CARBON TRUST

Unlocking the next generation of offshore wind: step change to 132kV array systems

Summary report of the Offshore Wind Accelerator High Voltage Array Systems project

Contents

Glossary

Alternating current (AC)	one of the two common forms of electric current used for power transmission, where electric current oscillates periodically with respect to time, in contrast to direct current which does not.
Array	the section of an offshore wind farm between the turbines and the offshore substation.
Array cable	the cable used to connect adjacent turbines to each other and to the offshore substation.
Array life cycle costs	a subset of the electrical life cycle costs of an offshore wind farm, found by considering the Capex and Opex of the array system only (i.e. the equipment from the WTG transformer to the offshore substation grid entry point), and excluding the export system.
Capital expenditure (Capex)	the amount of money spent on physical assets of an offshore wind farm.
Cigré	the International Council on Large Electric Systems – a collaborative global community committed to the development and sharing of power system expertise.
Commercial readiness	definition given in Appendix.
Cost benefit analysis (CBA)	methodology to compare the strengths and weaknesses of alternative approaches, typically through financial comparison.
Dry cable	cables with an impermeable (typically metallic) sheath that is designed to keep the cable insulation and conductor dry by preventing water ingress, to be contrasted with a wet cable, which does not have such an impermeable sheath.
Electrical life cycle costs	the Capex and Opex of the complete electrical infrastructure of the wind farm from the WTG transformer to the onshore point of connection; this includes the WTG transformers, array cables, offshore substation switchgear, transformers and cable compensation, export cables and onshore substation switchgear, transformers, export cable compensation and reactive compliance equipment.
High Voltage Array Systems (Hi-VAS) project	the OWA project whose methods and results are discussed in this report.
IEC	The International Electrotechnical Commission – an international standards organisation.
J-tube	curved tubes used to protect cables at the cable entry point between the seabed and the turbine foundation.
Offshore substation (OSS)	housed on an offshore platform within the offshore wind farm, it collects power from individual array cables, increases the voltage, and sends power to the export cable to shore.
Offshore Wind Accelerator (OWA)	the Carbon Trust's flagship collaborative research, development and demonstration programme, in collaboration with nine leading offshore wind farm developers.
Operational expenditure (Opex)	the amount of money spent on operating an offshore wind farm, which for this study includes electrical losses and unavailability due to equipment failure.
SF_6	Sulphur hexafluoride – a gas used to increase the safety of electrical components due to its insulative properties; however, it is a greenhouse gas.
String	a series of WTGs, typically in a line or row, that are all connected to one another and then the OSS by array cables.
Transition piece	the section of the support structure of a WTG that is located between the foundation and the tower, which typically houses the switchgear and other electrical components.
Technology readiness	definition given in Appendix.
Wet cable	cables that do not have an impermeable barrier and allow the water to migrate into the cable insulation and conductor.
Wind turbine generator (WTG)	generic term used to describe the combination of the turbine, the tower, the transition piece and the foundation.

The Offshore Wind Accelerator

The Offshore Wind Accelerator (OWA) is the Carbon Trust's flagship collaborative research, development and demonstration programme. The joint initiative, which has been running since 2008, is a collaboration between the Carbon Trust and nine offshore wind developers. Its aim is to reduce the cost of offshore wind to be competitive with conventional energy generation, to accelerate the deployment of offshore wind globally, and to drive industry standards and best practice.

The High Voltage Array Systems project

The OWA High Voltage Array Systems project is a joint industry project set up within the OWA with the aim of developing industry-wide consensus on the optimal future array voltage level (above the current standard, 66kV) and how the transition to the next voltage level can be best made. The project follows on from a previous study of the OWA conducted in 2010 that reviewed the technical and economic benefits of migrating array cables to voltages greater than 33kV in response to an increase in Wind Turbine Generator (WTG) capacities. The 2010 study set 66kV as the global standard array voltage, and this remains the standard today. The project is driven and funded by ten international offshore wind farm developers and operators: EnBW, Equinor, Ørsted, Ocean Winds, RWE, ScottishPower Renewables, Shell, SSE Renewables, TotalEnergies and Vattenfall.

Acknowledgements

This report provides an executive summary of the OWA High Voltage Array Systems project recently delivered by TNEI Services and Petrofac for the Offshore Wind Accelerator. TNEI and Petrofac worked closely with the Carbon Trust and the High Voltage Array Systems project partners over the course of the project. They also received inputs from Hellenic Cables and Orient Cable who were contracted to develop concept designs for various high voltage array cables. During the project, TNEI and Petrofac also engaged numerous technology manufacturers, array system installers, system operators, regulators, universities, and research institutions. We would like to thank all those who provided input.

Executive summary

132kV will be the next array operating voltage level.

Urgency to transition to 132kV to avoid suboptimal future wind farm design.

The Carbon Trust's Offshore Wind Accelerator High Voltage Array System (OWA Hi-VAS) project was launched to future proof the array system by determining the optimal array voltage level above the current 66kV standard to accommodate wind turbine generators (WTGs) larger than 14MW.

Robust and detailed engineering analysis, in conjunction with life cycle cost-benefit studies, concluded that 132kV operating voltage is the cost-optimal next array voltage. For example, for a 1200MW offshore wind farm with a single offshore substation, cost savings are predicted in the range of £32M to £50M relative to the equivalent 66kV system.

The industry's last voltage shift began in 2010, when the Offshore Wind Accelerator drove the change from 33kV to 66kV. This change in turn enabled 8-12MW turbines to be brought to market and was considered a key factor in offshore wind's success in the past decade. Since then, the industry has grown rapidly in both wind farm and turbine size. Ensuring this continued growth is efficient and cost effective will be key to the continued success of the global offshore wind industry, which is the motivation for the current project.

There is urgency to bring 132kV technologies to the market. In the OWA Hi-VAS project, it was found that 132kV offers significant cost saving potential over 66kV, even for wind turbines of 14MW, which are currently available at 66kV. However, the project found that the earliest 132kV wind farms could be operational is the end of the 2020s, and even this timescale is dependent on significant proactive work being carried out by developers and the supply chain immediately. To ensure the most efficient voltage level is used for future offshore wind farms, it is critical no time is lost. The industry must focus on 132kV technology development to ensure the dramatic cost savings that 132kV will bring are realised as soon as possible.

1. Introduction

As offshore wind turbines are set to increase in size beyond 14MW, the current standard array voltage of 66kV could become the limiting factor in array design and overall output potential of offshore wind farms. To futureproof offshore wind array systems, a higher array voltage will be necessary to allow more power to be transmitted through array cables. This in turn will enable cost-effective string lengths and layout designs; reduce electrical losses; lower the ecological footprint of offshore wind farms; and ultimately enable the deployment of larger turbines. However, until now, there has been no clear path for the industry to move above 66kV since the next voltage level was uncertain and hence most array system components have not been offered on the market at any voltage greater than 66kV.

The Offshore Wind Accelerator (OWA) identified and responded to this challenge by conducting a study to determine the optimum AC array voltage for the next generation of bottom-fixed wind turbines. The study was conducted through consultation with industry and investigation of the technical and economic feasibility of a range of different technologies. The primary objectives of the study were to:

- Determine the optimum voltage for high voltage array systems based on robust technical, cost-benefits and risk assessments.
- De-risk future wind farm projects that will use the new array voltage level through concept and detailed engineering design and analysis.
- Promote the optimum voltage as a global standard.
- Inform wind farm developers, the supply chain, regulators and other relevant stakeholders about when the change to the higher voltage is likely to occur and the critical path to transitioning to the next voltage.

This report summarises the key findings from the project.

