

28 July 2021

# HVDC R&D Strategy (Coordinate Offshore)

## To meet 2030 & 2050 net-zero targets

This paper, produced by ‘The National HVDC Centre’, describes the HVDC sector research and development required for Great Britain (GB) to deliver a coordinated approach to offshore renewables connections to meet the 2030 and 2050 net zero targets.

The Centre occupies a unique position within the Industry; having close engagement with manufacturers, developers deploying HVDC in GB and academic institutions with whom it engages in research; and the Electricity System Operator (ESO), and Transmission Operators (TOs) who are our partners supporting the Centre’s activities.

In this paper, a proposed R&D Strategy is presented, building on previous relevant analysis by the Centre. It may be read alongside the paper the Centre has also released on its review of the current HVDC supply chain position: “HVDC Supply Chain Overview (Coordinate Offshore)” dated 28 July 2021.

The strategy is presented, along with the reasons such a strategy is now required, and the key next steps and priorities to realise its delivery.

Delivery of this strategy has the potential to both increase further the available cost savings from offshore coordination, further mitigate environmental impacts in the delivery of offshore growth, and support overcoming the delivery challenges as presented in the HVDC Supply chain report paper.

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

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# 1 Executive Summary

The department for Business, Energy and Industrial Strategy (BEIS) commissioned The National HVDC Centre to produce a research and development (R&D) strategy on high voltage direct current (HVDC) infrastructure to enable the delivery of coordinated offshore connections to meet 2050 net zero targets in Great Britain (GB).

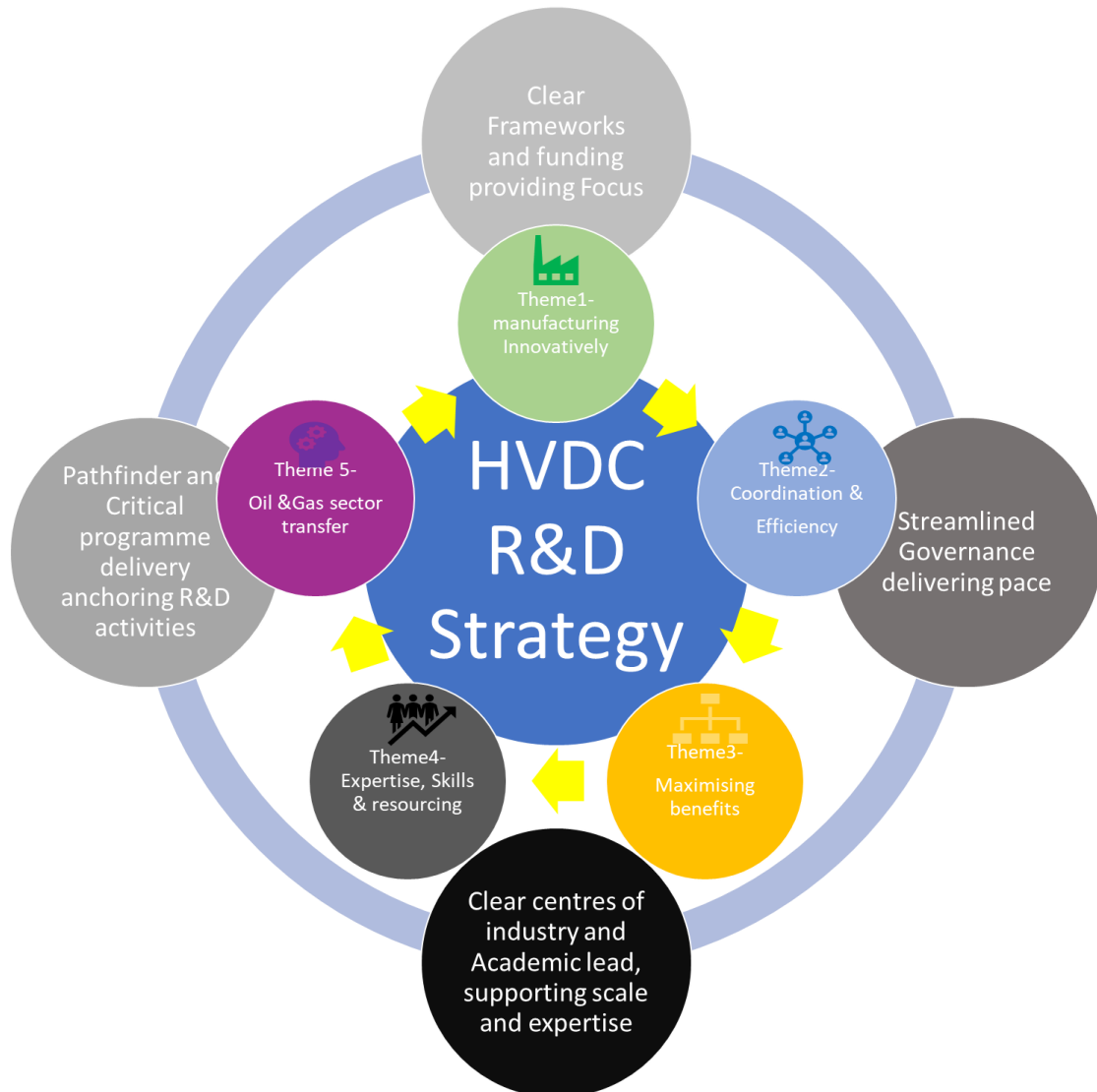


Figure 0.1 Our R&D strategy proposal.






The pace and scale of offshore wind, onshore reinforcement and interconnector growth in GB means that HVDC infrastructure will play a pivotal role in the delivery of the 2050 net zero targets. Innovation in this sector will provide GB with the ability to drive and optimise the implementation of the technology as it is deployed, reducing costs in deployment, getting the most out of the assets introduced and enhancing opportunities to export expertise in constructing, designing and asset managing HVDC technologies being deployed.

Significant progress already made towards Net Zero in the GB Power system, with GB delivering many key innovations to date<sup>1</sup>. With the pace of further change, GB will encounter many of the key implementation challenges earlier than other nations; these relating to the transitioning from conventional generation connected to Alternating Current (AC) Power systems, to HVDC and other non-synchronous generation converter systems dominating power supplies and the control and support functions required to operate the power system securely and reliably.

By driving the key R&D themes, GB can demonstrate technical and commercial leadership in defining the new uses and releasing the new benefits of the technology required here and internationally; such as network stability, inertia and short circuit level support, and support this across the pace of energy transition as more low-carbon technologies replace the conventional synchronous generation sources. Not driving the R&D themes would result in a risk of higher cost and less secure delivery of the transition to new technologies, together with lost opportunities in implementing the transition.

This HVDC R&D strategy describes the benefits to supporting coordinated approaches to offshore connections, together with other use cases of the technology, highlights key challenges being addressed by the strategy, outlines the HVDC innovation potential and summarises approaches for delivering the HVDC innovation strategy outcomes at pace.

The key HVDC R&D themes identified for integrated offshore HVDC development in GB are:

-  **Theme 1: Upscaling HVDC manufacturing innovation**
-  **Theme 2: Advancing Coordinated and Efficient HVDC schemes**
-  **Theme 3: Maximising the Benefits of Integrated Offshore Solutions**
-  **Theme 4: Leveraging Technical Expertise, Skills Development and Resourcing**
-  **Theme 5: Grow domestic capability via knowledge transfer from oil and gas sector**

We have also published in parallel to this report, our “HVDC Supply Chain Overview (Coordinate Offshore)” report within which we outline supply challenges and opportunities relating to the scale and pace of the transition. These are linked topics and our two reports may be read together to illustrate these key linkages.

As discussed within the HVDC Supply Chain Overview report, by 2050, GB integrated offshore networks would require additional HVDC infrastructure comprising at least 5000 km of HVDC cables, 40 offshore converter platforms, 40 onshore converter stations, 16 onshore HVDC circuit breakers and 8 HVDC switching stations, to achieve the connection of up to 75GW offshore wind<sup>2</sup>. This represents a scale of network development not seen within GB since the mid-1960s; and the proposed R&D themes also capture the areas where innovation can support both the scale and pace in HVDC delivery being achieved more effectively & efficiently.

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<sup>1</sup> ENA (2020). Electricity Network Innovation Strategy. Available at: <https://www.energynetworks.org/industry-hub/resource-library/electricity-network-innovation-strategy-2020.pdf>

<sup>2</sup> ESO (2020). Offshore Coordination Project Phase 1 – Sensitivity Study Report.

We summarise our analysis of the scale and urgency of intervention across the R&D themes below to inform next steps.

Innovation Potential	Current Level of Innovation	Size of Opportunity	Action required by		
			0-2yrs	2-5yrs	5-10yrs
<b>🏭 Theme 1: Upscaling HVDC manufacturing innovation</b>					
1.1 Demonstrate HVDC Circuit Breakers in Europe	Medium	💡💡💡	Start	Delivery	
1.2 Develop capability for high-power plastic-insulated HVDC cables	Low	💡💡		Available	Use
1.3 Improve high voltage subsea connections and dynamic cables for deep-water systems	Low	💡💡		Trial	Available
1.4 Develop integrated battery storage integrated with HVDC, including hybrid asset solutions	Medium	💡💡💡		Trial	Available
<b>⚙️ Theme 2: Advancing Coordinated and Efficient HVDC schemes</b>					
2.1 Design and test new control functions for grid integration of complex HVDC	Medium	💡💡💡	Specify	Trial	Deliver
2.2 Develop reconfigurable HVDC replica controls and demonstrate mobile testing option	Low	💡💡💡	Develop	Delivery	
2.3 Explore GB use of overhead line circuits for DC transmission and DC substations for MPIs	Medium	💡💡		Specify	Trial
2.4 Enable delivery of dispersed Bipole HVDC offshore addressing other sea user interactions	High	💡💡💡	Complete	Specify	Deliver
<b>🏠 Theme 3: Maximising the Benefits of Integrated Offshore Solutions</b>					
3.1 Develop control and protection approaches for lower fault level networks	Low	💡💡💡	Trial	Standards	Deploy
3.2 Expand GB strengths in wide area control and manufacturing of complex HVDC applications	Medium	💡💡		Trial	Delivery
3.3 Enhance supervisory controls & asset management telemetry on HVDC projects	Low	💡💡		Trial	Delivery
3.4 Review and inform the application enhanced controls for MPIs and offshore grids	Low	💡		Investigate	Propose
<b>👨‍🎓 Theme 4: Leveraging Technical Expertise, Skill Development and Resourcing</b>					
4.1 Nurture and develop early-year teaching of HVDC and STEM-based subjects with industry	Low	💡💡	Define	Incentivise	Sustain
4.2 Improve HVDC R&D capability in UK Universities & focussed doctoral centres across industry need	Low	💡💡💡	Define	Fund	Grow
4.3 Increase efficiency of hardware-in-the loop testing capability for complex HVDC schemes	Low	💡💡	Start	Trial	Deliver
4.4 Enhance HVDC operator training using simulators and export of technical expertise	Medium	💡💡	Expand	Refine	Sustain
<b>🛡️ Theme 5: Grow domestic capability via Knowledge transfer from Oil and Gas Sector</b>					
5.1 Optimise offshore converter platform design, operation, maintenance and floating structures	Low	💡💡💡	Start	Trial	Delivery
5.2 Repurpose existing O&G manufacturing hubs & offshore assets for HVDC-O&G & H2 applications	Low	💡💡		Start	Available
5.3 Exchange skills and innovation in offshore operation & re-training personnel	Low	💡💡	Start	Sustain	Accelerate
5.4 Optimise seabed and environmental surveys	Medium	💡💡💡	Start	Areas	Whole GB

**Key**

Considerations	Key	Description
Current level of Innovation	Low	Emerging innovation area to date
	Medium	Developing innovation area to date
	High	Significant innovation to date
Size of Opportunity	💡	Moderate potential. Relevant to 2050 net-zero targets.
	💡💡	High potential. Significant enabler of net-zero targets
	💡💡💡	Major potential. Crucial enabler of 2050 net-zero targets.
Action Required by	0-2yrs	Short term (now until 2023)
	2-5yrs	Medium term (2023 – 2025)
	5-10yrs	Long term (2025 – 2030)

An R&D strategy alone is aspirational, without the focus of a framework for its incentivisation and focussed delivery. We note further key factors in this area below.

