The National HVDC Centre

Part of Scottish & Southern Electricity Networks

De-risking Integrated Offshore Networks in GB

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Executive Summary

The UK Government has set an ambitious target to achieve around 40GW by 2030 of installed offshore wind capacity as outlined in the Queen's Speech of December 2019, up from about 10GW in 2020; and potentially rising to 75GW by 2050, based on the Committee for Climate Change report. The Office for Gas and Electricity Markets (Ofgem) is currently exploring regulatory options to support the development of an offshore grid to enable the four-fold increase in offshore wind generation by 2030. Coordination of transmission connections linking offshore wind generation with onshore grid developments can foster the delivery of low-cost offshore networks with reduced offshore cable assets and reduced onshore construction.

High Voltage Direct Current (HVDC) transmission is suitable for connection of large-scale offshore wind generation located far from shore compared to alternating current transmission, which has been used to date in Great Britain. HVDC is the key technology relevant to future offshore transmission designs, enabling higher capacity transmission of power to the onshore transmission system via a smaller number of cables, with much longer cable distances allowing the infrastructure to be used to pool the power of several projects offshore onto a more efficiently designed offshore platform arrangement, in comparison to cumulative HVAC developments.

HVDC has been used for a number of large offshore wind farm connections in continental Europe. However, the GB grid with its declining system strength will present significant challenges involving system control, protection and stability aspects to network operators and developers. Therefore, The National HVDC Centre was requested to support work between the Offshore Wind Industry Council, Electricity System Operator and all Onshore Transmission Owners, on how to develop and de-risk integrated offshore transmission approaches in GB. The HVDC Centre analysis identifies three (3) key recommendations:

- **Integrated offshore transmission is technically feasible** and realisable in the medium term (for projects that are in technical design stage), but introduces additional control and protection complexity into the implementation of offshore designs which would need to be addressed across an equally co-ordinated across design, construction and compliance activity to ensure solutions deliver as intended. The later integrated solutions are developed, the lower the opportunity to realise their full benefits and the greater risk of technical challenges needing to be addressed post deployment limiting the intended capacities available in the interim period;
- **Integrated solutions can be built incrementally** with anticipatory assets for future extension and offer enhanced flexibility and reliability for the offshore project, reduced asset footprints & options to present boundary benefits and a lesser impact to the onshore system, and the opportunity for modular standardised approaches to be adopted to reduce costs and risks in deployment of these solutions; and
- **Integrated Bipole VSC-HVDC with metallic return** would **appear more cost effective** and technically efficient compared to HVDC radial monopole solutions, and HVAC offshore solutions, with a reduced offshore asset footprint, including a more limited offshore cabling requirement; and can offer flexible operation during outage conditions.

The objective of the Centre's study is to deliver a "tool-kit" of Integrated HVDC offshore options; how they may be staged and applied such that these options can inform offshore and onshore transmission system planning across the onshore TOs and the ESO. This report summarises drivers for integrated offshore transmission; status of HVDC technologies, high-level analysis of integrated transmission designs; and outlines technical/codes challenges and opportunities.

Abbreviations

Abbreviation	*Meaning*
DCCB	HVDC Circuit Breakers
ESO	Electricity System Operator
ETYS	Electricity Ten Year Statement
HVDC	High Voltage Direct Current
LVDC	Low Voltage Direct Current
NGET	National Grid Electricity Transmission
NOA	Network Options Assessment
Ofgem	Office of Gas and Electricity Markets
OFTO	Offshore Transmission Owner
OWF	Offshore Wind Farm
OWIC	Offshore Wind Industry Council
SCL	Short Circuit Level
SQSS	Security and Quality of Supply Standard
TO	Transmission Owner
WTG	Wind Turbine Generator

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1 Drivers for Integrated Offshore Transmission

In Great Britain, Ofgem is currently exploring regulatory options to support the development of an offshore grid to enable a four-fold or more increase in offshore wind generation by 2030 [1]. In its role as the technology workstream lead for the Offshore Wind Industry Council (OWIC) transmission group, the National HVDC Centre has been requested to identify opportunities for implementation of integrated HVDC transmission solutions, as informed by but not limited to the existing onshore and offshore HVDC experience, referencing previously developed technology readiness assessments, and as such represent pragmatic options in meeting the 2030 offshore wind targets.

Integrated HVDC solutions require less infrastructure than individual connection solutions, including less offshore cabling. Being HVDC in nature, such solutions do not have the same technical constraints related to maximum distances of radial cable solutions that are present within HVAC solutions and so offer greater flexibility in how and where such integrated solutions may be connected into the onshore GB transmission system. These integrated solutions provide increased connection resilience in comparison to individual projects and offer the opportunity of additional power flow capacity across the onshore GB Transmission system by connecting across a number of locations; providing increased flexibility and power system benefits allowing onshore transmission owners to consider less extensive network reinforcements to support offshore transmission capacity than would otherwise be required.

In providing the "toolkit" of integrated offshore design capacity, the HVDC Centre analysis with inputs from the OWIC Transmission Group has considered:

- The range of offshore development zone scales across to 2050;
- The distances these new offshore projects would be from the coastline of the onshore system, and
- Description of solutions which could be applied within these zones.

This work does not explicitly consider offshore parallel transmission circuit developments, interconnected arrangements across offshore development zones or HVDC interconnections, however the considerations within this report may be used to inform such further broader consideration, and do not necessarily preclude use of similar such toolkit designs as described here.

1.1 Offshore development zone growth to meet new Offshore Wind Targets

As discussed in [2], OWIC has described potential growth scenarios addressing the new targets of wind connection. The new offshore wind schemes developed under these cases, whilst principally in the North Sea, are also located at transmission distances of 100km or more from the shore and have power ratings of above 1000MW. Figure 1 shows examples of existing and planned offshore wind areas [2].

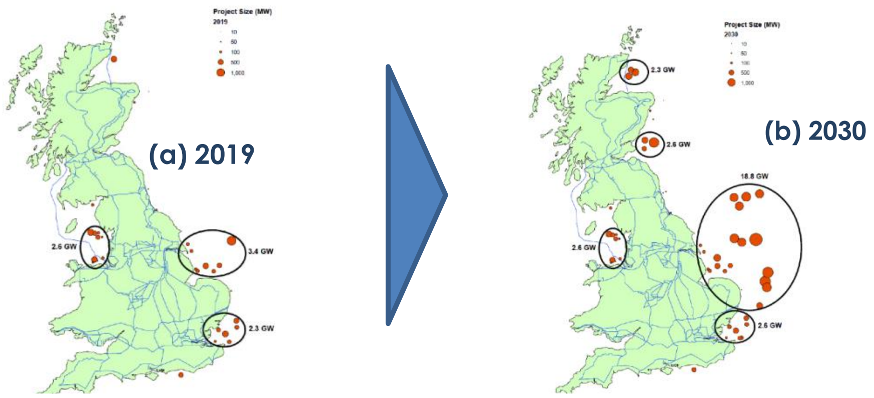

Figure 1: Example Offshore Wind Areas in GB. (a) 2019 (b) 2030.

