Transition to 132 kV offshore wind farms: industry update

SUMMARY REPORT OF THE HIGH VOLTAGE ARRAY SYSTEMS PHASE 2 WORK PACKAGE 5: INDUSTRY RE-ALIGNMENT

June 2025

THE HIGH VOLTAGE ARRAY SYSTEMS PROJECT

The High Voltage Array Systems (Hi-VAS) project is a joint-industry project set up within the Offshore Wind Accelerator (OWA). In 2022, Phase 1 of the Hi-VAS project identified 132 kV to be the next array operating voltage above the current standard (66 kV). This consensus was achieved through extensive stakeholder engagement, engineering design studies, risk analysis and cost-benefit analysis. In 2023, Hi-VAS Phase 2 commenced, with the aim to accelerate and de-risk the transition to 132 kV. This aim is being addressed through an experimental cable testing programme to provide evidence which will contribute to the development of qualification standards for wet-static and dynamic 132 kV array cables; and also through industry re-alignment as discussed in this report. The project is driven and funded by eleven international offshore wind farm developer project partners: EDF Renouvelables (Phase 2 only), EnBW, Equinor, Ørsted, Ocean Winds, RWE, ScottishPower Renewables, Shell, SSE Renewables, TotalEnergies and Vattenfall.

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.

ACKNOWLEDGEMENTS

This report provides a summary of the outcomes from the industry re-alignment work package (WP5) within Hi-VAS Phase 2, delivered by the Carbon Trust. The Carbon Trust worked closely with the Hi-VAS project partners over the course of WP5, and engaged numerous supply chain companies, regulators, and transmission system operators. We will not list all those who provided input for confidentiality purposes; however, we would like to thank all those who provided input.

1. Key findings: 132 kV technology development status

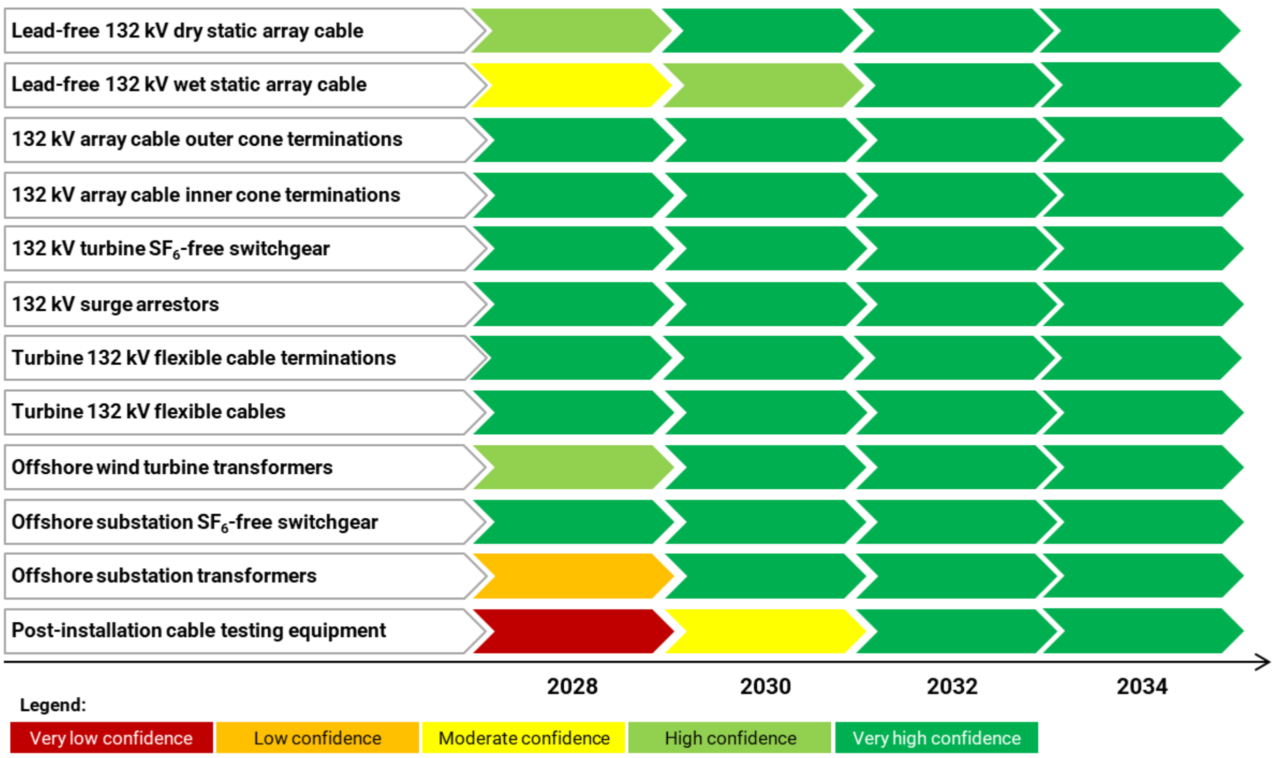
As offshore wind projects continue to grow in scale and complexity, decisions around array cable voltage should be driven by optimal wind farm design, considering factors such as turbine capacity, overall wind farm size, layout, and export system design. Determining the appropriate voltage standard for future offshore wind farms is therefore a strategic decision that rests with key players, including governments, regulators, transmission system operators (TSOs), developers, and original equipment manufacturers (OEMs).

