Executive Summary

Offshore Wind Accelerator – TWG-E

DC-AS – DC Array System Technology Revisit

March, 2021

The Offshore Wind Accelerator

The Offshore Wind Accelerator (OWA) is the Carbon Trust's flagship collaborative research, development and deployment programme. The joint initiative was set up between the Carbon Trust and nine offshore wind developers in 2008, with the aim to reduce the cost of offshore wind to be competitive with conventional energy generation, as well as provide insights regarding industry standard (and best practice) health and safety requirements.

The current phase involves participation and funding from eight international energy companies: EnBW, Equinor, Ørsted, RWE, ScottishPower Renewables, Shell, SSE Renewables, and Vattenfall Wind Power, who collectively represent 75% of Europe’s installed offshore wind capacity. This project also received partial funding from the Scottish Government.

Acknowledgements

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1. Introduction

The Offshore Wind Accelerator ("OWA") investigates the opportunities and technological barriers towards implementing DC arrays in offshore wind farms (OWFs). This innovative approach could potentially remove the requirement for offshore substations, using instead DC array cables that could transmit power directly to shore, from long distances. This has been a subject of ongoing research by academic and industry bodies looking at cost reduction opportunities for offshore renewables for many years, including the OWA in their original DC Array project in 2011, and the Refresh Study concluded in 2018.

This executive summary report contains a high-level summary of the main findings from the DC Array System - Technology Revisit study.

2. Technology and market analysis

Figure 1 shows a general topology for an offshore wind farm with DC connection and the required technologies to fulfil such a topology.

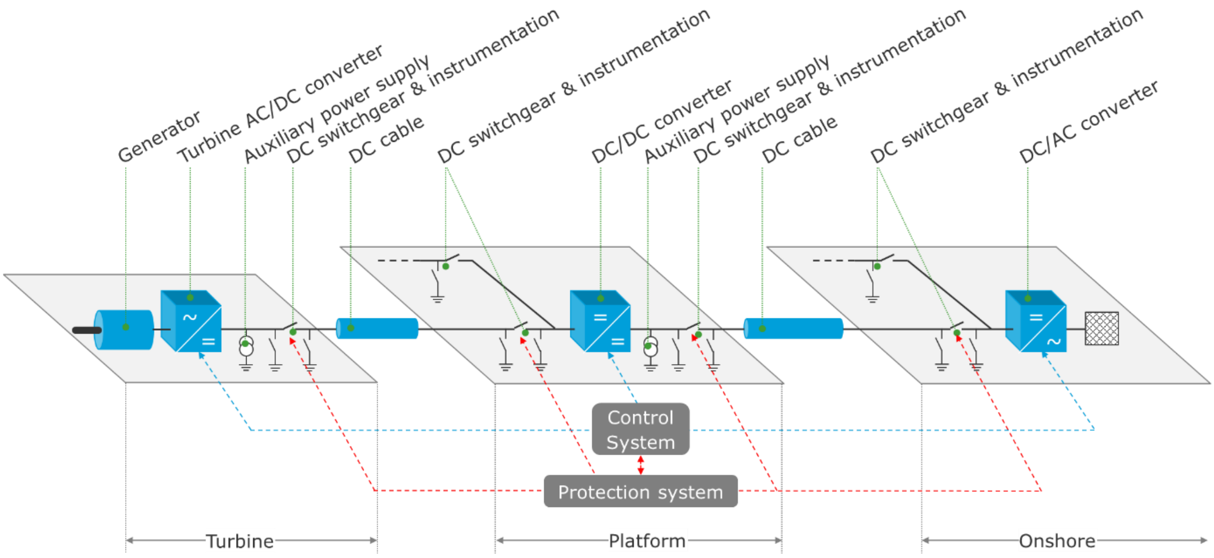

Figure 1: Schematic topology diagram of a typical offshore wind farm connection

In the MVDC array system topology the power from the wind turbine generators would essentially go directly through MVDC connections to the onshore system with a much smaller or even completely without the offshore substation platform.

In this project a review of the state-of-the-art and ongoing research and development, and an assessment and detailing of the required technology maturity levels were conducted. This included strong engagement and contact with both industry and academia. In total 21 OEMs and 12 academic and research institutions were contacted. The findings of the technology maturity level assessment are summarised in Table 1.

Table 1: Technology readiness levels of key technologies for MVDC arrays.