2. What is the next optimum array voltage?

The study considered the nominal voltages of 90kV, 110kV, 132kV and 150kV as candidates for a new higher voltage array standard across a range of different turbine sizes (14MW, 17MW and 20MW) and several offshore wind farm sizes and configurations common in industry. The conclusion from the technical, economic, regulatory and risk assessments, in conjunction with consensus from the supply chain industry, is that **132kV** should be the next optimum array operating voltage (145kV U_{max}). The main reasons include:

- 132kV array systems have the best benefit to cost ratio of the voltages studied, driven primarily by cheaper cables and wind turbine switchgear compared to 150kV.
- 132kV is a standard power distribution and transmission voltage and aligns with existing equipment standards that will facilitate international supply chain buy-in.
- Equipment and accessories are either in development or already available from a range of suppliers and are expected to be competitively priced due to economies of scale.
- The time to market for 132kV SF_6-free compact switchgear is much quicker than for 150kV as commercial products already exist.
- Time to market for 132kV array cable and accessories would be much quicker than for 150kV as several manufacturers have ongoing research and development into 132kV technologies.

3. Why was 132kV selected?

132kV has been selected as a result of an in-depth study of the costs, benefits and risks of various higher voltage levels, which in turn has been informed by significant stakeholder engagement across the supply chain, and through detailed engineering analysis.

3.1 132kV array system engineering study

To inform the overall cost benefit analysis (see section 3.3 below) and to identify any potential barriers that would prevent the use of 132kV, a detailed array system engineering design study was performed. As described in more detail below, this design study showed that 132kV array systems are technically feasible, uncovering no technical showstoppers.

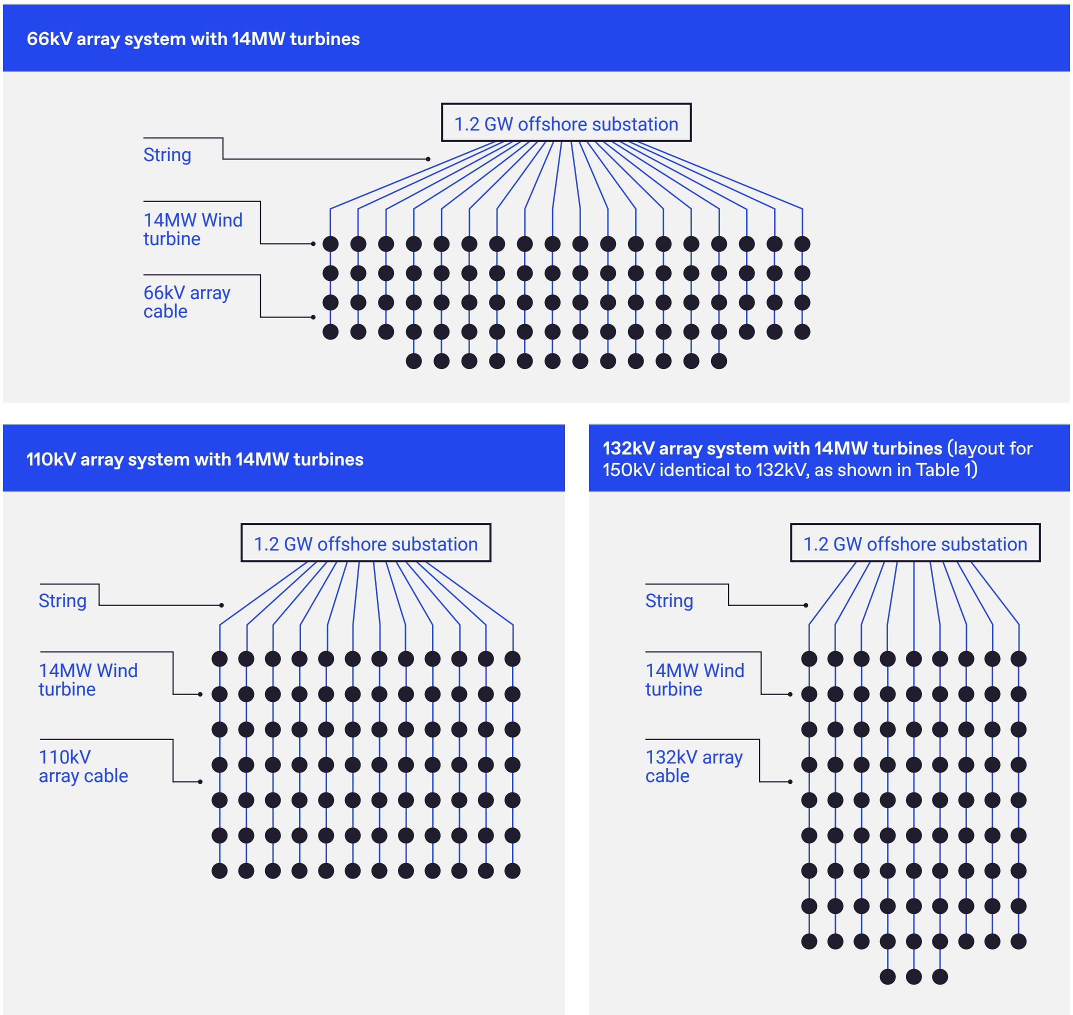
Regarding the study, several different wind farm configurations and layouts were assessed with 14MW, 17MW and 20MW WTGs, using array voltages of 66kV, 110kV, 132kV and 150kV. One of these design scenarios was selected for the detailed engineering design study and cost assessment. The scenario selected was a 1200 MW wind farm with a single offshore substation equipped with three 440MVA transmission circuits and located 75km offshore. This was selected for the detailed design study as it is believed to be characteristic of future wind farms that will use the next array voltage level. A summary of the design scenarios and array layout is provided in the table and diagrams below.

Table 1: Example of one scenario studied in the project (~1200MW wind farm with one OSS).

Wind Turbine Rating	14MW	17MW	20MW
Wind Farm Rating	1176MW	1224MW	1200MW
Number of turbines	84	72	60
String arrangement (tapered) at 66kV	12 x 5WTGs+ 6 x 4WTGs	18 x 4WTGs	6 x 4WTGs + 12 x 3 WTGs
String arrangement (tapered) at 110kV	12 x 7WTGs	12 x 6WTGs	12 x 5WTGs
String arrangement (tapered) at 132kV	6 x 9WTGs + 3 x 10WTGs	9 x 8WTGs	6 x 7WTGs + 3 x 6WTGs
String arrangement (tapered) at 150kV	6 x 9WTGs + 3 x 10WTGs	9 x 8WTGs	6 x 7WTGs + 3 x 6WTGs

Table shows how the array layouts for this scenario change with array voltage and turbine capacity. Four other scenarios were also studied, but not shown here for conciseness.

Figure 1: Wind farm layout changes with voltage level.



This is shown for 14MW turbines. Similar layouts were constructed for 17MW and 20MW turbines, as shown in Table 1.

The length of each string increases, but the number of strings and overall length of cable reduces with voltage.

3.1.1 Transition piece design and layout

A detailed engineering design study was undertaken. One of its aims was to determine if 132kV switchgear and cables would fit inside the transition piece of a 14MW turbine. Likely switchgear configurations, cable connections, and installation and access requirements were informed by input from several offshore wind farm developers. The design and equipment layout for the transition piece showed that the higher voltage equipment could be installed, and the cables could be successfully pulled in and terminated, while leaving sufficient space for operating and maintenance, as well as the removal of faulty equipment.

