OWA Report 2018

Executive Summary

Offshore Wind Accelerator – Electrical Systems

DC Refresh – DC Array System Refresh Study

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DC Array Refresh Study – Executive Summary

On behalf of the Carbon Trust and Offshore Wind Accelerator (OWA), TNEI has undertaken a fresh investigation into the feasibility of DC arrays as a means of connecting offshore wind farms. The premise of DC arrays is to use medium voltage DC (MVDC) array cables rather than conventional 66kV or 33kV AC array cables to connect each wind turbine to the offshore substation(s). 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. This Refresh Study considers the advancements in DC technology in the intervening years.

This report contains a high-level summary of the findings from the study.

Figure 1 shows five connection options for a 1,000MW offshore wind farm, used as a basis for the analysis in this study.

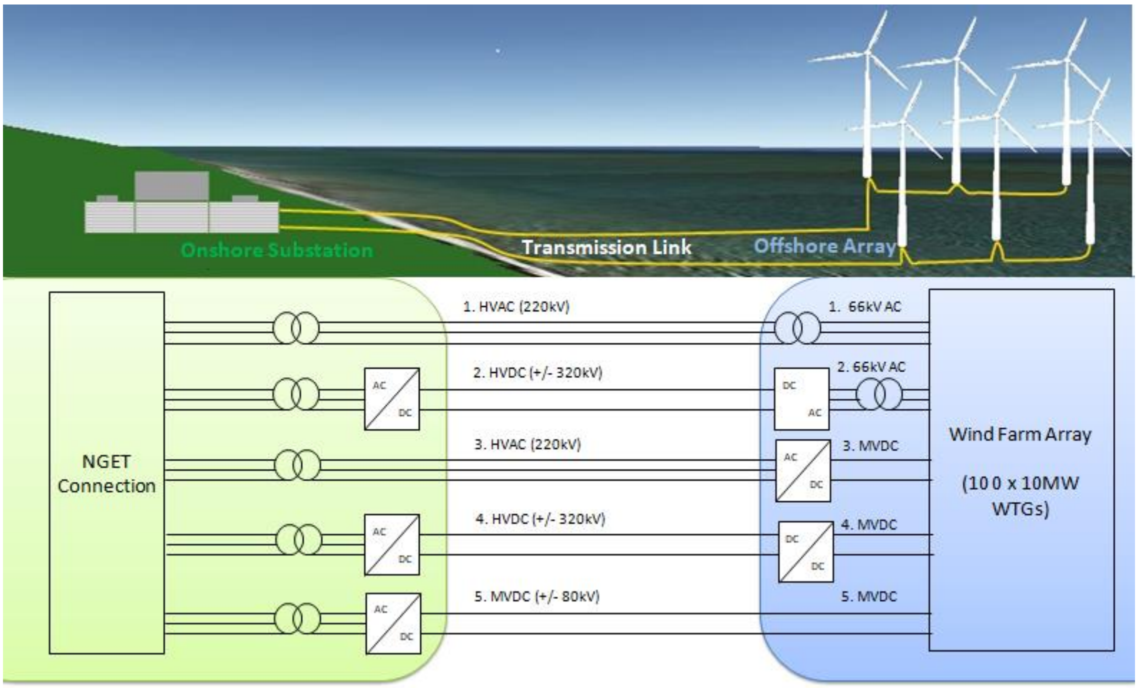

Figure 1: Five Electrical Connection Topologies

- Options 1 and 2 are industry business as usual, included for comparison.
  - Option 1 is a standard offshore wind farm design, using a HVAC transmission link and a 66kV AC array.
  - Option 2 is a standard design with an HVDC transmission link, which can reduce electrical losses over long distances. An AC/DC converter is required at each end of the link.
- Options 3 to 5 feature MVDC arrays at the offshore wind farm. For all these options, the wind turbines must be capable of connecting at DC.
  - In Option 3 the MVDC array connects to a standard HVAC transmission link, via an AC/DC converter on an offshore platform.
  - In Option 4 the MVDC array connects to an HVDC transmission link, via a DC/DC converter on an offshore platform.
  - In Option 5, the MVDC array connects directly to the shore via an MVDC transmission link (this is known as "Direct-to-Shore MVDC").