Sub-components and supporting infrastructure

The supply chain expects that the critical sub-components and supporting infrastructure will be ready to deploy wind farms with 132 kV arrays from 2030. Figure 1 shows the consolidated view of the relevant supply chain companies that they will be able to deliver the listed components for a commercial-scale offshore wind farm commissioning in the respective years.

Industry feedback also showed that there have been positive developments on the technical and commercial readiness of these components since the publication of the Hi-VAS Phase 1 report in 2022, as detailed in Section 3 below.

Figure 1. Industry confidence in 132 kV systems' commercial availability and expected timelines



132 kV wind turbines

The above findings show that the sub-component supply chain is progressing with the critical sub-components and supporting infrastructure and expects to be ready by 2030-2032. However, a gap remains between sub-component readiness and wind turbine development: just because the sub-components are ready, does not necessarily mean a wind turbine will be ready. 132 kV wind turbines require additional engineering and testing to incorporate novel, higher voltage sub-components.

No 132 kV offshore wind turbine is yet commercially ready. One leading wind turbine OEM has publicly opposed the move to 132 kV wind turbines by 2032. However, other leading wind turbine OEMs have taken different strategies. See Section 4 for more details.

Without international, cross-industry realignment on expectations for the timing of the transition to 132 kV, these different strategies would lead to only some wind turbine OEMs offering 132 kV turbines by the early 2030s. This causes uncertainty to policy makers, regulators, TSOs, sub-supply chain companies, offshore wind farm developers and the wind turbine OEMs themselves.

Summary

There is a broad confidence that the sub-component supply chain will be ready for the transition to wind farms with 132 kV arrays by around 2030. However, several key developments remain necessary, including:

- availability of wind turbines compatible with 132 kV systems;
- development of qualification tests for 132 kV wet-static and dynamic array cables (being addressed by Hi-VAS Phase 2 and CIGRE Working Group B1.92). It should be noted that, while the availability of wet design array cables may offer cost savings, it is not a requirement to proceed with the transition to 132 kV. 132 kV dry-static cables are commercially available and so the cable does not provide a barrier to connecting wind turbines at this voltage level, see Section 3.2.1 for more details;
- clarity around the cost of 132 kV systems, including wind turbines. The lack of pricing information makes detailed economic analysis difficult and raises questions about the cost-effectiveness of 132 kV systems compared to alternatives like continued use of 66 kV systems;
- clarity on 132 kV projects, to enable the supply chain to invest in manufacturing capacity for 132 kV components. While governments, transmission system operators (TSOs), and developers are beginning to define future requirements for wind farms with 132 kV arrays, and the supply chain is responding to the transition to 132 kV, uncertainty remains on timing. The timeline for commercial deployment will depend not only on technical readiness but also on the ability to align investment decisions with the timely qualification of all critical components.

2. Background on Hi-VAS Phase 2 industry re-alignment

Need for industry re-alignment

Since the publication of the Hi-VAS Phase 1 report in June 2022, there have been fast moving developments within the industry from a regulatory and technology perspective. For example:

- the German governmental agency BSH has recently announced that, for wind farms commissioning from 2033 onwards, 132 kV will be used as the standard connection concept for the connection of wind turbine generators to converter platforms. [1]
- in France, the government has included in its plans for upcoming offshore wind areas that turbines shall be connected via 132 kV array cables, with these wind farms expected to be built from 2032.[2]
- the UK government's Department for Energy Security and Net Zero (DESNZ) announced a legislation change in the UK to grant a transmission license exemption for 132 kV array cables.
- CIGRE WG B1.92 has been set up to focus on Qualification of Lead-free Submarine Cables at 72.5 kV<U_m<170 kV, which covers the 132 kV array cable operating voltage.

However, whilst we have seen big steps towards the development of 132 kV systems, uncertainty remains in some areas, for example, when next-generation 132 kV turbines will be commercially ready. See Section 4 for more details.

For this reason, both developers and the supply chain are seeking clarity on what recent industry developments mean for the transition to 132 kV. Lack of alignment in the industry may lead to an inefficient transition, increasing cost and risks for developers, supply chain, TSOs, and governments, and hence ultimately consumers.

To address these needs, this report aims to refresh the industry understanding around the transition to 132 kV, to bring clarity on progress made and the areas requiring further development since the publication of the Hi-VAS Phase 1 report in 2022.

Approach

This report presents the outcomes of a round of stakeholder engagement conducted by the Carbon Trust to assess the offshore wind industry's status and readiness to transition to 132 kV array systems. The engagement was carried out through a questionnaire and follow-up interviews with a range of stakeholders across the offshore wind industry. Participants included developers, cable manufacturers, cable termination manufacturers, switchgear manufacturers, surge arrestor manufacturers, transformer manufacturers, testing equipment manufacturers, turbine manufacturers, regulators, and TSOs. The feedback gathered was consolidated and analysed to identify consensus around the technology and commercial readiness of key components needed for the transition to 132 kV.