To deliver the necessary framework, focussed and centralised arrangements for funding and governance to directly drive the delivery of the above strategy may wish to be considered; to address barriers otherwise formed in response to “risk appetite” and the conflicting priorities of engineering innovation present broadly within in the energy sector, and limiting the delay of decision making; the recent innovation fund for transition of electrification across the Distribution sector<sup>3</sup> being one possible model.

Identification of “pathfinder projects” or mechanisms supporting the delivery of demonstration within real projects is also highlighted, measured adoption of risk against defined benefit may also support an improved pace of adoption of necessary strategies given that HVDC delivery will need to be delivered in a staged, incremental form where early delivery complements future stages of combined HVDC solutions.

Achieving such Holistic Designs requires key areas of technical and Techno-economic engineering to be delivered in innovation:

- **Technically** it is critical that “sandbox” environments supporting the combination of detailed and open realistic models of the components, simulating the operation and functions of co-ordinated HVDC solutions can be used to define what is required from vendor solutions, and how they need to act together. These in time can be used to support vendors delivering solutions in a compatible manner with one another and allowing those individual solutions to be simulated and tested comprehensively across deployment as the Holistic Design for 2030 and beyond is implemented.
- **Techno-economic** analysis needs to evolve to support decision making surrounding the extent to which co-ordinated solutions should be taken forward- informed by expected “maps” of envisaged development across the whole timeframe. HVDC developments are discrete and sizeable in nature and not readily modified retrospectively to deliver additional capacity or new forms of coordination/ extension; these aspects need to have been identified and optimised ahead of delivery. New approaches for cost benefit assessment innovating how delivery is future proofed and scaled should be taken forward to inform how initial specification can be “future proofed”.

Of critical priority and linked to the consideration of centralised measures is the need to establish a “pipeline” of skilled resource entering the industry to support the transition; complementing key skill areas across: designing, consenting, constructing, controlling, developing, testing, commissioning and operating HVDC projects. These are areas for which international skills deficits exist to support 2030 and 2050 targets and which risk developers, manufacturers and Transmission Owners and Operators each competing for the same limited resource, ultimately frustrating the overall pace of transition. Doctoral Centres or equivalent arrangements with strong links to industry focussed on delivering both inception level R&D in the above relevant areas, together with focussed graduate training towards specific areas of industrial application may be a possible solution which has had some prior success within engineering disciplines to date. This could be complemented with the incentivisation of early years industry exposure and placement-based learning to secure and stimulate interest for the future careers in this sector.

This Strategy represents areas which we believe are core to the GBs focus on delivery of Co-ordinated Offshore solutions at pace and scale.

HVDC technology development scale and capability are key enablers to the 2030 and 2050 targets for Net Zero with HVDC innovation providing the key ingredient to ensure across the next 30 years HVDC delivery is

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<sup>3</sup> <https://www.ofgem.gov.uk/publications-and-updates/ofgem-delivers-300-million-down-payment-rewire-britain>

optimised. The delivered solutions realise the full opportunities of the evolution of Offshore Wind towards HVDC technology-based connection, and the ever-increasing variety of purposes for which it is used.

This strategy may be used to realise further cost efficiencies and new onshore network support capabilities that ultimately benefit the end consumer and can reduce the environmental impacts of co-ordinated solutions still further from the Phase 1 offshore coordination baseline benefits.

To do this, it is necessary to introduce, at pace, a framework within which key research programmes with an implementation focus to Coordinated Offshore by 2030 may be funded, alongside key pathfinder projects demonstrating solutions aligned to these 5 key themes of activity. This should be complemented both with a streamlined governance of the allocation of that funding to inject pace together and strong stakeholder collaboration, with aforementioned centralised initiatives such as those transitionally funding innovation across Distribution sector electrification again providing a potential model for doing this. To provide scale and add expertise; core academic centres for delivery of innovation and supporting the growth of relevant industry capability and expertise should also be established to support the scale of delivery.

**There are a number of areas, which require priority actions to ensure that they do not become a blocker which prevents achieving the 2050 targets.** The following list of priority innovation areas is a subset of the longer list of innovation areas; highlighting the most immediate, most beneficial and largest transitions needing urgent attention.

	Required Innovation	Action Required
1.1	<b>Demonstrate HVDC Circuit Breakers in Europe</b> Identification of practical cases for DCCB implementation to start within the next 2 years.	<b>Implementation Support</b> Support Developers/OFTOs/TOs in a targeted support funded project to specify and install an HVDC circuit breaker on the GB Network targeting a delivery date of 2027 or earlier to provide in service experience ahead of being required in a given holistic design.
1.2	<b>Develop capability for high-power plastic-insulated HVDC cables.</b> Development of an improved 3.6GW Bipole capacity plastic cable capacity by early 2030s to support delivery of 3.6GW Bipole solutions.	<b>Supplier Engagement &amp; Incentivisation</b> Broaden current supply base and encourage new entrants; and provide clarity on routes to market for new solutions, potentially including trial installation.
1.4	<b>Develop battery storage integrated with HVDC, including hybrid asset solutions.</b> Trial demonstration of HVDC controls augmenting the grid forming capability of a battery device, comparing and contrasting with use of grid forming wind with HVDC connections, in the next 2 years. Follow with a real project demonstration of this approach in the next 5 years.	<b>Trial/Demonstration</b> Support targeted funding trial and demonstration of battery integrated with HVDC asset (by 2027 at the latest) to provide options for augmenting the solutions delivered by Pathways in retrofit and enduring solutions; supporting onshore network stability.
2.1	<b>Design and test new control functions for grid integration of complex HVDC</b> Within the next 2 years establish new sandbox environments to support new control design, multi-vendor design & delivery further inform the allocation of technical roles and responsibilities.	<b>Sponsor project to deliver a Test environment for coordinated controls</b> Sponsor a project to assess functional designs of supervisory wind and dynamic performance of integrated offshore networks across illustrative GB case studies (scope as proposed by the HVDC Centre).

	Required Innovation	Action Required
<b>2.2</b>	<p><b>Develop reconfigurable HVDC replica controls</b> Within the next 2 years, establish a project to develop reconfigurable replicas (with vendors) to support the testing of multi-terminal and multi-vendor interoperability (to be delivered by 2026).</p>	<p><b>Identify preferred funding path &amp; GB partners.</b> Facilitate the development of reconfigurable replicas (with vendors).</p>
<b>2.4</b>	<p><b>Enable delivery of dispersed Bipole HVDC offshore addressing other sea user interactions</b> Within 2 years establish clear requirements supporting faster and more efficient design of co-ordinated offshore solutions within the marine environment.</p>	<p><b>Development of specifications/ standards</b> BEIS and Crown Estate to work together to develop industry guidance.</p>
<b>3.1</b>	<p><b>Develop control and protection approaches for lower fault level networks</b> Within 5 years trial and standardise new AC protection approaches to accommodate the dominance of HVDC solutions on the onshore system, and protections deployed offshore.</p>	<p><b>Progress research project</b> Green deal proposals on progressing open models should be followed up in a research project to allow flexible management of the challenges of multi-vendor and multi-terminal management at the scale, complexity and pace inferred by the offshore coordination work.</p>
<b>3.2</b>	<p><b>Expand GB strengths in wide area control and manufacturing of complex HVDC applications</b> Within the next 2 years, leverage action 2.1 above to grow and inform GB-Wide Area Control expertise, supporting onshore and offshore control needs of new HVDC solutions.</p>	<p><b>Develop Industry Solution</b> Support the development of an industry ready solution for wide area and supervisory controls (for coordinated offshore solutions).</p>
<b>4.2</b>	<p><b>Improve HVDC R&amp;D capability in UK Universities &amp; focused doctoral centres</b> Within 2 years identify a framework for clusters of academic learning, potentially via Centres of Doctoral Training or equivalent to support industrial requirements across system planning, design and operation, technology development and wide area and supervisory control. Within 5 years accompany the preferred model with associated funding and direction, allocating responsibility to clearly defined core research programme activities delivering elements of the R&amp;D strategy above.</p>	<p><b>Develop HVDC-focused R&amp;D Capabilities</b> IET, UKRI, BEIS, EPSRC, ENA, Catapults and Ofgem to review integrated offshore skills gaps, opportunities and funding arrangements.</p>
<b>5.1-5.4</b>	<p><b>Grow domestic capability via knowledge transfer from Oil and Gas industry</b> Engage with Oil and Gas sector to develop a plan in the next 2 years, to focus and accelerate knowledge and skills transfers to offshore HVDC system installation, asset management, environmental assessment, and resourcing its operation.</p>	<p><b>Facilitate industry capabilities transfer.</b> We would suggest that relevant organisations are convened to identify opportunities (including Scottish Enterprise, OGA, OWIC, OGUK, BEIS, Ofgem, Crown Estate and the ESO).</p>

The HVDC Centre has expertise in many of these areas and is ready to support taking forward these actions as required.

We believe that all of these Innovations need to be addressed as a matter of priority to protect the feasibility of GB' 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<sup>4</sup>. 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<sup>5</sup>, and summarised in Figure 2.2.

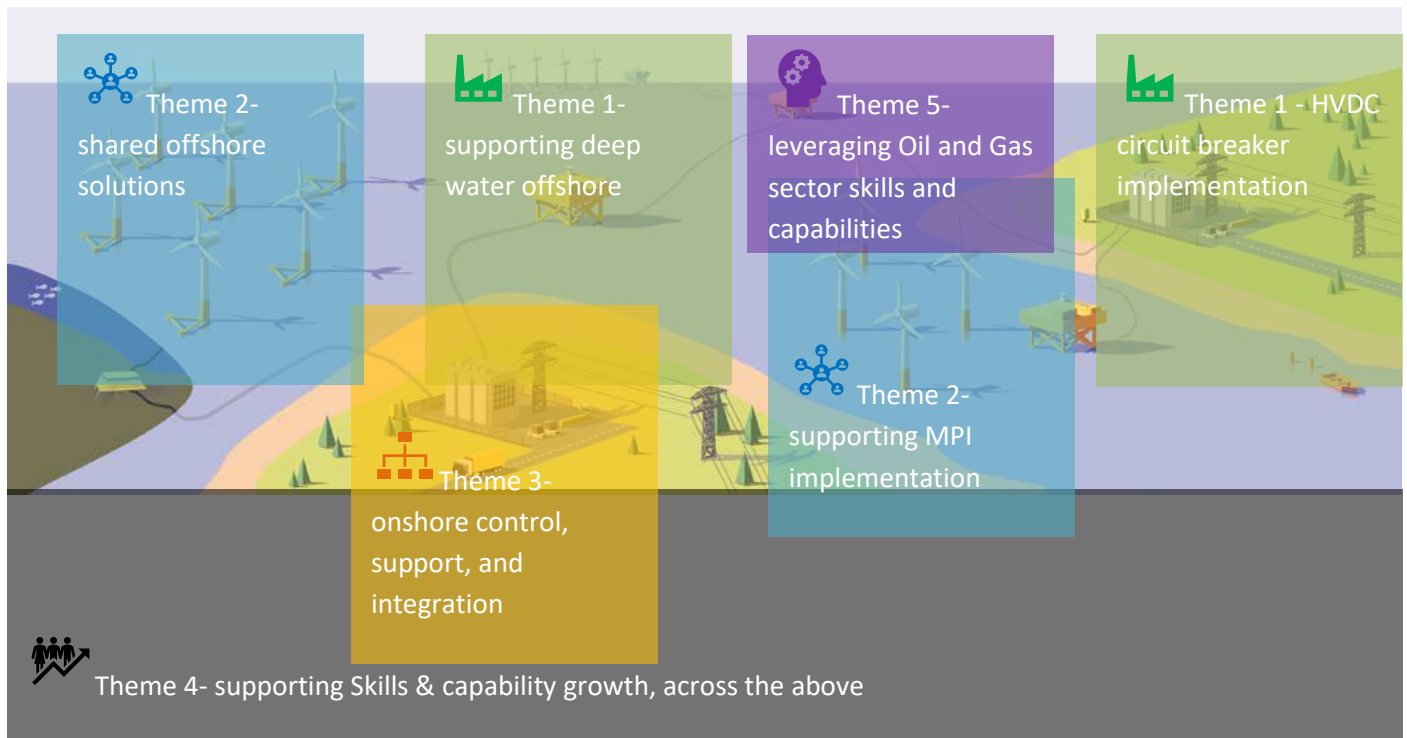


Figure 2.1 illustration of R&D themes and application {raw graphic courtesy of SINTEF; WinDCollect Green Deal proposal}