<table>
<tr><th colspan="3">Technology</th><th>TRL</th><th>Maturity status</th><th>Notes</th></tr>
<tr><td rowspan="5">DC wind turbine</td><td colspan="2">DC WT integration</td><td>3</td><td>Immature</td><td>Limited progress. No interest from suppliers. Much depending to market pull.</td></tr>
<tr><td colspan="2">WTG</td><td>9</td><td>Mature</td><td>Technology is ready, 11 MW commercially available in a few years.</td></tr>
<tr><td rowspan="2">WT Converter</td><td>AC-DC</td><td>8-9</td><td>Semi-mature</td><td>Technology is possible, but not proven for WT applications.</td></tr>
<tr><td>DC-DC</td><td>3-4</td><td>Immature</td><td>Technology is possible, but not demonstrated and not for WT.</td></tr>
<tr><td colspan="2">DC switchgear</td><td>7-8</td><td>Early stage</td><td>Technology is possible for other applications, without much interest in WT.</td></tr>
<tr><td colspan="3">MVDC-DC converter</td><td>6</td><td>Early stage</td><td>Technology is demonstrated for other applications, but not for offshore WF.</td></tr>
<tr><td>MVDC protection</td><td colspan="2">DC circuit breaker</td><td>7-8</td><td>Semi-mature</td><td>Technology is available, but in limited applications, more for HVDC and stay costly.</td></tr>
<tr><td colspan="3">MVDC cable</td><td>9</td><td>Mature</td><td>Technology is ready.</td></tr>
</table>

Since the last MVDC array study was conducted in 2016-2018, it was concluded that while there is academic research to support the development of DC array technology, breakthroughs in the market by OEMs has not occurred at the same pace and scale. It was observed that there had been limited progress in terms of technology readiness levels, especially in DC WT integration technology, where a whole system consisting of several subcomponents is considered.

In summary, MVDC cable systems are seen as a mature technology for MVDC arrays. MVDC cables are already commercially delivered to the market and there are several projects in operation where the MVDC cables are implemented in different DC voltage levels. MVDC protection technologies are also available, still in an early stage but considered ready for commercial use. For DC circuit breakers, there are different solutions available. Both mechanical and hybrid circuit breaker in MV-level have been demonstrated in projects and MVDC switchgear has also been reported to be used.

DC-DC converters and dedicated DC wind turbines are seen as the most critical components for MVDC arrays. So far, DC-DC converters have not been used commercially for HV and MV transmission applications. DC wind turbines have not attracted much market attention with only a few OEMs actively involved in development, however this remains at an early stage.

A critical review of high-power DC-DC converters was conducted in this project, with particular emphasis paid for key indicators that might influence the cost, efficiency, footprint, control flexibility, and semiconductor utilization of DC-DC converters. From the state-of-the-art, it was observed that recent research focuses on modular designs, e.g. the front-to-front HB-MMC based DC-DC converters, input-parallel output-series DC-DC converters, etc. These topologies avoid as much as possible the use of series connected semiconductors and are characterised by flexible expansion, low harmonics and fault isolation, so they can be flexibly applied in MVDC system.

3. Cost benefit analysis

The offshore wind farm industry, has experienced a continuous decrease in levelised cost of wind energy based on existing AC solutions. During the course of this study the CFD auction for offshore wind cleared at £39.65/MWh for the delivery year 2023/24. This is compared to £57.50/MWh for the delivery year 2022/23 in 2017, and £114.39/MWh from the first CFD round in 2015.

A cost-benefit model was developed to compare the benefits of two different DC array topologies against current baseline AC topology when applied to a 'benchmark wind farm'. The analysed MVDC array topologies are shown in Figure 2 and Figure 3, which were developed during the project as possible configurations for MVDC array offshore wind farms. Other topologies denoted A and C were also studied during the course of the project, but they are not included in this report, thus only topology B and D are shown below.

