicts with other uses of the ocean, such as fishing and shipping, and garnering public support for both onshore and offshore infrastructure development and modernization requirements. Stable and transparent regulatory frameworks, which also maintain an element of flexibility will be key, particularly frameworks that lay out clear and long-term rules on regulatory requirements for offshore grids, including cost-benefit cost-sharing requirements, owner and operator obligations and roles and responsibilities of stakeholders.

3.1.2 EU Electricity Market Design Reform

As mentioned above, offshore hybrid projects could represent up to one third of all offshore wind capacity by 2050. However, these projects are inherently riskier than point-to-point connections, especially as wind projects shift from dedicated to shared infrastructure.

Depending on the market setup, the wind farm output from an offshore hybrid project could fully depend on available cross-zonal transmission capacity. In situations where internal congestions in the onshore network occur, system operators may carry out operational deratings which reduce the availability of cross-zonal transmission capacity. This could mean that the offshore windfarm is curtailed.

In March 2023, the European Commission released a proposal to reform the EU's electricity market design[12]. The proposed reform is part of the Green Deal Industrial Plan and foresees revisions to several pieces of EU legislation – notably the Electricity Regulation, the Electricity Directive, and the REMIT Regulation. As part of the proposal, the European Commission explicitly attempts to reduce the investment risk for offshore hybrid projects and to ensure that these projects have full market access to the surrounding markets. The proposal suggests that TSOs guarantee access of the offshore project to the capacity of the respective hybrid interconnector for all market time units. If the available transmission capacities are reduced, the TSO or operators responsible for the limitations should be enabled to compensate the project operator using congestion income.

3.1.3 Governance Frameworks

Across all areas of policy and regulation, financing, sustainability, design, construction, operation and maintenance, a clear governance framework will be an essential enabler for the accelerated development of offshore grids. Too often, debates on infrastructure development focus on the financial or the technology challenges, thereby neglecting the governance considerations. While the current point-to-point connection approach is relatively clear, the shift to meshed offshore grids with multiple terminals and vendors, will introduce significant complexity. An effective governance framework should clearly outline roles and responsibilities (and the limit of those responsibilities) of all the stakeholders, involved in the planning, development, operation, and maintenance of offshore grids, based on a comprehensive consultation period.

An obvious example would be the requirement for a governance framework to clearly identify what ‘stakeholder’ (or group of stakeholders) will be responsible for the safe operation of which parts of a meshed offshore grid, what ‘stakeholder’ (or group of stakeholders) regulates the operation of a meshed offshore grid and what stakeholder (or group of stakeholders) could be relied on to take remedial action in the event of a fault. In the development of these governance models, existing frameworks which have been developed for the onshore grid could be re-utilized including e.g., the definition of control areas, responsibilities of the system operator, grid connection processes. Reutilization of existing frameworks could also avoid the creation of an artificial barrier between the onshore and offshore grid, but must take into account the specificities of offshore grids.

The need for Governance Frameworks – a working example

For the current point to point system to work, taking an interconnector as an example, normally 2 grid codes and 2 customers (e.g., Transmission System Operators (TSOs) are involved. The 2 TSOs will often form a Special Purpose Vehicle (SPV) to manage the interconnector. Technology providers then engage with the SPV, and existing regulatory, legal, and financing frameworks ensure that the process is efficient. With the move to meshed offshore grids, new issues appear. These grids will likely involve three or more countries and customers adopting different approaches to ensure the delivery of power from offshore wind farms. In addition, if a new node is added to the meshed grid, how are the existing stakeholders impacted? What are the regulatory, legal, and financial frameworks needed to govern this additional complexity?

3.2 A Financing Perspective

There are many aspects around financing to consider, particularly since the level of investment required to build out high volumes of offshore wind, as well as the meshed offshore grid infrastructure and the energy islands, will be significant.

3.2.1 Anticipatory investment

Anticipatory investment is investment which goes beyond the needs of the immediate offshore development or developments. CAPEX investments should incorporate an understanding that further expansion is likely and therefore an initial project may need to invest in higher cable capacity than required or enhanced system performance, while at the same time considering that further expansion may impact the connected wind farm’s business model. Equally, the multi-terminal connections being built must incorporate the technology to manage being part of a larger meshed system in the future. This will require a careful balance between cost and longer-term value.

Anticipatory investments will contribute to the acceleration of the deployment of offshore hybrids and meshed offshore grids since a more holistic view supported by appropriate forward-looking financing will enable all stakeholders to move towards a common vision, while being better able to evaluate the risks. This might also create long term strategic partnerships and relationships between different stakeholders building more trust and further enhancing the speed of deployment.

An EU Strategy to harness the potential of offshore renewable energy was released in 2020 including a focus on preparing for higher future volumes of offshore energy and more innovative and forward-looking grid solutions. The strategy proposed that regulatory frameworks should incorporate anticipatory investments, for instance to develop offshore grids with a larger capacity than initially needed. The EU's revised TEN-E regulation from 2022, specifically mentions offshore grids for renewable energy, and the likelihood that they will incur higher risks than comparable onshore infrastructure projects, including regulatory risks, financing risks such as the need for anticipatory investments, market risks and risks pertaining to the use of new innovative technologies.

3.2.2 Reducing uncertainty / derisking

Developing offshore grids will require high amounts of capital and the operational costs must also be considered given the harsh offshore environment. Financiers will expect stable but flexible policies and standards, as well as innovative business models to provide them with sufficient investment certainty.

Given the level of investment and collaboration required to build out an offshore grid, financial support from government will be essential. Public-private financing is useful where projects are too complex for complete market financing, and where sharing of risk is possible. The sharing of technology risks is not a new concept for Europe and funding through the EU Horizon initiative or the Connecting Europe Facility (CEF)[13] is well understood. These types of financing tools should also play a role in ensuring the required anticipatory investments are prioritized.

3.3 An Environmental Perspective

Electricity becoming the backbone of the evolving energy system will represent a crucial opportunity to keep global warming at 1.5 degrees Celsius. Offshore wind will play a central role in decarbonizing our economy, helping Europe to meet its climate targets, while also achieving energy independence. Unleashing the full potential of offshore wind as a domestic clean energy source requires allocating adequate ocean space for offshore wind and the electricity grid that supports it, while also ensuring that offshore energy infrastructure can co-exist harmoniously with other marine activities.