Future scenarios developed by OWIC transmission group identify that the largest offshore wind growth between 2019 and 2050 is **17.6GW** in an offshore area and by 2030 is **11.4GW** in the same area. However, the smallest shift between 2019 and 2050 is 2.5GW in another offshore area. Accordingly, we have developed topologies that can be incrementally developed across that range or meet an illustrative maximum target level of capacity within that range.

Electricity connections to GB offshore windfarms are typically built by offshore wind farm developers through a regulated competitive process and then transferred to an offshore transmission owner (OFTO) under the OFTO regime [3]. Co-ordination of offshore transmission infrastructure could deliver optimal designs with shared assets, which occupy less space, reduce community impacts and deliver boundary capacity benefits to the onshore electricity transmission operators. However, this would require appropriate frameworks for development of shared infrastructure, staging of incremental build approaches and analysis and mitigation of technology risks and interactions.

2 HVDC-connected Offshore Wind Farms

HVDC schemes based on voltage source converters (VSC) is the key technology for integrated offshore transmission networks that can facilitate the connection of large-scale offshore wind generation at transmission distances typically beyond 100km. Offshore HVDC-connected windfarms were pioneered in Germany, by Tennet and there are currently 9 in operation, 3 in construction, and 2 in planning, with symmetrical monopole topology, long submarine DC cables, significant lengths of DC land cables and at power ratings up to 900MW [4]. Figure 2 shows the simplified electrical system of HVDC-connected windfarms.

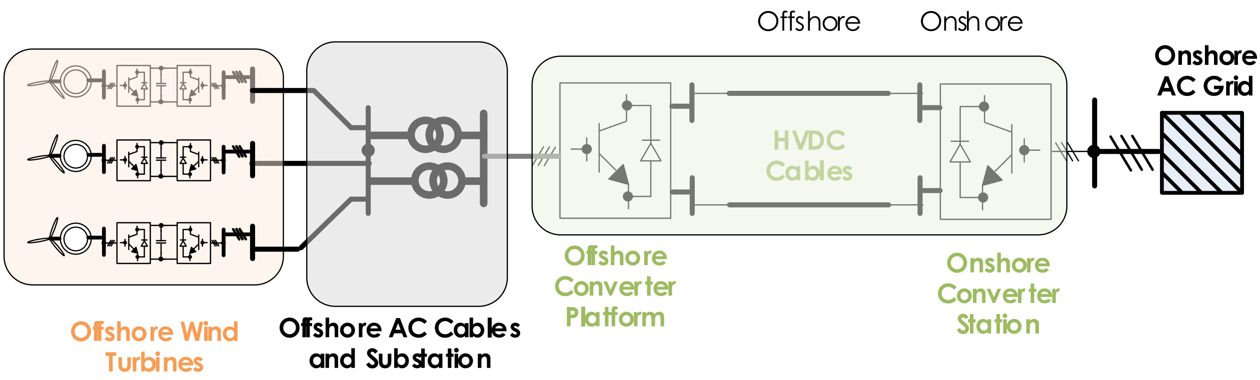

Figure 2: Simplified Electrical System of HVDC-connected Offshore Wind Farms.

The key components of HVDC-connected offshore wind farms are:

- Offshore HVAC collection system: comprising array cables rated at AC voltages 66kV, step-up transformers for AC voltages up to 220kV for transmission to for offshore converter, reactive power compensation devices and possibly harmonic filters to maintain power quality of the offshore AC grid.
- Offshore converter platforms: hosting the converter station, which creates the offshore grid AC voltage and transforms the alternating current from the offshore wind generation into direct current transmission; and
- HVDC submarine and land cables: linking the onshore grid to the offshore wind generation; and
- Onshore converter station: to transform the direct current into alternating current for power transmission into the terrestrial grid.

This first phase of the HVDC Centre analysis of integrated networks summarised in this report. The HVDC Centre analysis explored:

- VSC-HVDC configurations based on symmetrical monopole and bipole options;
- Multi-terminal DC solutions in comparison to HVDC links with AC paralleling offshore.
- Integrated HVDC solutions compliant with the Security and Quality of Supply Standard (SQSS); and
- Boundary capacity benefits for onshore Transmission Operators.

Beyond this, there is geography to consider which informs multi terminal HVDC options versus HVDC links with parallel offshore AC cables. **Hybrid HVDC schemes comprising interconnectors and offshore wind connections were considered out of scope.**

2.1 Configuration

An integrated offshore HVDC network may be based on one of the following approaches: (i) HVDC schemes with parallel offshore AC cables; or (ii) multi-terminal HVDC option. This section describes the main HVDC configurations considered in the HVDC Centre analysis of integrated offshore networks connecting wind farms across offshore zones at high transmission voltages in the range of ±300kV DC to ±600kV DC and rated power transfer capacities above 1000MW. Also, an analysis of transmission losses associated with the different configurations of HVDC solutions with parallel offshore AC cables is considered.

2.1.1 HVDC Links with Offshore Parallel AC connections

In each of the HVDC solutions considered below, offshore AC parallel networks are required which may operate open pre-fault, but which would be required to couple post-fault, and which it would be desirable to run coupled as often as load factors of offshore wind generation allow.

The scale of AC coupled generation would be limited to 1320MW, corresponding to the maximum infeed loss within the SQSS for a single fault in the offshore network. This would be done given the coupled AC networks with limited short circuit level and inertia would not be expected to ride through an offshore fault without additional significant commitment in infrastructure and/or additional HVDC and Wind Turbine performance capabilities, which would not be realisable in meeting the 2030 deployment objective.

A higher maximum loss of 1800MW would enable the designs to be utilised more efficiently in intact operation without introducing a higher overall loss risk than the maximum 1800MW loss risk that is available across onshore connections including the analogous HVDC developments, some of which exceed 1320MW in scale. We would therefore recommend that this loss risk level offshore should be reviewed in enabling the most efficient future integrated offshore designs.