[1] BSH (2025) Area development plan 2025 for the German North Sea and Baltic Sea

[2] CRE (2024) DÉLIBÉRATION n°2024-154

3. 132 kV array system supply chain

3.1. Technology and commercial readiness

To assess the technology and commercial readiness of 132 kV array system technologies, stakeholders were asked to provide their company's technology and commercial readiness of specific components that they manufacture. Table 1 summarises the industry's feedback, highlighting the consolidated technology readiness level (TRL) and commercial readiness index (CRI) reported for each component.

The technology and commercial readiness of key technologies were assessed using respective industry standard indices, detailed in Appendix 1:. These are the same indices as used in the Hi-VAS Phase 1 report, to allow for direct comparison since 2022. TRL has a maximum score of 9, whilst CRI has a maximum score of 6.

Table 1. Summary of updated TRL and CRI levels established in Hi-VAS Phase 2 (2025)

Technology	TRL			CRI		
	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation
Lead-free 132 kV dry static array cable	6	8	2	2	6	4
Lead-free 132 kV wet static array cable	4	6	2	1	5	4
132 kV array cable outer cone terminations	3	9	6	1	4	3
132 kV array cable inner cone terminations	8	9	1	6	6	0
132 kV turbine SF_6-free switchgear	6	6	0	3	3	0
132 kV surge arrestors	9	9	0	6	6	0
Turbine 132 kV flexible cable terminations	9	9	0	4	6	2
Turbine 132 kV flexible cables between the nacelle and the transition piece	8	9	1	4	6	2
Offshore wind turbine transformers	8	9	1	1	3	2
Offshore substation SF_6-free switchgear	8	8	0	6	6	0
Offshore substation transformers	8	9	1	6	6	0
Post-installation cable testing equipment	7	7	0	4	4	0

3.2. Discussion on development status of each 132 kV component

3.2.1. Lead-free 132 kV static array cables (wet and dry)

Array cables are the cables used to connect adjacent turbines to each other and to the offshore substation. Dry design cables are cables with an impermeable (typically metallic) sheath that keeps the cable insulation and conductor dry by preventing water ingress. In contrast, wet design cables do not have an impermeable barrier and allow the water to migrate into the cable. In this report, "lead-free" is used to refer to any submarine cable without a lead sheath, and this includes both wet and dry designs. This report focuses on static cables for bottom-fixed offshore wind and does not focus on dynamic cables for floating offshore wind.

Dry design static 132 kV array cable

Existing materials suitable for lead-free 132 kV dry design static array cables have been developed and deployed in an offshore environment. Several manufacturers are in late stages of development of lead-free 132 kV dry design static array cable. Feedback from the industry is that the technology could be commercially available in the next 3 years, provided there is enough commercial interest in the technology.

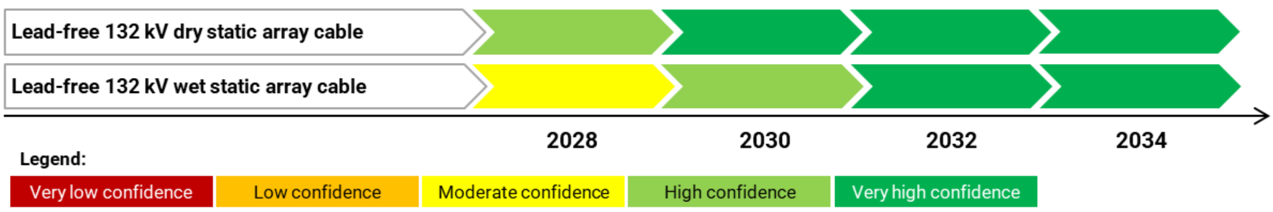
Wet design static 132 kV array cable

Several manufacturers are actively engaged in the development of 132 kV lead-free wet design static array cables, with testing currently underway at both model and full-scale levels. However, testing standards and qualifications specific to 132 kV wet design cables are still under development. Most manufacturers expect the technology to become commercially available within the next five years, depending on progress of ongoing testing and standardisation efforts. Cable suppliers have pointed to a lack of clarity in the market contributing to the extended timeline for commercialisation for wet cables.

Readiness of wet and dry cable

Feedback from the industry concludes that lead-free 132 kV dry design cables can be brought to market more quickly than wet cables.

Figure 2. Expected timelines for lead-free 132 kV static array cable technology commercial availability



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 in 2022, making a two-level increase in TRL since then. This rise was also reflected by progress in the technology's commercial readiness, which is now considered to be at the highest level - "bankable" grade asset class, Table 2.

The technological and commercial readiness of dry cables is higher than for wet cables. In the Hi-VAS Phase 1 report, the technology readiness for wet design 132 kV array cable was assessed as level 4 based on reports that several manufacturers had started the research and development of the technology. These designs are now being developed and have reached higher technology readiness.

Table 2. Lead-free 132 kV array cables TRL and CRI comparison against Hi-VAS 2022 report

Technology	TRL			CRI		
	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation
Lead-free 132kV dry design array cable	6	8	2	2	6	4
Lead-free 132kV wet design array cable	4	6	2	1	5	4

Since 132 kV dry design array cables are commercially available, there is no barrier to connecting wind turbines at this voltage level. While the availability of wet design array cables may offer cost savings, it is not a requirement to proceed with the transition to 132 kV.