Fora, such as the Offshore Coalition for Energy And Nature (OCEAN), are assessing how to ensure that marine activities, including the development of offshore wind and grid infrastructure, contribute to the achievement of Europe's climate and biodiversity goals. Researchers are investigating topics such as the underwater noise created when laying subsea cables and constructing offshore structures, as well as the impact of power cables on the navigational capabilities of fish and the impact of electromagnetic frequencies (EMFs) on sea life. Additionally, experts are exploring the risk of collision mortality with offshore wind turbines, as well as displacement of sea life due to disturbance (including noise impacts), barrier effects (also including noise impacts), potential habitat loss; and indirect ecosystem-level effects.

On the other hand, there are examples of how clean energy infrastructure can positively impact oceans:

- Marine biodiversity loss is an increasing concern, happening for a variety of reasons including over-fishing. A potential solution could come from offshore energy infrastructure. Marine biologists are examining the effects of planting coral larvae at the base of offshore structures, with the aim of growing new reefs.

- 12 x 3D-printed reef structures[14] have been deployed on the seabed between the wind turbines at a wind farm in the Greater North Sea ecosystem. Among other things, overfishing, increasing oxygen depletion, and habitat loss have resulted in a decline of the cod stock in this area for the past 20 years. It is hoped that the project will have positive effects on the cod stock and in turn contribute to a healthier, more resilient marine ecosystem with improved biodiversity.

- There is also evidence that in some circumstances where fishing has been restricted near offshore wind farms and subsea cables, a fishery 'reserve effect' is observed where marine fauna tend to aggregate, thus improving fish stocks.

Clarity on how to sustainably build large energy infrastructure in our seas and oceans which deliver on broad system value, while fostering biodiversity in our seas and oceans will be key to accelerating the build out of offshore wind and grids in a sustainable way.

Reducing CO_2 emissions through integrated planning

In Great Britain, the former Department for Business, Energy and Industrial Strategy (BEIS) launched the Offshore Transmission Network Review in 2020 to ensure that the transmission connections for offshore wind generation are delivered in a planful holistic manner, finding an appropriate balance between environmental, social and economic costs. Moving on from the original radial approach to connecting offshore wind farms, BEIS envisaged a more centralized and strategic approach to network planning, by integrating the connection of offshore wind farms to shore with the capability to transport electricity around Great Britain. Led by the Electricity System Operator (ESO), the Holistic Network Design was produced in 2022 and provides connection recommendations for 23 GW of offshore wind and the associated transmission network infrastructure to get the power to where it is needed. It will enable the connection of 50 GW of offshore wind in Great Britain by 2030.

- The HND estimates overall net consumer savings of approximately **£5.5 billion** by applying an integrated approach. While the additional offshore infrastructure will result in capital costs of £7.6 billion, these are outweighed by the £13.1 billion savings in constraint costs that are expected to result from the additional network capacity this infrastructure provides. This equates to a saving of £2.18 per year on the average customer electricity bill.

- Environmental impact will be reduced due to the **offshore infrastructure footprint being up to a third smaller** as a result of the increased use of HVDC technology, including reducing the impact on the seabed.

- Reducing cumulative CO_2 emissions from gas powered generation between 2030 and 2032 by **2 million tons of CO_2** through transporting power produced by offshore wind to where it will be used more of the time, reducing the need for fossil fuel generation to be used in its place[15].

3.4 A Technical Perspective

The technology to make meshed offshore grids a reality is available today and is ready to be deployed at speed and scale. Technical organizations, such as CIGRE, have been working on the required developments to build out offshore grids, as identified by gap analyses, since 2010. While the technology is available, of course there is also room for more improvement and the need to continuously innovate to increase functionality, reduce price and, in the case of the HVDC breaker, reach commercial stability.

A number of EU Research & Development projects under the EU Horizon framework are addressing the existing gaps, and the ongoing InterOPERA project, which is discussed in Section 4.3, will likely be the precursor to a full-scale HVDC multi-terminal, multi-vendor, multi-purpose project by 2030. However, planning, building, operating, and maintaining these new grids will be challenging. There are still some technical aspects which must be considered:

3.4.1 Functional and operational requirements

While the European Commission Regulation 2016/1447 establishing a Network Code on requirements for grid connection high voltage direct current systems and direct current-connected power park modules (or Network Code on HVDC connections)[16] defines what a HVDC system should be capable of, this is focused on the AC-interface and the common point of connections onshore and offshore. It does not cover DC grid functional requirements at DC-side connection points, which will be needed once multi-terminal systems are deployed.

DC grid functional requirements must include all DC subsystems and DC grid elements and define connection requirements at DC-side connection points. Operational requirements and rules for DC grid systems (e.g., a DC overlay grid) covering, for example how an operator can leverage an offshore grid in the case of a black start, will also need to be developed and agreed.

Already, work has been carried out by CENELEC[17] and the IEC[18] to establish a standard for a framework to describe the technical interfaces and parameters needed. Not only will these functional and operational requirements be essential to establish governance e.g., actions by stakeholders and the order of command, but they will also be essential for procurement. This is also discussed in Section 4.5.

Connection Requirements for Offshore Systems

An Expert Group on the Connection Requirements for Offshore Systems has been formed by the EU Stakeholder Committee for Grid Connection. The members are currently working on the amendments needed to the existing EU Network Codes to facilitate the development of offshore transmission systems and the effective integration of offshore renewables.

3.4.2 Market Rules

An efficient offshore grid requires a market fit-for-purpose. The market setup for hybrid projects must ensure both a stable investment framework and optimal dispatch. There must be an incentive for grid owners and generators to investment in offshore hybrid projects and offshore grids instead of separate assets. There is an urgent need to start getting projects on the grid that will serve to create learnings for future projects, while ensuring progress in wind energy build-out. Taking an exemption approach for early pilot projects could be an important catalyst.

There are two market setups currently under consideration: either the wind farm forms part of the bidding zone (price area) of its ‘home market’ or a new ‘offshore bidding zone’ is defined, into which the wind farm bids its power. Whether it makes sense to create a new bidding zone, or whether it makes sense to integrate offshore hubs into existing home markets, depends on the project, market fundamentals, and national circumstances. A one size fits all solution may not be achievable or desirable. However, both options come with the need to adapt regulatory frameworks to a new type of shared infrastructure.