Technology and Market Analysis

TNEI's previous assessment of DC technology identified four barrier technologies which required development to enable the implementation of DC arrays. Table 1 shows the current status of these key enabling technologies in terms of technical and commercial maturity.

Table 1: Summary of progress against key technical barriers to DC arrays

Enabling Technology	Technology Readiness	Commercial Maturity	Notes
Platform scale DC/DC Converters	6-7	Immature	Further academic development, but no commercial products available.
DC Protection	7-8	Early Stages	Products available but cost remains high.
DC WTG Integration	5-6	Immature	Limited progress in this area since original study. One WTG manufacturer involved in academic demonstration.
MVDC Cables	9	Semi-mature	Established technology but limited applications at present – remains costly.

Based on the findings of this research and stakeholder engagement, the technology areas requiring the most technical development include DC WTG Integration and Platform Scale DC/DC conversion.

DC WTG Integration in particular is mission critical, as it is required for all MVDC array designs. It was found that at present there is little activity or serious interest from turbine manufacturers in pursuing the development of DC-connected turbine technology, rather they are focused on optimising their AC-connected turbine offerings. The early progress made by GE who demonstrated a 6 MVA passive boost converter arrangement for use in the base of a WTG tower in 2012/13 has not been significantly progressed or developed by any other parties.

1.1.1 Current Industry Trends

Since the original study, it would appear that whilst academic investigations have continued in this area, there has been limited progress from OEMs and Developers in terms of product development and full scale demonstration for some of the key enabling technologies. Speaking to key market players, a number of trends were identified regarding the development of technologies for use in DC arrays, including:

- The development of MVDC for onshore applications, more specifically for distribution network reinforcement. This is leading development in converter technology which will be an important enabler for offshore DC arrays, and will also facilitate cost reduction as the onshore market grows.
- The focus on HVDC for offshore wind and in making it more cost-effective. Several equipment manufacturers are actively engaged in this through various measures, including reduction of offshore platform weight, adapting converters to remove the need for conversion at the individual WTGs and a modular approach to connection configuration.

Cost Benefit Analysis

The above market and technology findings are viewed against the background of an ever decreasing levelized cost of wind energy based on existing AC electrical solutions. During the course of the study the 2017 CFD auction for Offshore Wind cleared at £57.50/MWh for the delivery year 2022/23 compared to £114.39/MWh from the first CFD round in 2015. A rapidly decreasing cost baseline such as this makes it more challenging to encourage technical innovation, as the cost savings appear to be diminishing in comparison with the "business as usual" AC approach.

A cost-benefit model was developed to compare the benefits of various DC array topologies against current baseline AC topologies when applied to a "benchmark wind farm". The array topologies shown in Figure 1 were compared.

The resulting lifecycle costs of the electrical transmission system for a windfarm 50km offshore are shown in Figure 2, and for a windfarm 100km offshore in Figure 3. These assume the mid case scenario for capex and availability. It is also assumed the HVAC solution makes use of dynamically rated cables.

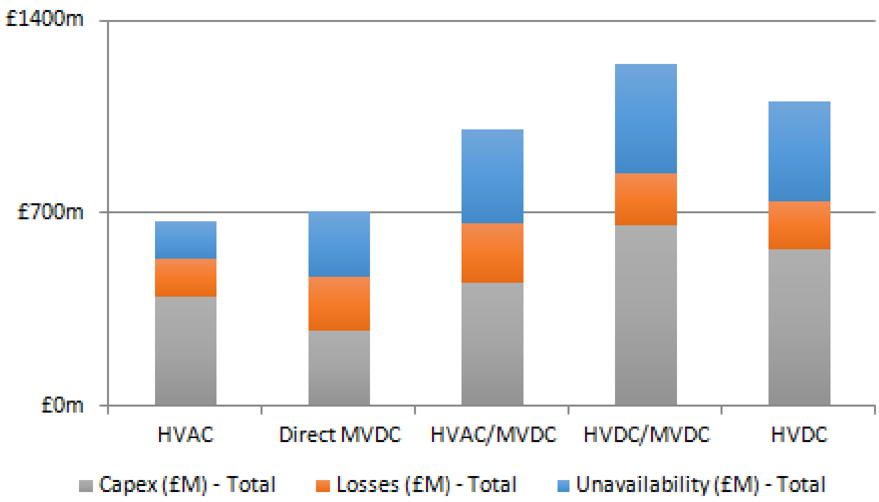

Figure 2 Comparison of Electrical System Lifecycle Costs for a Wind Farm 50 km offshore

