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28 July 2021

HVDC Supply Chain Overview (Co-ordinated Offshore)

This report has been compiled by The National HVDC Centre to provide a high-level overview of the HVDC supply chain required to deliver the transmission capability required to meet the 2030 and 2050 offshore wind targets (assuming a coordinated approach to offshore development is progressed).

This paper may be read alongside the report that the Centre has also released on the proposed R&D Strategy for HVDC: "HVDC R&D Strategy (Coordinate Offshore)" dated 28 July 2021.

We welcome feedback on both reports and look forward to contributing further in these areas with stakeholders over time.

Contents

1 Executive Summary

The department for Business, Energy and Industrial Strategy (BEIS) commissioned The National HVDC Centre to review the supply chain that will be required to deliver a coordinated approach to offshore connections to meet the 2050 net zero targets in Great Britain (GB).

GB is currently well positioned to benefit from increasing renewables generation, with high volumes of offshore wind farms (OWF) connected through Alternating Current (AC) connection to the GB network and a mature offshore investment regime. However, to efficiently deliver the 2050 commitments, a coordinated approach to offshore connections is required.

This requires a scale of development not seen within GB since the mid-1960s; and the limited supply chain needs a more centralised strategy to ensure that GB can meet the scale and pace of HVDC project delivery that is required.

The Centre undertaken a high-level review of the HVDC supply chain, though supplier/project engagement and literature review; based on our review we have identified three Key Challenges, and three Key Opportunities for GB.

Key Challenges

	Challenge	Recommendation
1	The current 'point-to-point' connection of offshore wind farms (OWFs) is not sustainable. A coordinated approach OWFs connections is required to reduce the strain on the supply chain.	Support the ESO (and the Central Design Group) in the development of a Coordinated Approach to OWF connections. *Action: ESO & HVDC Centre.*
2	Converter Interoperability, and composite testing.	GB needs to develop an approach to increase pace and scale of converter interoperability and composite system testing. (see R&D paper for further supporting actions) *Action: ESO & HVDC Centre.*
3	There are potential 'bottlenecks' for both converters and cables (and the associated cable laying vessels) supply.	Industry engagement is required to understand potential solutions (and opportunities to develop production capabilities is GB). *Action: BEIS to instigate industry engagement discussions.*

Key Opportunities

	Opportunity	Recommendation
1	Develop GB production capabilities.	Promote investment in manufacturing capabilities and development of the supporting infrastructure in GB. *Action: BEIS to consider.*
2	Seek to advance the transition of related skills within the Oil and Gas industry towards HVDC connected offshore windfarms.	Engage with the UK Oil & Gas industry to develop a plan for transition of skills and capabilities. *Action: BEIS to consider.*
3	Exploit areas of existing GB expertise; including interoperability, Wide Area Control and supervisory control, system monitoring and Asset Management.	Develop a strategy to leverage and grow GB capabilities in key areas. *Action: BEIS, Ofgem, ESO, TOs and the HVDC Centre to work together to develop a strategy.*

The HVDC Centre does not have expertise in many of these areas and therefore we have left recommendations at a high level, noting further work may be necessary to develop specific plans.

However, we believe that all of these Challenges and Opportunities need to be addressed as a matter of priority to protect the feasibility of GB's 2050 net-zero ambitions.

2 Context

Over the last 10 years GB has seen one of the highest levels of offshore wind adoption in the world[1]. Whilst it is important to recognise and build upon those efficiencies previously achieved; in delivering the increase of scale from 10GW today to a minimum of 40GW by 2030 and 75GW by 2050, new approaches and innovations illustrated in Figure 2.1 will need to be adopted to address a new environment in the transition to integrated offshore arrangements as discussed within the ESO's Offshore Coordination Project[2].

Figure 2.1 illustration of R&D themes and application { graphic curtesy of SINTEF; WinDCollect Green Deal proposal}

The ESO's Offshore Coordination Project concludes that to meet the offshore wind targets, a coordinated approach is required to create the required electricity network to connect these renewable energy sources. Even with a coordinated design, significant investment is required.