- **Symmetrical Monopoles**: The symmetrical monopole configuration with offshore parallel HVAC cables has been used in some HVDC-connected offshore wind farms in Germany at rated power of up to 900MW and DC voltages of up to ±320kV DC. There is little or no DC stress on AC transformers, hence can use conventional AC transformers. However, this configuration requires additional HVDC cables compared to a bipole configuration to achieve equivalent power transfer capability and improved redundancy. Also, it could occupy more space on offshore platforms due to the DC insulation and clearance requirements within the valve halls. Figure 3 shows the schematic diagram of two symmetrical monopoles to be connected with parallel offshore AC cables to achieve higher power ratings.

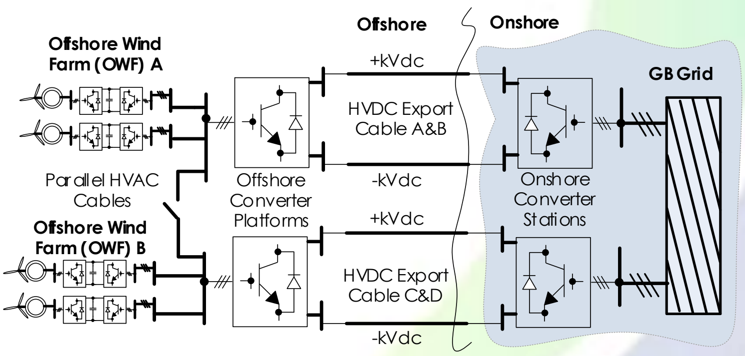

Figure 3: Two symmetrical monopoles that can connect in parallel using offshore AC cables

- **Bipole with third return cable**: can offer greater flexibility, reduced offshore cable asset compared to two equivalent symmetrical monopoles, and improved space savings on offshore platforms due to DC voltage insulation and clearance requirements. Also, it can achieve half capacity operation during single cable or converter outage but has slightly higher losses during half capacity operation following a single cable fault due to rated current flowing through the third low voltage DC cable (as seen in Table 3). Figure 4 shows the schematic diagram of a bipole HVDC with return cable scheme, which connects two offshore wind farms to an onshore grid.

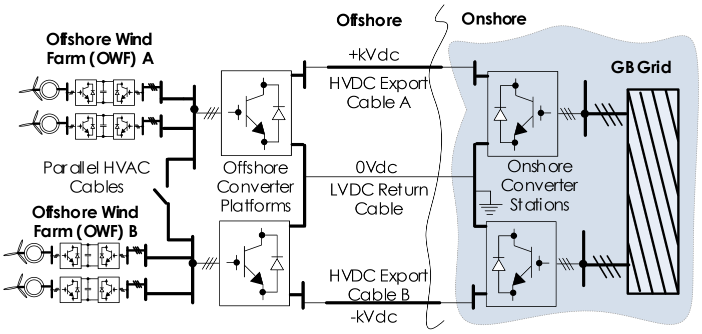

Figure 4: Bipole HVDC scheme with third return cable

- **Bipole without third return cable:** This arrangement does not require a third metallic return cable but relies on use of the sea or earth as a return path from the offshore converter to the onshore grid. Typically, this is not used in GB due to environmental issues linked to sea return, hence it offers limited redundancy during a single cable fault on the HVDC cable. Figure 5 shows the schematic diagram of the Bipole HVDC without return cable.

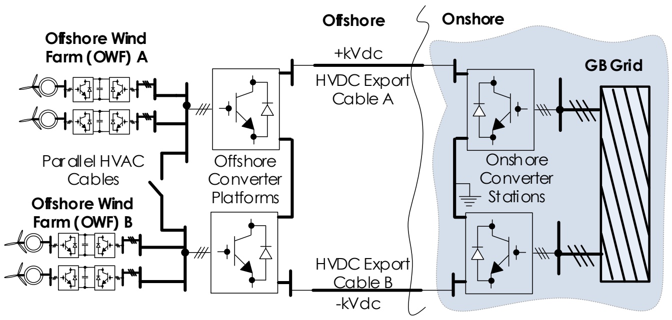

Figure 5: Bipole HVDC scheme without third return cable

2.1.2 Multi-terminal HVDC Systems

Multi-terminal HVDC options can facilitate the connection of two or more offshore converter platforms (within up to 200km of one-another) collecting power from different offshore windfarms to shore. The HVDC Centre analysis considered the requirements for multi-terminal HVDC options, but its advantages over the bipole configuration with return cable scheme presented in this report are not obvious. The three-terminal scheme in Figure 6 will require oversizing of both the HVDC export cable (A) and the onshore converter station, and also require an additional offshore HVDC switching platform for hosting HVDC switching and protection devices. This may require higher anticipatory investments compared to the HVDC links with offshore AC parallel connections.

Figure 6 shows an example four-terminal DC system based on the symmetrical monopole configuration used for connection of two offshore wind farms to an onshore grid.

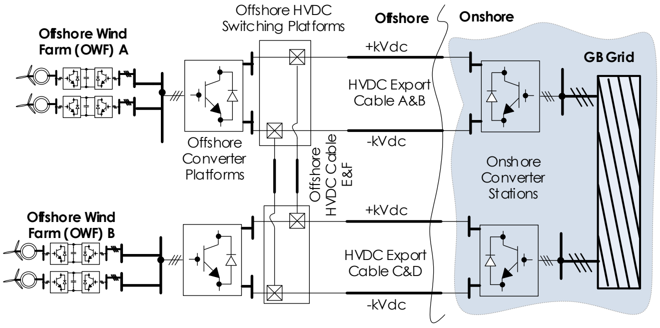

Figure 6: Four-terminal HVDC connecting two offshore wind farms to an onshore grid

The potential benefit of not building any more offshore cables could be limited by the need for more offshore converter platforms, additional offshore platforms for HVDC circuit breakers (DCCB) or DC switchgear and the potential risk of a single point of failure on the export DC cable or onshore converter station. Also, there will be cost of DCCBs located in some cases offshore and so occupying platform space and weight, but no additional operational benefit at this stage. In approaches that were not the subject of this analysis - for example OWFs with T-connection into Embedded HVDC links or Interconnectors; or offshore hub locations where HVAC interlink cable will be lengthy, could be a potential candidate for this multi-terminal HVDC arrangements. These multi-terminal options could form the subject of future technical and cost benefit analysis at a later stage.