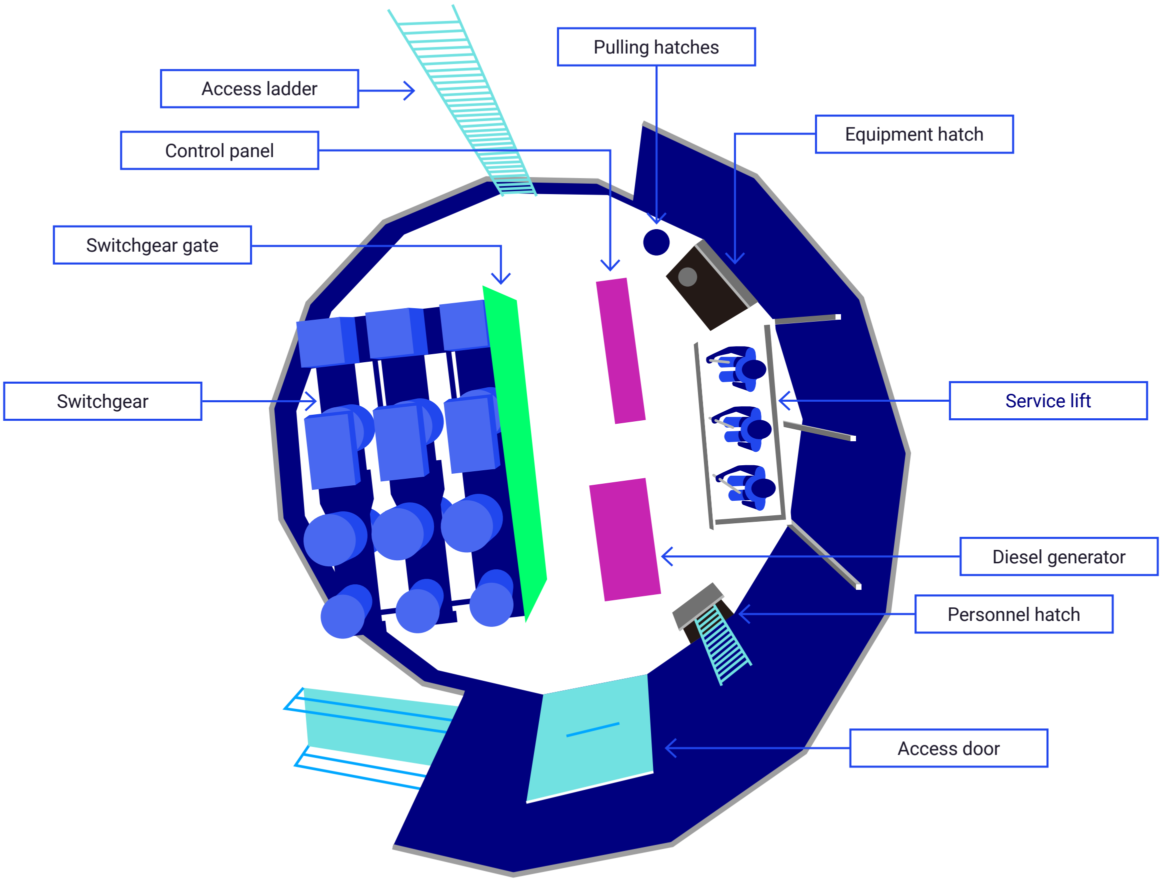
A turbine tower with an 8.0m diameter base and 100mm wall thickness was used as a conservative representation of future large wind turbines. The layout utilised 150kV switchgear of an SF_6-free design based on input from equipment manufacturers. This was considered a “worse case” design, recognising that 132kV SF_6-free switchgear would be smaller, and if the design worked for 150kV switchgear, it would equally work for 132kV switchgear.

In accordance with the developers’ requirements a removeable barrier to segregate the HV switchgear from the rest of the working area was included along with a control panel, diesel generator, lift and hatches for accessing the cable deck below.

Two array cables were modelled with an installation bending radius of 3.7m and a finished (dressed) bending radius of 1.4m. These bending radii, estimated at the time, were verified by Hellenic Cables and Orient Cable as realistic and in-line with the mechanical characteristics of the concept 150kV cables.

The layout design (Figure 2) demonstrated that a transition piece with an 8.0m diameter could accommodate a three circuit breaker arrangement utilising standard substation 150kV (and therefore also 132kV) switchgear of an SF_6-free design, in a workable configuration. The diameter was also sufficient to enable the installation and termination of two array cables. The study also verified that the transition piece access door can remain the same size as with current 66kV designs, due to the modularity of the switchgear equipment.

Figure 2: Transition piece equipment layout on switchgear deck utilising high voltage switchgear



3.1.2 Offshore substation design

A single offshore substation design was developed for the base case 1200MW wind farm with three 440MVA 220/66kV transformers on a single offshore platform. The design included three 75km 2000mm2 submarine transmission cables connecting the wind farm to the onshore substation, each with a 136MVAr reactor on the platform for reactive power compensation.

Utilising higher voltage array cables was found to have no impact on the structural design or layout of the offshore substation. This is because 132kV or 150kV switchgear are already currently used due to the high current ratings required, and because the cable deck spacing is set by the requirements of the export cable which is larger than any of the array cables. Furthermore, any minor change in loading on the jacket substructures due to increased cable size, which would also require an increased size of J-tube and hence attract a higher level of hydrodynamic loading, is likely to be offset by a reduced number of array cables which would yield a cleaner design and result in lower hydrodynamic loads. In addition, the bulk of the equipment weight is contained in the transformers and reactors, which are largely unaltered by the change in array voltage.

Higher voltage cables potentially require much larger testing equipment than what is currently used for 66kV, and therefore provision needs to be made for sufficiently large temporary laydown areas during commissioning and sufficiently rated cranes to lift the testing equipment.

3.1.3 Array system reactive compensation

Existing 66kV array systems typically rely on the reactive power compensation of the WTGs for optimal power transfer. The requirements for reactive power compensation increase with voltage, and this was assessed during the study. It was determined that the requirements at 132kV are still within the capability of the WTGs. As a result, additional equipment for reactive power compensation or harmonic filtering of the array circuits is not deemed necessary.

3.2 132kV cable design, qualification, and testing

Through engagements with a wide range of cable suppliers, views on future design of high voltage array cables were gathered. To ensure the project was receiving sufficiently detailed information on possible future cable designs, Orient Cable and Hellenic Cables were contracted via a competitive tender process. They provided the project with a wide range of possible cable designs (including wet and dry 132kV cables), clarifying their electrical and mechanical properties, and providing an indication of their market readiness, costs and engineering challenges.

From this work, the project concluded that 132kV cables are technically feasible and so do not present a showstopper to transitioning to 132kV; however, challenges remain in building confidence in 132kV array cables and further work is required to define suitable qualification and testing standards for 132kV cables.

Existing standards and guidelines such as IEC 60840 and Cigré TB 490 could be used to qualify 132kV lead-free cables of a dry design. However, standards such as IEC 63026 and Cigré TB722 only cover wet design cables up to 66kV, and so these standards would need to be revised or new ones developed to qualify 132kV wet design cables.

Developers have also expressed a requirement for testing standards that cover terminations and earth leads, and for consensus in the industry with respect to the test standards and methodologies to be used for post-installation testing of 132kV array systems. These subjects could be covered as part of the scope of follow-on work in the OWA.

3.3 Cost Benefit Analysis

The above engineering design and cable design work fed into a cost benefit analysis (CBA) study, which was completed to understand the business case for moving to high voltage array systems and to identify the optimal next voltage level. The analysis concluded that 132kV is the optimum higher voltage.

3.3.1 How the cost-benefit was performed

The CBA was undertaken assessing the multiple wind farm scenarios mentioned above (see section 3.1). In the CBA, each of these scenarios was modelled at 66kV, 110kV, 132kV and 150kV and with 14MW, 17MW and 20MW turbines.