Currently, the HVDC supply chain is configured towards the support of sporadic project focussed activity, taking vendor sourced solutions and fitting these project by project, case by case to each projects requirements. As a result there is limited capability to achieve standardisation and scale. Whilst offshore co-ordination increases the complexity of application of HVDC solutions it also with it identifies an opportunity to support the scale and pace of more continuous orders of HVDC components and associated technologies with more standardised and modular components more attuned to this new way of working. Within this is a challenge of how manufacturers can stage delivery and commissioning of initial offshore connections as part of a larger plan of delivery which grows over time and required the initial stages of delivery to remain compatible with an ultimate design which may include multiple vendors of HVDC and offshore wind technologies; what that subdivision of responsibilities looks like and how the individual and overall solution is designed, evaluated, tested, operated and maintained; providing the confidence to upscale and implement solutions.

[1] HM Government. Ten-point plan for a Green Industrial Revolution. Nov. 2020.
[2] ESO (2020). Offshore Coordination Project – Phase 1 Final report. https://www.nationalgrideso.com/future-energy/projects/offshore-coordination-project

To give an idea of the scale of the investment, the following table summarises the volumes and costs associated with the key technology components.

Component	2030 Requirements	2050 Requirements
Onshore Converter	16-45 Units	36-67 Units
Offshore Convertor	16-45 Units	36-67 Units
Subsea HVDC Cable	2261 - 5236 km	5450 - 7385 km
HVDC switching station	2	8
DCCB	8	16
Total CAPEX	**£ 23.4 billion**	**£ 26.8 billion** *(additional)*

The lower quantities in the table above are based on a coordinated approach being developed from 2025, and the higher quantities show the impact on a delay to 2030. It could therefore be taken as a minimum number with the higher value giving an idea of the sensitivity to delay.[3]

Although the market can provide the components there is little depth to the supply and a limited experience globally. Further, there is an integration challenge both with regards to true interoperability allowing a modular design and with maintaining overall power system stability. International approaches and key research finding to address these challenges have been highlighted however there remains a wide scope across which BEIS can have a positive influence on the success of offshore development. There are however opportunities within this:

- GB is a leader in interoperability, having the experience to date of high degrees of power electronic integration including IFA (interoperability across vendors) and CMS (multiterminal with multivendor capability built in to spec), having delivered the first interoperable HVDC solution on its network and having sustained its effective operation since the mid 1980's. A "shovel-ready" solution to challenges of scale and complexity has been developed and awaits only the funding to drive delivery.

- We have demonstrated the ability to deliver supervisory controls between technologies in GB to minimise risk and optimise benefits across them. This is an area where GB has world leadership with a number of the companies proficient in these areas having leading solutions to managing system stability, voltage, thermal and frequency management. Provided that within the Central Design Group clarity on functional needs are defined and a common "sandbox" modelling platform is provided (see R&D strategy), these areas of expertise can be grown to meet the co-ordinated offshore system need and lead the way in exportable capabilities across the world.

- Within GB we have the insights and experiences of highly developed and mature grid code and associated processes which are internationally referenced and emulated. Proven streamlined developments of these codes can inform clarity to the vendor and developer community of what needs to be delivered to what basis will emerge to support offshore co-ordination. GB also benefits

[3] Sensitivity study on the effect of change in the starting date of offshore grid coordination (DNV GL, National HVDC Centre, EPNC). https://www.nationalgrideso.com/document/183026/download

[2] ESO (2020). Offshore Coordination Project – Phase 1 Final report. https://www.nationalgrideso.com/future-energy/projects/offshore-coordination-project

from a variety of both Power Hardware in the Loop and Control Hardware in the Loop capabilities, but again not with the scale or focus required to support and deliver testing enabling delivery. By innovating in how testing is done, and by providing focus in the roles and needs of testing facilities the challenges of pace and scale can be addressed.

2.1 Challenge Description

The United Kingdom ('UK') Government has an ambition to achieve 40 GW by 2030 of installed offshore wind capacity, potentially rising to at least 75 GW by 2050. To achieve this a massive increase in the scale and pace of investment is required with regards not just to the generation but also the connection infrastructure over the coming ~30 years. At present there is circa 1 HVDC link being commissioned in the UK per year but by 2030 this is expected to be 2-3. This increase is a trend globally.[4]

Currently, each offshore wind project has a separate connection to shore. Without a change of approach, the required increase in volume and pace of network development is expected to lead to issues including: lack of suitable cable landing points onshore; adverse impacts on transmission system stability; project delays due to the unavailability of equipment and resources due to stresses on the supply chain, and failure to deliver economies that would be expected with a large-scale increase in development volumes. Combined, these issues could lead to increases to the overall cost and ultimately risk that connections for offshore wind projects will not be delivered. The challenges to the supply chain however do not purely reside within production but on the scale of available skilled resources available to the HVDC sector to design, construct, deliver, install, commission and maintain the HVDC infrastructure associated. Bottlenecks in the specialised resource associated with commissioning and installation tasks in particular should be addressed in the construction of pipelines of resourcing into the sector from school and academia over the next 8-9 years. Discussion on possible approaches to achieving this are discussed in the HVDC R&D strategy paper for meeting 2030 and 2050 targets that has been published alongside this report.