4.

Facilitating the Vision

The following enablers will be essential to accelerate the evolution from point-to-point connections to offshore hybrid projects to the final vision of meshed offshore grids:

4.1 Key Enabling Technologies

While it is important to sustain our focus on innovation and development, the good news is that the technologies required for the achievement of near- and medium-term goals (e.g., until 2030 and beyond) already exist, also when it comes to meshed offshore grids.

4.1.1 Hybrid HVDC Breakers

A key component in the development of multi-terminal connections, offshore hybrid projects and meshed offshore grids is the HVDC Breaker.

If a HVDC short-circuit fault (e.g., an insulation fault) occurs on the interconnected DC-side, in the worst case, the voltage can collapse near to zero at the fault location. For a section of HVDC grid connected by HVDC cables, a short-circuit fault typically must be cleared within a few milliseconds, in order not to disturb converter stations as far away as 200 km, a significantly different challenge compared to AC fault clearing times, which are longer.

Prior to recent advancement, any faults appearing on the HVDC side of a connection were cleared by opening the interfacing AC-breakers and isolating the complete HVDC network. Only once the specific fault section was identified

FIGURE 3. Hitachi Energy's ultra high-voltage test hall in Ludvika, Sweden, where the highest voltage products are tested for both AC and HVDC projects.

Source: Hitachi Energy

and isolated could the rest of the network then be re-energized. This process tends to take up to one second and is acceptable if the fault is very unlikely, if the fault is not system critical (e.g., leading to black out) and the reconnection is automatically sequenced. In fact, this solution is already in operation in existing systems.

The introduction of larger and more interconnected offshore grids will increase the impact of these very unlikely events and hence the solution of using AC-breakers to clear a fault becomes more problematic. With HVDC breakers, the HVDC grid can now be split into different protection zones and the protection can be coordinated in a similar way as with the selectivity in the existing AC grids. In other words, in the event of a fault on one of the lines/cables, HVDC breakers can very quickly isolate the faulty part, while the rest of the network can stay in operation.

HVDC breakers based on semiconductors can easily overcome the limitations of operating speed but tend to generate significant transfer losses, typically in the range of 30% of the losses of a voltage source converter station. And so, a Hybrid HVDC breaker has been developed and tested in a high voltage test facility, an example of which is show below in Figure 3, as part of the PROMOTioN project[19] discussed in Section 4.3). The hybrid design has negligible conduction losses, while preserving ultra-fast current interruption capability and will be a critical component of meshed offshore grids.

HVDC Breakers are now classed with a Technology Readiness Level of 8[20], according to the IEA, indicating that the technology is in full scale deployment in final conditions. This is based on the demonstration in Europe through the PROMOTioN project and the Zhangbei flexible DC power grid test demonstration project in China[21].

FIGURE 4. Gotland HVDC Link

Credit: Hitachi Energy

4.1.2 Voltage Source Based HVDC Converters

High-voltage direct current (HVDC) power transmission allows high volumes of power to be transported across large distances. A HVDC transmission link includes a converter station, converting AC voltage into DC voltage, a transmission line and another converter station at the other end of the line, converting DC voltage back into AC voltage.

The Gotland HVDC Link (see Figure 4) was the world's first commercial HVDC transmission link using the first submarine HVDC cable. It connected the Island of Gotland to mainland Sweden. The 96 km-long cable used mass-impregnated technology.

Today, there are two types of HVDC technologies, Line Commutated Converter (LCC) since the 1960s and Voltage Source Converter (VSC) since the 1990s. They have mostly been used for point-to-point connections, as well as smaller multi-terminal systems. While long-distance DC corridors first emerged in the 1960s, it was not until the 1990s following advancements in power electronics and control systems, that the first multi-terminal HVDC system was commissioned between Quebec and Boston[22].

In 2017, the North East Agra line in India became the world's first multi-terminal ultra-HVDC transmission link, transmitting hydro power from India's northeast region to the city of Agra over 1,728 km. The Shetland link, currently under construction, and due for completion in 2024, will complete the first multi-terminal HVDC system in Europe using voltage-sourced converter technology. The Shetland interconnector will connect to the existing 320kV Caithness-Moray Link in the UK to form a three-terminal HVDC network.

HVDC technologies are housed in converter stations, either on land or offshore, such as that in Figure 5 below. During the last 25 years the evolution of the voltage source technology built on insulated gate bipolar transistor (IGBT)-based VSC HVDC converters, has scaled in voltage level and power range to the point where they can now facilitate cost-effective construction of multi-terminal meshed DC grids.

These modern IGBT-based HVDC systems offer clear technological advantages, especially in controllability and efficiency. Features like fast active power control, incorporated fast and dynamic AC voltage control through reactive power compensation, and black start capability give the network operator a perfect tool for enabling an energy transmission system with high availability and grid resilience. This has been progressively demonstrated in the VSC HVDC systems commissioned during the last 20 years. The power level is today matching the largest generator plants in the European system and easiness of integrating them in existing onshore AC systems has been key to ensuring grid integration and system stability.

As meshed offshore grids develop further, i.e., expand beyond multi-terminal connections to offshore hybrid projects and meshed grids, it is worthwhile to consider that they will likely be a mix of AC and DC technologies.

FIGURE 5. An offshore converter station at Dogger Bank, United Kingdom

Source: Hitachi Energy Credit: Aibel

FIGURE 6. HVDC Light Valve Hall

Credit: Hitachi Energy

4.1.3 Control and Protection Systems for Meshed Offshore Grids

A meshed offshore grid, and its integration with existing onshore grids, will require advanced protection and network control systems.

Each connected HVDC Converter station will have its own dedicated Control and Protection (C&P) system that governs the internal and very fast control and protection functions. These functions protect the installed equipment during fault events by ensuring adherence to applicable grid codes and agreed functional behavior. The role of the Hybrid HVDC breakers in the meshed offshore grid protection approach is described in Section 4.1 above.

The control systems ensure the coordination of the DC grid, through a common system between individual converter stations and the dispatch center. It monitors and sends set-points to manage the power flow through the grid, including active and reactive power control and dispatch sequences. Algorithms generally work to guarantee the expected power transfer as well as deal with wind power forecasting errors. The control system will also be used to support the interface with the existing AC grid, redistributing power flow as necessary to reduce the risk of AC contingencies and contribute to reducing wind power curtailment. However, the fundamental integrity of the AC system will ultimately be handled by controlling the frequency and voltage within the predefined operational limits.