2.2 Asset Count Analysis

A single symmetrical monopole represents a single mode failure, as a single cable or converter outage will result in loss of total power transfer capability and this arrangement will not deliver any boundary capacity benefits to the onshore transmission network owners. However, if two symmetrical monopoles are considered, they have the ability to cross-connect at the offshore AC network between the two HVDC links by locating the two offshore hubs close together to minimise the extent of AC cabling and can deliver boundary capacity benefits to the onshore network.

However, this approach whilst similar in functionality with a Bipole does not have the same asset benefits. The symmetrical monopoly arrangement will require 4 offshore cable circuits insulated to DC transmission voltages, instead of two such cables plus a metallic return requiring lower insulation in a Bipole arrangement. There are also indirect benefits relating to the top-weight of platform.

Assets associated with each pole of a bipole are less by comparison to those of symmetrical monopole designs as there is a greater controllability of DC voltage available. It is expected that this again will translate to savings. Therefore, the HVDC centre analysis focused on the use of Bipole with metallic return solutions for integrated offshore transmission.

In comparison to the Bipole with return cable scheme, multi-terminal HVDC will require:

- Extra HVDC circuit breakers (DCCB) needed to ensure losses are contained during faults;
- More complex devices involving more DCCBs if multi-terminal bipole configuration is used;
- Same submarine cable size limitations so no additional capacity benefit; and
- Increased complexity in control strategy of the multi-terminal system.

However, multi-terminal HVDC links may still be a viable option, particularly if there is an advantage in constructing an integrated arrangement across different offshore zones, where HVDC with parallel offshore AC cables was too expensive otherwise. In conditions where alternative options exist, these could be considered first before extension to multi-terminal systems.

2.3 Load Factor

The transmission infrastructure linking offshore wind generation to the onshore grid is typically fully rated at up to the installed offshore generation capacity. The average load factor of GB offshore wind farms is within the range of 40% to 70%. Figure 7 shows load duration curves from GB offshore wind farms [5].

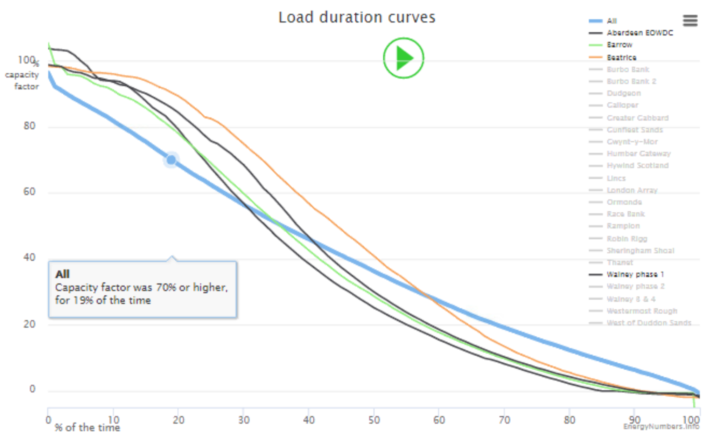

Figure 7: GB Offshore Wind Load Duration Curve

The average load duration curve from all GB offshore wind farms (see blue trace in Figure 7) indicates the average load factor was:

- Above 40% for 46% of the time; and
- Above 70% for 19% of the time.

Also, Figure 8 shows the average fleet capacity factor of GB offshore wind farms is about 40% in 2019 [6].

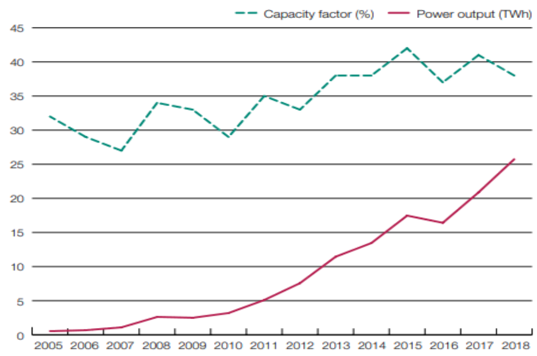

Figure 8: Average GB fleet capacity factor. Source: Crown Estate

Therefore, the surplus available offshore transmission capacity should be available to be used for onshore constraint management consistent with the planning levels used within NETS SQSS for peak conditions on the network with potentially higher still capability available year-round to support outage planning across both onshore and offshore grids.

2.4 HVDC Technology Status

HVDC-connected offshore wind farms have to date used symmetrical monopoles for radial point-to-point connections, which on an individual basis is justified. However, for integrated offshore solutions, bipole configuration gives greater flexibility and higher capacities, which could reduce the extent of cables required and potentially avoid the need for HVDC circuit breakers. Table 1 is a summary of technology status for voltage source converters (VSC) and HVDC submarine and land cables [7]-[14].

Table 1: Summary of HVDC VSC and Cable Technology Status

Technology		Maximum ratings per Converter Bipole/Cable Bipole (except stated otherwise)					
		Installed (until 2019)		Under construction (up to 2026)		Achievable (up to 2030)	
		Capacity (GW)	Voltage (kV)	Capacity (GW)	Voltage (kV)	Capacity (GW)	Voltage (kV)
VSC	With overhead lines (Asia) [7]	3	± 500	5	± 800	7	± 1100
Extruded Cables	Cross Linked Polyethylene (XLPE) [8]; [9][10]; [14] [15]	1 (Symmetrical	± 400 Monopole)	2	± 525	3	± 640
	High Performance Thermoplastic Elastomer (HTPE) [11]; [14]	Not recorded (N/A)	N/A	2	± 525	3.4	± 600
Mass Impregnated Non-Draining Cables	Paper Insulated [12]; [14]	1	± 500	1.4	± 525	2.4	± 525
	Paper Polypropylene Laminate (PPL) [13]; [14]	2.2	± 600	N/A	N/A	4	± 800

The analysis presented in this report considers cables and converter technologies rated up to 1.3GW per pole (2.6GW per Bipole) at DC voltages up to ±640kV, which are achievable by 2030 and consistent with current SQSS requirements for offshore connections.

The first project in supporting the first half of a bipole arrangement, including its metallic return would lead to considerations of initial anticipatory assumptions of further project development against which the end solution would be cost optimal.

The maximum scale of HVDC solutions to be deployed in GB will be subject to SQSS requirements, available cable capacities and offshore platforms. In Germany, largest VSC-HVDC radial connection till date for offshore wind is 900MW and ±320 kV. There is some but very limited experience of multiple vendor bipole projects onshore. In these cases, a consistent control strategy and design is used, which does not naturally fit with the current position in VSC-HVDC development and associated IP management, as such it is envisaged that where bipole based solutions were utilised, at least in the first instance of integrated solutions being developed, each individual bipole utilised would need to be vendor specific.