2.2 Coordinated Solutions[5]

Work led by the ESO considered if there would be benefits from using an 'coordinated' approach for offshore transmission development that is more similar to the approach used onshore. A coordinated offshore network design approach could enable: shared use of offshore transmission assets between connections (e.g. wind, interconnectors); incremental development of offshore transmission infrastructure that matches the pace required for offshore wind projects, and a more holistic network development to be achieved (e.g. also enabling issues elsewhere on the transmission system to be addressed).

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4 Mike Barnes, et al, "*VSC-HVDC NEWSLETTER | Vol. 9, Issue 4*", Department of Electrical & Electronic Engineering, University of Manchester, 28/4/2021

5 Holistic Approach to Offshore Transmission Planning in Great Britain (DNV GL, National HVDC Centre, EPNC). https://www.nationalgrideso.com/document/177221/download

In Figure 2.2 an illustration of the offshore network in 2050 developed using this method can be seen. It is based on the use of a mixture of the available technologies to most optimally meet the network requirements. It should be noted that the solution is dominated by the use of HVDC.

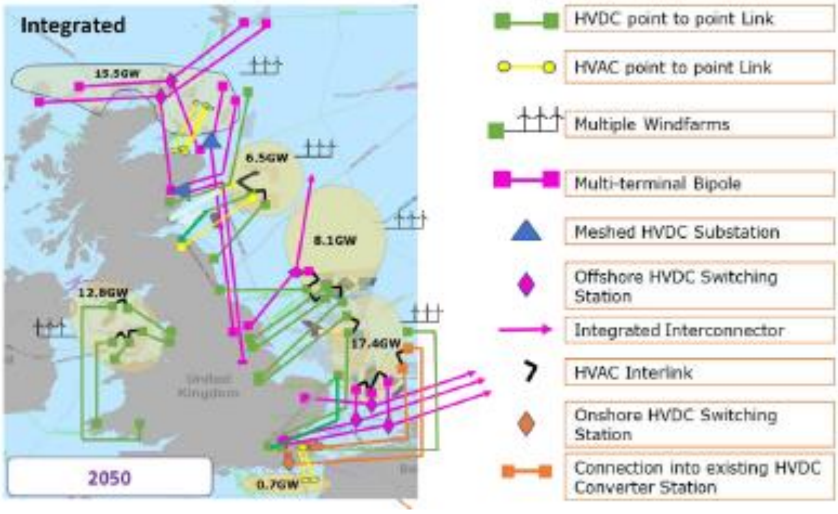

Figure 2.2: 2050 View of Co-Ordinated Offshore Development to Meet Offshore Wind Targets[6]

[6] Modified Figure, Holistic Approach to Offshore Transmission Planning in Great Britain (DNV GL, National HVDC Centre, EPNC). https://www.nationalgrideso.com/document/177221/download

3 Overview of Key Components

The typical arrangement of an HVDC link is given in Figure 3.1. Moving away from point to point connections would further require the introduction of DC breakers to allow only the faulted section of network to be taken out of service during fault conditions (or else loose an unacceptable amount of generation for a single fault).