The innovation associated with the adoption to date of offshore wind has focussed on:

- One particular form of technology: High voltage AC technology, for the submarine cables, platforms and supporting technologies (e.g. reactive compensation) to deliver the performance needed for GB onshore transmission system connection and reliable offshore operation;
- Point-to-Point connection between a single offshore area and project to a single point of onshore connection; and
- Concentration on particular coastal locations limiting overall offshore transmission distances to limit the challenges with and maintain the feasibility of the High Voltage AC transmission offshore.

<sup>4</sup> HM Government. Ten-point plan for a Green Industrial Revolution. Nov. 2020.

<sup>5</sup> ESO (2020). Offshore Coordination Project – Phase 1 Final report. <https://www.nationalgrideso.com/future-energy/projects/offshore-coordination-project>

This past adoption of offshore wind has been highly successful in driving organic project innovation in refining the implementation approaches and technology solutions of the above which has driven both cost and delivery efficiency over the last 20 years, and supported the scale and success of Offshore wind operation within GB.

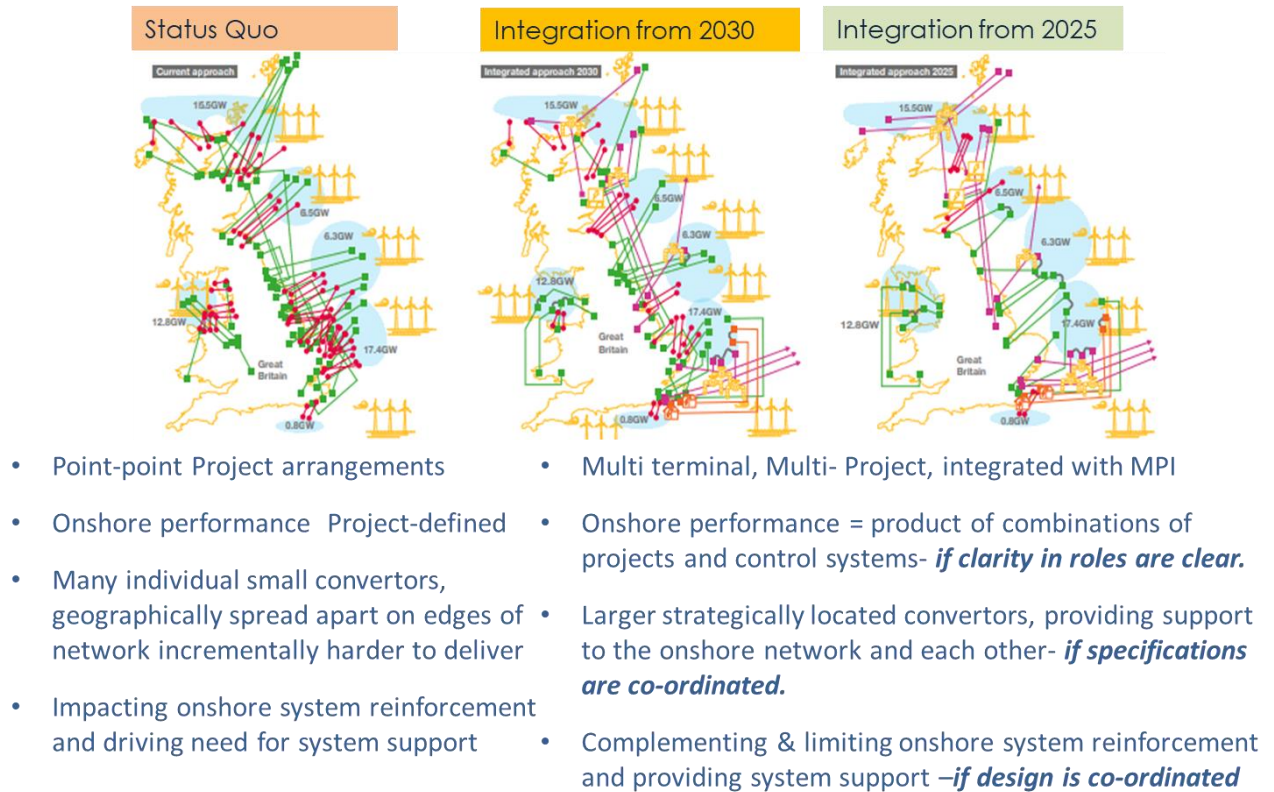


Figure 2.2: Illustration of changes of approach emerging from the GB offshore coordination transition

Unlike our last 20 years of experience, individual developer, OFTO and manufacturer innovation in isolation cannot be relied upon to produce increased efficiency in delivering at pace the scale offshore coordination above, requiring multiple actors to implement staged delivery of solutions which ultimately will be multi-project, multi-HVDC circuit / multi-terminal, multi-HVDC vendor and multi-wind vendor related solutions, with multiple purposes (included but not limited to supporting hybrid wind and Hydrogen production needs, supporting onshore transmission power boundary flow, supporting onshore and offshore network stability and support, supporting cross national border interconnection).

All the available technologies exist today, but have yet to be implemented at the pace and scale now required or under the new environment of coordination discussed above. The benefits achieved by doing so are estimated at ranging from £3bn-£6bn over the period up to 2050, together with environmental benefits to coastal communities from reduced construction, readily visualised in Figure 2.2 above.

The last 20 years has been accompanied by a parallel adoption of increasingly capable forms of technology over that same period which Figure 2.3 below illustrates.

Combined with the displacement of conventional technologies which have been used both to provide power supply but also support a range of areas of support to the transmission system, the transition to date has resulted in new trends in declining system strength (system inertia to frequency movement nationally and

locally, provision of short circuit current supporting protection operation and Fault Ride- Through, and fast complementary dynamic voltage support to the network being some of the key changes<sup>6</sup>).

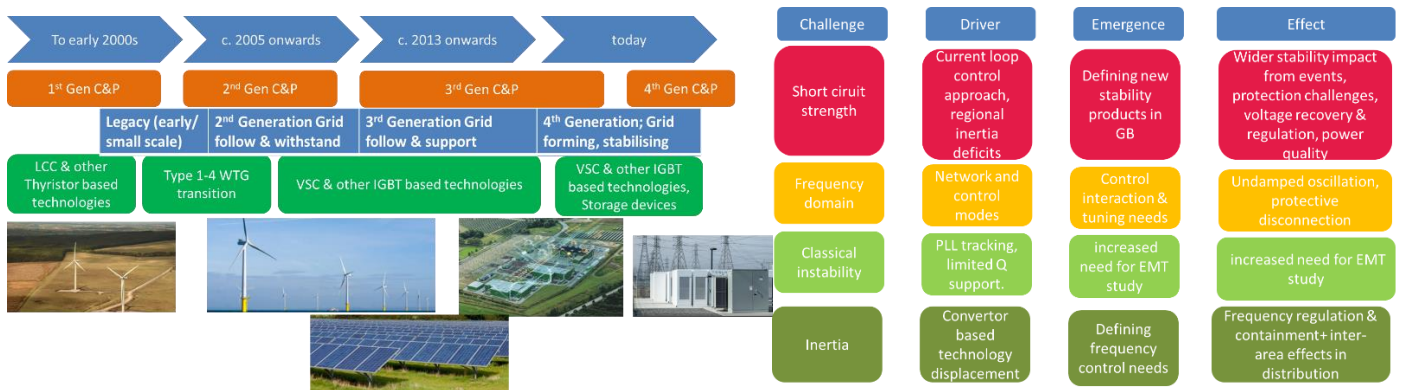


Figure 2.3 Evolution of capability and types of Net Zero technologies (left) and emergent onshore integration challenges (right).

To ensure continued reliable and flexible operation of the transmission system these trends need to be addressed or adapted to as the energy transition to Net Zero technologies is achieved. The new control technologies now available to HVDC and other converter based technologies present a huge opportunity to not only deliver the energy transition needed in MW, but also in these other areas of support to the onshore power system, and given the expected scale of the converters both HVDC and other needed to support the transition could represent the dominant forms of onshore network support from 2030 onwards.

As noted in our HVDC supply chain report<sup>7</sup> whilst GB has relevant skills across the areas of transition, the existing scale of that skill base and the locations of it, do not necessarily complement the “step change” required. Nor does the current niched nature of HVDC project development which itself has been oriented toward project by project “one-offs” in design, delivery and associated testing and operation necessarily complement future co-ordinated modular “at scale” delivery of integrated solutions required.



Reflecting on the above holistically the “size of the prize” of a successfully enabled transition is significant, of the order of £billions over the period. Being a medium scale Electricity network in international definition, highly integrated onshore with a faster implementation of renewables technologies over the period, presents the opportunity for GB oriented academic institutions and industries to become world leaders in the integration of offshore wind and large proportionate volumes of HVDC technologies into GB. Not only does this give GB the potential domestically to benefit from development of these capabilities in the short to medium term via an R&D strategy but to look to generate additional benefit in exporting these capabilities across the medium - longer term to nations on a longer transition path to ourselves who will be encountering the same challenges but at a later juncture.

<sup>6</sup> ESO (2021). Operability Strategy Report. <https://www.nationalgrideso.com/document/183556/download>

<sup>7</sup> HVDC Centre (2021). Coordinated Offshore HVDC Supply Chain Overview report

### 3 Required Innovations addressing Gap Analysis

Based on the discussion above on the nature of the Gaps and the insights from the ESO 'Coordinate Offshore Project (Phase 1)' report<sup>8</sup>, PROMOTION project<sup>9</sup> and COMPOSITE project<sup>10</sup>; we have analysed and consolidated the technology gaps, to develop a strategy for the innovation activity required to deliver a coordinated approach to offshore renewables to meet the 2030 and 2050 net zero targets; categorised under the five R&D themes. We adopt the energy sector description of NASA's Technology Readiness level system<sup>11</sup> as refined for relevant HVDC R&D, developed and approved by ENTSO-e under the PROMOTION project<sup>12</sup>.