2.5 International Experience

Figure 9 illustrates examples of integrated offshore networks in Norway and Germany. These offshore network designs rely on offshore AC circuits to facilitate shared use of HVDC transmission system for connection of offshore wind generation in Germany [4] or offshore loads in Norway [16]. The VSC-HVDC schemes are based on symmetrical monopole configuration. These represent solutions where the two HVDC connections being paralleled with AC network offshore are from two separate vendors, thereby illustrating that across symmetrical monopoles there is no reason to expect bipole projects to be any different, multiple vendor solutions may be combined, provided the associated vendor assurance processes are appropriately defined and managed. Also, industry experience on de-risking of HVDC control, protection and testing solutions for multi-terminal ready designs including the Caithness Moray Shetland project and multi-vendor HVDC schemes are reported in [16][17] [18].

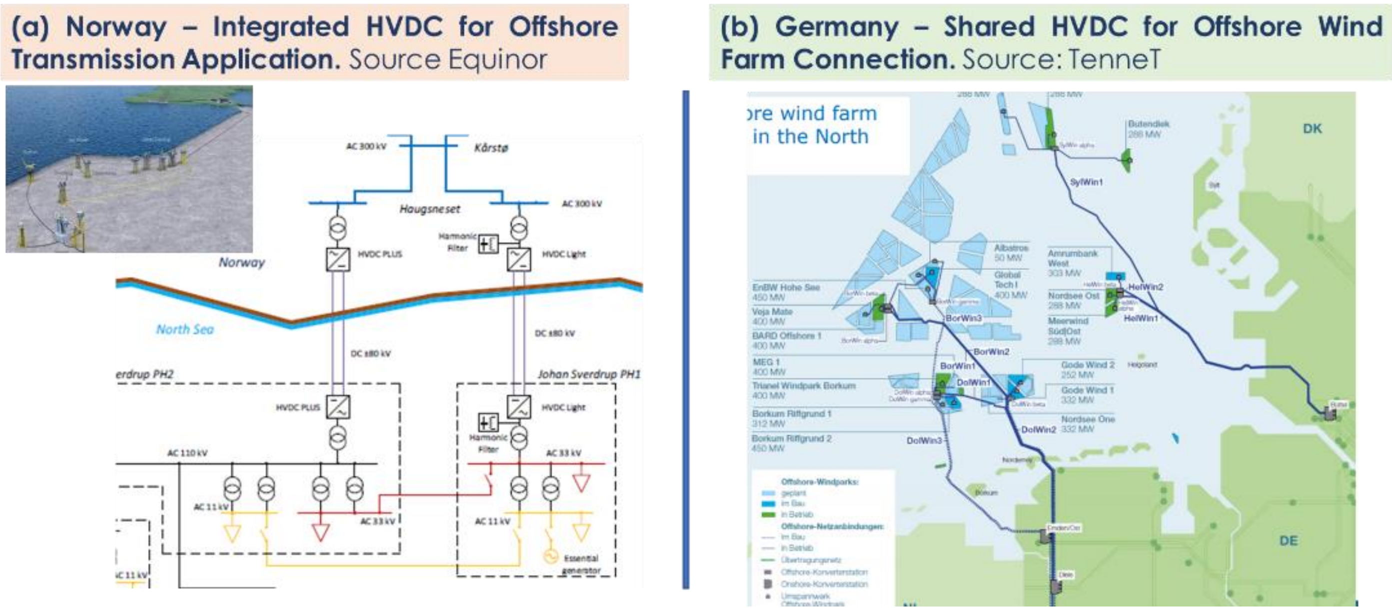

Figure 9: Examples of integrated Offshore HVDC networks. (a) Norway. (b) Germany

3 Integrated Network Design

The HVDC Centre analysis explores the use of Bipole HVDC with return cable and offshore parallel AC cable designs that are SQSS-compliant for connection of GB offshore wind generation across different scales in the range of 2.6GW to 10.4GW.

Bipole HVDC with metallic return cable can facilitate:

- Power transmission from large far-from-shore offshore wind farms to onshore grids;
- Improved boundary capacity for constraint management on onshore transmission networks;
- Operation at half-capacity during single cable or converter outage;
- Reduced number of HVDC cables, offshore transmission assets and grid reinforcement; and
- Potential cost savings associated with delivery of the benefits outlined above

3.1 2.6GW Offshore Area Case Study

For a 2.6GW offshore wind generation area, the use of Bipole HVDC solution with metallic return is analysed. Figure 10 is an illustration of the Bipole HVDC transmission scheme, with VSC stations and HVDC cables each rated at 1.3GW and offshore AC cables with maximum rated capacity of 1GW. An example power flow condition is outlined across the offshore network.

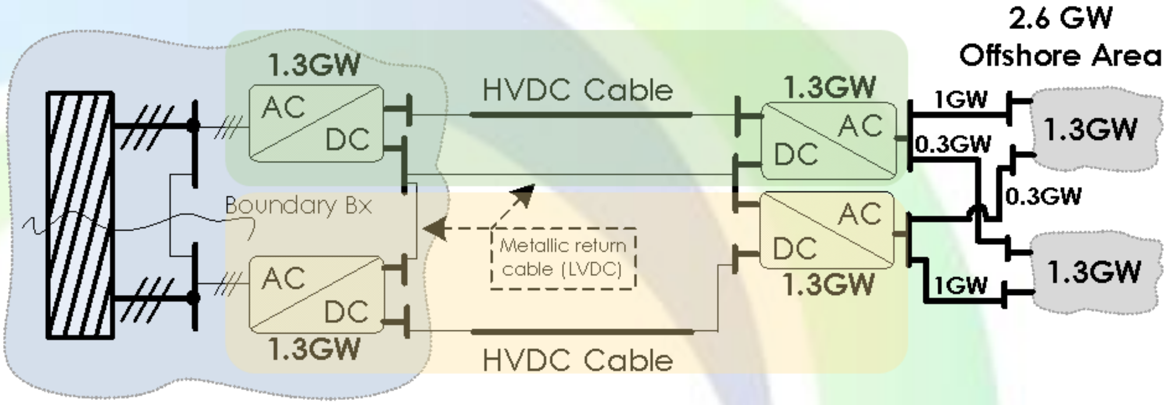

Figure 10: 2.6GW Bipole HVDC offshore network design

This Bipole HVDC arrangement with metallic return can be built sequentially as:

- Stage 1 (see green area in Figure 10): 1 offshore rectifier; 1 onshore inverter; 1 fully rated HVDC subsea cable and 1 LVDC return cable;
- With anticipatory LVDC switchgear at offshore and onshore stations;
- Stage 2 (see brown area in Figure 10): Other offshore rectifier, onshore inverter; adjacent HVDC cable and onshore LVDC cable.