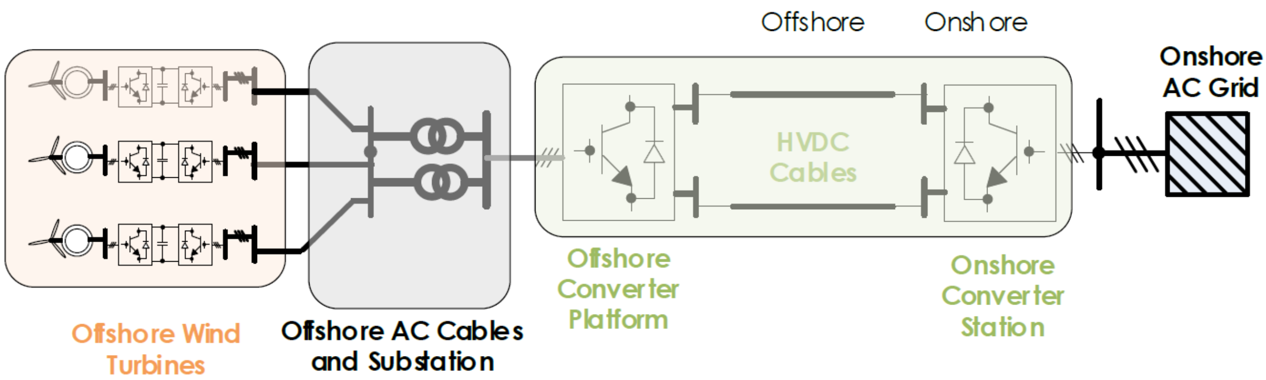

Figure 3.1: Simplified Electrical System of HVDC-connected Offshore Wind Farms

The following table highlights the highest ratings available advertised by manufacturers, the highest in-service example and what would be required by the proposed solution.[7]

Item	Required	In Service	Advertised
VSC Converter	≥2 GW @ ≥ ±525 kV	3 GW @ ±500KV	5 GW @ ±800KV
Subsea HVDC Cable [Technology 1) Mass Impregnated 2) XLPE]		1) 2.2 GW @ ±600KV 2) 1 GW @ ±400KV	1) 3 GW @ ±640KV 2) 4 GW @ ±800KV
DCCB		3 GW @ ±500KV	[Limited information]

The following sections give details of the manufacturers available to provide the required technology for the proposed solution. It should be noted that given the uplift in volumes required both in the UK and internationally a thorough supply chain assessment would be required to assess the ability to meet the demand.

[7] https://www.hvdccentre.com/wp-content/uploads/2020/06/De-risking-Integrated-Offshore-Networks_v2.0_25June2020.pdf

3.1 Convertors

There are several cable suppliers internationally that indicate that they could provide suitable cables however there is limited in-service history globally. The following table contains the key suppliers and their base location but may not be exhaustive

Supplier	Base Location
CEPRI	China
GE	UK
Hitachi-ABB	Sweden
Mitsubishi Electric Co.	Japan
NR Electric	China
RXPE	China
Siemens	Germany
Toshiba	Japan
XJ	China

Most of the suppliers listed would normally provide both the valves and the associated controls for a project. As there is increased standardisation it may be possible to split out these elements.

3.2 Cables

There are several cable suppliers internationally that indicate that they could provide suitable cables however there is limited in service history globally. The following table contains the key suppliers and their base location but may not be exhaustive

Supplier	Base Location
Iljin	South Korea
LS	South Korea
NBO	China
Nexans	France
NKT	Denmark
Prysmian	Italy
Sudkabel	Germany
Sumitomo	Japan
ZTT	China

3.3 DCCBs

There are a limited number of suppliers of this technology globally and in-service experience is limited to recent developments in China[8]. Through the PROMOTioN project, this technology has been successfully demonstrated[9] but remains at a lower level of technology readiness (and therefore higher level of risk) as compared to the other key components. The following table contains the key suppliers and their base location but may not be exhaustive, it should be noted that not all suppliers are at the same level of development for this technology.

Supplier	Base Location
GE	UK
Hitachi-ABB	Sweden
Mitsubishi Electric Co.	Japan
NR Electric	China
SciBreak	Sweden

[8] https://www.hvdccentre.com/wp-content/uploads/2019/07/Operators_Forum_2019_Khilar.pdf
[9] https://www.promotion-offshore.net/fileadmin/PDFs/2020_04_06_-_Press_release_-_PROMOTioN_project_Technology_maturity_of_HVDC_circuit_breakers_proven_by_successful_full-scale_high-power_demonstration.pdf

4 Supply Chain Challenges

Potential barriers to the delivery of offshore network infrastructure that facilitates 2030 and 2050 targets being achieved, have been identified as part of our assessment. At a high level there are considerations of:

- Integrated offshore transmission network challenges and other (in addition to offshore wind connections) potential use that could be made of offshore transmission networks;
- Technology maturity and pipeline including areas of technology developments expected over the next 30 years;
- HVDC technology specific (interoperability, standardisation and supplier availability) and system integration (different HVDC voltages, mixed converter technology and HVDC grid protection) barriers;
- Regulatory framework rules that may constrain future offshore transmission development options; and
- Risks to achieving more coordinated offshore transmission network development.