132 kV cable qualification and testing

While technical development is progressing, further work is required to define suitable qualification and testing standards for 132 kV cables. The testing period for lead-free wet cables is long, and the necessary international standards and qualification methods for this voltage level are still missing or in early stages of development, since current guidelines only cover up to 72.5 kV (U_m). For this reason, several stakeholders emphasised the need for the development of industry cable testing standards extending to at least 132 kV (U_0), particularly for wet cables, with the timelines for its development directly impacting the development timeline for these components.

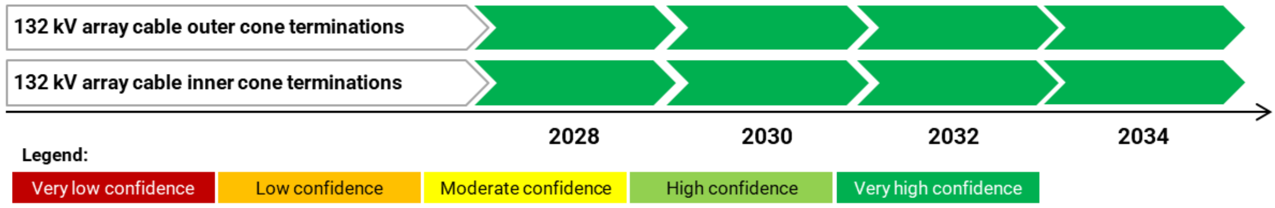
In this regard, a CIGRE Working Group (B1.92) has been set up to focus on Qualification of Lead-free Submarine Cables at 72.5 kV<U_m<170 kV, which covers 132 kV (U_0). Hi-VAS Phase 2 is also conducting an experimental testing programme to provide evidence which will contribute to the development of qualification standards for wet-static and dynamic 132 kV array cables. Relevant results from the Hi-VAS Phase 2 testing programme will be made available to the CIGRE Working Group B1.92 via its UK representative to assist the development of new standards.

The work developed on Hi-VAS Phase 2 follows the recommendations of the Hi-VAS Phase 1 publication from 2023 ('132 kV array cable requirements and the need for improved testing standards'), which provides more details on the technical design, performance requirements, and the gaps in qualification standards for 132 kV array cables (both wet-static and dynamic cables).

3.2.2. 132 kV array cable terminations

Some manufacturers have already started the development of 132 kV outer cone terminations, with commercial availability expected by 2028. 132 kV inner cone terminations are already commercially available, building on existing technologies, materials and well-defined standards for materials and qualification.

Figure 3. Expected timelines for 132 kV cone termination technology commercial availability



The development of array cable outer cone terminations has accelerated in recent years. In 2022, supply chain feedback indicated that the technology was at a ‘proof of concept’ stage (TRL 3), with testing yet to be completed. Since then, increasing industry interest has driven the technology forward, and it is now progressing through testing and qualification, with a reported TRL of 9.

Inner cone terminations were already at mature in 2022 as indicated in Table 3.

Table 3. 132 kV array cable cone terminations TRL and CRI comparison against Hi-VAS 2022 report

Technology	TRL			CRI		
	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation
132kV array cable outer cone terminations	3	9	6	1	4	3
132kV array cable inner cone terminations	8	9	1	6	6	0

Preferred cable terminations and bushing interface standardisation

Industry feedback indicates that there is no preferred method for terminating 132 kV cables, with termination solutions instead selected on a case-by-case basis depending on project-specific design, installation, and operational considerations.

In addition, manufacturers see the benefits of developing a standardised bushing interface for outer cone terminations.

Termination installation

Cable manufacturers also note that installing 132 kV dry cables does not present a greater challenge than current 66 kV array or export cable systems. However, the quality of termination installation is a key area that needs to be addressed. Currently, terminations are where the majority of cable failures occur. This will be even more critical for 132 kV array cables, especially if longer string configurations are utilised. The OWA Quality and Quantity of Qualified Termination Specialists (QQQTs) project is currently working on defining, improving and standardising training and control procedures for termination jointers, in order to help improve the quality of terminations up to 132 kV.

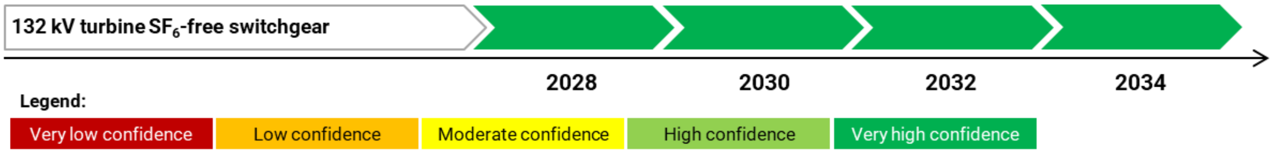
3.2.3. 132 kV turbine SF_6-free switchgear

SF_6 refers to sulphur hexafluoride, a gas used to increase the safety of electrical components due to its insulative properties; however, it is a greenhouse gas. Wind turbine SF_6-free switchgear uses alternative gases for insulation, with a potential for a 99% reduction in global warming when compared to the previously used SF_6 gas.