4.1.4 Power Electronics

Power Electronics (PE) is the term used when electronics are used to control and convert electric power. PE are used by people every day e.g., when charging our smartphones and electric vehicles. PE are also used to efficiently transmit power across countries and seas through HVDC transmission.

The first high-power HVDC valve devices were made using mercury-arc valves. The first power electronic devices were using thyristors and in the 1990’s the next step was taken by insulated-gate bipolar transistors (IGBTs) introduced in VSC HVDC. Today, power conversion is performed at very high speeds and with minimum losses, still using power semiconductor devices such as IGBTs (insulated-gate bipolar transistors). A valve hall, as shown in Figure 6, is a building which contains the valves of the static inverters of a HVDC. The valves consist of thyristors, or at older plants, mercury arc rectifiers. The valve hall is an important component of the HVDC system.

Power Electronics systems are supervised and controlled by digital controllers. The controllers perform millions of calculations per second using many inputs that are measured thousands of times per second. The evolution of digital technologies facilitates even higher controllability of the system and improves visibility by gathering and analyzing data thus improving decision making and control outcomes. Edge and cloud solutions help to increase controllability of the asset, the fleet, and the interaction of PE solutions with the power grid. Augmented reality, machine learning and digital-twin technologies further improve serviceability and asset health management and allow new concepts of training and safety assurance.

4.1.5 Digitalization and Digital Technologies

Digitalization is essential to making electricity the backbone of the entire energy system and advancing a sustainable energy future for all. It will be one of the most important enablers to the integration of offshore renewables and the development of offshore grids, providing benefits that will span across the whole value chain, from planning and design to real time control, operations, and maintenance.

Digital technologies already automate complex processes and facilitate information sharing in the energy sector, and software already plays a significant role in managing our energy systems. These technologies will facilitate performance improvements and cost savings through a combination of automation, optimization, and the enabling of new business and operational models, particularly when it comes to offshore grids.

As a concrete example, a digital twin is a digital representation of a system. It is designed to monitor and automate the system it replicates. Already, digital twins are available of HVDC converter stations and other power quality solutions. The digital twin provides all the relevant asset information, analytics and operational data to the user, even including 3D interactive visualization of the complete asset, combined with access to all the associated plant and equipment information.

In December 2022, ENTSO-E and the EU DSO Entity agreed to jointly develop a Digital Twin of the EU electricity grid[23]. The aim is to enhance the efficiency and smartness of the grid throughout the energy system. The digital twin will not be created as one single product but will be a continuous and ongoing investment and innovation effort, also ensuring synergies with upcoming initiatives on virtual worlds.

Five focus areas have been agreed: observability and controllability; efficient infrastructure and network planning; operations and simulations for a more resilient grid; active system management and forecasting to support flexibility and demand response; and data exchange between TSOs and DSOs. Incorporating offshore grids into this model from the outset will be essential.

4.2 Global Supply Chains

Resilient and diverse supply chains will play a primary role in ensuring timely metal and material availability to support the build out of large quantities of offshore wind and an offshore grid infrastructure in an efficient and affordable manner. A supply chain of skilled resources will also be critical to fill the positions that will be created from the deployment of offshore wind farms and the build-out of a meshed offshore grid.

4.2.1 Clean Energy Supply Chains

The supply chains for energy transition, including offshore wind and offshore grid development, have been historically underestimated in public discourse. These supply chains can become bottlenecks and even represent missed opportunities for Europe.

Globally we are looking at 4 times increase in generation capacity and a 3-fold increase in transfer capacity as the share of electrification in Europe's energy system goes from 20% up to as much as 70-80% by 2050. Even considering circular economy initiatives, production capacity must triple for the ambitious expansion plans worldwide not to be thwarted by a shortage in key components such as wind turbines, cables, and transformers.

Europe's ambition levels and latest energy security push, weaning away from fossil fuel dependance, means clean energy supply chains have risen to become a top priority. Building resilient supply chains is crucial for both countries and companies. Several supply chain related challenges must be overcome to enable the timely build out of meshed offshore grids.

- **Time delays** - We are currently seeing a multitude of time delays across the supply chain. Hangovers from the global pandemic are keeping ships in ports longer than expected or are still resulting in product manufacturing delays. Delays in part deliveries can wipe out profit margin for project developers. The increased availability of specialized ships for laying subsea cables will also be crucial. With relatively few of these cable laying ships available globally, projects need to factor in time requirements for the ship's arrival. Other critical elements are marine cable factory capacities and access to suitable yards and ports for the manufacturing of offshore platforms. A recent UK report[24] recommends that up to 11 ports around the UK will need to be transformed as fast as possible into new industrial hubs to facilitate the expected offshore infrastructure growth.

- **Cost Increases** – Across the world, project developers and manufacturers are experiencing cost increases as the prices of commodities, such as copper and electrical steel (e-steel), which will be critical for the build-out of meshed offshore grids, are trading at higher levels than seen since 2018. While prices dipped slightly in early 2023, and e-steel capacity is expected to come online in the coming years, capacity constraints are likely particularly if the EV markets continue to increase. Open and fair trade remains important, enabling technology providers to leverage global supply chains while also enabling project developers to manage costs.

- **Leveraging global supply chains** - A global supply chain is of paramount importance when trying to ensure energy transition momentum. While irregular disruptions across the supply chain will impact project times and costs, ultimately a more resilient global supply chain enabling manufacturers to leverage resources across the world, will ensure a speedy build-out of the offshore wind and grids needed to take our energy systems to the next level. In parallel, this will also require Europe diversifying sources of imports and managing its raw materials more effectively.

- **New policy and regulatory approach as well as forward looking business models** - The current supply chain disruptions and geopolitical challenges highlight the importance of moving away from single project approvals and developing holistic forward looking and integrated approaches when it comes to onshore and offshore grid development as well as the refurbishment and modernization of existing grids. When technology providers are given a long-term planning horizon, this improves their ability to control and harden their supply chains, but also incentivizes capacity investments e.g., to increase transformer or marine cable factory capacity. While the EU's TEN-E guidelines[25] provide some visibility of Projects of Common Interest across Europe through ENTSO-E's Ten-Year Network Development Plan (TYNDP)[26], this type of long-term approach also needs to be reflected in procurement practices from project developers.