4.1 Key Challenges

	Challenge
1	The current 'point-to-point' connection of offshore wind farms (OWFs) is not sustainable. A coordinated approach OWFs connections is required to reduce the strain on the supply chain.
2	Converter Interoperability, and composite testing.
3	There are potential 'bottlenecks' for both converters and cables (and the associated vessels) supply.

4.2 Converters

The main challenges concerned to this part of the technology solution are related to interoperability between different: converter topologies (converter configurations and controls); and vendors' technologies (proprietary / patented techniques). [10]

There is also understood to be a limited capacity for the main European converter suppliers to meet the scale of new converters required; therefore, these suppliers will either need to increase production capacity significantly, or new entrants to the market will be required. Clarity on the anticipated project pipeline and scale of capacities will provide appropriate signal to manufacturers and inform investment priorities.

[10] http://www.bestpaths-project.eu/contents/publications/d93--final-demo2-recommendations--vfinal.pdf

4.3 Cables

Each manufacturer will have different capabilities depending on their factories but would be expected to be able to produce 100's of kilometres of cable each year. Given the forecasted requirement for the UK which is echoed globally the manufacturing of HVDC cables is a potential bottleneck for achieving the required offshore network.

Another consideration with cables is the ability to install them. The majority of the UK requirement will be subsea which requires specialist vessels for laying. There are 7 of such vessels available globally which is a potential bottleneck given the volumes of cable forecast to be required internationally. For reference, a 180km subsea cable run would take a circa 4 months to lay and bury depending on cable type and other design choices/factors. Depending on the location of the factory where the cable is manufactured there could be significant travel time to pick up the cable. For very long runs, this could require multiple trips to the factory. Exploring approaches for increasing domestic cable manufacturing capabilities and cable installation equipment and vessels could facilitate the realisation of coordinated offshore networks at pace.

4.4 DC Protection and DCCBs

In Europe HVDC grid protection has been achieved by means of HVAC-side breakers in a non-selective philosophy meaning that a complete HVDC system is removed from service for a HVDC fault. Moving to an integrated HVDC network this would no longer be an acceptable loss to the system. HVDC grid protection philosophies and the building blocks (such as DCCBs) to create these are ready to use however the choice needs to be made through standards and codes to define which of the many options could be applicable to GB. The choice of protection philosophy will have fundamental impacts on the design of the system, which is why, even if HVDC grid protection is not required at the initial stages, the choice needs to be made early.[11]

4.5 Offshore Structures

Although floating wind is somewhat established there is still the missing link of an equivalent for an offshore substation and dynamic cable connection solutions at high transmission voltages beyond 60kV AC. For deeper water applications floating foundations for substations housing convertors etc will need to be realised.[12] Technology developments including dynamic cables, subsea connectors and subsea switching devices will be required to facilitate the efficient connection of floating offshore wind farms in GB.

4.6 Ancillary services (incl blackstart)

Traditionally, conventional power plants (typically gas or coal) have provided key system and balancing services such as inertia however as these sources are displaced by renewable sources and interconnectors there will be a requirement to provide these essential functions through alternative means. [13] Early design,

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[11] https://www.promotion-offshore.net/fileadmin/PDFs/D4.7_Preparation_of_cost-benefit_analysis_from_a_protection_point_of_view.pdf
[12] https://www.dnv.com/article/floating-substations-the-next-challenge-on-the-path-to-commercial-scale-floating-windfarms-199213
[13] National Grid ESO launch Stability Pathfinder phase one | National Grid ESO

factory testing and grid-scale trials of the HVDC ancillary services control schemes will increase industry confidence performance across system restoration applications[14].

4.7 Composite Testing

Composite testing of the transmission and generation equipment supplied by different manufacturers will be needed to de-risk the integration of complex connections into the existing electricity infrastructure. It is also a key enabler in multi-vendor solutions for the co-ordinated incremental development of an offshore grid. [15]

4.8 Integration

As the system changes it brings challenges in the overall integration. A key example of which is the changing performance during faults means that existing protection system may not operate as expected since the assumptions underpinning their operation no longer hold true.[16] The HVDC centre commissioned two innovation projects in collaboration with GB universities and specialist research institutions to investigate HVDC impact on AC network protection[17] and AC protection performance in lower fault current networks[18].