Required Innovations	Current Status	Next Step	Action Required
 <b>Theme 1: Upscaling HVDC manufacturing innovation</b>			
1.1 Demonstrate HVDC Circuit Breakers in Europe	<b>TRL: 8</b> Manufactures have demonstrated at MVDC scale, and currently offer HVDC for sale.	<b>Network Installation</b> There is no technical barrier for Developers/TOs specifying and purchasing HVDC circuit breakers.	<b>Installation Support</b> Support Developers/ TOs to specify and install an HVDC circuit breaker on the GB Network.
1.2 Develop capability for high-power plastic-insulated HVDC cables	<b>TRL: 8</b> Current cable installation in GB are up to 1.2GW, and manufactures offer 2GW capacity.	<b>Manufacturer Led Innovation</b> Cable manufacturers are understood to be innovating in this area.	<b>Supplier Engagement</b> Broaden current supply base and encourage new entrants to the market and provide clarity on routes to market for new solutions.
1.3 Improve high voltage subsea connections and dynamic cables for deep-water systems	<b>TRL: 3</b> This was part of WinDCollect project scope that was not funded by EU.	<b>Industry Led Innovation</b> Required to raise TRL of >66kV subsea connection systems.	<b>Trial/Demonstration</b> Incentivise demonstration of high voltage subsea grid infrastructure.
1.4 Develop battery storage integrated with HVDC, including hybrid asset solutions	<b>TRL: 3</b> This was part of WinDCollect project scope that was not funded by EU.	<b>Supplier Led Innovation</b> Assess benefits of HVDC-OWF with integrated battery.	<b>Trial/Demonstration</b> Support trial/ demonstration of battery with HVDC asset.
 <b>Theme 2: Advancing Coordinated and Efficient HVDC schemes</b>			
2.1 Design and test new control functions for grid integration of complex HVDC	<b>TRL: 3</b> COMPOSITE testing project illustrated compliant OWF models can perform differently when connected via HVDC.	<b>Co-create HVDC functional design project scope</b> Test coordinated HVDC controls using generic models of integrated offshore network components.	<b>Test coordinated controls</b> Assess functional designs and dynamic performance of integrated offshore HVDC networks across illustrative GB case studies.
2.2 Develop reconfigurable HVDC replica controls and demonstrate mobile testing options	<b>TRL: 4-5</b> This was part of WinDCollect project scope that was not funded by EU.	<b>Industry led innovation TRL-7-8</b> whilst individual projects may see risk in driving this, a central body such as The National HVDC Centre could equally take this approach forward with one or more manufacture & developer to replicate a project currently in delivery and prove	<b>Identify preferred funding path &amp; GB partners.</b> GB developers and key vendors were involved in preceding Green Deal approach which can be revived and augmented for a GB implementation focus



<sup>8</sup> ESO (2020). Offshore Coordination Project Phase 1 Final Report. Available at: <https://www.nationalgrideso.com/future-energy/projects/offshore-coordination-project>

<sup>9</sup> PROMOTION (2020). EU Horizon 2020 project. Available at: [https://www.promotion-offshore.net/news\\_events/final\\_conference\\_2020/](https://www.promotion-offshore.net/news_events/final_conference_2020/)

<sup>10</sup> HVDC Centre (2021). COMPOSITE project final report. Available at: <https://www.hvdccentre.com/composite/>

<sup>11</sup> [https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology\\_readiness\\_level](https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level)


<sup>12</sup> <https://www.entsoe.eu/Technopedia/trls/>

Required Innovations	Current Status	Next Step	Action Required
		out the approach and provide a resource for multiple future projects within an innovation project similar to the Green Deal.	
<b>2.3 Explore GB use of overhead line circuits for DC transmission and DC substations for MPIs</b>	<b>TRL: 4-5</b> Innovation projects on medium voltage DC demo exist in GB. HVDC OEMs <sup>13</sup> assessed potential benefits for higher power transmission <sup>14</sup> .	<b>Industry-led innovation</b> Identify lessons from recent international experience <sup>15</sup> , across fault ride through for DC overhead lines, full-bridge VSC HVDC performance, retrofit of AC pylons, insulation and EMF aspects.	<b>Collaborative opportunity analysis</b> Perform detailed investigation of network areas where conversion of AC to DC overhead lines could offer significant benefits to consumers.
<b>2.4 Enable delivery of dispersed Bipole HVDC offshore addressing other sea user interactions</b>	<b>TRL: 6</b> A range of options exist, and in part have comparable deployment experience (e.g. the Moyle interconnection)	<b>Clarity to industry</b> TRL7/8 Clear criteria to mitigate compass deviation and other environmental concerns need to inform implementation	<b>Industry optimisation to requirements</b> TRL9 Specification/ standards minimising cost & environmental impacts
 <b>Theme 4: Maximising the Benefits of Integrated Offshore Solutions</b>			
<b>3.1 Develop control and protection approaches for lower fault level networks</b>	<b>TRL: 3</b> To our knowledge limited work has been done in this area outside the existing HVDC projects	<b>TRL 9</b> it will benefit the management of onshore integration of convertors, particularly in areas of potential interaction if the TO and ESO supporting the design of co-ordinated designs have access to the range of approaches and their high level characteristics in order to identify necessary areas of onshore analysis and planning.	Green deal proposals on progressing open models should be followed up in a research project to allow flexible management of the challenges of multi-vendor and multi-terminal management at the scale, complexity and pace inferred by the offshore coordination work.
<b>3.2 Expand GB strengths in wide area control and manufacturing of complex HVDC applications</b>	<b>TRL: 7</b> Concept is achievable but no focussed requirements inform development- as such no standardisation or coordination with HVDC control possible	TRL9 wide area control deployment aligning with HVDC control development, maximising the benefits from each co-ordinated offshore solution	Use “sandbox” models of co-ordinated controls to inform and focus development of wide area control solutions and supervisory control schemes
<b>3.3 Enhance supervisory controls &amp; asset management telemetry on HVDC projects</b>	Same as 3.2 above	TRL 8 specify and standardise and combine with 3.1 above within projects	Deliver complete and standardised project telemetry needs
<b>3.4 Review and inform the application enhanced controls for MPIs and offshore grids</b>	See 3.3 above	See 3.3 above	See 3.3 above
 <b>Theme 4: Leveraging Technical Expertise, Skill Development and Resourcing</b>			
<b>4.1 Nurture and develop early-year teaching of HVDC and</b>	Identify opportunities for industry to support early	Co develop industrial sponsorship, placements etc.	Review and develop proposals for nurturing a pipeline of GB resource

<sup>13</sup> <https://www.siemens-energy.com/global/en/offerings/power-transmission/portfolio/high-voltage-direct-current-transmission-solutions.html>

<sup>14</sup> ABB(2018). Convert AC to HVDC for higher power transmission. <https://new.abb.com/news/detail/11828/convert-from-ac-to-hvdc-for-higher-power-transmission>

<sup>15</sup> Ampirion. Ultranet project. <https://www.amprion.net/Grid-expansion/Our-Projects/Ultranet/>

Required Innovations	Current Status	Next Step	Action Required
STEM-based subjects with industry	exposure to HVDC technology and delivery		
<b>4.2 Improve HVDC R&amp;D capability in UK Universities &amp; focussed doctoral centres across industry need</b>	Identify core academic centres delivering areas of expertise specifically relevant to offshore HVDC delivery	Identify frameworks for a CDT or equivalent for HVDC R&D priorities above	IET, UKRI, BEIS, Catapults and Ofgem to review integrated offshore skills gaps, opportunities and funding arrangements.
<b>4.3 Increase efficiency of hardware-in-the loop testing capability for complex HVDC schemes</b>	<b>TRL: 6-7</b> Use of a combination of approaches (as identified within a recent Green Deal proposal) to streamline delivery	TRL: 9 Demonstrate within real project delivery	Current approaches whilst effective, would limit pace of delivery and significantly affect costs without this work
<b>4.4 Enhance HVDC operator training using simulators and export of technical expertise</b>	Custom operator training offered as part of Factory Testing / commissioning by equipment supplier.	Develop operator training for day-in-the-life scenarios based on composite performance of multi-device systems.	Have the ability to train future operators of co-ordinated offshore systems to ensure familiarity and competence is developed ahead of commissioning and maintained thereafter
 <b>Theme 5: Grow domestic capability via knowledge transfer from Oil and Gas industry</b>			
<b>5.1 Optimise offshore converter platform design, operation, maintenance and floating structures</b>	These are considered key enablers for developing coordinated offshore infrastructure, however these are not areas of expertise for the HVDC Centre.	Stakeholder Consultation To quantify GB relevant O&G supply chain capabilities that can support integrated offshore HVDC solutions.	We would suggest that relevant organisations are convened to identify opportunities (including Scottish Enterprise, OGA, OWIC, OGUK, BEIS, Ofgem, Crown Estate and the ESO).
<b>5.2 Repurpose existing O&amp;G manufacturing hubs &amp; offshore assets for HVDC-OWF &amp; H2 applications</b>	We understand this may take two forms- Deployed platforms Having a dual purpose of supporting floating turbine deployment as electrification under the sector deal progresses, and repurposing of O&G platform construction expertise towards offshore platform delivery- however these are not areas of expertise for the HVDC Centre.	Same as 5.1.	Same as 5.1.
<b>5.3 Exchange skills and innovation in offshore operation &amp; re-training personnel</b>	We note that existing programmes in this area exist and may need to be accelerated to support meeting the resource pipeline as discussed in Theme 4- however these are not areas of expertise for the HVDC Centre.	Same as 5.1	Same as 5.1
<b>5.4 Optimise seabed and environmental surveys</b>	Recommended as part of offshore coordination project Phase 1.	Holistic planning of spatial and electricity network asset for offshore lease areas.	<b>Strategic Collaboration</b> needed across BEIS, Crown Estate, ESO, TOs, developers etc.

## 4 Priority Focus Areas and Next Steps

As highlighted in the section above, there are a number of areas, which we believe require priority actions to ensure that they do not become a blocker which prevents achieving the 2050 targets.

These areas are summarised in the table below where action is in some cases required in the next 2 years.

We have identified topics' criticality by reference to our earlier Gap analysis and evaluated the current level of innovation, size of opportunity and action required across stakeholders to define a plan of delivered innovation outputs across the period up to 2030 which we would expect to support informing and sustaining the activity thereafter.