If the two onshore converter stations are located across an onshore transmission boundary, then this integrated Bipole HVDC scheme with return cable can deliver between 400MW to 800MW of boundary capacity benefits beyond 50% of the time to onshore transmission operators at a load factor between 70% to 40%. The sequential build approach described for the 2.6GW Bipole solution can be extended to examples of other offshore wind areas.

The technical requirements for delivery of boundary capacity improvements are:

- Implementation of switching arrangements at offshore HVAC cable collection system;
- Design, testing and demonstration of power sharing controls for HVDC converter stations; and
- Coordinated controls for HVDC links, offshore HVAC collection system and onshore grid.

In terms of the AC and DC protections offshore, the proposed solutions are standard and similar to existing schemes in Germany and Norway offshore examples where the AC interconnection is normally open. Also, example of wide area control and protection considerations required for coordination operation across the offshore substations is outlined in [16].

Table 2 is a summary of the high-level comparison of the converter station requirements, cable assets, availability and boundary capability for the 3 different HVDC configurations using the case of a 2.6GW scheme.

Table 2: Summary of 2.6GW HVDC Connection Arrangements

Arrangement	Converter Requirement		Cable Requirements	Availability	Boundary Capability
	Offshore Platform	Onshore Station			
Bipole with Metallic Return	2 Rectifiers	2 Inverters	**2** HVDC Cables **1** LVDC Cable	Half capacity during single cable or converter outage.	Yes. During normal operation.
Bipole without Metallic Return* (*typically not used in GB due to environmental considerations)	2 Rectifiers	2 Inverters	**2** HVDC Cables	Half capacity during converter outage. Zero output during single cable outage.	Yes. During normal operation
Two Symmetrical Monopole	2 Rectifiers	2 Inverters	**4** HVDC Cables	Half capacity during single cable or converter outage.	Yes. During normal operation.

For a symmetrical monopole-based HVDC scheme, a DC cable or converter fault removes the whole link. Where DC circuit breakers (DCCBs) are used in multi-terminal HVDC systems, only a protected area of the DC circuit is lost, and other convertors are reinstated within fault clearance times. For a Bipole circuit, a single fault will only remove half the power transfer capacity, with modern bipole protection and control enabling monopole restoration within a similar protection timeframe, whether the fault be a pole, cable or metallic return loss. These arrangements allow the Bipole with metallic return scheme to effectively have a similar topology resilience in comparison to two AC circuits on the onshore system, without using HVDC circuit breakers.

Furthermore, analysis of transmission losses for the different HVDC configurations is performed for the case of intact operation at full capacity and single cable fault operation at half-capacity. Table 3 is a summary of the power losses in the transmission link, excluding the losses in the converter stations.

Table 3: Analysis of transmission losses for different HVDC connection arrangements

HVDC Circuit Arrangement	Intact (Full capacity)			Single cable fault (Half capacity)		
	Cable Count	Resistance	**Total Losses**	Cable Count	Resistance	**Total Losses**
Bipole with Metallic Return	2 HVDC cables 1 LVDC Cable	2*R 1*R	**2.0001*R*I^2**	1 HVDC Cable 1 LVDC Cable	1*R 1*R	**2*R*I^2**
Bipole without Metallic return (Typically not used in GB due to environmental considerations)	2 HVDC cables Earth Electrode	2*R 0.5*R	**2.00005*R*I^2**	1 HVDC Cable Earth Electrode	1*R 0.5*R	**1.5*R*I^2**
Two Symmetrical Monopoles	4 HVDC Cables	4*(2*R)	**2*R*I^2**	2 HVDC Cables	2*(2*R)	**1* R*I^2**
	4 HVDC Cables	4*(2.5*R)	**2.5*R*I^2**	2 HVDC Cables	2*(2.5*R)	**1.25 * R*I^2**
	4 HVDC Cables	4*(3*R)	**3*R*I^2**	2 HVDC Cables	2*(3*R)	**1.5* R*I^2**

It is assumed that:

- R is the total resistance per pole, and I is the rated current per pole of a fully rated 1.3GW HVDC cable;
- Converter losses (i.e. conduction and switching) is about 0.7% to 1% of rated power per station [19];
- Cable losses is in the range of 0.1% to 0.3% of rated power per 100km for HVDC cable [19];
- The current flow in the return path of a Bipole scheme is assumed to be in the range of 1% to 2% of full rated current during intact condition and 100% during half-capacity operation [20]; and
- The resistance of earth return is assumed to be half of the resistance of an equivalent LVDC cable [20].

The cable losses and converter conduction losses typically come from the resistance of circuits and depend on the square of the current carried by the circuit (I2R). It is assumed that the current flowing in the symmetrical monopole circuit is half the current flowing in the Bipole circuit.

A sensitivity study is performed using three values of cable resistance per pole (1R, 1.25R and 1.5R) for the symmetrical monopole system:

- For the intact condition: cables losses of the Bipole configuration has a good match with the symmetrical monopole scheme in the case of 1R, but as the cable resistance increases to 1.25R and up to 1.5R, the cables losses due to the symmetrical monopole will become higher than the Bipole scheme.
- Single cable fault: cable losses of the Bipole configuration is slightly higher than the two symmetrical monopoles in all cases are resistance per pole increases from 1R to 1.5R.

3.2 Case Study of 4.4GW and 5.2GW Offshore Area

The integrated offshore analysis presented in Section 3.1 is applied to the case of a 4.4GW and 5.2GW offshore wind area, which require two parallel Bipole HVDC schemes with a third cable. Figure 11 shows the integrated offshore network designs for the 4.4GW and 5.2GW offshore wind areas.