Some European TSOs have already started to embrace new and innovative business models by issuing long term tenders e.g., Tennet, the Dutch TSO, has awarded a "large-scale" offshore tender and framework agreement, including a repetitive approach in design of a convoy of projects, to connect 40 GW of new offshore wind capacity in Germany and the Netherlands by 2030. Energinet, the Danish TSO, has also announced the development of strategic partnerships for the build-out of grid connections to meet the Danish off-shore wind targets. It is worthwhile to note that standardization and repeatability between projects enables the transfer of learning between projects, reduces design time, and enables more efficient manufacturing and construction which ultimately reduces project costs and timescales.

4.2.2 Skills and Labor Supply Chains

One of the most complex and enduring supply chain disruptor is the talent challenge. The skills needed to accelerate energy transition are changing, along with demographics and employee expectations. It is becoming more difficult to fill positions searching for skilled workers. Thanks to Europe's ambitious offshore wind targets, WindEurope estimates that the European industry will need 150,000 new workers, up from today's 300,000 jobs, by 2030. In addition, the meshed offshore grids of the near future will need skilled resources to plan, build, operate and maintain them.

TSOs, regulatory bodies, OEMs, and developers will all need to find and retain people with the relevant skills to deliver on the clean energy transition ambitions. New skills will also need to be cultivated in areas from digitalization and robotics to health and safety. The power sector can attract people from oil and gas and other industries, but workers will need both reskilling and upskilling in the short-to-medium term. Collaborations will also be needed to design skills academies and harmonized training in cooperation with universities and schools across Europe.

4.3 Interoperability

To enable further exploitation of offshore wind energy on a large scale, an optimized onshore and offshore grid architecture is essential. The most efficient way of transporting offshore wind power long distances is via HVDC technology, as part of meshed offshore grids. To achieve this, we must unlock the interoperability of multi-vendor, multi-terminal, and multi-purpose HVDC systems. Already, a lot of work has been completed, the next step required is a full-scale project.

Interoperability of a transmission system, its subsystems and components refers to their ability to function together, connecting and communicating with one another readily, now or in the future, even if they were developed by different manufacturers. Interoperability reduces technical implementation risks, increases cost efficiency, and opens the marketplace for harmonized solutions e.g., 'plug and play' of HVDC solutions.

The possibility to manage the interoperability of multi-terminal HVDC transmission network development has been demonstrated through the EU Horizon 2020 funded project PROMOTioN. The results from this project emphasized that the technologies for a meshed offshore grid in Europe are ready for use – political will and action at all stakeholder levels is needed now. The technologies and their interoperability have reached a maturity level which requires a full-scale project to be developed as the next step, with special attention on Grid Code Functional Specifications (TSO driven) and DC Grid Control (supplier driven).

However, interoperability is about much more than just technology. In parallel, interoperability frameworks focusing on regulatory compatibility, system compatibility, functional compatibility and contractual compatibility are now essential. Clear technical scope definition is critical to ensure intellectual property (IP) protection for stakeholders, while still encouraging technical differences between suppliers but also enabling further development and improvement of the system. Alignment on governance, including roles, responsibilities, and the limits of responsibilities, will also be required as per Section 3.1.

Once frameworks for interoperability have been established, open standards can be developed which will create the common language and a common set of expectations that enable interoperability between systems and/or devices.

The following are just some of the projects which have contributed (or are currently contributing) to the increase in interoperability of the HVDC systems required for offshore grids.

4.3.1 PROMOTioN

The EU funded Horizon2020 project PROMOTioN 'Progress on Meshed Offshore HVDC Transmission Networks' ran from 2016 – 2020[27]. The project addressed the technical, legal, regulatory, economic and financing challenges in the development of a meshed offshore HVDC transmission network in the North Sea. The project entailed a tailored approach in which vendors jointly built a commonly specified multi-terminal system. As part of the project's HVDC technology demonstration, a full-scale prototype of a hybrid HVDC circuit breaker was successfully tested in 2020 in the independent KEMA Laboratories (see Figure 7 below). This demonstration contributed to the IEA assigned Technology Readiness Level (TRL) of 8 for HVDC Breaker – Meshed HVDC Grid.

Based on the work performed, PROMOTioN reached a number of conclusions, including:

- There are no technological showstoppers for multi-terminal HVDC transmission network development.
- Significant standardization work is still required to enable multi-vendor HVDC network integration.
- TSOs and vendors need to align on common, technology-neutral functional performance requirements and adopt common communication protocols and standards for HVDC equipment.
- Procurement and contractual best practices must be adapted to enable multi-vendor system integration.
- Collaboration and coordination between national governments, TSOs and other offshore space users is key to implementing regulatory and legal recommendations and to aligning national offshore renewable energy plans with transmission planning.

According to PROMOTioN, the best way to overcome the remaining challenges and initiate the collaborations necessary to do so is through the realization of a full-scale cross-border offshore grid project which would demonstrate the technology's viability, showcase international collaboration models, and deliver the socio-economic benefit of multi-terminal transmission systems.

4.3.2 Interoperability Workstream Roadmap

In 2021, ENTSO-E, T&D Europe and WindEurope developed the Interoperability Workstream roadmap, engaging all relevant stakeholders around the development of a full-scale HVDC multi-terminal, multi-vendor, multi-purpose demonstrator that can address real world technology interoperability challenges. This project is structured in three phases – the first two are focused on derisking activities (and will be addressed by the InterOPERA project described below) and the third phase will be the realization of a commercial large scale project to be launched around 2025. Only an industrial scale project can lead to full-scope engineering activities, which will be necessary to deliver a market ready solution.

InterOPERA

The EU funded project InterOPERA 'Enabling interoperability of multi-vendor HVDC grids' was launched in January 2023 and will run until 2027 with EU funding of EUR50 million. The project's main aim is to make future HVDC systems mutually compatible and interoperable by design, and to improve the grid forming capabilities of both offshore and onshore converters. As part of this, InterOPERA will bring together more than 20 European partners, from TSOs to vendors to developers and will define the future interoperability standards of multi-terminal multi-vendor HVDC systems.