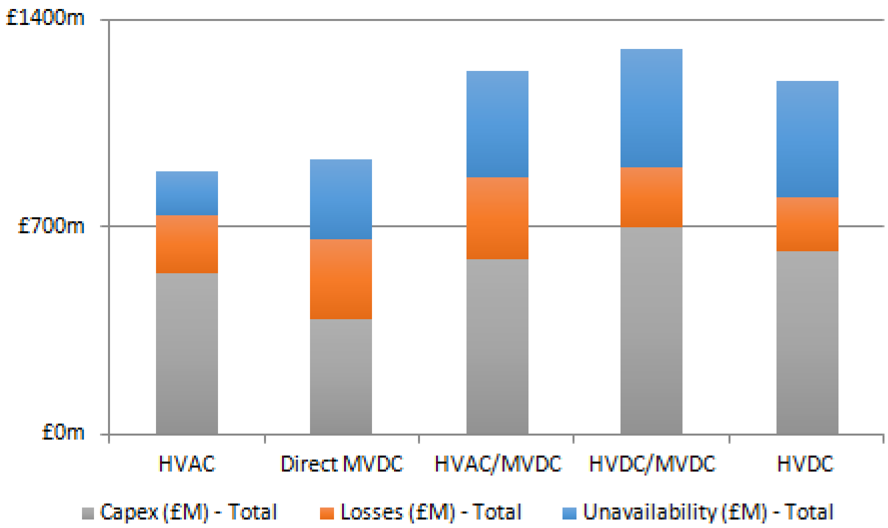

Figure 3 Comparison of Electrical System Lifecycle Costs for a Wind Farm 100 km offshore

The results of the CBA suggest that the Direct MVDC topology could offer a comparable overall lifecycle cost of the electrical system as the conventional HVAC solution. The main benefit of a Direct

MVDC solution however is the potential capital cost saving in equipment and cabling. Whilst the alternative HVDC topologies (#2 and #4 above) remain prohibitively expensive close in to shore due to the costs of the converter stations, for the Direct MVDC topology the converter is onshore and there is only one stage of conversion and the offshore platform is avoided entirely, this keeps the capital costs low.

Table 2 shows the comparison of the capital costs of the Direct MVDC solution compared to the conventional HVAC solution. Using mid case cost assumptions MVDC would appear to offer a significant capital cost saving of approximately 30%. It is acknowledged that there is uncertainty on the cost of array type DC cables so a sensitivity study was undertaken to consider more pessimistic or optimistic views on DC cable manufacturing costs. It can be seen that even in the case of the highest cost scenario for DC cabling costs, there remains a reduction in capital costs from the use of direct to shore DC arrays.

Table 2 Sensitivity to DC Array Cabling Cost Assumptions (50km offshore)

Capex Costs of Direct to Shore MVDC compared to HVAC Baseline			
HVAC (assuming dynamically rated cables)	**Direct MVDC Best Case DC cable Cost Scenario**	**Direct MVDC Mid Case DC cable Cost Scenario**	**Direct MVDC Worst Case DC cable Cost Scenario**
£384-407m	£233-239m	£270-276m	£371-376m

We note that capital cost savings may weigh more heavily with developers than lifecycle costs when considering the business case behind any particular technology. If viewed from this perspective, MVDC would appear to offer real potential for benefit, and this may be sufficient to encourage future development of the concept.

The direct MVDC solution does however require 5 DC cable circuits back to shore compared to 3 circuits for the AC baseline. This could pose challenges for the seabed cable corridor easements.