The CBA considered the impact on Capex and Opex resulting from increases in array voltage.

For each wind farm design concept, the "electrical life cycle costs" were derived for the complete electrical infrastructure of the wind farm from the WTG transformer to the onshore point of connection including, WTG transformers, WTG switchgear, array cables, offshore substation switchgear, transformers and cable compensation, export cables and onshore substation switchgear, transformers, export cable compensation and reactive compliance equipment. Both losses and unavailability were capitalised based on a 25-year wind farm lifespan. The CBA also calculated the "array life cycle costs" as a subset of the electrical life cycle costs by considering the Capex and Opex of just the array system, i.e. the equipment from the WTG transformer to the offshore substation grid entry point.

Capex costs were generally derived from stakeholder feedback. Except for lead-free high voltage array cables, all equipment is currently available within the market and thus cost uncertainty is minimal. However, the expectation is that the adoption of higher voltage array systems would inevitably result in currently available equipment being developed or modified specially for use offshore, much in the same way as the step change from 33kV to 66kV, resulting in additional cost savings. The CBA reflects that 150kV equipment is currently more expensive than equipment at 132kV and lower voltages.

The CBA considered input cost data for 110kV, 132kV and 150kV array cable based on the concept designs and cost estimates from Orient Cable and Hellenic Cables. These specifically included options with aluminium and copper conductor and both wet and dry lead-free designs. Both cost sensitivity and different design options were included in the CBA to ensure conclusions drawn were robust.

3.3.2 Cost-benefit results

The findings show that:

- Costs savings directly relate to cable technology. Maximum savings are shown for wet cable designs which are cheaper, lower loss and have higher current carrying capacity. Dry type cables however remain cost beneficial vs 66kV for all turbine sizes.
- Though wet cables are generally cheaper than dry cables, the cost range (cost sensitivity) utilised in the CBA results in an overlap between the predicted overall cost savings achieved when using wet cables and when using dry cables (i.e. whilst wet cables are generally cheaper than dry cables, greater cost savings are predicted when using the minimum predicted cost of dry cables than when using the maximum cost of wet cables).
- Cost savings improve with increasing WTG rating, but even at 14MW turbine sizes 132kV is significantly beneficial vs 66kV.
- Cost savings are independent of cable conductor material (copper or aluminium). It was noted that for aluminium cables, relative savings are higher for losses and lower for Capex than the equivalent copper cable options. This was driven by the higher resistance and cost multipliers associated with aluminium cables versus copper cables.
- Results were found to be robust irrespective of the base case cable costs (Base/Max). The studies undertaken were based on cost multiplier, from a base case cost, associated with changes in voltages and cable technology. Increasing base case cable cost (even by double) has no significant impact on the validity of the conclusion drawn that higher voltage systems are more beneficial than 66kV.

Figure 3: Projected array life cycle cost savings for 110kV, 132kV and 150kV, relative to 66kV, showing sensitivities of varying conductor material (aluminium / copper) and varying cable costs (minimum expected cost of wet cables, maximum expected cost of wet cables, minimum expected cost of dry cable, maximum expected cost of dry cables)

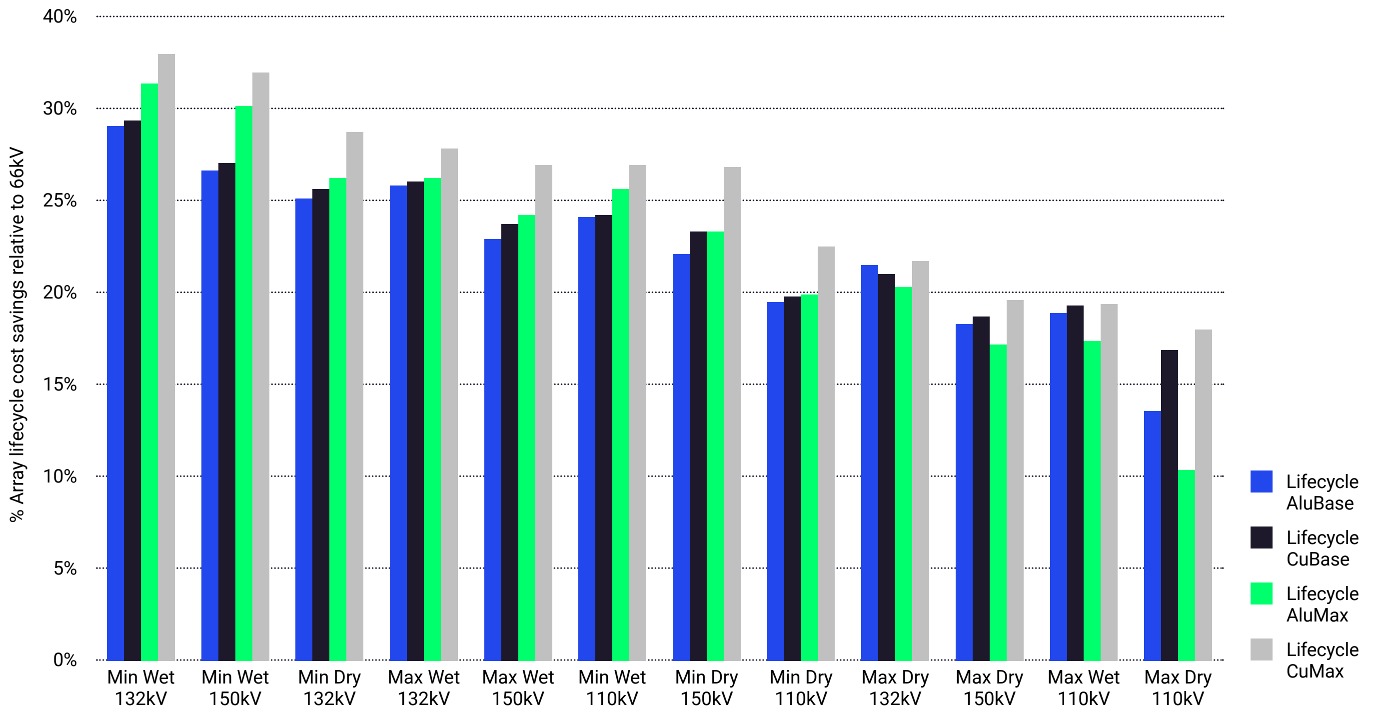
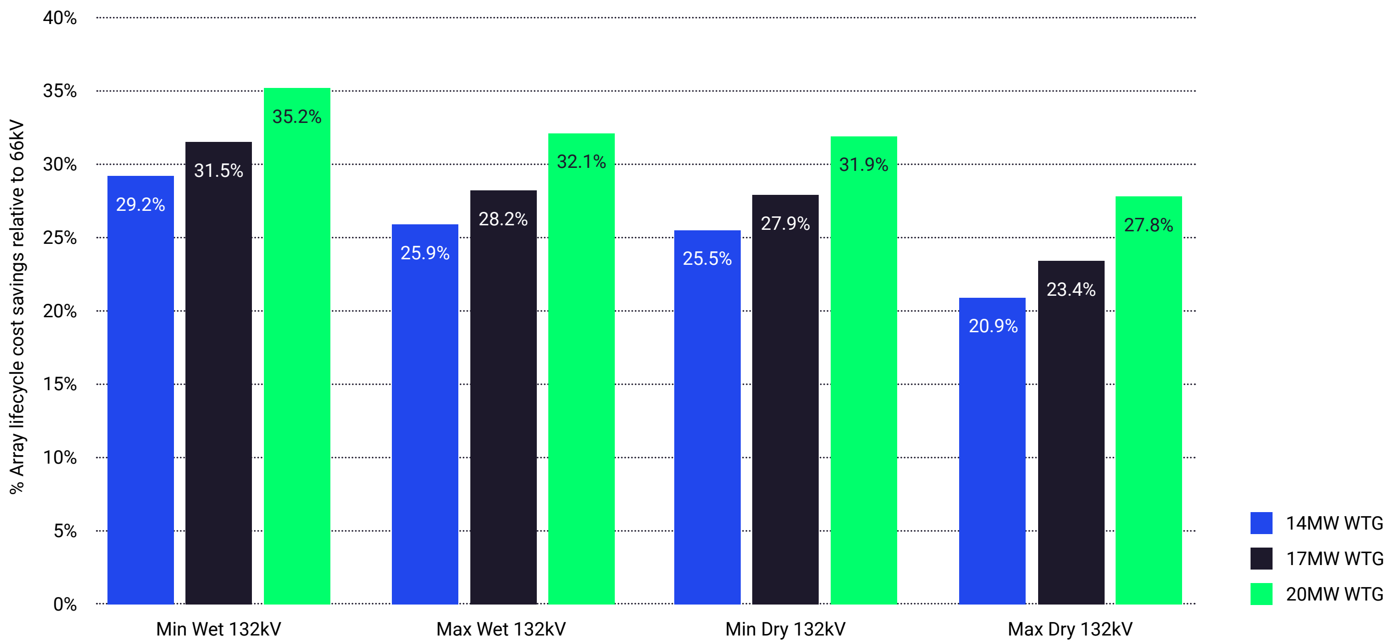