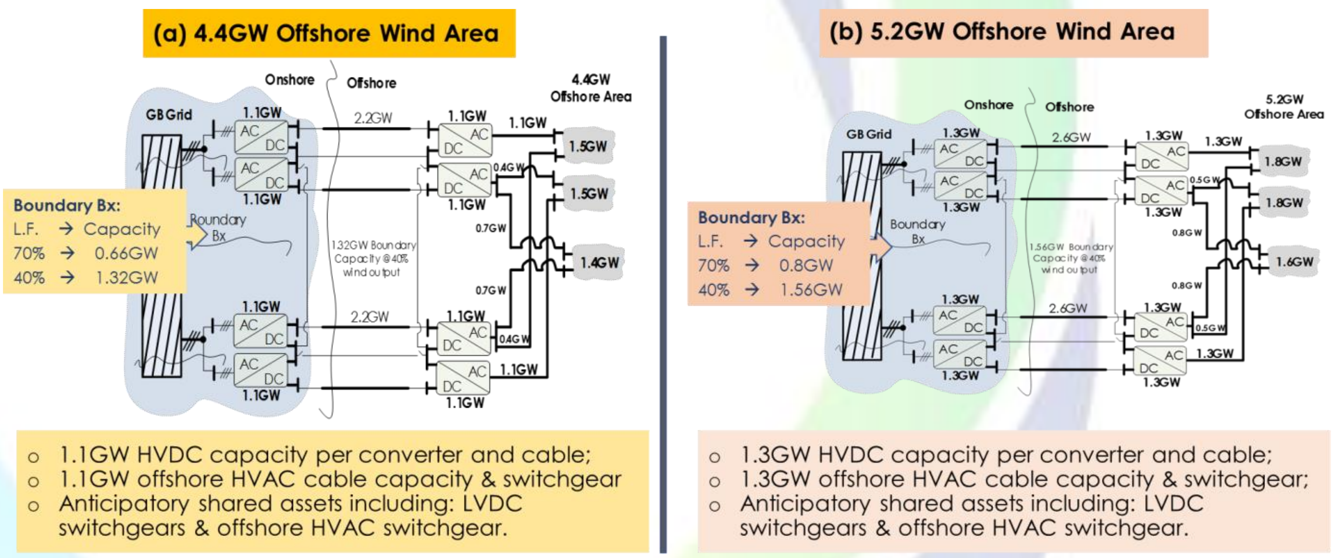

Figure 11: Integrated Offshore Network Design. (a) 4.4GW capacity. (b) 5.2GW capacity.

The maximum capacity of HVDC converters and offshore cables (both HVDC and HVAC) required for the 4.4GW integrated offshore design is 1.1GW (see Figure 11(a)), and that of the 5.2GW design is 1.3GW (see Figure 11(b)). Both designs could require shared infrastructure for LVDC switchgear and offshore HVAC switching devices and controls. If all offshore platforms are located nearby, there may be options for the two Bipole schemes to share a single offshore LVDC return cable, but this would require an additional LVDC cable for connection of the onshore converter stations. As an alternative, each of the biople HVDC schemes could be equipped with a dedicated LVDC cable for the return path. The optimal arrangement of the LVDC cable scheme can be the subject of cost benefit assessment. Also, the integrated network can be built sequentially as described for the 2.6GW offshore area.

3.3 Case Study of 7.8GW and 10.4GW Offshore Area

This section analyses and compares the case of a 7.8GW offshore wind area, which will require three parallel Bipole HVDC schemes with a third cable and a 10.4GW offshore area, with four parallel Bipole HVDC schemes.

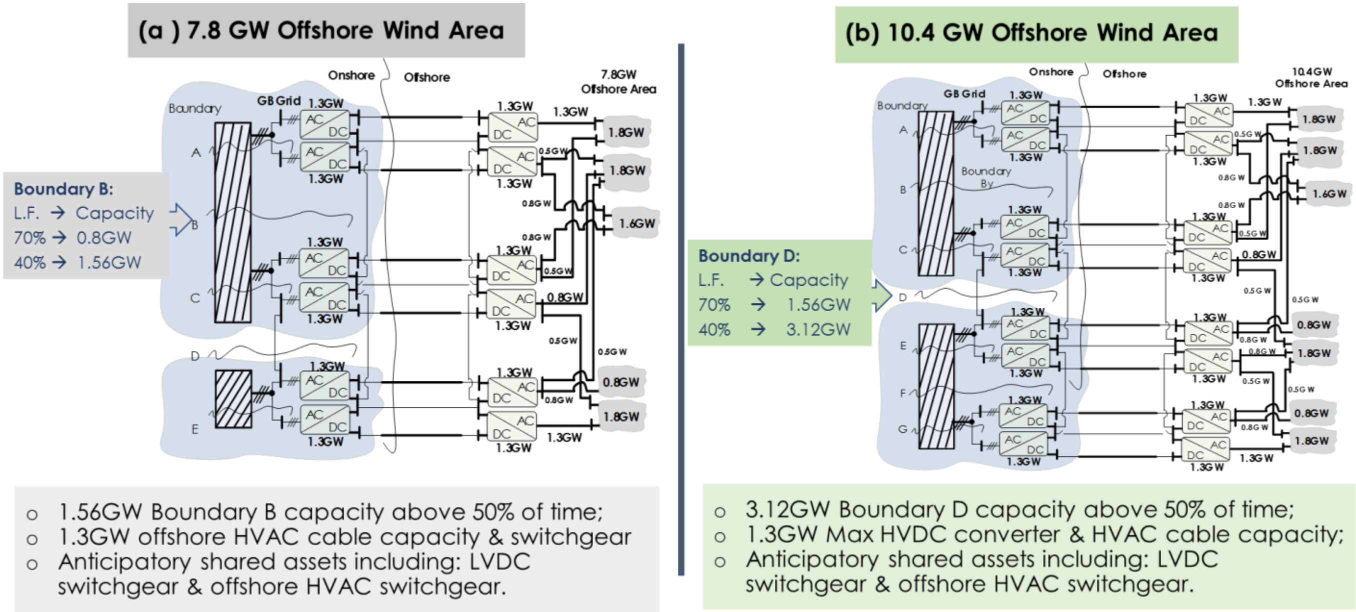

Figure 12: Integrated offshore network design. (a) 7.8GW offshore area (b) 10.4GW offshore area

The 7.8GW integrated offshore network design could potentially offer boundary capacity in the range of 0.8GW to 1.56GW to the onshore network across boundary B (seen in Figure 12(a)), and between 1.56GW and 3.12GW across Boundary D for the 10.4GW design (see Figure 12(b)), depending on the load factor of the offshore wind generation.

This integrated offshore network deigns can be built sequentially using the approach described for the example 2.6GW offshore area (seen in subsection 3.1).

4 Offshore Network Challenges and Opportunities

This section outlines opportunities for de-risking technical challenges and highlights codes and standards requirements to enable the development of integrated offshore networks.

4.1 Technical Challenges

Technical opportunities exist for both AC paralleling of offshore HVDC links and use of bipole HVDC configuration. Table 4 is a summary of technical challenges and opportunities for integrated offshore networks.