132 kV turbine SF_6-free switchgear technology is currently available for onshore applications. Pilot studies being carried out will determine the timeline for deployment of this technology in offshore wind

turbines on a commercial scale. Manufacturers believe 132 kV solutions will be market ready within 3 years, motivated by increasing demand for solutions compliant with EU F-gas regulations coming into force in 2028.

Figure 4. Expected timelines for 132 kV SF_6-free switchgear technology commercial availability



Despite the high confidence around the technology's readiness and expected availability, there has been limited progress in advancing its commercial deployment, with TRL and CRI levels remaining unchanged since the Hi-VAS Phase 1 report in 2022.

Table 4. 132 kV turbine SF_6-free switchgear TRL and CRI comparison against Hi-VAS 2022 report

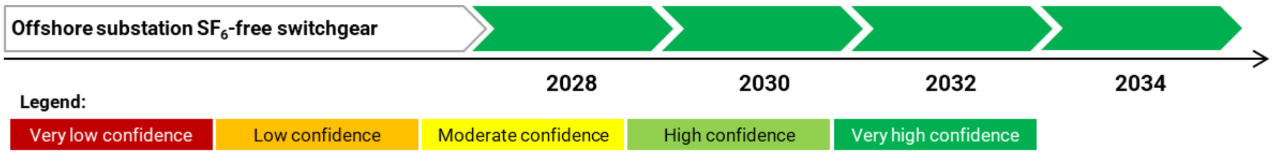
Technology	TRL			CRI		
	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation
132 kV turbine SF_6-free switchgear	6	6	0	3	3	0

3.2.4. Offshore substation 132 kV SF_6-free switchgear

SF_6-free switchgear for offshore substations is already being delivered at 145 kV by some manufacturers. As noted above, international regulatory pressure to reduce SF_6 use is accelerating its adoption, and manufacturers are confident the technology will be available within the next three years.

However, manufacturers have identified two key advancements needed to ensure the reliability and scalability of SF_6-free switchgears. These include the approval of Low Power Instrument Transformers (LPITs) for metering purposes, improved dielectric performance of alternative insulation gases, and the standardisation of testing protocols for vacuum interrupters/g^3 gas systems.

Figure 5. Expected timelines for offshore substation 132 kV SF_6-free switchgear technology commercial availability



There has been no further progress in the TRL and CRL levels for this technology, as it is already being delivered by some suppliers.

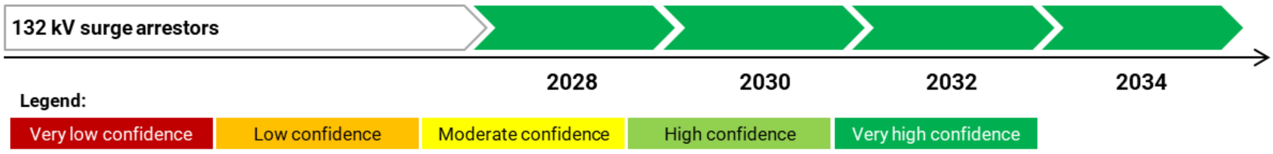
Table 5. Offshore substation 132 kV SF_6-free switchgear TRL and CRI comparison against Hi-VAS 2022 report

Technology	TRL			CRI		
	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation
Offshore substation SF6-free switchgear	8	8	0	6	6	0

3.2.5. 132 kV surge arrestors

132 kV surge arrestors are commercially available today and require only adaptation to relevant plug-in solutions.

Figure 6. Expected timelines for 132 kV surge arrestors technology commercial availability



Since 2022, 132 kV surge arrestors have maintained the highest levels of technology and commercial readiness, due to its availability for onshore applications and the minimal modifications required for offshore use.

Table 6. 132 kV surge arrestors TRL and CRI comparison against Hi-VAS 2022 report

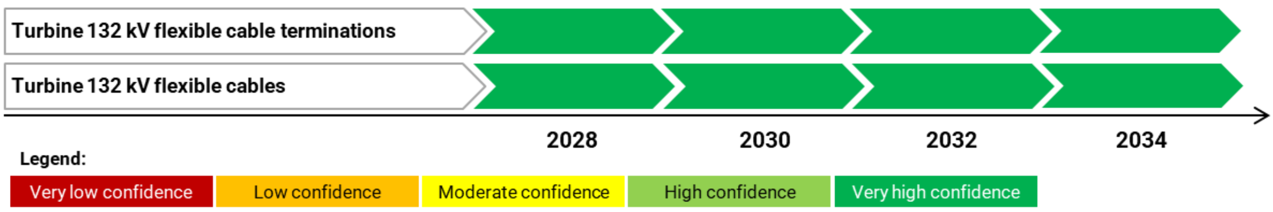
Technology	TRL			CRI		
	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation
132kV surge arrestors	9	9	0	6	6	0

3.2.6. Turbine 132 kV flexible cable and terminations

Flexible high voltage cables are used to connect the switchgear in the transition piece to the transformer in the nacelle, crossing the tower and nacelle interface.