Figure 4: Projected array life cycle cost savings of 132kV (only), relative to 66kV, for different turbine sizes and showing sensitivities of varying copper cable costs (minimum expected cost of wet cables, maximum expected cost of wet cables, minimum expected cost of dry cable, maximum expected cost of dry cables)



The CBA findings indicate that array life cycle cost savings could be as high as 35% for 132kV arrays compared to the 66kV base case under the most favourable conditions (20MW turbines, 132kV wet cables). However even under the least favourable conditions (14MW turbine, 132kV dry cable), the minimum cost savings are still in excess of 20% as shown. If the life cycle cost of the transmission system is added to the array life cycle cost, then the electrical life cycle cost savings resulting from 132kV arrays are between 3.6% and 6.9% relative to the 66kV base case.

In general, higher voltage systems are more cost effective than 66kV systems as they:

- Result in a reduction of installed cable length in comparison to 66kV due to the reduced number of strings and hence fewer final connections to the offshore substation.
- Result in a reduction in electrical losses in comparison to 66kV; predominantly due to lower current flows.
- Result in a reduction in cost of unavailability in comparison to 66kV; predominantly due to less cable; the impact of failures is higher put the probability of failure is lower.

Capex was found to be the dominant driver in the CBA, and since 132kV components (particularly cables and switchgear) are expected to be cheaper than 150kV components, this led the CBA to showing that 132kV is the cost optimal next array voltage.

4. Roadmap: how does industry transition to 132kV?

4.1 Urgency to transition to 132kV

Whilst the current project has shown there are no showstoppers for the transition to 132kV, challenges remain to coordinate the industry to make the transition. The main challenge is to ensure the transition happens as quickly as possible. As shown in section 3 above, even 14MW turbines, which are already on the market, will be cost beneficial at 132kV compared to 66kV. Making the transition to 132kV is therefore urgent in order to ensure the offshore wind industry gains the benefits of the higher voltage as quickly as possible, and hence avoids suboptimal wind farms being designed and constructed.

4.2 Technology and Commercial Readiness

The technology and commercial readiness of the key technologies that make up high voltage array systems were assessed using respective industry standard indices (Appendix). The outcome is summarised in Table 2.

Table 2: Technology and commercial readiness of 132kV array system technologies

Technology	Technology Readiness 1 (low) to 9 (high)	Commercial Readiness 1 (low) to 6 (high)	Notes
Lead free 132kV dry array cable	**6**	**2**	Several manufacturers have started developments of 132kV lead-free dry design array cable. The expectation is that such cables could be available in the next 1-2 years as existing technology, materials and qualification standards could be used. Could be used until wet-design cables become available.
Lead free 132kV wet array cable	**4**	**1**	Several manufacturers have started research and development into 132kV lead-free wet design cables. Feedback from industry is that 132kV wet cable could be commercially available in the next 2 -3 years.
132kV array cable outer cone terminations	**3**	**1**	Outer cone (F-type) connectors exist for 66kV but have not yet been developed for 132kV as there has been no market demand. Manufacturers see no technical barriers and could develop within the next 2 years based on demand. Existing inner cone terminations could be used in the interim.
132kV array cable inner cone terminations	**8**	**6**	Should outer cone technology not be ready for the first 132kV wind farms, 132kV inner cone connectors can be used instead. These are commercially available and used in land-based substations. Engineering design studies carried out on this project have shown that offshore application is feasible.
132kV turbine switchgear (SF_6-free)	**6**	**3**	Several manufacturers already have 132kV SF_6-free switchgear that is commercially available for land-based applications. Compact versions of the switchgear need to be developed for offshore applications.
132kV surge arrestors	**9**	**6**	Existing surge arrestor products for onshore applications can be used offshore without any modification.
Turbine 132kV flexible cable terminations	**9**	**4**	132kV flexible cable connections do exist, but only from selected manufacturers.
Turbine 132kV flexible cables between the nacelle and the transition piece	**8**	**4**	Some manufacturers already have 132kV flexible cables (single phase) which can be used to connect the transformer in the nacelle to the switchgear in the transition piece. Others see no technical barriers and believe 132kV solutions could be market ready within 2 years if there is sufficient demand.
Wind turbine transformers	**8**	**1**	132kV transformers are commonly available in the distribution industry but have not yet been implemented in an offshore setting. Technology is mature, but commercial products have not yet been designed.
Offshore substation (OSS) Switchgear	**8**	**6**	132kV and 150kV switchgear is already. being used on the OSS for 66kV arrays due to the high current rating required. SF_6-free land-based versions can be deployed as is.
OSS transformers	**8**	**6**	220/132kV transformers are not common but can be designed and manufactured using existing technology.
Cable testing equipment	**7**	**4**	Cable installers continue to develop new test methods and equipment for post-installation testing, and equipment is available that could be used to test 132kV array cable.
Wind turbines supporting 132kV systems	**4**	**1**	These wind turbines don't exist yet, but some work is underway and 132kV is not envisaged to be a problem once there is demand for it from developers.

4.3 Technology Roadmaps

Technology roadmaps for wet and dry 132kV cable array systems were developed based on the above technology and commercial readiness assessments of the various technologies and are presented in Figure 5 and Figure 6. The elements of the roadmaps are covered in more detail in the sections below.

Developers have a fundamental decision as to whether the first 132kV wind farms will use wet or dry cables. Work carried out in this project concludes that dry cables can be brought to market more quickly; however, wet cables are cheaper and provide performance benefits over dry cables.

In the long term, it is expected that wet cables will be used; however, it is not yet clear which type of cable will be used in the first 132kV wind farms, which is why roadmaps for both wet and dry-cabled 132kV wind farms are presented. It may be that the first 132kV wind farms use 132kV dry cables in order to bring 132kV wind farms online quickly, before the industry then transitions to 132kV wet cables. However, it may be that developers go straight for 132kV wet cables, due to their cost and performance benefits. The OWA will seek to give clarity to cable suppliers regarding developer preference on wet or dry cables in follow-on work within the OWA.