FIGURE 7. Demonstration of HVDC circuit breaker performance in the KEMA Lab's high-power laboratory during PROMOTioN project

Credit: Photo taken from KEMA's report to the European Commission

While the InterOPERA project will be structured around the above-mentioned multi-terminal multi-vendor HVDC demonstration project, an additional goal is to develop and demonstrate interoperability frameworks and make them generically applicable to all future projects and export the learnings globally. To ensure the interoperability of HVDC systems provided by different vendors for the same project, the appropriate technical, operational, and regulatory frameworks together with standard interfaces must be defined. Additionally, the right cooperation, legal and commercial frameworks will be essential. InterOPERA has been working in this direction.

4.3.3 Project Aquila

In 2022, the former BEIS department in the UK announced Project Aquila, comprising of a new HVDC Switching Station at Peterhead in Scotland as one of the UK's first tranche of 'Pathfinder' projects which are being are being progressed under the government led Offshore Transmission Network Review Early Opportunities workstream. By integrating HVDC systems through multi-terminal and multi-vendor interoperability, this project will optimize the number of HVDC Convertor Stations required for future HVDC links, reducing costs, and minimizing community and environmental impacts, as well as helping to accelerate the development of offshore wind in Great Britain.

4.4 Energy Islands

Energy islands will serve as hubs for electricity generation from nearby offshore wind farms, as well as potentially hubs to produce green hydrogen and e-fuels, which can be used to decarbonize industry and power heavy transportation. The energy islands will be connected to, and will transmit power between, multiple countries. Offshore technical equipment such as energy storage technologies, hydrogen or electrolysis plants could also be sited on these energy islands. Energy islands could be existing islands or could require the construction of an artificial island or platform.

The Danish Parliament agreed in 2020 to construct two energy islands, one in the North Sea and one in the Baltic Sea. The ambition is for the two energy islands to be established with 5-6 GW connected by 2030 or sooner. The energy island in the Baltic Sea will be the existing island of Bornholm which will serve as an offshore wind energy hub with a total capacity of 3 GW (upgraded in 2022 from the original 2 GW). The energy island in the North Sea will require the construction of an artificial structure and will have a total capacity of 3 GW initially with the potential for up to 10 GW.

Necessary collaborations have already been initiated. The Danish and German Governments signed an agreement to progress with the interconnection of the Bornholm Energy Island to both Denmark's and Germany's mainland. The relevant TSOs from both countries (Energinet from Denmark and 50Hertz from Germany) have been collaborating on the construction and operation of the cables and facilities which will transmit the produced power.

Energinet has compared the business case for an electricity interconnection with both Germany and Denmark against an electricity connection to Denmark alone. While there are economic gains from both options, the hybrid interconnection (an electricity connection both bringing wind power ashore in two countries and interconnecting their electricity markets) brings approximately EUR2.7 billion more value[28].

Meanwhile, Belgium, through the TSO Elia, will start building their own energy island in concrete modular form in 2024, in the Princess Elisabeth Zone in the Belgian part of the North Sea where 3.5 GW of new offshore wind is planned. As well as connecting to Denmark's new North Sea Island, the viability of using this island as the landing point for a new Belgium-UK interconnector is being explored. In February 2023, Elia awarded an Engineering, Procurement, Construction, and Installation contract to a joint venture made up of two global players in offshore construction[29]. This contract covers the remaining design and construction of the Princess Elisabeth Island. Contracts for high voltage infrastructure will follow. Commissioning is expected between 2026 and 2030.

Another example is the North Sea Wind Power Hub[30] led by Energinet, Gasunie and TenneT. All elements of this hub and spoke project including substructure, HVDC infrastructure, offshore electrolysis and hydrogen infrastructure are technically feasible. This visionary project will be transnational (potentially connecting Denmark, Netherlands, Germany, UK, Belgium and Norway), hybrid (combining interconnection with the connection of offshore wind) and cross-sector (integrating different energy sectors and energy carriers). Operation is expected to begin in the early 2030s.

These energy islands will be some of the largest energy infrastructure projects ever conceived and will signal a new era in the use of offshore energy, where wind farms become drivers of transnational cooperation.

4.5 Offshore Grid Codes and Models

The Network Code on HVDC Connections does not cover DC grid functional and operational requirements at DC-side connection points, as noted in Section 3.4. This Network Code could be amended to incorporate the specificities of offshore transmission systems. National grid codes will still be required but could be based on the Network Code making it easier to align grid codes across countries and achieve both speed and scale.

The development of, and agreement on, grid codes that specify how an offshore grid should be operated will be a key technical catalyst, accelerating the development of meshed offshore grids. The grid code, also known as the transmission code in some countries, is the set of rules a transmission system operator (TSO) uses to define conditions for accessing the electricity grid. Both Network codes and grid codes will need to address topics such as the offshore wind park modules, the HVDC installations connecting to these wind parks, as well as the interface with on-shore ac-grids.

Additionally, both the updated/new Network Code and the individual grid codes should reflect the full value of the HVDC technology's capability to transfer power, but also ensure grid resilience through the provision of auxiliary services such as voltage support and black start. This work has already been started by organizations such as CENELEC and IEC to establish a standard for a framework to describe the technical interfaces and parameters that should be included.

Appropriate simulation models are also essential to assist with understanding the expected dynamic performance of the system. These models must be available in the definition phase of the system and must properly reflect the assets' electrical behavior. The performance of any system in steady-state and dynamic conditions must be evaluated and so far, interoperable HVDC and Wind Park Module supplier models both for control and protection have already been developed. These software models can already demonstrate the capability of the proposed solutions and will remain accessible to all relevant parties for system engineering studies in a multi-vendor environment.

4.6 Collaboration

The challenge of developing meshed offshore grids will require the next generation of ambitious multistakeholder and cross-border collaborations. Stakeholders will need to collaborate within and across geographies, within and across sectors and across different stakeholder groups to design and implement the needed legal and regulatory frameworks, governance frameworks, and to raise sufficient financing in a timely manner.

In February 2023, the TSOs 50Hertz, Amprion and TenneT, in collaboration with the German Federal Ministry for Economic Affairs and Climate Protection (BMWK) presented initial plans[31] for interconnecting offshore wind farms (up to 10 GW) in the North Sea to Germany and neighboring European countries e.g., Denmark and the Netherlands. These offshore hybrid projects will enable increased European electricity trading and will increase security of supply in Germany, as well as in Europe, while also ensuring increased power line utilization.