Three-core 132 kV flexible cables are not currently available. However, single core 132 kV flexible cables, as well as their associated terminations exist and are commercially available today, but only from selected manufactures.

Figure 7. Expected timelines for turbine 132 kV flexible cables terminations technology commercial availability



The technology for 132 kV flexible cables terminations has progressed in recent years, from early-stage commercial deployment to full commercial availability, as other mature technologies (Table 7).

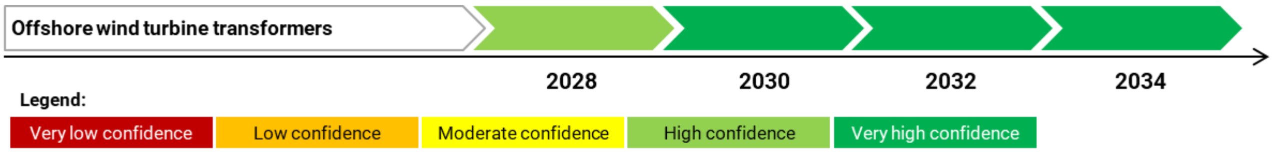
Table 7. Turbine 132 kV flexible cables and terminations TRL and CRI comparison against Hi-VAS 2022 report

Technology	TRL			CRI		
	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation
Turbine 132kV flexible cable terminations	9	9	0	4	6	2
Turbine 132kV flexible cables between the nacelle and the transition piece	8	9	1	4	6	2

3.2.7. Offshore wind turbine transformers

Offshore wind turbine transformers for 132 kV systems exist and are nearing commercial readiness from multiple suppliers. These transformers could become commercially available by 2028, with deployment by 2030 considered very likely.

Figure 8. Expected timelines for 132 kV offshore wind turbine transformer technology commercial availability



Over the past three years, wind turbine transformers have achieved full technology readiness.

Table 8. Offshore wind turbine transformers TRL and CRI comparison against Hi-VAS 2022 report

Technology	TRL			CRI		
	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation
Offshore wind turbine transformers	8	9	1	1	3	2

3.2.8. Offshore substation transformers

Transformers to transform 132 kV up to export voltages are available, but current lead times for transformer technologies exceed two years, meaning that supply chain pressures foreseen with the growth of the offshore wind market can impact the availability of these components.

Figure 9. Expected timelines for offshore substation 132 kV transformers technology commercial availability

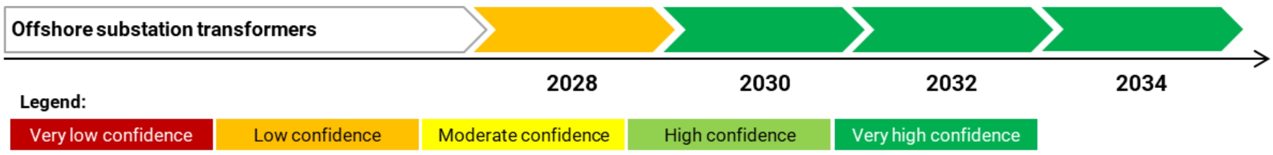


Table 9. Offshore substation transformer TRL and CRI comparison against Hi-VAS 2022 report

Technology	TRL			CRI		
	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation
Offshore substation transformers	8	9	1	6	6	0

3.2.9. Post-installation cable testing equipment

This section refers to post-installation cable testing equipment, which is used to test arrays for any defects or damage from installation during the commissioning phase of an offshore wind farm.

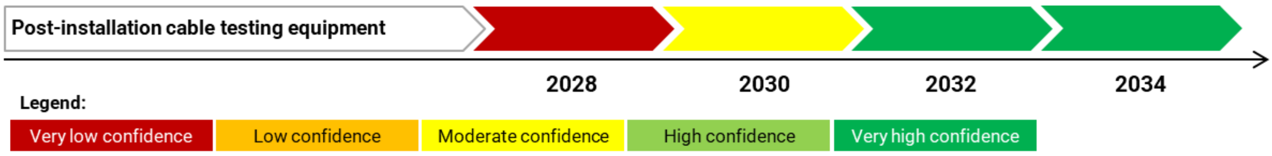
Test methods and equipment for post-installation testing of 132 kV array cables are under development, with proof of concept demonstrated on smaller systems.

There is a high level of confidence that the technology will be commercially available by the end of the decade. However, its development is dependent on the availability of customers with HV cable systems where non-standard-compliant testing could be performed. The use of non-specific industry standards for cable testing equipment can impact both warranty conditions offered by cable OEMs and the applicability of insurance policies, since manufacturers typically limit their warranty coverage when non-standard voltage wave shapes are used during testing, unless there is evidence that any resulting issues are not related to the test method.

Limited testing opportunities are seen as a barrier to broader deployment and validation of testing technologies. However, cable installers remain confident in the capability to deploy the technology by 2030.

The OWA currently has an ongoing project called Testing of Array Cables, which is assessing the application of various test methods up to 132 kV and the practicality of the test equipment. This project is expected to provide some more insight into the feasibility of certain post-installation test methods.