Gaps & Risks – Industry Perspective

Risk and gap analysis was undertaken for all DC array topologies. Both technology-related and commercial risks were explored and the results have been discussed with key stakeholders at a public workshop. The comments from the workshop attendees showed that from a technology standpoint, there is a reasonable consensus on the risks and gaps identified. It was noted that none of the technical challenges presents a fundamental technology barrier to the development of DC arrays; however there are individual components which require further development and demonstration.

The main obstacle to implementing DC arrays currently is from the commercial side; in particular the greatest risk is uncertainty in the cost and cost reduction potential of key equipment, handling and installation.

Table 3 below summarises the technology key risks relevant to Direct MVDC arrays, as this is the most promising DC array topology.

Table 3: Summary of risks for MVDC arrays

Topology	Low Risk – some mitigation needed, solutions available	Medium Risk – significant mitigation may be required	High Risk – critical obstacle to projects
All	Supply availability of MVDC cables – limited number produced. Certification process for turbines. Training of offshore personnel.	Uncertainty in reliability and typical availability of DC wind turbines. MVDC protection technology not fully developed.	Uncertainty in cost of DC wind turbines. Project funding may be difficult to acquire due to risks.
Direct to Shore MVDC (Option 5) only	MVDC/AC Onshore Converter - only available at smaller scale, risk of high costs. Unclear regulatory position regarding OFTO regime.	Large cross-section array cables may pose installation challenges. Cost uncertainty of MVDC/HVAC conversion technology.	

Consideration of Larger Wind Turbines

An additional consideration going forward is that next generation WTGs will exceed 10 MW and possibly approach up to 15 MW capacity. This will result in a reduction in the number of WTGs that can connect per string and overall wind farm capacities may increase as more power can be yielded from the same area with these larger turbines. This will present several challenges relating to an increased number of strings, and potentially increased offshore substations to accommodate these, which will contribute to increased costs for an overall project.

The increase in WTG size could act as a significant technology driver fort the Direct MVDC topology as DC arrays would provide cost savings on offshore platforms and also facilitate a much larger number of WTGs able to connect per string. Depending on array cable sizing, conceptual studies suggest that between 200 and 300 MW could be accommodated on a single ±80kV DC string.

Roadmap to DC Arrays

The most critical risks have been investigated further, using road-maps to lay out the necessary steps to develop both commercial and technical capability to construct an offshore wind farm implementing DC arrays.

DC WTG integration

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. A demonstration project involving a full scale wind turbine will be critical to addressing operational concerns and physical space requirements. The earlier GE demonstration utilised a novel approach to back-feed arrangements to allow a small amount of ancillary power to be back-fed through the passive rectifier. The limits of this approach could be investigated further in the lab prior to a new demonstration project.

There are several offshore demonstration facilities designed for testing innovative or novel WTG design ideas, however because the connection design is fundamentally innovative, it is expected that a purpose built demonstration wind farm with a small number of WTGs close to shore would need to be developed to fully demonstrate a DC WTG. The timescale to get to this point is estimated to be approximately 8-10 years. Only after this stage would it be realistic to consider the potential deployment of DC Connected Wind Turbines in a full scale offshore wind farm.

Commercial Project Development/Funding

It has been noted throughout the study that the industry is conventionally risk averse, partially due to project financing requirements, and partly given the practical challenges of operating and maintaining equipment offshore and therefore any projects incorporating new technology will have a high risk associated due to the lack of operational experience and their unknown performance. Further work may be required to sufficiently de-risk the business case for a commercial party to undertake the development of a wind farm utilising DC arrays.

Practical offshore demonstration projects at a smaller scale can be extremely valuable in de-risking the technology components and providing increased confidence in reliability, availability and operational considerations. Demonstration projects are often implemented at a smaller scale compared to typical offshore wind farms with limited commercial risk - often subsidised by external or government partners.

In our roadmap, the technology demonstration phase is followed by work to de-risk the commercial aspects of the project, including:

- Regulatory treatment of 80kV DC arrays under the OFTO regime
- Project insurance
- Project costs compared to AC benchmarks

There are significant timescales involved in the development of individual components as well as the overall system, suggesting that currently the first full scale offshore wind farm utilising DC arrays could be over 10 years away.