### Priority Actions

<b>Action 1.1</b> HVDC Circuit Breaker first European implementation	<p>We would expect the identification of practical cases of DCCB implementation to Start across the next 2 years, to then inform the construction of necessary arrangements to demonstrate practically connecting solutions by 2030.</p> <p>The timeline in delivery is intentionally ambitious noting; that the key area of gap is in-service confidence against a European specification; the delivery timeline results in allowing at least a 3 year period of confidence for a DCCB to be operated in a less critical capacity within an early project where its presence is not essential for the success of the solution (i.e. could easily bypass that breaker without issue) to build up practical experience of operation before being used "in anger".</p>
<b>Action 1.2</b> High-power plastic-insulated HVDC cable availability	<p>We identified an opportunity in phase 1 coordinated offshore design work for an improved 3.6GW capacity plastic cable availability in the early 2030s to support delivery of 3.6GW bipole solutions. At present this capability is limited to one supplier and no in service experience. We would expect manufacture innovation over an intervening 5 year period should organically deliver a broader range of products supporting this; or alternatively may require direction.</p> <p>This would in turn support project use in the early 2030s against a background of developing in service experience internationally by that time. SQSS review on the offshore normal infeed loss could result in an increase to 1800MW, aligning to the onshore loss standard. Were that to be delivered to the market it would strongly signal intent. In turn delivery of 3.6GW solutions would serve to reduce further the asset requirements of co-ordinated solutions, their cost and the scale of impact to coastal communities arising from the larger capacity solutions then available.</p>
<b>Action 1.4</b> Energy storage and hybrid solutions	<p>This activity is critical to supporting onshore grid forming support from the array of HVDC solutions connecting onshore. Such an approach allows these large HVDC developments to become "lodestones" of stability support to the onshore system, with greater flexibility and without the risk of introducing instability to the offshore generation whilst providing this support. Whilst both technologies are mature, the stability supporting control is emergent, and the optimal combination of HVDC and storage has yet to be demonstrated. Such demonstration in simulation complimented with real control hardware should be taken forward in the next 2 years, enabling solutions to be taken forward in the next 5 years, supporting early HVDC project adoption. This demonstration is a planned topic area for research under the 2022 round of the Horizon 2020 research programme; however as yet, no relevant work in this area has been taken forward.</p>
<b>Actions 2.1 and 2.2</b> Grid integration design, testing and	<p>It is critical within the next 2 years that new approaches supporting and focussing multi-terminal and multi-vendor interoperability are taken forward. Recently (January '21) a Green Deal program from the European Commission requested proposals in this area which were ultimately not taken forward with any party. This has led to a gap that will need to be domestically plugged; otherwise the continued used of process designed for a limited volume of detailed testing will become quickly overwhelmed by the scale and complexity of solutions, leading to the testing and de-risking of converter integration to become a bottleneck in terms of resource. Actions across use of reconfigurable replica controls (to limit testing facility space</p>

reconfigurable replicas	needs and the overall costs involved), delivery of a “sandbox” environment to combine the intended elements of holistic design solutions, demonstrate their capabilities and define vendor requirements, activity outlining key tests experimenting with more open key controls or their settings within available models, development of mobile test capabilities following project installation and streamlined testing capabilities, in our view need to be initiated in the next 2 years to deliver solutions within the next 5 years to support delivery of co-ordinated solutions across the next 5-10 years; with certain stages such as “sandbox” models required within the next 18 months to support early Vendor delivery, if the upscaling is to be sustained.
<b>Action 2.4</b> Dispersed Bipole HVDC offshore	Currently “case by case” discussions of seabed use common environmental regarding magnetic compass deviation, impact across marine populations and military considerations have in a similar manner to early turbine impact discussions lead to considerable resource and time being invested into both understanding the concerns present and iterative development of acceptable solutions. These challenges are present both for AC and DC solutions offshore, although the specific design considerations are different in nature. Against the scale and Confidentiality aspects, collaborative approaches are being taken forward by industry and key stakeholders to test the performance of mitigation options.
<b>Action 3.1</b> New control and protection approaches	As the onshore and offshore systems develop in complexity and scale of connected converters, both the AC and DC protection solutions deployed will increase in scale and complexity. As DC protection solutions evolve, their testing and definition within the detailed sandbox environments becomes ever more important and the innovation in defining need and specification complements that earlier described innovation task. The Centre is actively supporting a multi-year innovation project following from its earlier work which is led by SHE Transmission supported by other Transmission Operators, which seeks to define new approaches allowing new solutions in AC protection to be assessed, tested and receive real network implementation experience (in open loop- as such not operating on the system) that will support onshore AC solutions over the next 3.5 years, and these insights are assumed to support further innovation and deployment experience thereafter
<b>Actions 3.2</b> Wide area control & Supervisory controls	Actions 3.2 (and 3.3) we have identified wide area control as a key growth area. At the Centre we are currently investigating a range of Wide area control applications for HVDC and would expect in the medium term for this to be complemented on both onshore and offshore wide area approaches to be defined and tested within a combination of the above “sandbox” models of the holistic designs as combined with suitable models of the onshore GB system. In the same way as vendor HVDC solutions can be demonstrated and tested in these environments, so also may the wide area and supervisory controls associated with a given solution going forward. Simpler modelling focussed on developing the system monitoring needs for these solutions, and supporting their asset management would follow to the same complementary timeline.
<b>Actions 4.2</b> University R&D <b>Actions 5.1-5.4</b> Oil & Gas linkages	These actions logically follow the timelines and priority that the above gap discussion would infer, but given we are not experts in these areas, we would suggest would benefit from further stakeholder engagement and review before being taken forward.

As discussed above, the timing of this R&D is opportune, as many areas of priority innovation work is needed imminently to enable removal of potential blockers across delivery or to realise opportunities to that delivery. We believe that our summary of the steps, and their rationale allows targeted initial actions to take place and the HVDC R&D strategy is delivered.

# Appendix I – Gap Analysis

Figure I.1 below developed as part of the ESO co-ordinated offshore project identifies key expectations of innovation and development strategy which were consulted upon with industry and academia across the period of the project. Specific technical challenges of network operability, ancillary services provision and compliance testing of integrated solutions were also identified within the Holistic planning report.



Figure I.1 . High level expectations of enabling activities to support offshore coordination

The high-level objectives of these innovation and Development strategy are also, we believe, valid objectives for an overall R&D strategy to seek to achieve up to 2030.

In the figure below we categorise these in respect of the key areas of industrial and academic R&D capability before then reviewing the scale of the transition necessary.

Topic	Area	Owner	Transition	Benefit	Related R&D theme(s)
<b>New conceptual design efficiencies</b>	Innovation strategy	Academia-technology options Industry- new applications	Academia- focus towards application rather than concept. Industry; existing and planned framework transitions	Identification of new asset approaches aligned to industry need as technology evolves	Theme 4
<b>Focus Research effort</b>	Innovation strategy	Academia	From all potential areas of R&D to themes of R&D being prioritised	Improved support of the Net Zero transition	Theme 4
<b>Identify new opportunity areas</b>	Innovation strategy	Academia	Identify new themes over time which further deliver beyond 2030.	Avoids short horizon thinking	Theme 4
<b>Develop designs towards GB application</b>	Development strategy	Industry	Develop vendor specific standardised and more modular solutions and more efficient solutions to deliver at pace	Lower cost, domestic solutions that can be exported.	Themes 1&2&3
<b>Identify "quick wins"</b>	Development strategy	Industry	Many pre-existing solutions exist today which can be focused towards GB application and with innovation meet early deployment, within existing frameworks and codes.	Early deployment	Theme 1

Topic	Area	Owner	Transition	Benefit	Related R&D theme(s)
<b>Progress interoperability</b>	Development strategy	Industry	Interoperability is not a barrier today but requires significant common analysis within hosted simulation environments which take time and would require significant scaling without the development of new innovations	Faster more flexible approaches to demonstrate interoperability which rationalise hardware needs	Themes 2& 3
<b>New testing of modular technologies</b>	Development strategy	Industry	Above interoperability innovations, combined with modular solutions enables initial commissioning to better facilitate future stages of offshore network growth now required	Opportunity for Streamlined compliance and commissioning approaches supporting pace and scale	Theme1
<b>Build Supply capabilities</b>	Development strategy	Industry – assets, resource, and process academia- resource pipeline	Pipelines of domestic capacity, transitions of existing skills base towards HVDC project delivery	Avoidance of supply limitations, expertise in GB applications and ability to export these capabilities	Themes 4&5
<b>Update codes and standards</b>	Derisking	Industry	Existing industry frameworks review	Increased clarity for manufacturers and developers stimulating pace and implementation efficiencies	Non R&D strategy
<b>Enable composite testing and design</b>	De-risking	Industry	Today- individual project design and commissioning, tomorrow collaborative design and testing via hosted environments.	Avoiding incomplete design/testing or barriers to delivery	Themes 2&4
<b>In service verification</b>	De-risking	Industry	Enhanced monitoring and comparison to simulation models and replica control and protection performance	Ensure reliability and resilience of power system is maintained	Themes 2&3
<b>Integrated GB operation</b>	De-risking	Industry	Review and refine control strategies maximising benefit from solutions across deployment	Harness opportunities of technology to present more operator options for supporting power system	Themes 3&4

Figure 1.2 . Analysis of Innovations

The nature of the R&D gap may be considered from both a resource and activity perspective. Current resource in HVDC R&D are summarised in figure 1.3 below. Currently within Academia no key focus for HVDC research priorities exist, and there are no existing centres of Doctoral expertise or equivalent that are recognised in funding or strategic focus. Nevertheless, there are recognised areas of expertise within GB which will benefit from specific ESPRC grants, and industry funded activity, who in turn support relevant doctorate research and undergraduate study. Beyond that there are broader sources of engineering and other capability in related training that will support industry and form part of its resource pipeline. As the energy transition increases the volumes and complexity of deployed HVDC solutions, we would expect to see a proportionate increase in specialist and associated resource, both addressing research priorities and supporting the pipeline of expertise within the industry that will need to be recruited and sustained. Industry R&D will similarly be expected to proportionately grow to reflect the increased activity required.

In relation to the activity and with respect of our analysis of the required innovation outlined above, we have identified below how a number of key ‘gaps’ where the current activity/funding is not sufficient to enable the development of the technology required, which are motivators to the 5 Research themes being identified. By presenting these we also note where activity is underway today, and we also recognise that other R&D work also exists in relation to these themes but is less critical or of lesser value to those highlighted.

We summarise in Figure I.3 below the outcomes of this gap analysis followed by a non-exhaustive discussion of the underpinning analysis.







R&D Themes	Gap Analysis Summary
 <b>Theme 1: Upscaling HVDC manufacturing innovation</b>	<p><b>This theme identifies the HVDC components which require development activity, specifically:</b></p> <ul style="list-style-type: none"> <li>● HVDC Circuit Breaker first European implementation</li> <li>● High-power plastic-insulated HVDC cable availability to support scale of implementation and limit scale of assets required.</li> <li>● Subsea connections and dynamic cables (for deep-water systems)</li> <li>● Energy storage (e.g. battery &amp; hydrogen systems) integrated with HVDC</li> </ul>
 <b>Theme 2: Advancing Coordinated and Efficient HVDC schemes</b>	<p><b>This theme identifies the developments required to ensure the stability and integrity of the GB network during the transition to a net-zero network, specifically:</b></p> <ul style="list-style-type: none"> <li>● Grid integration design and testing</li> <li>● Reconfigurable replicas</li> <li>● DC overhead lines and MPIs</li> <li>● Dispersed Bipole HVDC offshore</li> </ul>
 <b>Theme 3: Maximising the Benefits of Integrated Offshore Solutions</b>	<p><b>This theme identifies the enabling developments for offshore grids, specifically:</b></p> <ul style="list-style-type: none"> <li>● New control and protection approaches</li> <li>● Wide area control &amp; Supervisory controls</li> <li>● Asset management telemetry</li> <li>● Enhanced controls for MPIs and offshore grids</li> </ul>
 <b>Theme 4: Leveraging Technical Expertise, Skill Development and Resourcing</b>	<p><b>This theme identifies the skills gaps and developments required to address, specifically:</b></p> <ul style="list-style-type: none"> <li>● Early-year teaching</li> <li>● HVDC R&amp;D in UK Universities</li> <li>● Hardware-in-the loop testing capability</li> <li>● Operator training using simulators</li> </ul>
 <b>Theme 5: Grow domestic capability via knowledge transfer from Oil and Gas industry</b>	<p><b>This theme identifies specific synergies between Oil and Gas innovations the requirements of a coordinate offshore approach, including:</b></p> <ul style="list-style-type: none"> <li>● Offshore converter platform design &amp; operation</li> <li>● Repurpose O&amp;G assets</li> <li>● Skills exchange &amp; re-training</li> <li>● Optimise surveys</li> </ul>

Figure I.3. R&D Gap analysis summary

## Theme 1: Upscaling HVDC manufacturing innovation

This section describes the points underpinning the aforementioned offshore coordination messages in gap identification, that were considered for establishing the **Theme 1 on Upscaling HVDC manufacturing innovation**.