Figure 10. Expected timelines for offshore substation 132 kV post-installation cable testing technology commercial availability



Industry feedback indicates that the technology and commercial readiness levels are mature but that there has been limited progress in the technology and commercial readiness of testing equipment over the last 3 years, and several stages remain before it can reach full development and commercialisation.

Table 10. Post-installation cable testing TRL and CRI comparison against Hi-VAS 2022 report

Technology	TRL			CRI		
	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation	Hi-VAS Phase 1 2022	Hi-VAS Phase 2 2025	Variation
Post-installation cable testing equipment	7	7	0	4	4	0

4. 132 kV offshore wind turbines

Current status of 132 kV wind turbine development

To date, no 132 kV wind turbine has completed technical testing. However, according to industry sources, Siemens Gamesa is currently testing a wind turbine with 132 kV equipment in Østerild, Denmark.

Current status of larger-capacity wind turbine development

As discussed in the 2022 Hi-VAS report, the expected growth in turbine capacity (in MW) is one key driver for the transition to 132 kV. As turbines grow in capacity, higher voltages are beneficial to ensure efficient overall wind farm design, particularly driven by reduced cable length. The larger the turbine capacity, the greater the benefit of moving to 132 kV.

However, since the 2022 Hi-VAS report, industry expectations on the rate of wind turbine capacity have changed. There is now an expectation that wind turbine capacities will not grow as quickly as previously thought, and indeed some key wind turbine OEMs and offshore wind developers are expecting a pause in wind turbine capacity growth.

Vestas has publicly stated its strategic decision to pause turbine development at its 15MW wind turbine (which is a 66 kV wind turbine)[3], and has warned against transitioning to 132 kV prematurely, citing concerns around the system costs.[4] Siemens Gamesa has announced their focus on industrialising the 14 MW wind turbine.[5] However, Siemens Gamesa does have ongoing testing of a 21.5 MW prototype at the Østerild test site in Denmark, indicating longer-term consideration of larger turbines and, therefore, potentially higher voltage capabilities.[6] Further, multiple Chinese wind turbine OEMs have ongoing testing of wind turbines over 20MW.[7]

Other drivers towards 132 kV offshore wind farms

It is not just wind turbine capacity that is driving the need for 132 kV array voltage in offshore wind farms. Individual wind farms are forecast to grow in capacity.[8] For instance, markets like the Netherlands and Germany are moving forward with the so-called 2 GW Program, which plans to connect multiple 2 GW offshore wind farms via HVDC by 2032.[9] As wind farm sizes grow, the benefits of 132 kV compared to 66 kV increases, driven by improved layouts of the wind turbine strings. Further, the overall wind farm layout arrangement and the export system employed (such as direct link to grid connections,

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[3] Reuters (2024) Wind turbine makers halt race for size to focus on cost, delivery

[4] ReNews (2024) Vestas warns on German grid shift

[5] Siemens Gamesa LinkedIn page (2025) WindEurope fair 2025 – Marc Becker interview

[6] Recharge (2025) Power of Siemens Gamesa's secretive record-sized wind turbine confirmed

[7] Recharge (2024) Chinese wind giants unveil trio of 25MW offshore turbines

[8] Interreg (accessed in June 2025) Future Energy Industry Trends

[9] TenneT (accessed in June 2025) The 2GW Program

including large capacity offshore hubs) can also lead to benefits of 132 kV compared to 66 kV since it reduces the number of cables connecting to the transmission system. Reducing the number of cables subsea also has benefits on reducing the environmental footprint of offshore wind farm.

Retrofitting existing 66 kV wind turbine models vs new 132 kV wind turbine models

Across the industry, there is general consensus that retrofitting existing wind turbine models from 66 kV to 132 kV is not commercially viable. This implies that enabling wind farms with 132 kV arrays will require the development of new turbine models which are designed specifically to cater for 132 kV.

With the major wind turbine OEMs focusing commercially on their current 66 kV wind turbine models (see above), these existing wind turbine models will not be able to accommodate 132 kV. The next generation of wind turbine models should be designed to accommodate 132 kV; however, as mentioned above, different wind turbine OEMs currently have different strategies, so there is uncertainty as to when 132 kV turbines will be commercially available.

Technical feasibility and commercial availability of 132 kV wind turbines

Progress is still required before 132 kV wind turbines move from concept to commercial deployment, and two key milestones need to be reached:

1. **Technical feasibility**

Based on the engineering design work done in Hi-VAS and from engagement with wind turbine OEMs, there is nothing preventing the technical feasibility of 132 kV turbines, which is indeed being proven by the operational Siemens Gamesa prototype turbine in Østerild. Further, from the above sections, it is clear that the sub-component supply chain is progressing with the critical sub-components and supporting infrastructure and expects to be ready by 2030-2032.

132 kV wind turbines require additional engineering and testing to incorporate novel, higher voltage sub-components. While the validation of a 132 kV wind turbine already is under-way, testing cycles are long, and technical validation alone does not equate to commercial readiness of these assets.