Figure 5: Proposed 132kV array technology roadmap – wet cables

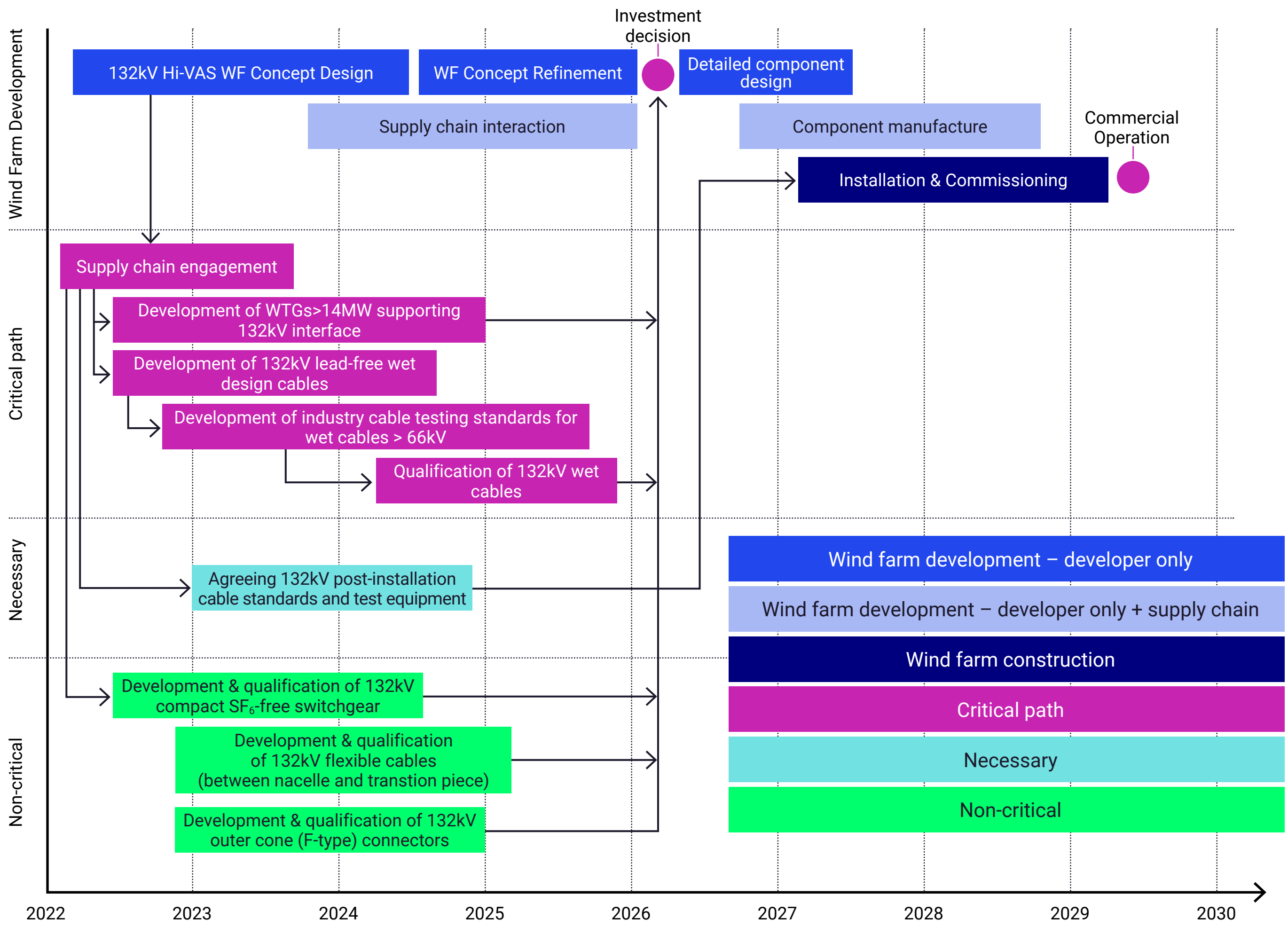
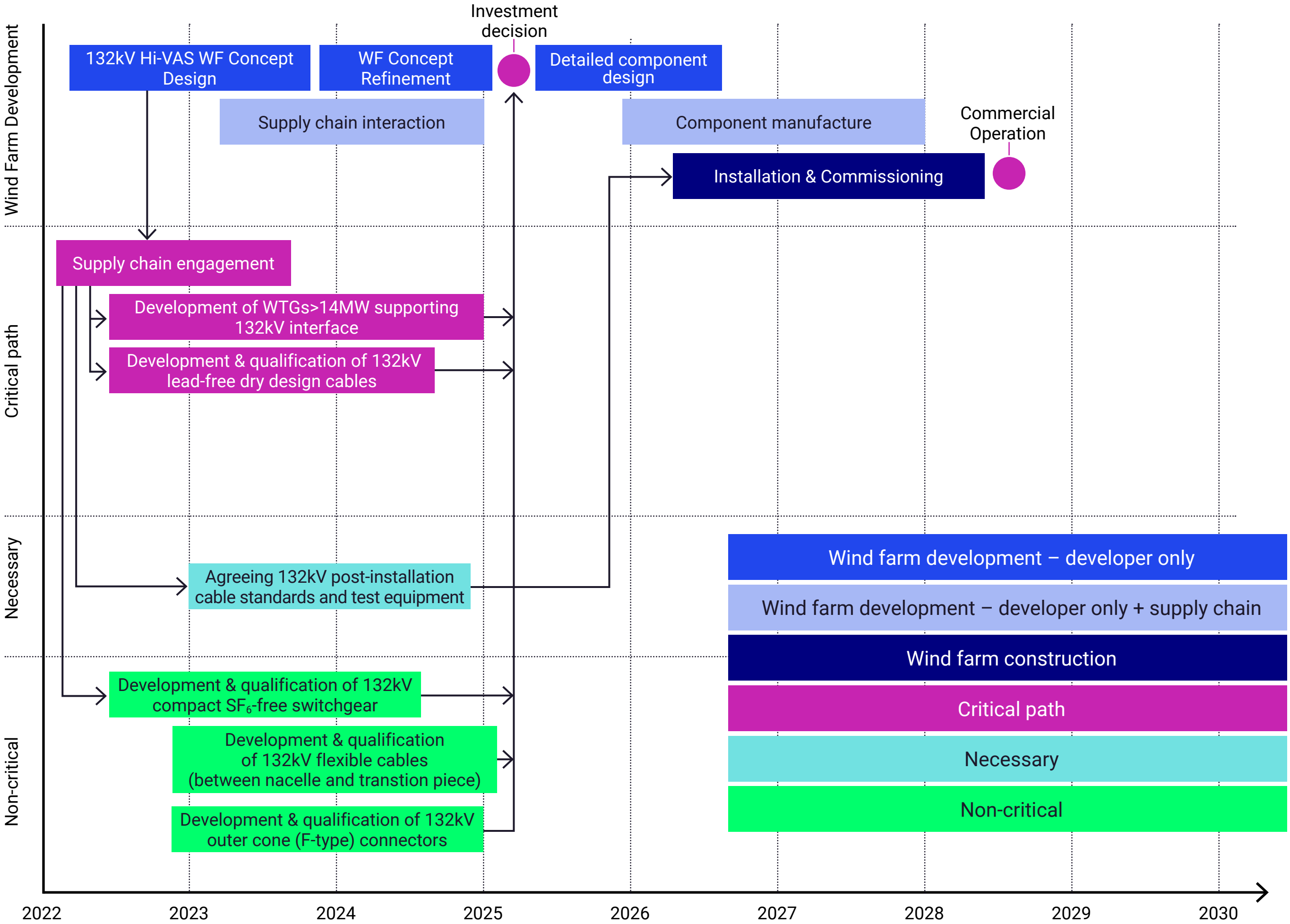


Figure 6: Proposed 132kV array technology roadmap – dry cables



4.3.1 Transition drivers

The development process is driven by the concept design of future wind farms informed by the potential cost savings of 132kV array systems compared to conventional 66kV systems. Once the different array voltage designs have been conceptualised, developers should engage the supply chain to determine the availability and cost of the two key components, namely 132kV array cable and wind turbines with 132kV interfaces to inform the design and investment decision.