4.9 Non-Technology Challenges

New areas of regulatory and legal instruments will be required to facilitate the efficient delivery of integrated offshore network developments. Were such changes not implemented this: would not provide a set of applicable regulatory framework rules with equivalent transparency to those that have been established under the Electricity Act to date; restrict network design options; and might exclude integration of generation not situated within GB or its offshore waters.[19]

[14] HVDCCentre (2019). Maximising HVDC Support for Black Start and System Restoration. https://www.hvdccentre.com/our-projects/maximising-hvdc-for-black-start/
[15] COMPOSITE Testing of HVDC-connected Offshore Wind Farms – The National HVDC Centre 2021
[16] North Sea Link Protection Coordination Testing – The National HVDC Centre
[17] https://www.hvdccentre.com/innovation/dc_with_ac_protection/
[18] https://www.hvdccentre.com/protection-overview/
[19]National Grid ESO, “Holistic Approach to Offshore Transmission Planning in Great Britain”, https://www.nationalgrideso.com/future-energy/projects/offshore-coordination-project

5 Supply Chain Opportunities

By working towards a co-ordinated solution it can mean the required development can be delivered with less overall construction needed and less log jams at key resourcing pinch-points such as: consenting (rather than project by project focussed, more area focused to support holistic decision making, and achieve that GB view more time and cost effectively); supervisory control design (focus on clearly defining objectives of supervisory control across the various Holistic solutions to provide clarity in their early design and the effect of vendor convertor design upon them); interoperability management (driving growth in the capacity to do this and streamlining existing process for doing this); testing and commissioning (increasing the resource and streamlining the process; and asset renewal (driving asset extension methods to smooth the jump in asset replacement to avoid it occurring at the same time as the key jumps in new offshore network construction).

This is also where the value of standardised and modular vendor solutions could be most beneficial (allowing a more efficient production, more streamlined implementation and commissioning and smoothing the production rates to meet targets whilst promoting a smoother build-up of capacity, and reducing & standardising maintenance requirements and cost).

As has been recently been seen in the Oil and Gas sector, there may also be opportunities for in service assets such as existing Oil and Gas platforms, as part of their Sector deal for electrification to serve additionally as hubs for floating wind installations in relevant areas, although noting their retrofit for other purposes such as HVDC platform use appears to be infeasible at this time

5.1 Key Opportunities

	Opportunity
1	Develop GB production capabilities.
2	Seek to advance the transition of related skills within the Oil and Gas industry towards HVDC connected offshore windfarms.
3	Exploit areas of existing GB expertise; including interoperability, Wide Area Control and supervisory control, system monitoring and Asset Management.

Given the step increase in demand, there is a significant opportunity to promote investment in factories and supporting infrastructure. The development of the supply chain market will need to be driven by practical engagement with the global supply chain to provide a tangible “line-of-sight” from project definition through to planning, delivery and ultimately offshore network optimisation.

An offshore HVDC network could stimulate investment in new component manufacturing capacity for HVDC converters. Component manufacturing investment decisions are based on the global demand for electrical systems or where there are centres of technical excellence. Presently, the UK market is not large enough to influence suppliers’ manufacturing strategy.

The UK offshore oil and gas sector has sustained a supply base for offshore platform construction. This provides strong expertise and its availability to the offshore renewables industry is growing but it is highly dependent on the demand from the oil and gas sector. Suppliers with expertise in oil and gas platforms, with further investment could be used for HVDC offshore substation platform fabrication but the large size of facilities needed for HVDC substation structures may be a limiting factor.

GB is a world-leader in areas of: interoperability, Wide Area Control and supervisory control, system monitoring and Asset Management; having the experience to date of high degrees of power electronic integration including IFA (interoperability across vendors) and CMS (multiterminal with multivendor capability built into the specification). We have demonstrated the ability to deliver supervisory controls between technologies to minimise risk and optimise benefits across them.

There are numerous testing facilities within the UK well placed to deliver the required testing. There is also a highly developed and mature grid code and associated process to instigate required changes. By co-ordinating efforts and evolving processes (e.g. reconfigurable replicas), these approaches can be scaled to avoid a log-jam of capability testing and commissioning today.

6 Examples of Approaches

Within the PROMOTioN project, a roadmap for meeting the North Sea wind targets was developed (a copy of the summary can be seen in Figure 6.1[20]. As highlighted within the PROMOTioN work, there is a requirement for TSOs, government, regulators, manufactures and other stakeholders to collaborate to find a viable solution.