 <b>Theme 1: Upscaling HVDC manufacturing innovation</b>	<p><b>This theme identifies the HVDC components which require development activity, specifically:</b></p> <ul style="list-style-type: none"> <li>● HVDC Circuit Breaker first European implementation</li> <li>● High-power plastic-insulated HVDC cable availability to support scale of implementation and limit scale of assets required.</li> <li>● Subsea connections and dynamic cables (for deep-water systems)</li> <li>● Energy storage (e.g. battery &amp; hydrogen systems) integrated with HVDC</li> </ul>
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### ***HVDC breaker first European installation.***

Currently, no active project in GB or Europe has specifically committed to HVDC breaker installation. The challenges of HVDC breaker installation within GB were reviewed in the ESO-led Holistic planning report for the Co-ordinated Offshore Project- and the conclusion which continues to apply is that HVDC circuit breaker technology is mature in concept- and is a product offered by a number of European vendors today with standards for its testing, specification and implementation developed under the PROMOTioN project which included also the practical testing of an ABB DC circuit breaker product. The challenge is how to incentivise the “jump” to deployment within a practical project either in GB or Europe more generally that would inspire confidence via in service experience. This could be achieved either via new or existing HVDC installations including such equipment in a non-essential role, and the learning from its implementation and operation disseminated, potentially via a pathfinder project, ahead of needing to be used to support solutions from 2030 onwards.

The benefit of having HVDC circuit breaker technology available to co-ordinated offshore designs is that onshore convertor substation and onshore AC transmission infrastructure are limited (the alternative would be several point to point HVDC circuits connecting onto the onshore system with attendant onshore reinforcements to support power flow, where offshore areas are highly separated geographically (greater than 30-60km) but still would benefit from coordination within a larger HVDC solution). HVDC circuit breakers would significantly save on capital cost and amenity associated with the deployment of offshore targets or risk a less co-ordinated approach with greater deployment challenge where not taken forward.

### ***High-power plastic-insulated HVDC cable availability***

To support scale of implementation and limit scale of assets required, currently a single vendor exists for solutions above 525kV DC which limits either the scale of offshore solution selected or the resource available to support the pace of installation. As discussed within the Supply Chain report, new supply capacity is required and within that growth is the opportunity to ensure new options are available or that the scale of resource towards existing but limited options is increased. As illustrated within the Holistic planning report the availability of higher rated cables in earlier timeframes than considered (supported by other relevant industry code review) has the potential to further reduce the cost and scale of co-ordinated offshore deployment. Not taking forward vendor sourced innovation to achieve this as GB supply capability increases would represent a lost opportunity against this objective.

### ***Subsea connections and dynamic cables (for deep-water systems)***

Delivery across the period 2030-2050 will increasingly drive deep water installations of offshore wind and associate HVDC platform technologies. In order to not limit the potential to exploit these deep-water areas, either a complement of HVDC platform, and flexible AC and DC cable installations will be required or solutions enabling higher voltage wind farm AC network arrays to connect over longer distances to HVDC hubs situated within shallower waters. In principle the solutions for floating installations should not be challenged in medium term delivery<sup>16</sup> given we understand both that analogous technologies have emerged to support Oil and Gas industries and existing discussions in transitioning such activities have in some cases translated to early project activity in this direction<sup>17</sup>. Some further benefit may result from the consolidation and prioritisation of these activities to meet the now accelerated deployment timeframe and scale of Offshore wind.

We note that within existing ScotWind tender areas, there already exists potential for floating wind deployment before 2030 and that as subsequent rounds emerge, the proportions of floating wind connection requirement are expected to increase. Current floating wind deployment is small in scale and often of a demonstration nature. Within 5 years an optimised approach for implementation, should be delivered.

Note: Demonstration of floating wind and other technology at scale is defined within the innovation strategy associated with the Horizon 2020 research programme; however as yet no relevant work in this area has been taken forward.

### ***Energy storage (e.g. battery & hydrogen systems) integrated with HVDC***

As discussed within the holistic planning report, by 2030 the scale of new convertor installations supporting GB will be approaching half of peak GB transmission demand, and exceeding the minimum system demands as presented within the ESO future electricity scenarios (FES). This means that the role of these convertors will be ever more important in the operation of the GB system, and could with effective design, support a range of system stabilisation functions. To achieve this range of solutions, energy storage would need to be used to support the arrangements and for increasingly complex solutions storage devices operating as part of a co-ordinated solution with the HVDC convertor or within the convertor itself would become advisable over arrangements supporting these capabilities offshore. GB has within recent Grid code modifications and the ESO stability pathfinder pioneered new definitions and specifications of its requirements internationally, together with pioneering solutions against these requirements and has the potential to pioneer HVDC solutions. Should this opportunity not be realised, the costs of alternative solutions together with independent arrangements for each HVDC convertor would be expected to exceed that of a combined solution with less efficient design and operation resulting from this.


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<sup>16</sup> ORE Catapult (2021). Floating Offshore Wind Cost Reduction Pathways. <https://ore.catapult.org.uk/wp-content/uploads/2021/01/FOW-Cost-Reduction-Pathways-to-Subsidy-Free-report-.pdf>

<sup>17</sup> ORE Catapult (2020). Benefits of floating offshore wind to Wales and the South West: Supply Chain Report. <https://ore.catapult.org.uk/wp-content/uploads/2020/01/8996-OREC-Wales-Report-WEB.pdf>

## Theme 2: Advancing Coordinated and Efficient HVDC schemes

This section describes the points underpinning the aforementioned offshore coordination messages in gap identification, that were considered for establishing the **Theme 2 on Advancing Co-ordinated and Efficient HVDC schemes**.

 <b>Theme 2: Advancing Coordinated and Efficient HVDC schemes</b>	<p>This theme identifies the developments required to ensure the stability and integrity of the GB network during the transition to a net-zero network, specifically:</p> <ul style="list-style-type: none"> <li>• Grid integration design and testing</li> <li>• Reconfigurable replicas</li> <li>• DC overhead lines and MPIs</li> <li>• Dispersed Bipole HVDC offshore</li> </ul>
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### **Grid integration design and testing**

Where large converters, be they Flexible AC Transmission System (FACTS) devices supporting voltage and other areas of support, or HVDC converters, interoperability is a key area of Gap analysis.

Interoperability is not a new area of risk and has been managed across HVDC projects in GB effectively since in 1986 the GB- France interconnectors were installed with two different vendors at that time supplying French and GB convertor stations. The risk is managed by the combination of software-based simulation across project and vendor elements, complemented and verified by Real time Hardware in the loop simulation, including replica controls and protection which in the case of IFA are hosted by the French operator RTE.

The most recent examples of interoperability and associated de-risking have been conducted at the National HVDC centre, which hosts project relevant replica control and protection hardware of the Caithness- Moray VSC-HVDC link, which with its Shetland extension will represent the first multi-terminal VSC- HVDC project in Europe- with the control replica for this extension being available at the Centre to support many of the activities of design test and commissioning of the solution. The Centre is able to act as a hosted environment within which detailed models of onshore and offshore systems may be combined with detailed and highly sensitive vendor specific control & protection models of HVDC and convertor-based generation to support a range of de-risking analysis.

The Gap going forward relates to the scale and complexity of interoperability in the future. In scale currently incremental connections of ~3GW per year of installed offshore wind capacity projects would be required to meet targets of 40GW by 2030 and this would need case by case interoperability considerations and assessment. In order to deliver the vision of net zero transition, between 50% - 65% of installed capacity of projects by year may be inferred to require interoperability assessment<sup>18</sup>. In complexity, multi-vendor, multi- terminal HVDC is also becoming *multi-purpose* in nature and the hierarchy of the various controls fulfilling a range of purposes and the transitions between those control priorities, and interaction with other converters becomes ever more important. By 2030 the scale of converter connections to GB is forecast to

<sup>18</sup> Based on asset savings identified in Offshore Coordination Project - Phase 1.

<https://www.nationalgrideso.com/future-energy/projects/offshore-coordination-project>

exceed the minimum demand times of GB, and by 2050 will exceed the GB demand at all times. This is driving an increasing dependence on the performance of the GB system from such converters as HVDC; their robustness and flexibility.

The current approach to interoperability is no longer sustainable as:-

1. Project-specific replica control and technology at this scale will be limited in the footprint of the simulation centres required and numbers of replicas required to be present at all times.
2. The range of scenarios to be considered will rapidly out-reach the time available to support the delivery of de-risked individual projects, as analysis for each will require a number of years across an ever-increasing need for skilled resources to support the activities involved.
3. Future-proofing of a project at time of design will become increasingly more challenging, with updated controls and functions of HVDC devices becoming more common over the life of installation.
4. The range of functions of HVDC and range of potential interactions across them will increase and risk security of supply if not appropriately addressed via sustained interoperability analysis
5. The need to monitor and refresh de-risking activities during normal operation will increase and need to be flexibly supported.

Activities to close this gap relate to;

- Advancing the use of reconfigurable hardware replicas to rapidly reflect a range of different projects
- Advancing techniques for verification of models against hardware to manage the physical environment
- Streamlining operability analysis processes (identifying new key tests and thinking about how to do these more innovatively e.g. use of open-control models to support directed vendor testing, using mobile testing approaches etc)

The National HVDC centre is funded via its RIIO-T2 allowance within the overall SHE transmission plc price control, this supports the anticipated activities incrementally but does not include innovation allowance to progress such activities without other external funding. This is a consistent challenge across the HVDC industry which may seek to obtain additional research grants in relevant topics, but where topics for research funding are neither specific nor prioritised against particular HVDC development objectives.

### ***DC overhead lines and MPIs.***

Within rural communities the introduction of long cable easement corridors to available or optimal convertor locations can potentially prove problematic. This can relate to a variety of considerations, including potential sterilisation of land associated with these cable routes. Internationally, with many examples in both China and Canada, HVDC transmission has been implemented by repurposing overhead line routes for the running of DC circuits across such corridors- which has other considerations, relating to visual amenity, management of EMF fields and the Earthing shielding of the routes and the adopted tower topologies, but is in principle achievable technically. Within GB Medium Voltage DC viability was tested within the Scottish Power Distribution project “Angle-DC” but the generated learning has yet to be applied to higher voltage applications. MPIs fulfil different technical functions (beyond typical interconnection between countries) which means their operation and performance are defined via standards of more than one TSO;

within more than one regulatory body. Application of innovation across three broad areas including **MPI topologies, technical codes and design considerations**, will play a key role in informing the appropriate regulatory and commercial frameworks.

- **Assessing MPI Topologies:** MPIs may be implemented in a number of ways/concepts (including offshore island hubs, 3-terminal DC schemes, or 4-terminal systems with two offshore hubs split across two different countries); and that several of the technical control and protection functions of an MPI may be provided across a variety of parties involved in that design;
- **Developing offshore network codes:** Understanding how these technical functions are practically delivered would influence how regulatory framework could be delivered and this can be best achieved if first there is early clarity given in the TSO onshore requirements both in GB and at the external TSO end, critically being combined with a clear GB Grid code on requirements offshore, and in the application of existing SQSS requirements for the offshore connection elements of an MPI design to the GB system; and
- **De-risking Technical Design Considerations:** This allows MPI to be consistently designed to be compatible with other designs it may interconnect with including the implementation of appropriate master control and protection arrangements. It also allows different external TSO requirements to be reconciled within the MPI design and common infeed loss risks avoided and security of supply maintained across the range of practical approaches to MPI that are possible.