4.3.2 Critical developments

The critical technology developments in the roadmap are shown in pink in Figure 5 and Figure 6 and include:

- Technology and commercial development of 132kV lead-free array cable (which is required for 132kV dry cables, as well as wet cables)
- Development of industry cable testing standards extending to at least 132kV for wet cables
- Qualification of 132kV array cables (which is required for 132kV dry cables, as well as wet cables)
- Development of wind turbines >14MW supporting 132kV systems

The development, testing and qualification of 132kV lead-free cables is central to realising commercial 132kV array systems. Qualified cables are deemed essential to reduce risk before making investment decisions in wind farms.

Should wet cables be preferred by developers for the first 132kV wind farms, a key part of this is the development of suitable cable testing standards for wet cables which do not currently exist. Feedback from the supply chain and test labs who were involved with the development of 66kV standards (such as Cigré TB722 and IEC 63026) have suggested that a 2–3-year lead time should be expected for developing wet cable testing standards up to 132kV. Should dry cables be preferred by developers for the first 132kV wind farms, dry cables could be qualified using existing standards such as IEC 60840 and Cigré TB490, and therefore have a quicker route to commercialisation.

The technology readiness for wet design 132kV array cable was assessed as level 4 based on reports that several manufacturers have already started development of the technology in the laboratory. Through cable design work carried out as part of this project, technical challenges surrounding insulation technology and materials, as well as manufacturing challenges remain, but are not believed to be major technical barriers, and feedback suggests that commercial solutions for wet cables could appear within the next 2-3 years. Since lead-free dry-design cables can be developed using existing materials and technology, the technology readiness of dry cables was assessed as level 6. Commercial readiness of dry cables is higher than for wet cables, and solutions are expected within the next 1-2 years.

In parallel, it is very important that wind turbine suppliers commence and/or continue the development of turbines that can support 132kV systems. The required developments may include changes to the generator and/or inverter for some turbines, or just be limited to transformer changes for others. However, all turbine suppliers should aim to develop solutions for 132kV transformers and flexible cables and have them available at the same time that qualified 132kV wet-cables cables are expected to become available. If 132kV turbines become available sooner, then dry-design cables could be utilised. Continued engagement and co-ordination between stakeholders will be necessary to align turbine and cable developments, which will be a focus of follow-on work in the OWA.

4.3.3 Non-critical developments

Non-critical technology developments are indicated in green on the roadmap. These technologies range in technology readiness from 6 to 9, however their development and qualification are not deemed critical to the investment decision as viable alternatives already exist. For example:

- Should compact SF_6-free switchgear not be developed prior to 132kV cables and turbines being qualified, existing 132kV land-based SF_6-free switchgear could be used in the transition piece in lieu of compact versions, as has been verified through the design and engineering studies carried out as part of the project.
- Some 132kV turbine flexible cables already exist, although they are only available from selected manufacturers.
- Should outer-cone connectors not be developed prior to 132kV cables and turbines being developed, 132kV inner cone connectors could be used instead of outer-cone connectors, even though they take up more space and their use adds complexities.

The timeframe for the development of these technologies as shown on the roadmap is based on industry feedback; however, they are subject to manufacturers receiving commercial commitments.

4.3.4 Necessary developments

Several post installation cable testing methods already exist for 132kV (as per Cigré Technical Brochure 841 for example). However, feedback from cable installers is that there is often disagreement about which test methods should be used. For 132kV arrays to succeed, it is essential that the industry reaches an agreement on the test methodology and standards, especially given the increased importance of testing at higher voltages to verify correct installation, and this could be included in the scope of follow-on work in the OWA. Fortunately, some 132kV test equipment already exists for land-based applications, and only minor modifications will be necessary for offshore wind farm applications.

4.3.5 Wind farm development timeframe

The top part of Figure 5 and Figure 6 includes a timescale showing the main development steps of an offshore wind farm project. This is based on industry experience and is intended to indicate the earliest possible date that the industry could expect to see a 132kV wind farm becoming commercially operational. Current estimates make this 2028 for dry-design cables and 2029 for wet-design cables. However, this assumes that the investment decision and notice to proceed with construction is subject to all components having been qualified and commercially available (i.e. commercial readiness 3 or above).

Where developers are less risk-averse, the investment decision could be taken while the 132kV cables and other system components are still being qualified, in which case commercial operation of 132kV offshore wind farms could happen as early as 2027.

4.4 Recommendations

The following recommendations are aimed at mitigating any possible roadmap delays.

4.4.1 Ongoing supply chain engagement

Continuous supply chain engagement is needed to promote and support the switch to high voltage arrays for offshore wind farms to be built in the second half of the 2020s. Suppliers need a clearer picture of market demand/volumes, or firm orders, to justify R&D investments to develop the required 132kV products. A collaborative approach of wind farm developers is needed to provide clear signals and increase confidence levels. Formal commercial engagement with the supply chain should start immediately to have 132kV products ready when >14MW wind turbines will dominate the market. One potential route is to engage with the supply chain (particularly cable suppliers) in follow-on work in the Offshore Wind Accelerator programme.

4.4.2 Updates to technical standards

Existing cable testing standards could be used to qualify future 132kV lead-free dry cables. However, offshore wind developers require new qualification standards for 132kV wet-design array cables before 132kV wind farm projects can be funded and approved. The relevant Cigré and IEC technical committees will consider the development of suitable testing standards when there is clear and strong market requirement. Requirements should be raised with the Cigré B1 Study Committee immediately as the development duration for new standards could take up to three years. The Offshore Wind Accelerator programme can accelerate this process by co-ordinating between developers and the supply chain to facilitate expedient and consistent messages to Cigré of the new testing requirements.

4.4.3 Clarifying regulation

An assessment of standards and regulations across the major offshore markets in Europe and the United States identified the UK's SQSS (Security & Quality of Supply Standard) as the only potential regulatory impediment to 132kV array system rollout. Current UK regulations are not sufficiently clear about whether 132kV direct-to-grid, i.e. no offshore substation connections, would be regarded as generation or transmission assets.

Regulations need to be clarified with the UK regulator Ofgem as soon as possible to avoid cable ownership risk and potential project delays. The Offshore Wind Accelerator programme could facilitate this engagement on behalf of the UK offshore wind industry. Engagement with project developers to better understand the number of projects requiring 132kV direct-to-grid connections should start as soon as possible.

4.4.4 Further work in the OWA

The OWA intends to accelerate the transition to 132kV through a follow-on initiative, High Voltage Array Systems (Phase 2). The scope for this initiative is still being finalised but could involve developers and supply chain working together to ensure a smooth transition to 132kV. Areas of key importance will be:

- the development of suitable standards for 132kV cables;
- the development, qualification and testing of 132kV cables to those standards;
- understanding the implications of 132kV on floating wind;
- the development of improved cable connectors and testing methods at 132kV.

Appendix – Technology and Commercial Readiness Indices

Technology Readiness Level (TRL)

Technology Readiness Level (TRL) methodology is an industry-recognised development scale used to qualitatively assess the maturity of different technologies. It was initially developed by NASA for the space programme in the early 70s and continues to be widely used.