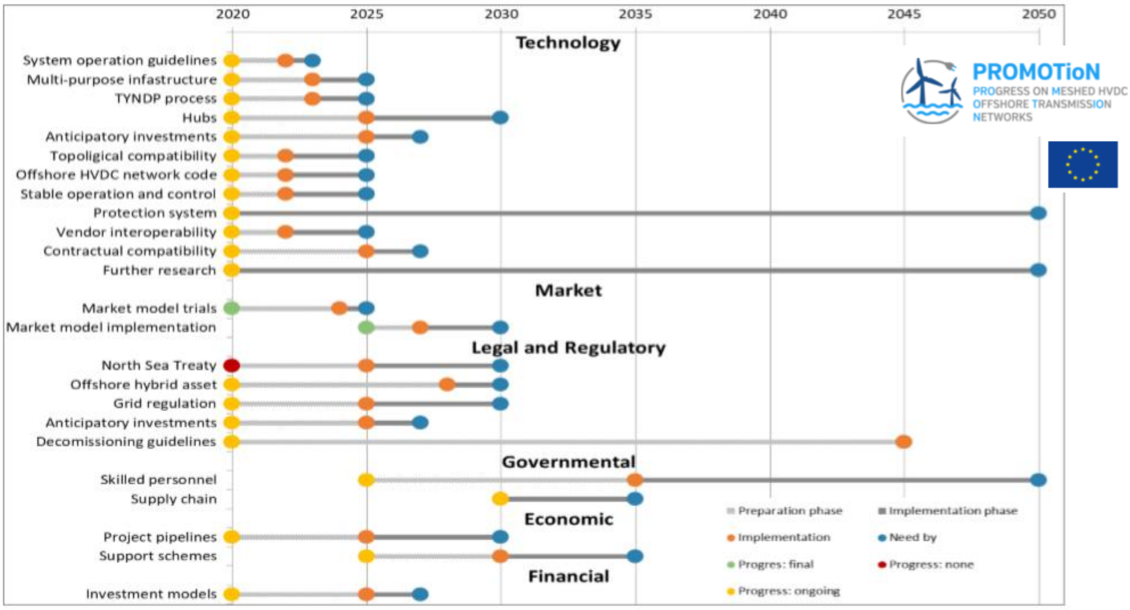

Figure 6.1: Roadmap to a Meshed Offshore Grid, presenting the recommendations, their progress and their timing

TenneT, the TSO (Transmission System Operator) in Northern Germany and The Netherlands, faces a similar challenge to the GB TOs for the integration of offshore wind. Their approach has been to develop a standard 2GW HVDC solution and involve manufacturers ahead of required delivery to help develop the technology and give confidence in the performance ahead of implementation.

Recently a collective of European TSOs have of signed a Memorandum Understanding launching 'Eurobar', a concept whose focus is the interconnection of offshore wind. Their idea is to evolve to an interlinked offshore network or "busbar alike system". Their press release highlights that the importance of standardisation of interfaces and technology.[21]

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[20] https://www.promotion-offshore.net/fileadmin/PDFs/D12.4_-_Final_Deployment_Plan_Distributed_Version.pdf
[21] https://www.amprion.net/Press/Press-Detail-Page_31552.html

7 Conclusion

All the required technology components are available however there are limitations in the depth of the market and the in-service history. There is also the challenge of moving from a single-vendor (turn key solution) to a multi-vendor (modular approach).

There is considerable scope to increase manufacturing capability as well as further research and development (or indeed scale trails) of the required interoperable solutions. Engagement with wider stakeholders is paramount in resolving the outstanding questions over how this could and should be delivered.

It is not just a question of the technology being available to meet the targets but having a viable framework to facilitate the development. There is a lot of clarification regarding the markets, legalities and regulation required before a coordinated approach can be realised.

A methodology needs to be put in place which allows offshore integrated networks to be developed, connecting multiple wind turbine projects of differing design and vendors to large scale AC and HVDC networks of multiple terminals, operating states and dynamic devices. As part of this, innovations to reduce the cost and time for multi-vendor multi-device interoperability assessments are required. These and other key research and innovation themes for integrated offshore networks are summarised in the HVDC R&D Strategy (Coordinate Offshore) commissioned by BEIS and delivered by the HVDC Centre to meet the 2030 and 2050 net-zero targets[22].

[22] HVDC R&D strategy report to meet 2030 and 2050 net zero targets. Commissioned by BEIS and delivered by HVDC Centre (2021).