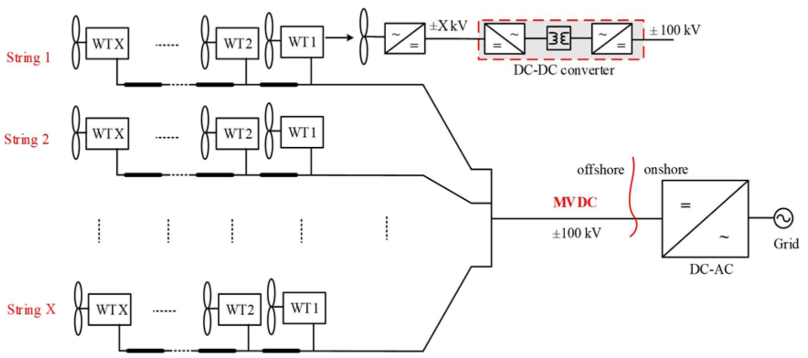

Figure 2: Topology B – WTs connected in strings

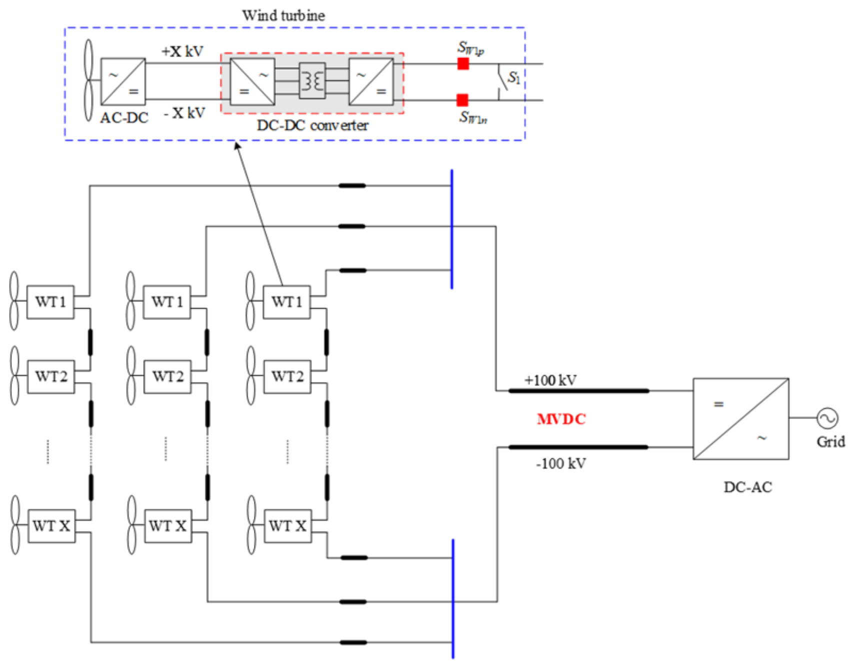

Figure 3: Topology D – WTs in series connected in strings.

The resulting lifecycle costs for the offshore wind farm systems considering 810 MW installed capacity, 15 MW WTs, 20-year lifetime, energy cost £48/MWh, 100 kV DC systems, 100 km offshore, are shown in Figure 4.

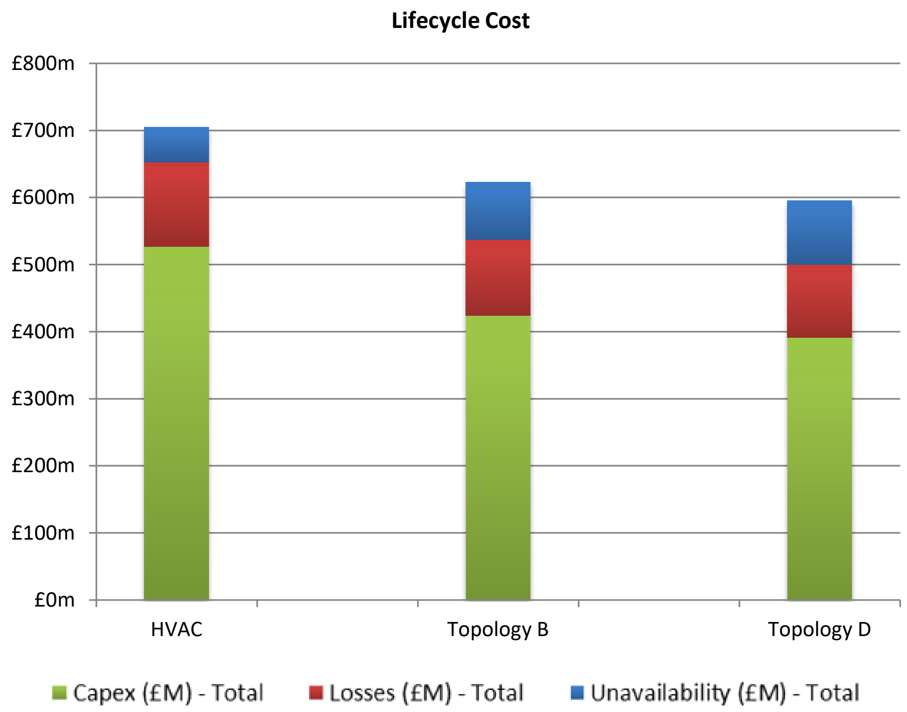

Figure 4: Lifecycle cost comparison.