The nine levels stretch from establishing the basic principles at TRL1, the lowest stage, to a TRL9 where the technology is operational and commercial. Table 3 describes each of the nine TRL stages through objective scenarios and checkpoints which helps with identifying where a particular technology is in relation to achieving full commercial operation.

Table 3: Technology Readiness Level scale and descriptions [1]

Phase	TRL	Stage	Description
Operations	9	Operations	The technology is being operationally used in an active facility.
Deployment	8	Active Commissioning	The technology is undergoing active commissioning.
	7	Inactive Commissioning	The technology is undergoing works testing and factory trials, but it will be on the final designed equipment, which will be tested using repeatable and accurate scenarios reflective of operational conditions. Testing at or near full capability will be expected.
Development	6	Large Scale	The technology is undergoing testing at or near full-scale size. The design will not have been finalised and the equipment will be in the process of modification. It may only participate in a limited range of input conditions and won't be running at full capability.
	5	Pilot Scale	The technology is undergoing testing at small- to medium-scale size in order to demonstrate specific aspects of the design.
	4	Workbench Scale	The technology is starting to be developed in a laboratory or research facility.
Research	3	Proof of Concept	Demonstration, in principle, that the invention has the potential to work.
	2	Invention and Research	A practical application has been invented or the investigation of phenomena, acquisition of new knowledge, or correction and integration of previous knowledge.
	1	Basic Principles	The basic principles of the technology have been established and confirmed.

It is worth noting that as a qualitative measure, TRLs may not be evaluated or compared arithmetically. That is to say a technology at TRL4 is not twice as mature as a technology at TRL2, nor can an average be ascertained of a technology through two TRLs of different components. Even though most technologies will take a longer time to get from TRL3 to TRL9 than it will to go from TRL7 to TRL9, care must be taken not to always assume that a technology with a low TRL today is a riskier choice than that of a higher TRL.

For some proven technologies, there are cases where TRL levels may vary, depending on the environment. For example, a technology may be considered TRL9 in a specific area, such as an onshore environment, however the TRL may be adjusted to reflect uncertainty in performance if in a new environment (e.g. an offshore environment), or where a new capability which has not featured operationally in the same environment, is added. Table 4 highlights certain applicable scenarios and details the evaluation of new TRL levels (assuming a starting TRL of 9), where a particular proven technology is used in a new environment.

Table 4: TRL Special Circumstances

Change applied	Description	New TRL
Testing the existing technology in a new setting.	The technology/capability is used commercially in another, but the new setting is similar.	8
The technology/capability is commercially available but used in a different industry.	No expected modifications and expected to work within operation ranges, therefore only needs to undergo Inactive Commissioning.	7
The technology is in use elsewhere for a similar requirement, but the operational conditions may change.	Technology is not expected to require modification; it still needs a full-scale test that simulates the new operational conditions.	6
The technology is in use elsewhere for a similar requirement, but the operational conditions may change, and a modification is required.	Well-understood modifications are needed to be implemented for the technology to perform under the new operational conditions.	5
The technology is in use elsewhere for a similar requirement, but the operational conditions may change, and major modifications are required.	Modifications that may not be very well understood are needed to be implemented for the technology to perform under the new operational conditions.	4
Individual items are used elsewhere, and these are combined to create a new offering.	Information on all individual components should be available and the information for the modifications required. Testing may begin at bench scale.	4
The technology is used commercially but the operational conditions need to be changed.	Although the technology is well-established, the difference in environment and operational changes means significant changes are envisaged.	4

Commercial Readiness Index (CRI)

The Commercial Readiness Index (CRI) framework is a novel framework developed by the Australian Renewable Energy Agency (ARENA) that aims to provide a complementary index to the TRL by moving beyond assessing the technical performance of technologies towards an evaluation of the commercial readiness [2].

The CRI framework assesses various indicators which influence the commercial and market conditions beyond just the technology maturity. This enables key barriers to be addressed to support the commercialisation of a technology. CRI has six stages to identify the commercial readiness of the technology which are summarised below.

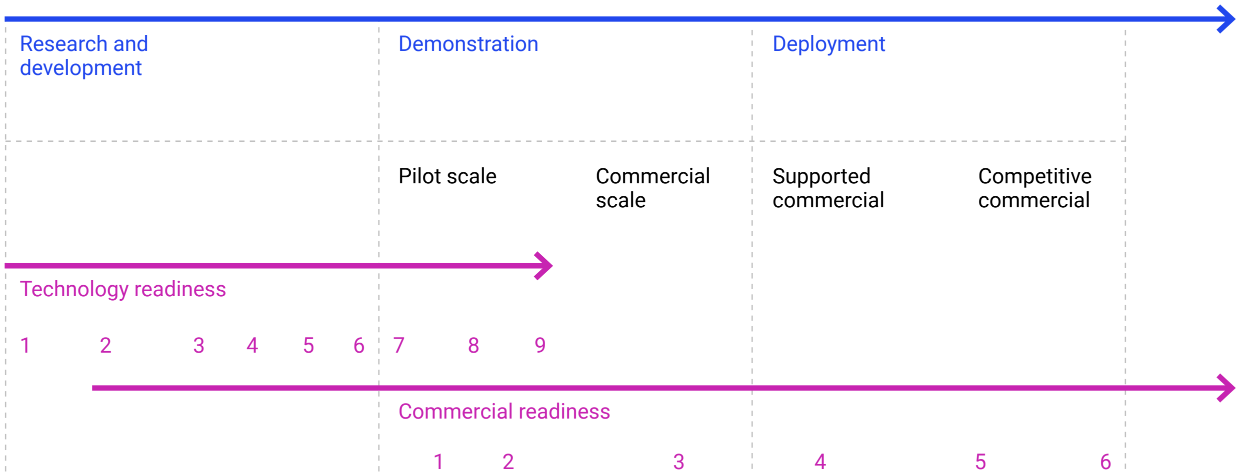
Table 5: CRI phases and definitions [2]

Phase	CRI	Stage	Description
Deployment	6	"Bankable" grade asset class	"Bankable" grade asset class driven by same criteria as other mature energy technologies. Considered as a "Bankable" grade asset class with known standards and performance expectations. Market and technology risks not driving investment decisions. Proponent capability, pricing and other typical market forces driving uptake.
	5	Market competition driving widespread deployment	Market competition driving widespread deployment in context of long-term policy settings. Competition emerging across all areas of supply chain with commoditisation of key components and financial products occurring.
	4	Multiple commercial applications	Multiple commercial applications becoming evident locally although still subsidised. Verifiable data on technical and financial performance in the public domain driving interest from variety of debt and equity sources however still requiring government support. Regulatory challenges being addressed in multiple jurisdictions.
Demonstration	3	Commercial scale up	Commercial scale up occurring driven by specific policy and emerging debt finance. Commercial proposition being driven by technology proponents and market segment participants – publicly discoverable data driving emerging interest from finance and regulatory sectors.
	2	Commercial trial	Small scale, first of a kind project funded by equity and government project support. Commercial proposition backed by evidence of verifiable data typically not in the public domain.
	1	Hypothetical commercial proposition	Technically ready – commercially untested and unproven. Commercial proposition driven by technology advocates with little or no evidence of verifiable technical or financial data to substantiate claims.

A visual representation of the relationship between the TRLs and CRI is shown in Table 5. It shows that CRI begins once research has shown that the technology is feasible (TRL2).

The CRI extends to when the technology is commercially deployed and has become a bankable asset class (CRI6).

Figure 7: TRL and CRI mapped on the technology development chain [2]



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