In parallel, the German government has commissioned a study to assess the benefits of an international offshore grid in the North Sea and initial results indicate that such as grid would have environmental benefits (by reducing greenhouse gases), energy system benefits (by increasing security of supply), societal benefits (by making more efficient use of available space) and economic benefits (by saving on considerable costs compared to other options). In addition, Germany expects that these offshore grids will increase the quantities of electricity possible to be integrated into the pan-European system. According to initial modelling, even in times of high electricity demand, electricity prices are expected to be lower than without interconnections and wind farm curtailment levels are shown to be minimized.

The next step for the TSO collaboration is the incorporation of their plans into official German and European planning processes. Subject to the engagement of neighboring country's TSOs, the foundations for an international offshore grid in the North Sea are being laid. This point is worth highlighting again – a meshed offshore grid in Europe should be part of a holistic European grid planning exercise (as opposed to a coordinated planning of multiple national grids as is the case today). The industry should ensure that while overcoming national borders offshore, it must also avoid creating a new artificial border between onshore and offshore grids, due to a lack of collaborative planning.

Decision-makers will need to commit to cross-disciplinary cross-border coordination and cooperation to capture the full societal, environmental, economic and technical value of meshed offshore grids. Initiatives such as the North Seas Energy Cooperation agreement between governments will be key to promote and cultivate the type of collaboration needed to ensure effective coordination across the whole plan, build, operate, maintain chain. Without intense collaboration, the development of meshed offshore grids to meet Europe's climate and energy targets, will be jeopardized.

5.

Turning Vision into Action

Short-medium term actions out to 2030 which can be taken for efficient and effective delivery of meshed offshore grids are included here and are aligned with the key messages in the Executive Summary.

- **To achieve 2030 offshore wind ambitions, countries across Europe must make provisions to ensure a step increase in connecting new offshore wind projects to the grid.** According to WindEurope, in 2022 2.5 GW of offshore wind (306 turbines) were connected to the grid in Europe. This is the lowest capacity connected to the European grid in a single year since 2016 and 30% less than forecasted. Countries across Europe must streamline and accelerate permitting and approval processes, activate the right market signals to boost investments, and shore up their manufacturing bases to achieve Europe's ambitious climate and energy goals.

- **Electricity is becoming the backbone of an evolving energy system and offshore wind energy as part of the energy mix will play a crucial role to keep the target of 1.5 degree warming by 2050 alive.** Unleashing the full potential of offshore wind as a domestic clean energy source requires allocating adequate ocean space for offshore wind and the electricity grid that supports it. Clarity on how to sustainably build large energy infrastructure in our seas and oceans which deliver on societal, economic, environmental, and technical benefits, and how offshore wind infrastructure can co-exist with the marine ecosystem and other sea activities, is needed.

- **A shift away from point-to-point offshore connections towards offshore hybrid projects and ultimately offshore grids will deliver on multiple socio-economic benefits.** Offshore hybrid projects and offshore grids in Europe's sea basins will provide benefits such as optimizing infrastructure build-out and on-land beach crossings, increasing infrastructure utilization rates and improving the ability of the power system to match supply and demand. More clarity is needed at the European level however to mitigate investment risks and to accelerate the deployment of such offshore projects.

- **The technologies are available to meet our near- and medium-term goals – now we must deploy them at speed and scale.** These clean energy technologies, including enabling technologies for the evolution from point-to-point connections to offshore hybrid projects and ultimately to meshed offshore grids, already exist. While the industry must innovate to improve efficiency and reduce cost, coordinated deployment of these technologies at 'speed' and 'scale' will now be critical. A full-scale offshore grid project deployment, combined with amending the existing network codes to make them fit-for-purpose for such deployments, is now necessary to respectively enable and highlight the benefits of meshed offshore grids. In addition, the continued efficient development and modernization of Europe's onshore grids will also be crucial to ensure that the power generated and transported offshore can reach its final destination – homes, industries, and businesses.

- **While the technologies are available, work is still needed to develop the frameworks and specifications needed to plan, build, operate and maintain meshed offshore grids.** New functional specifications, and amendments to the existing network codes will be necessary. Procurement and contractual frameworks will need to be designed and agreed amongst stakeholders. Business model innovation will be essential to develop viable projects. Interoperability, which is not only a technical matter, will also be required at a regional level across these frameworks and specifications.

- **The potential for interoperability of the critical HVDC components of meshed offshore grids has been demonstrated through innovation projects – immediate next step needed is a full-scale offshore grid project deployment.** The possibility to manage the interoperability of multi-terminal HVDC transmission network development has been demonstrated through projects such as the EU Horizon 2020 funded project PROMOTioN. The next step needed is to implement a meshed offshore grid in a full-scale high-voltage project. The EU funded InterOPERA project and UK funded Aquila project both aim to deliver on full-scale HVDC multi-terminal, multi-vendor, multi-purpose real-life applications by 2030.

- **Even as we strengthen local footprints, leveraging global supply chains will continue to be important.** Recent policy announcements globally point to a reshoring of manufacturing. Nonetheless, resilient global supply chains are of paramount importance when trying to ensure energy transition momentum. Supply chain disruptions impacting project timelines and costs are a reminder that a healthy global supply chain and open and fair trade, enabling manufacturers to leverage resources across the world, will be needed to ensure a speedy build-out of the renewables and grids to take our energy systems to the next level. This will also require Europe diversifying sources of imports and managing its raw materials more effectively.

- **Enhanced management and development of resilient supply chains is possible if technology providers have visibility of project development across a longer time frame. New policy and regulatory approaches, as well as new and innovative business models will be essential enablers for this holistic forward-looking planning.** Recent supply chain disruptions highlight the importance of policy makers and regulators moving away from single project approvals towards multi-project approvals and developing holistic forward looking and integrated approaches when it comes to on and offshore grid development, but also refurbishment and modernization of existing grids. Furthermore, a long-term approach also needs to be reflected in procurement practices from project developers. Project developers must embrace new business models based on long term integrated plans, including replicability. This long-term planning can provide manufacturers with the long-term visibility needed to secure the supply chain, including justifying investments in additional capacity and can provide justification for anticipatory investments into additional installed capacity or offshore grid technology enhancements.