The lifecycle cost consists of: capital cost, equivalent cost of electrical losses and cost of losses due to unavailability.

The lifecycle cost of both DC topologies is lower than HVAC transmission with conventional AC arrays due to the lower capital costs due to cost saving in equipment and cabling, and some reduction in losses. The main benefit and cost reduction of the MVDC technology is the possible size reduction or elimination of the offshore platform. On the other hand, higher unavailability is observed for both MVDC array topologies compared the conventional AC solution.

4. Topology comparison

The topologies shown in Figure 2 and Figure 3 offers different advantages and disadvantages as summarised.

Parameter		Topology B – series connected	Topology D – series/string connected
WTs and control		• No need for special design of controllers and generator-side AC-DC converters for WTs. • DC-DC converter with high voltage conversion ratio is required for each WT (likely require multi-stage conversion). • Insulation for each WT is defined by the WT maximum voltage. • Less requirement for WT control coordination and easier to adopt WTs from different manufacturers.	• WT converters and their controllers need to be specially designed to accommodate power/voltage variation of the series connected WTs. • Voltage overrating of WT converters may be required which could lead to higher power losses and cost. • WT insulation defined by the string (MVDC voltage) leading to higher voltage insulation requirements. • Close coordination for WTs required, more challenging to adopt WTs from different manufacturers.
System availability		• String cable outage – may lose the whole string (i.e. 13 WTs). • The use of individual DC-DC converter in WTs can effectively improve system availability during WT converter failure.	• String cable outage – loss of the whole string which has a large number (i.e. 26) of WTs. • Require voltage overrating of WT converters in order to provide adequate availability when certain WTs are out of service.
Protection	Offshore DC faults	• WT converters do not experience significant overcurrent, although DC capacitors will be discharged. • Onshore MVDC station potentially sees high fault current. • Faults in the string can lead to the power transmission interruption of the entire OWF, and the faulty string needs to be disconnected before resuming power transmission.	• WT converters do not experience significant overcurrent, although DC capacitors will be discharged. • Onshore MVDC station potentially sees high fault current. • Faults in the string can lead to the power transmission interruption of the entire OWF, and the faulty string needs to be disconnected before resuming power transmission.

		• Faults at the main MVDC cables will cause the loss of power transmission for the entire OWF.	• If the fault is inside of the WT, the faulty WT can be bypassed, and power transmission restored. • Faults at the main MVDC cables will cause the loss of power transmission for the whole OWF.
	Onshore AC faults	• DC choppers may be equipped to dissipate the surplus power to avoid DC overvoltage.	• DC choppers may be equipped to dissipate the surplus power to avoid DC overvoltage.
Installation		• Only a small offshore platform is needed to accommodate protection and control equipment as no centralised DC-DC converters are used. • Four cable joints are required at each WT.	• Only small offshore platform is needed to accommodate protection and control equipment as no centralised DC-DC converters are used. • The cable installation cost is lower due to the shorter cable length compared to topology B. • Only two cable joints are required at each WT, leading to higher reliability and reduced cable installation cost.
Efficiency		• Low current cables are needed but they are longer than that of topology D. • Likely requires two-stage DC-DC conversion in each WT leading to high losses (compared to topology D).	• Less DC-DC conversion stage leads to lower power conversion loss. • The losses of cables of collection network are lower than that of topology B, due to shorter cable length.

Note: other MVDC topologies are currently being developed for implementation of MVDC arrays and other solutions are possible. Future research and development should not be limited to the two possible topologies and configurations included in this report.

5. Gap and risk analysis

The risk and gap analysis consider amongst others, the technology maturity and market capabilities findings of this project and the analysis done in the previous OWA MVDC array study. The purpose is to determine the technical and commercial risks/gaps and the possible effects these will have on the development of MVDC arrays of offshore wind.

Similar to the results of the previous MVDC array study the main risks/gaps are related to the following areas:

1. Component level – risks and gaps associated with the individual technologies and components required to realise MVDC for offshore wind.
2. System level – risks and gaps associated with the complete products composed of several subcomponents, such as the DC WTG integration, and those associated with overall project development.
3. Market and policy level – risks and gaps associated with the market capabilities, regulation and policy.