2. **Commercial availability**

Once technical readiness is achieved, reaching commercial availability will require:

- demonstrated industry demand and a strong business case for wind farms using 132 kV arrays;
- system-level compatibility validation, including additional testing to ensure alignment with wind turbine OEMs' extended qualification and certification processes;
- ideally multiple wind turbine OEMs to offer 132 kV wind turbines to ensure competitive markets.

Conclusion on 132 kV wind turbines

132 kV systems remain a strategic long-term aim for next-generation offshore wind farms in a combination with next-generation offshore wind turbines due to economic and environmental benefits. However, there is a gap between this aim and the number of wind turbine OEMs with 132 kV focus.

Without international, cross-industry realignment on expectations for the timing of the transition to 132 kV, these different strategies would lead to only some wind turbine OEMs offering 132 kV turbines by the early 2030s. This causes uncertainty to key decision makers in governments, regulators, TSOs, sub-supply chain companies, offshore wind farm developers, and the wind turbine OEMs themselves. This uncertainty leads to the risk of narrowing the needed supply chain in the future and the Hi-VAS project calls on all key decision makers to maintain open dialogue to continue the coordination of the transition to 132 kV.

5. Next steps in the 132 kV transition

The next steps for the transition to 132 kV array systems depend not only on the technology and commercial readiness of individual components, but also on the decisions made by key industry players. The industry highlights that clear and consistent centralised decision-making, often led by governments and regulators, along with stronger industry-wide coordination to align investment timelines and signal demand to the supply chain, will be essential.

The following sections explore how these actions, as well as existing research work, can help de-risk 132 kV adoption, and what further action is needed to support a coordinated transition.

Centralised decision-making

In key European offshore wind markets, the transition to an array voltage of 132 kV is currently being defined primarily by national regulatory frameworks established by government authorities. Industry feedback reflects a mix of support and concern around mandated adoption of 132 kV array systems, with some believing it should be left to the market to steer the transition. Despite general support for the transition, hesitancy remains due to several factors, including supply chain constraints and the need for further technology development, leading many in the industry to view an extended use of 66 kV into the early 2030s as a way of mitigating risks.

Industry coordination

For several key components, the pace of development and market availability will be largely determined by market demand. Pending tests and qualification are unlikely to proceed without clear signals that these technologies will be required at scale, which can potentially delay is deployment timeline.

To ensure the timely commercial availability of key components, governments, regulators, TSOs, sub-supply chain companies, offshore wind farm developers, and the wind turbine OEMs need to collaborate across the sector, particularly in providing clarity on expected timelines, volume and cost. This is essential to inform investment decisions and enable the timely development of 132 kV array systems.

This coordination and collaboration is the main purpose of the Hi-VAS project, which will continue to provide a platform for the industry to work together during this transition.

Appendix 1: 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 1970s 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 11 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 11. Technology Readiness Level scale and descriptions[10]

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.

[10] NDA (2014) Report "Guide to Technology Readiness Levels for the NDA Estate and its Supply Chain"

	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.

Commercial Readiness Level (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.

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 12. Commercial Readiness Index phases and definitions

Phase	CRI	Stage	Description
Development	**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 Figure 11 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).

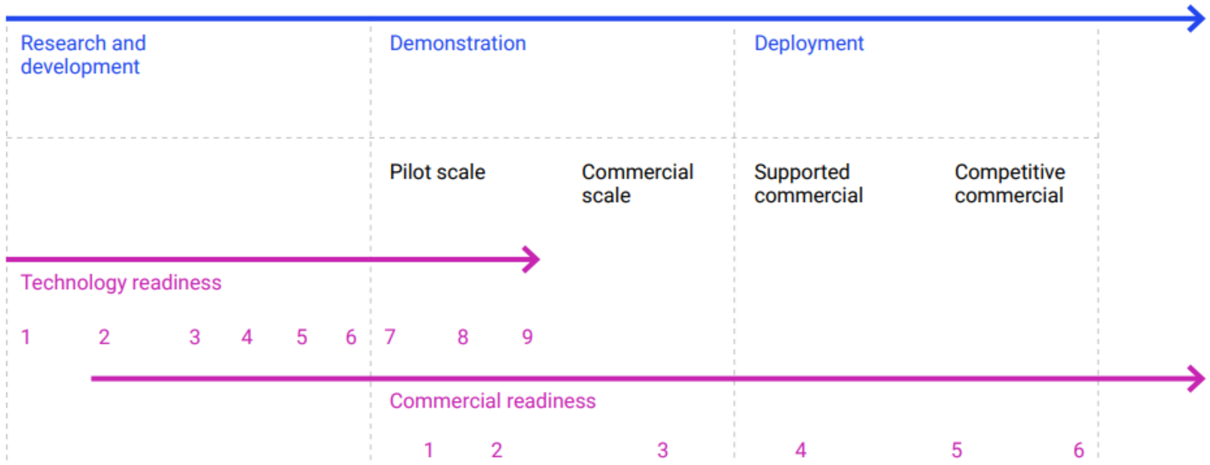

Figure 11. TRL and CRI mapped on the technology development chain [11]

[11] Australia Renewable Energy Agency (2014) Commercial Readiness Index for Renewable Energy Sectors

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