- **We must maintain a healthy supply chain of skills/talent as we continue to build out the infrastructure which the energy transition is depending upon.** One of the most complex and enduring supply chain disruptors is the talent challenge. To plan, build, operate and maintain meshed offshore grids, the power sector will need to attract and retain skilled workers, while also managing changing demographics and employee expectations. Starting at the grass roots and even incorporating ‘energy transition’ as part of academic curricula will be important, while also promoting more dedicated programs in universities and vocational institutes.

- **Energy islands will be some of the largest energy infrastructure ever constructed and will be a key steppingstone for meshed offshore grids.** Not only will energy islands serve as hubs, gathering electricity from surrounding offshore wind farms and transmitting it to neighboring grids, but they will also position wind power as a beacon of regional cooperation. Completion, and operation, of these energy islands as planned e.g., North Sea Island, Princess Elisabeth Island, will be essential to meet Europe’s climate and energy goals.

- **The challenge of developing meshed offshore grids will require the next generation of ambitious multi-stakeholder collaborations.** Stakeholders will need to collaborate within and across geographies and sectors, and across different stakeholder groups. Cross-border and cross-sector coordination and cooperation will be pivotal to capture the full societal, environmental, economic, and technical value of meshed offshore grids. Initiatives such as the North Seas Energy Cooperation agreement between governments will be key to promote and cultivate the type of collaboration needed to ensure effective coordination from planning to operation stages. This collaboration will be essential to ensure that Europe’s meshed offshore grids result from a holistic European grid planning exercise, as opposed to a coordinated planning of different national grids as is the case today.

- **Across all areas, from policy and regulation, financing, sustainability, design, construction, operation and maintenance, a clear governance framework will be an essential enabler.** While the current point-to-point connection approach is relatively clear, the shift to meshed offshore grids, with multiple terminals and multiple vendors and connecting clusters of wind farms as well as multiple markets, will introduce significant complexity. One example is the shift from dedicated to shared infrastructure e.g., multiple windfarms or interconnectors will now rely on common infrastructure, introducing benefit- and cost-sharing issues. An effective governance framework should clearly outline the roles and responsibilities (as well as the limit of those responsibilities), of all involved stakeholders. While new protocols may be required, the existing onshore grid frameworks and approaches should be reutilized to the greatest extent possible, but with the necessary amendments to reflect offshore grid specificities.

FIGURE 8. An offshore HVDC converter platform, BorWin1 project, in the German North Sea – the world's first HVDC grid connection from an offshore wind farm

Credit: Hitachi Energy

End notes

1. https://windeurope.org/newsroom/press-releases/iea-big-volumes-of-offshore-wind-are-key-to-europes-2050-climate-neutrality/
2. https://windeurope.org/intelligence-platform/product/enabling-europes-net-zero-vision-by-proactively-developing-its-power-grids/
3. Member States agree new ambition for expanding offshore renewable energy (europa.eu)
4. Electricity interconnection targets (europa.eu)
5. According to ENTSO-E, thermal properties of XLPE allow a continuous maximum conductor temperature of 90°C and a maximum short circuit temperature of 250°C and, therefore, higher transmission capacity per cable compared to other technologies. https://www.entsoe.eu/Technopedia/techsheets/hvdc-xlpe-cross-linked-polyethylene
6. NSL Interconnector between UK and Norway in regular operation | Statnett
7. https://windeurope.org/intelligence-platform/product/enabling-europes-net-zero-vision-by-proactively-developing-its-power-grids/
8. https://www.researchgate.net/publication/287814374_Electrical_Power_System_Essentials
9. Support for the Shetland Extension of the Caithness-Moray HVDC Link – The National HVDC Centre
10. Offshore Network Development Plans (entsoe.eu)
11. https://energy.ec.europa.eu/topics/infrastructure/trans-european-networks-energy_en
12. https://ec.europa.eu/commission/presscorner/detail/en/IP_23_1591
13. Connecting Europe Facility (europa.eu)
14. 3D-printed reefs to help restore marine biodiversity in the Kattegat in Denmark (orsted.com)
15. https://www.nationalgrideso.com/news/eso-publishes-pathway-2030-major-step-deliver-50gw-offshore-wind-2030
16. The Network Code on HVDC Connections specifies requirements for long distance direct current (DC) connections. These are used to link offshore wind parks to mainland or to connect countries over long distances. https://www.entsoe.eu/network_codes/hvdc/
17. E.g., CLC/TS 50654-1:2020 – HVDC Grid Systems and connected Converter Stations – Guideline and Parameter Lists for Functional Specifications – Part 1: Guidelines and CLC/TS 50654-2:2020 - HVDC Grid Systems and connected Converter Stations - Guideline and Parameter Lists for Functional Specifications - Part 2: Parameter Lists
18. The IEC Technical Committee (TC) 115 focuses on HVDC transmission for DC voltages above 100 kV. The Commit-tee has a number of Technical Specifications (TS) underway focusing on HVDC Grid Systems such as IEC TS 63291-1 and IEC TS 63291-2 based on the CENELEC TS mentioned above.
19. Photo taken from a PROMOTioN project report on HVDC Circuit Breaker Testing https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5d41494bd&appId=PPGMS
20. ETP Clean Energy Technology Guide – Data Tools - IEA
21. https://www.chinadaily.com.cn/a/202007/01/WS5efc061ea3108348172566e2.html
22. https://www.hitachienergy.com/de/de/about-us/customer-success-stories/quebec-new-england
23. ENTSO-E and DSO Entity signed today the Declaration of Intent for developing a Digital Twin of the European Electricity Grid (entsoe.eu)
24. https://www.offshorewind.biz/2023/03/15/uk-ports-need-gbp-4-billion-investment-to-help-unleash-floating-offshore-wind-industry-report/
25. REGULATION (EU) No 347/2013 on guidelines for trans-European energy infrastructure - https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:115:0039:0075:en:PDF
26. https://tyndp.entsoe.eu/
27. PROMOTioN - Home (promotion-offshore.net)
28. https://stateofgreen.com/en/solutions/energy-island-the-baltic-seas-nodal-point-for-intelligent-energy/
29. Elia awards EPCI contract for world's first energy island to DEME and Jan De Nul
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31. https://www.bmwk.de/Redaktion/DE/Pressemitteilungen/2023/02/20230227-bmwk-und-uenb-veroeffentlichen-plaene-zur-vernetzung-von-offshore-windparks-in-der-nordsee.html

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