Table 4: Summary of technical challenges and opportunities for integrated offshore networks

Opportunity	Description
1. Practical work on control and protection design, composite testing and implementation.	○ Fast DC protection to isolate and reconfigure to monopole/ manage metallic return loss ○ Co-ordinated monopole ramping and power management ○ Optimised platform configurations
2. Offshore network stability to GB specific considerations.	○ Frequency response, power oscillation damping and black start ○ Will require further optimisation of HVDC and WTG design.
3. Offshore resilience required to realise boundary benefits and limit scale of impact from onshore AC faults	○ Onshore-offshore intertrip and fast ramp control design ○ Generator islanding tests to ensure complementary fast ramp ○ Resilience to widespread voltage dip & strategies for management of power quality, across fast ramping action
4. Resilience to DC cable/ convertor loss	○ Supported in HVDC design, but needs complementing in wind turbine generator islanding resilience, and CBA for DC grid with HVDC Circuit Breaker. ○ Shared reactive power control strategies offshore to minimise effect of DC disturbances on offshore island.
5. Overall system verification and compliance.	○ Complexity and multivendor management possible with appropriate validation of overall system in multivendor hardware verification and sufficiently open and complete model exchange.

4.2 Composite Testing

Transmission connections to offshore wind generation typically consist of multiple technologies supplied by different manufacturers with each tested at the factory, but there is no composite modelling and testing capability currently available in GB, for testing of complex designs and combined solutions. Composite systems are where there are multiple power electronic devices, control and protections acting together in response to AC system requirements across the offshore and onshore network.

This is a problem as overall performance of the solutions may rely on an overall strategy of performance in control and protection that is provided by more than one device, and as such not only the devices performance, but its role within the overall solution and the effectiveness of that overall solution which also need verification. Devices are frequently commissioned at different times, and the overall solution may emerge in stages that also need testing for overall performance. If the overall performance cannot be demonstrated, there is the risk of unintended control and/or protection operation during eventual operation which may lead to a failure for the overall solution to meet its required performance and resilience when connected to the network.

The National HVDC Centre in collaboration with the ESO is currently taking forward an innovation project to investigate composite testing options and assess benefits of different methodologies and identify testing requirements across different stages of the compliance process.

4.3 Coordination of Offshore Reactive Power

If outage occurs on an offshore converter, which wholly supports the reactive power (Q) offshore with no or limited WTG Q support, the burden of Q support following convertor faults would fall back on the remaining nearby HVDC converters and that would drive a higher rating of offshore convertors.

Also, considering the low short circuit level of the offshore system, the size of voltage disturbances would be significant on the offshore AC network due to the loss of an offshore HVDC convertor e.g. to a DC fault. If balance of the reactive power support is shared between WTGs and HVDC convertors, the offshore AC system becomes less exposed to that condition, and the same rating requirement does not emerge.

It is possible to for some mitigations to be designed - for example into the offshore HVDC convertor a control mode to operate like a STATCOM when the DC cable is lost - but such schemes cannot cover the internal faults of the HVDC convertor.

Equally, connecting HVDC converters back into a weak offshore AC system (for STATCOM-mode operation) represents a significant technical challenge, which will require careful consideration and control design to avoid it driving adverse control interactions. Such issues have been overcome in point-point operation (e.g. virtual resistor controls in offshore HVDC projects in Germany), but those same STATCOM-mode solutions would need modification for the integrated offshore bipole HVDC arrangement proposed in this report.

4.4 Ancillary Services and Boundary Capability

To deliver ancillary services to the onshore grid, offshore converters and WTGs will be required to coordinate control actions required to meet the onshore system requirements. This could require options for the WTGs to operate to a wider range of offshore voltage and frequency for example different from operating range of the onshore system.

The frequency of the WTG responds to would naturally be the one that the balance of convertor and WTG ramping control presents to the offshore AC power island and complementary ramping rates and control would need to be part of any HVDC based OWF design.

Also, the delivery of onshore boundary capability benefits to would rely on coordination of both onshore and offshore control and protections solutions, inter trips and switching arrangements, which present a technical challenges and opportunities involving design, testing and implementation of appropriate controls.

4.5 Codes and Standards

Options for review of current codes and standards exist to realise full benefits from integrated offshore networks in GB. Table 5 is a summary of the opportunities for codes and standards.

Table 5: Summary of codes and standards opportunities

Opportunity	Description
1. Maximum Infeed Limits Offshore	○ A lower offshore maximum loss of 1320MW compared to the onshore 1800MW limits the resilience otherwise available from the discussed configurations and limits the pre-fault boundary transfer benefits that would otherwise be present. ○ Given the diversity within these designs, risks associated with offshore AC faults, and load factor of offshore wind, it is not obvious that this is the most optimal consideration.
2. Co-ordinated control systems	○ Given the extent of co-ordinated control systems associated with offshore design, and their relevance to supporting boundary capability specific consideration of the required robustness of these within the standard would appear relevant.
3. Fault Ride Through Requirements	○ The fault ride through requirements of offshore generation subject to onshore faults is very different in its presentation for integrated HVDC solutions, or indeed radial solutions. ○ Specific WTG test scenarios should be constructed to inform and ensure robustness.
4. Offshore AC Voltage and Frequency Control	○ Integrated solutions rely on an integrated offshore AC frequency and voltage regulation philosophy which could be best represented in code.
5. Data Exchange and Compliance Validation	○ Given the challenges of incremental and vendor specific development into complex overall design, code changes enhancing data exchange and supporting integrated compliance validation become critical in delivering these.

5 Summary

Integrated offshore transmission solutions offer enhanced flexibility and reliability for the offshore project, reduced asset footprint offshore, and offer options to present a lesser impact to the onshore systems in areas where new connection capacity are most problematic. The HVDC bipole with return cable solutions appear more cost and technically efficient to HVDC radial monopole solutions, and HVAC offshore solutions.

Our analysis identifies these solutions are not only feasible but realisable in the medium term (for projects that are in technical design stage). The later integrated solutions are developed, the lower the opportunity to realise the full benefits of these approaches.

Integrated solutions can be constructed in a staged manner- whilst the additional up-front investment can be minimised, frameworks for identifying and incentivising beneficial anticipatory investment would be required. Adopting such staging can provide additional resilience and availability for those early projects above and beyond the radial solution.

A review of SQSS offshore infeed limit may offer beneficial impact to integrated HVDC designs, which can further reduce the extent of offshore cabling and minimise onshore construction. In addition to a framework for investment, frameworks for de-risking the technical challenges and compliance testing of composite solutions are also needed across design, staged commissioning and in-service experience.

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