“Sandbox” detailed simulation environments need to be constructed to address both MPI and co-ordinated HVDC solutions. “sandbox” environments support the combination of detailed and open realistic models of the components of these systems, simulating the operation and functions of co-ordinated HVDC and MPI. Solutions can be used to define what is required from vendor solutions, and how they need to act together, including modelling in detail the requirements of supervisory control aspects. These in time can be used to support vendors delivering solutions in a compatible manner with one another and allowing those individual solutions to be simulated and tested comprehensively across deployment as the Holistic Design for 2030 and beyond is implemented.

We believe as the use of HVDC solutions increases the GB application consideration of DC overhead line circuits may have some potential value in releasing additional transfer capacity and providing flexible non-cabled options for bringing co-ordinated offshore HVDC solutions further onshore by overhead line rather than cable in environments where this is a more preferable approach for local communities. Overhead line approaches for DC transmission are well utilised across the world however GB specific questions surround use of extant AC transmission towers or variations of these familiar approaches within the GB landscape, management of EMF and lightning shielding to a GB standard have particular areas to focus upon and have the benefit of extending the design toolbox when available.

### ***Dispersed Bipole HVDC offshore***

In the ESO holistic planning of offshore networks report, the approach of a “dispersed” Bipole has advantage, this is specifically for the approach where either the scale of offshore generation in an individual location is insufficient to justify an optimally sized HVDC bipole but can be combined with geographically separate area to justify it, or where large but geographically separate areas of offshore development need to be combined. The holistic report identified two applications of such an approach associated with west of

Orkney and Shetland offshore development areas, but conceivably this approach could have furthermore wide spread application should intermediate stages of offshore coordination focused on smaller stages of offshore development occur in other areas. A “dispersed bipole” requires different routes of offshore cabling for each positive and negative pole of the arrangement where the low voltage return cable may be used to suppress the resultant magnetic fields present. An active area of offshore development for AC cables and DC cables offshore relates to the magnetic fields present and their management. OWIC together with Ministry of Defence (MOD), with Department for Business, Energy & Industrial Strategy (BEIS) and The Crown Estate, have set up a Joint Offshore Windfarm and Air Defence Mitigation Task Force to demonstrate and better understand the capabilities of mitigation solutions<sup>19</sup>.

Whilst the potential for magnetic field impacts has been investigated, as yet no standardised response to the challenge has been confirmed or indeed criteria established<sup>20</sup>. Solutions however are practical<sup>21</sup>- for example those applied on the Moyle interconnector<sup>22</sup>. Innovation focus on providing clear recommendations in management of the compass deviation challenge more generally will help support these more flexible and efficient approaches and provide a framework for further innovation.

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<sup>19</sup> OWIC (2020). Sector Deal Progress Update. Available at: <https://bit.ly/3vreVXn>


<sup>20</sup> [https://www.jicable.org/TOUT\\_JICABLE\\_FIRST\\_PAGE/2015/2015-B5-3\\_page1.pdf](https://www.jicable.org/TOUT_JICABLE_FIRST_PAGE/2015/2015-B5-3_page1.pdf)

<sup>21</sup> [https://www.jicable.org/2015/content/Programme/pdfCreator/088\\_B5.3\\_JICABLE15\\_0053.pdf](https://www.jicable.org/2015/content/Programme/pdfCreator/088_B5.3_JICABLE15_0053.pdf)

<sup>22</sup> [https://www.hvdccentre.com/wp-content/uploads/2019/07/Operators\\_Forum\\_2019\\_Hemphill.pdf](https://www.hvdccentre.com/wp-content/uploads/2019/07/Operators_Forum_2019_Hemphill.pdf)

## Theme 3: Maximising the Benefits of Integrated Offshore Solutions

This section describes the points underpinning the aforementioned offshore coordination messages in gap identification, that were considered for establishing the **Theme 3 on Maximising the Benefits of Integrated Offshore Solutions**.

 <b>Theme 3: Maximising the Benefits of Integrated Offshore Solutions</b>	<p>This theme identifies the enabling developments for offshore grids, specifically:</p> <ul style="list-style-type: none"> <li>● New control and protection approaches</li> <li>● Wide area control &amp; Supervisory controls</li> <li>● Asset management telemetry</li> <li>● Enhanced controls for MPIs and offshore grids</li> </ul>
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### ***New control and protection approaches for HVDC***

Both the protection of the DC circuits and AC circuits are challenged by increasingly dominated converter control sensitive injections of fault current. These are in turn interpreted by protection relays using ever complex protection algorithms within a protection relay, which cannot be represented in models at present given the IP constraints of relay manufacturers and the limitations within existing protection models. This drives real-time, or potentially a pseudo real-time hardware-in-the-loop environment to simulate set up and test protection relays, with the tests themselves and the ways in which confidence in new protection relays are proven expected to also need to change. SHE Transmission, supported by the National HVDC centre are taking forward leading-edge work to examine how best to identify, test, and accept new AC protection relay approaches for a future converter dominated AC system focussing in on transmission AC protection, however these issues are expected to be common both at distribution level and generation protections. The AC protection relay considerations are not independent of the role the converter whether relating to HVDC or non-synchronous generation or other FACTS devices plays in providing the network with a useful fault current for protection operation, and what innovations in the specification of this could help protection relay function, and what consequences for performance in other areas should flow from that. An emergent form of HVDC and other non-synchronous generation control - the GB Grid forming Converter specification, has the potential to benefit protection performance, if deployed effectively<sup>23</sup>. These gaps and the follow-on demonstrations of solutions of both protection relay and HVDC control may be addressed by a focus in this area.

### ***Wide Area Control & Supervisory Controls***

In the GB system as transitions to Net Zero, is also transitioning to a control-led basis for its performance and security. Above and beyond the individual convertor controls, there is a need for these controls to be co-ordinated in their combined support to the onshore or offshore networks where they operate in close proximity. So-called supervisory controls between the convertors involved are key to avoiding local area interactions between the convertors, such as a hunting of voltage support, and offshore to provide

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<sup>23</sup> ESO (2021). Minimum Specification Required for Provision of GB Grid Forming Capability.  
<https://www.nationalgrideso.com/industry-information/codes/grid-code-old/modifications/gc0137-minimum-specification-required>

combined and flexible support of voltage and frequency wherever co-ordinated wind solutions are implements. Supervisory controls are required across all HVDC or hybrid

Wide area controls concern overall control priorities of onshore network support across integrated HVDC systems, or indeed multi-terminal arrangements connecting to the onshore system across system boundaries. Such Wide area approaches are used to:

- Support onshore boundary capacity and other onshore system support or services;
- Define the distribution of support and recovery of the offshore system in response to the onshore system fault/ outage/ frequency disturbance across the various onshore interfaces of the HVDC system; and
- Define control strategies and priorities in response to a range of system fault/ outage/ frequency disturbance either onshore or offshore.

The UK has a unique opportunity in this area, with a record of several academic institutions and Industrial players within the UK working together on internationally ground-breaking applications of Wide Area control<sup>24</sup>. We also have one of only two facilities available across the European continent that can support in capability and experience in the analysis and testing of both detailed HVDC controls with wide area control (ourselves<sup>25</sup> and RTEi<sup>26</sup>). As these wide area and supervisory control systems become ever more complex and critical to GB system operation, there is a real opportunity to create industries at scale that both lead the way in GB offshore growth but are also at the cutting edge of then exporting these solutions to other areas of renewable integration onshore within GB, together with international opportunities.

An example of the value of this capability is the delivery of the Kriegers Flak<sup>27</sup> project between Denmark and Germany where an extensive wide area and supervisory control were implemented to support boundary transfer considerations across a HVDC link paralleling the two systems and supporting an offshore AC connection to the Danish network. In this case, the wide area control was separately procured and supported a supervisory control delivered by the vendor. In another example, that of Johan Sverdrup<sup>28</sup>, a supervisory control to co-ordinate the support of the offshore AC connection between an existing and new HVDC connection to shore, was supplied by a different supplier, but required detailed verification of the intended control within a hosted environment for simulation and testing, in this case supported by RTEi<sup>29</sup>. As such, these two areas of core expertise; in designing the controls and in demonstrating and testing them, are key to unlocking efficient and co-ordinated solutions, and areas UK is well placed to innovate further across industry and academia to achieve.

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<sup>24</sup> DIT (2017). UK Capability in communications and Electronics.

[https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\\_data/file/666944/UK\\_Opportunities\\_and\\_Capability\\_in\\_Communications\\_and\\_Electronics\\_Phillip\\_White\\_DIT\\_Dec\\_2017\\_pdf\\_\\_1\\_.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/666944/UK_Opportunities_and_Capability_in_Communications_and_Electronics_Phillip_White_DIT_Dec_2017_pdf__1_.pdf)

<sup>25</sup> The National HVDC Centre, UK. <https://www.hvdccentre.com/>

<sup>26</sup> RTE International. <https://www.rte-international.com/?lang=en>

<sup>27</sup> ABB (2021). Combined Grid Solutions.

<https://on24static.akamaized.net/event/31/11/98/5/rt/1/documents/resourceList1616172889435/combinedgridsolutionwebinarppthvdc0062revaapril141618384069519.pdf>

<sup>28</sup> Equinor (2020). Multi-vendor HVDC supplying O&G installations.

[https://ec.europa.eu/energy/sites/default/files/documents/10.\\_sharifabadi\\_kamran\\_-\\_multivendor\\_hvdc\\_links\\_supplying\\_oil\\_and\\_gas\\_installations.pdf](https://ec.europa.eu/energy/sites/default/files/documents/10._sharifabadi_kamran_-_multivendor_hvdc_links_supplying_oil_and_gas_installations.pdf)

<sup>29</sup> RTEi and HVDC Centre (2021). COMPOSITE Testing of HVDC-Connected Offshore Wind Farms Project report.

[https://www.hvdccentre.com/wp-content/uploads/2021/03/Composite-Testing-of-HVDC-connected-OWF\\_110321.pdf](https://www.hvdccentre.com/wp-content/uploads/2021/03/Composite-Testing-of-HVDC-connected-OWF_110321.pdf)

### ***Asset management telemetry***

The UK Offshore industry has developed to some 10GW of capacity over last 20 years resulting in a mature and varied asset base. This asset base will face key decisions surrounding replanting of assets and asset life extensions after the end of nominal asset lives across the next 30 years. There is a requirement, we believe to engage in and evolve asset management telemetry that supports the ability to enhance the availability and lives of the assets required. We also understand that within the UK Oil and gas industry there exist potentially transferable skills and tools to support the management of ageing offshore infrastructure; this combined with the increasing electrification of Oil and Gas within the UK North Sea Transition deal<sup>30</sup> presents an opportunity for shared technology solutions to support a range of related energy sector interests. The above development of Asset management telemetry further has the potential to extend the lives of current offshore project implementations, which may otherwise be encountering renewal decisions over the period up to 2050.

If asset management telemetry innovation is not developed, there is a risk that current approaches which are oriented around the within life management of the assets prove insufficient to support end of life decision making. This presents the industry then of both simultaneously replacing early offshore infrastructure, managing long down-times of that earlier infrastructure, whilst constructing new capacity. This simultaneous challenge would base on the discussion within the supply report place the delivery of 2050 targets at risk.