The risks are labelled as high, medium or low with a high-risk rating representing a critical obstruction to project development, a medium risk rating indicating that significant mitigation may be required (subject to further investigation and analysis) and a low risk rating showing that some mitigation would be required but this is a surmountable gap with known mitigation. A few of the main risks and gaps noted in the previous study are revisited.

Risk/Gap	**Area**	**Risk level**	**Comment**	**Mitigation**
Availability of MVDC subsea cables	Component	Low	From the study conducted in WP2 of this project and through the OEM interaction it is evident that several different cable manufacturers are supplying MVDC cables up to 100 kV.	No significant mitigation needed. Encourage other cable manufacturers to develop MVDC cables.
Current capacity of available MVDC cables and large cross-sectional area	Component and system level	Medium	To avoid high costs and get the benefit of utilising MVDC technology it was shown in WP2 and in this WP3 that it is required to have high current capacity in the MVDC cables and large cross-sectional areas.	Engage with cable manufacturers to determine the maximum possible current capability and cable sizes. Reduce cable costs to make it economically feasible to install more cables.
DC/DC converter technology function currently not proven	Component and system level	High	DC-DC converters are seen as immature from a TRL perspective. Although the technology is available, there is no proof that is has been tested for WT applications in a relevant or operational environment.	Continued research & development, and field tests are required to prove concept for WT and MVDC applications.

Risk/Gap	**Area**	**Risk level**	**Comment**	**Mitigation**
Conversion of MVDC to HVAC (onshore converter)	System00- level	Low	Onshore conversion scales are at lower voltage levels than those required for DC arrays. Technology is demonstrated for other applications but not for offshore wind.	Modification to existing technology is likely to result in suitable technology for MVDC onshore conversion.
Protection methods for MVDC systems	Component and system level	Medium	DC circuit breakers are available but in limited applications and cost is high, resulting in an impact on the protection on the MVDC offshore system. As a result, the unavailability for MVDC systems are also significantly higher compared to conventional HVAC systems.	Using alternative methods of protection and circuit isolation will reduce the technology risk. Use findings from PROMOtiON project. Development required from DC CB manufacturers to develop cost-effective solutions for MVDC applications.
Uncertainties in regulatory aspects	Market and policy level	Low	There are uncertainties how MVDC projects will be categorised under the same regulation as conventional offshore wind transmission assets and ownership frameworks.	For markets with opportunities for far offshore, development of MVDC array concepts may be feasible with additional conversion to HVDC or HVAC transmission solutions. A clear legal demarcation between the offshore wind farm and the offshore transmission asset would be required for development, ownership and remuneration purposes.
Lack of market pull	Market and policy level	High	There is currently limited progress and interest of the suppliers/OEMs to develop technology dedicated to MVDC WTG integration. Plans and interest is driven by market pull and costs.	A strong business case with a thorough risk investigation and mitigation strategy will provide additional confidence to the market. Realising a MVDC wind farm demonstration project.

6. Recommendations to progress MVDC OWFs

Based on the latest review, DC array technology still requires significant development before being used in an operational wind farm and utilisation could be over 10 years away. Despite this, final recommendations for stakeholders to proceed and develop the field of MVDC array technologies have been identified.

- **Develop and create market pull for enabling technologies**: The main recommendation to enable MVDC array technologies for offshore wind is to create a strong business case with a thorough risk investigation and mitigation strategy. Integrated DC wind turbines are a critical component of all DC array topologies and there has been limited progress in this area since the original study and based on the interaction with OEMs the main concern is lack of pull. A demonstration project will therefore be critical to addressing operational concerns, reducing key risks and providing increased confidence in reliability, availability and operational considerations, which will provide additional confidence to the market.
- **Further develop topologies and configurations**: The topologies used in the cost-benefit analysis were selected from a number of topologies and configurations for MVDC array OWFs. However, there are other topologies and configurations currently being developed and other solutions are still possible. Based on the assessment of power losses to find a suggested operation voltage level it was found that 100 kV was a suitable voltage level for MVDC applications, with 80 kV also being considered a relevant voltage level to explore. Also, as part of the cost-benefit analysis and sensitivity analysis it was determined that with larger power ratings for wind turbines the total losses and costs are reduced. From the CBA analysis it was concluded that the main advantage of the MVDC array technology compared to conventional AC technology, is the reduced size or possibly even elimination of the offshore platform.

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