### ***Enhanced controls for MPIs and offshore grids.***

Where offshore grids combine with MPIs, it is still more important that the basis and interface for offshore grid performance is standardised. This is because an Interconnector control is oriented towards satisfying competing (and potentially conflicting) performance needs between TSOs. Where conflict occurs, there is currently no clear route for arbitration ahead of ACER<sup>31</sup>. This risk does not normally occur in point to point Interconnector design as the opportunity is taken to specify a given project specific design satisfying each TSO need. A lack of standardisation offshore would mean that this approach would not be possible as offshore terminals would not have similarly clear specification. Within the hierarchy of HVDC control, avoidance of cascade failures of the offshore terminals is a key consideration to ensure the maximum loss of generation is contained to a level both TSOs are able to accommodate. Further the allocation of support to each TSO system needs to be clearly defined such that if both TSO systems require simultaneous support- e.g. for a loss of a parallel interconnector flow- such that these requirements do not again contradict. In these areas the specification of offshore control needs to be collaboratively innovated across interconnector, TSO, and developer communities to address these considerations, and realise the opportunities that MPIs represent in full. Within Horizon 2020 research programmes these topics have been identified but as yet, no research activity has been initiated to support them<sup>32</sup>.

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<sup>30</sup> BEIS (2021). North Sea Transition Deal.


[https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\\_data/file/972520/north-sea-transition-deal\\_A\\_FINAL.pdf](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/972520/north-sea-transition-deal_A_FINAL.pdf)

<sup>31</sup> EU Agency for the Cooperation of Energy Regulators (ACER). <https://www.acer.europa.eu/>

<sup>32</sup> EU Green Deal Call for Research Proposals. <https://bit.ly/3g0Zyj6>

## Theme 4: Leveraging Technical Expertise, Skills Development and Resourcing

This section describes the points underpinning the aforementioned offshore coordination messages in gap identification, that were considered for establishing the **Theme 4 on Leveraging Technical Expertise, Skill Development and Resourcing**.

 <b>Theme 4: Leveraging Technical Expertise, Skill Development and Resourcing</b>	<p>This theme identifies the skills gaps and developments required to address, specifically:</p> <ul style="list-style-type: none"> <li>● <b>Early-years teaching</b></li> <li>● <b>HVDC R&amp;D in UK Universities</b></li> <li>● <b>Hardware-in-the loop testing capability</b></li> <li>● <b>Operator training using simulators</b></li> </ul>
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### **Early-Years teaching**

The delivery of Net-Zero targets for co-ordinated offshore HVDC-based solutions is a challenge occurring over 30 years, and there is a real opportunity for GB for the secondary school age and early apprentices and undergraduates of today to become the industry expertise of the future as high value jobs across a variety of industry relevant areas grow to fulfil the scope of growth in the industry. This in a number of areas; techno-economic analysis and scenario planning, environmental skills and electrical engineering mirrors the grow needs of the onshore transmission system across the 1950s to late 1960s as the transmission and distribution systems grew to support un paralleled levels of growth in electricity demand over that period.

For this new network transformation- other skills in mathematics, big data analytics, software-based control engineering and electronics engineering are also prominent areas of importance. Whilst the National HVDC centre is not an expert in these areas there is a clear opportunity for early years teaching in STEM and other relevant disciplines to enthuse a pipeline of young keen and capable young adults towards the high value jobs supporting future HVDC delivery. At present, such capabilities are largely vendor sourced in project delivery, with the vendors, many of which are non-GB based having success in generating an interest and focus in these areas from within their own countries. As we grow the volumes of HVDC technology, there is not only an opportunity to repeat this success, but also amplify it with strong industry activity beyond the vendors themselves to encourage exposure to HVDC developments and collaboration with the schools/ colleges/ universities via bursary programmes, summer placements and sponsored apprentice and degree courses to build a pipeline in the generation of resource across 2030-2050, assuming this begins within the next 5 years.

### **HVDC R&D in UK Universities**

Within an academic setting, there are currently a limited number of universities supporting dedicated HVDC relevant learning with active Doctoral focus, and dedicated post-doc focus- given its niched skill requirements and the limited availability of funding and focus for HVDC related research- this in turn informing the tuition and ranges of activities in the area.

Currently no centralised funding for HVDC: there is no HVDC ENA strategy, no HVDC catapult, as such HVDC funding competes with all other funding relying on the funding from related sources these being, dedicated funding will be beneficial.

Within an academic setting, there are currently a limited number of universities supporting dedicated HVDC relevant learning with active Doctoral focus, and dedicated post-doc focus - given its niched skill requirements and the limited availability of funding and focus for HVDC related research- this in turn informing the tuition and ranges of activities in the area.

The related sources of funding include Strategic Innovation Fund (SIF) (previously NIC); Catapults; Innovate UK; UKRI; BEIS; EU Commission (Horizon 2020); EPSRC and Network Innovation Allowance. At the HVDC Centre, we have worked on most of these funding streams:

- NIC (e.g. Distributed ReStart; HVDC Centre<sup>33</sup> innovation programme<sup>34</sup>);
- NIA (e.g. PMUs project; New Protection project);
- EU Commission (e.g. PROMOTion); and
- EPSRC (we have supported various universities' EPSRC projects).

In GB, HVDC research and innovation funding gaps and opportunities exist as shown in the summary:

- The main GB funding in these areas are Ofgem's SIF and NIA innovation funds;
- Our concern with these funds is that they cover the whole range Electricity Network innovation projects from Distribution to Transmission; and tend to focus on distribution projects (since that is the larger part of the licensee's asset value and size of funding is typically suited to scaled demonstration projects at distribution level);
- We would suggest that, in order to protect the 2050 net-zero ambition, that a specific '2050 Net Zero' fund should be established (potential through BEIS or Ofgem) that focuses on delivering innovation at pace for enabling a more coordinated offshore HVDC development in GB and
- There also appears to be a specific gap in the funding for developing the skills required to deliver the scale of new electricity connections to meet the 2030 and 2050 offshore wind targets.

Therefore, we would suggest the BEIS lead an initiative to bring together IET, ENA and industry representatives to develop a skills development plan for 'Coordinated Offshore networks to meet 2050 net zero targets'. We would envisage that the solution is a combination of new training, industrial engagement in academia, and more collaborative research and innovation activities.

### ***Hardware-in-the-loop testing capability***

Within GB, whilst vendors have the ability to test individual devices and their associated control and protections to a low resolution or generic representation of the GB system during their compliance process, they are not in a position to test the equipment of other vendors with this arrangement, nor host more detailed and confidential models of the wider network and the various user specific models used for

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<sup>33</sup> <https://www.hvdccentre.com/completed-innovation/>

<sup>34</sup> <https://www.hvdccentre.com/current-innovation/>

planning and operation of that system. This means that co-ordinated offshore connections using different vendors HVDC solutions or different vendors of offshore wind farms or the component networks cannot be adequately represented to de-risk their design and function today.

Academic and other institutions also host the capability for real-time testing, but again confront challenges to the extent of confidential and IP sensitive equipment that can be hosted in that environment.

The National HVDC centre represents GB's only environment where currently these challenges may be addressed - this represents a cutting-edge position internationally, however - and within the immediate European continent, only GB and France have such capabilities.

These facilities are designed to host project-specific models and ultimately hardware replicas of the intended devices representing real projects being connected within respective networks. Whilst models can be managed and support design and development phases of de-risking, the project specific hardware hosting is both time and space intensive given the overheads of installation time and physical areas occupied within a given facility. As the range and number of power electronic devices increases, so do the space requirements of a facility. RTE France has recently relocated its capabilities to a purpose-built facility in Lyon to address this.

End-to-end de-risking as illustrated within the recent Johan Sverdrup project experience of managing the design evaluation and testing of a 2<sup>nd</sup> HVDC circuit from a different vendor into an existing facility took 3 years of offline and hardware in the loop of real-time simulation to address. These processes are robust and effective but are not practically scalable to the extent future co-ordinated offshore work would infer is required. To bridge this gap, we believe, based on research we have supported in this area it is necessary to identify ways of screening, prioritising and enhancing the tests conducted to free up time for the next project study- creating a more production environment for the analysis, together with limiting physical footprints of hardware across a variety of strategies of more flexibly constructing replica controls, and more flexibly applying the real time simulation environment. Without such measures, or a dramatic expansion of existing methods (the French example), the access to such testing environments could become a significant blocker to the pace of development.

There is an urgent need to develop streamlined testing principles for multiple HVDC co-ordinated connections that avoids current labour-intensive integration of project specific hardware within a hardware in a loop environment, then studying each and every control permutation. We have within a Green Deal proposal earlier this year identified process and technology changes that limit the footprint of devices required via reconfigurable replica approaches and mobile testing, and analysis to develop key tests from the higher level outer controls of convertors that streamlines analysis and testing to allow it to be more efficiently delivered in more complex environments, at greater pace, to a much reduced cost- we recognise that within GB the need for practical solutions for pace and scale occurs more rapidly than elsewhere in Europe and as such is an area we will need to take the initiative in.


### ***Operator training using simulators***

Whilst the key benefit arising from Coordination is the delivery of reduced asset HVDC solutions that deliver a range of functions for both onshore and offshore systems- it is essential for operators of these more complex projects have adequate training in practice to exploit these enhanced HVDC capabilities. Currently individual vendors will supply individual training tailored to the operation of their equipment focussing on that specific DC system. Going forward the DC system, the offshore AC systems and the onshore AC systems will be required to be operated in a co-ordinated manner and the training will naturally need to expand to cover these areas also; which will extend to solutions across vendors and across detailed and confidential network models and operating conditions on and offshore. Operational simulator training facilities within a hosted environment would be required to enable operator training at scale and increase confidence of network owners in understanding the performance of complex connections on the electricity network.

We have demonstrated via the Caithness-Moray project the value a training environment for complex HVDC implementation has in reinforcing confidence and capability in its operation- the co-ordinated approaches being developed for GB require similarly complex operating arrangements to be embedded and maintained to ensure they deliver the required functions to benefit the GB onshore system and complement its operation. These functions may be achieved by expansions of existing capabilities, or via establishing a new facility focussing upon this.

## Theme 5: Grow domestic capability via knowledge transfer from Oil and Gas industry

This section describes the points underpinning the aforementioned offshore coordination messages in gap identification, that were considered for establishing the **Theme 5 on Grow domestic capability via knowledge transfer from Oil and Gas industry**.

 <b>Theme 5: Grow domestic capability via knowledge transfer from Oil and Gas industry</b>	<p><b>This theme identifies specific synergies between Oil and Gas innovations the requirements of a coordinate offshore approach, including:</b></p> <ul style="list-style-type: none"> <li>● Offshore converter platform design &amp; operation</li> <li>● Repurpose O&amp;G assets</li> <li>● Skills exchange &amp; re-training</li> <li>● Optimise surveys</li> </ul>
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The centre notes a series of activities in this area, such as regional re-training activities<sup>35</sup> new innovations in asset management<sup>36</sup> existing centres of offshore platform construction<sup>37</sup> and an existing wealth of knowledge within the sector in marine environment management<sup>38</sup> that may be leveraged, together with opportunities present in the development of hybrid uses of existing platforms, and the sector deal on electrification. These present potential resource and more general supply capacity opportunities and that specifically aligned activity across the 4 topics areas identified. Activity in these areas would have the potential to bring benefit to the growth of HVDC development offshore.

The Centre recognises we have limited expertise in identifying the specific activities that could deliver in this area and would recommend broader engagement with relevant stakeholders in this sector in the months to come. This area is less a Gap but rather an opportunity to support the previously identified gap areas above.

<sup>35</sup> <https://www.gov.uk/government/publications/north-sea-transition-deal>

<sup>36</sup> <https://www.dnv.com/oilgas/laboratories-test-sites/article/cross-learning-between-oil-gas-and-floating-offshore-wind-optimizing-mooring-design-to-cut-cost-and-weight.html>

<sup>37</sup> <https://blogs.worldbank.org/climatechange/winds-change-can-big-oil-make-transition-offshore-wind>

<sup>38</sup> <https://www.nsenergybusiness.com/features/oil-companies-offshore-wind/>