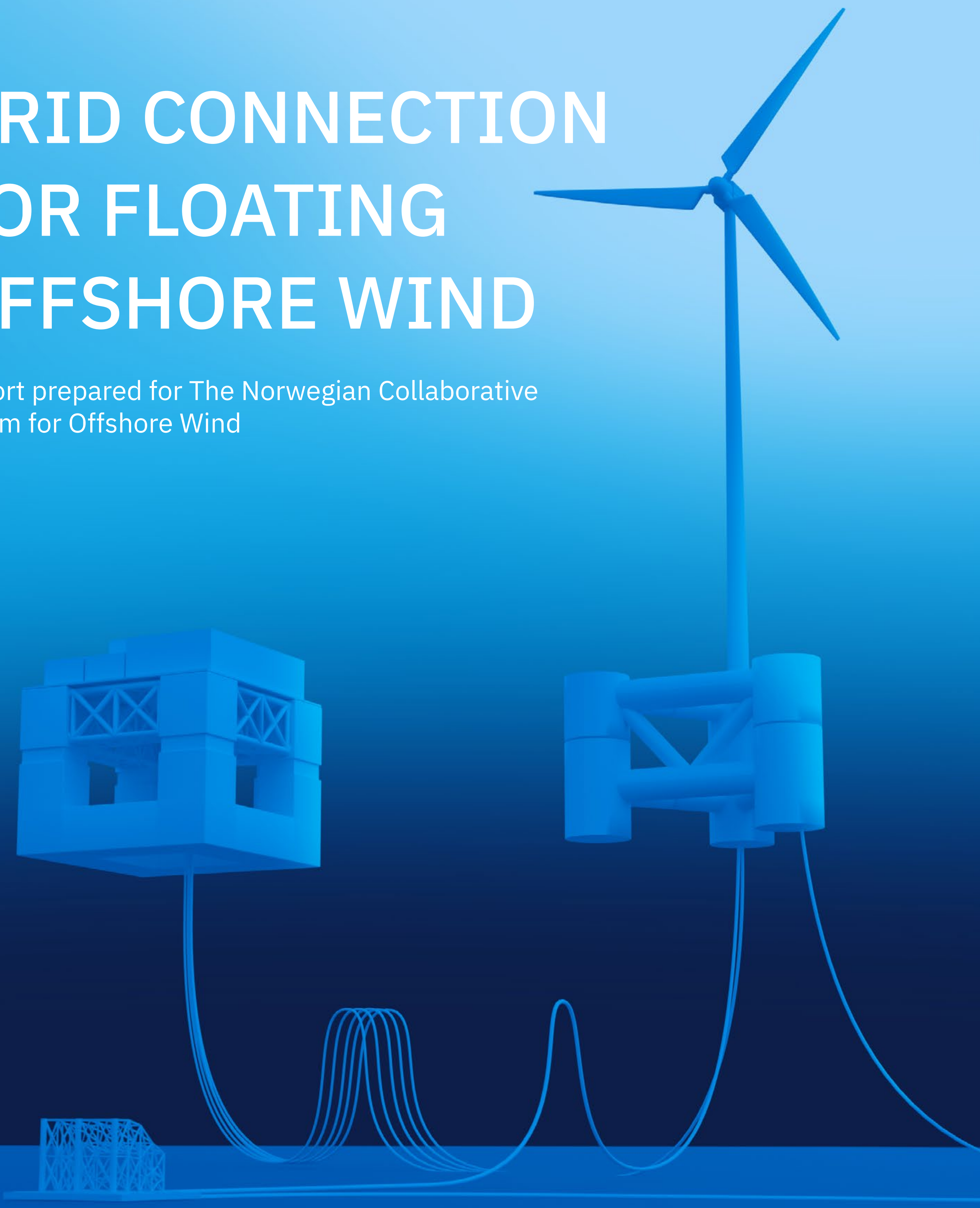
GRID CONNECTION FOR FLOATING OFFSHORE WIND

Report prepared for The Norwegian Collaborative Forum for Offshore Wind



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SUMMARY AND CONCLUSION

Mandate and Purpose[1]

The work has been carried out by an expert group as part of the efforts in the Collaborative Forum for Offshore Wind (Samarbeidsforum for havvind), with contributions from Working Group 2, «Industry and Technology Development,» and Working Group 3, «Infrastructure and Development of the Offshore Grid.» The work is based on the authorities' goal of allocating areas for the development of 30 GW of offshore wind by 2040. The purpose is to provide an overview of technology areas for grid connection of floating offshore wind, and to make recommendations for possible measures for further technology development. The technologies include grid connection with high-voltage alternating current (HVAC) and high-voltage direct current (HVDC), involving dynamic cables, floating offshore substations (transformer and converter stations), and underwater switching facilities («collectors»), see Figure 1.

It highlights possible technology gaps, along with technologies and concepts that may offer substantial cost reductions. Successful project execution and lower LCOE (Levelized Cost of Energy) is central to achieving increased acceptance and support for offshore wind, getting the projects realized, and in turn contributing positively to the energy system and climate goals.

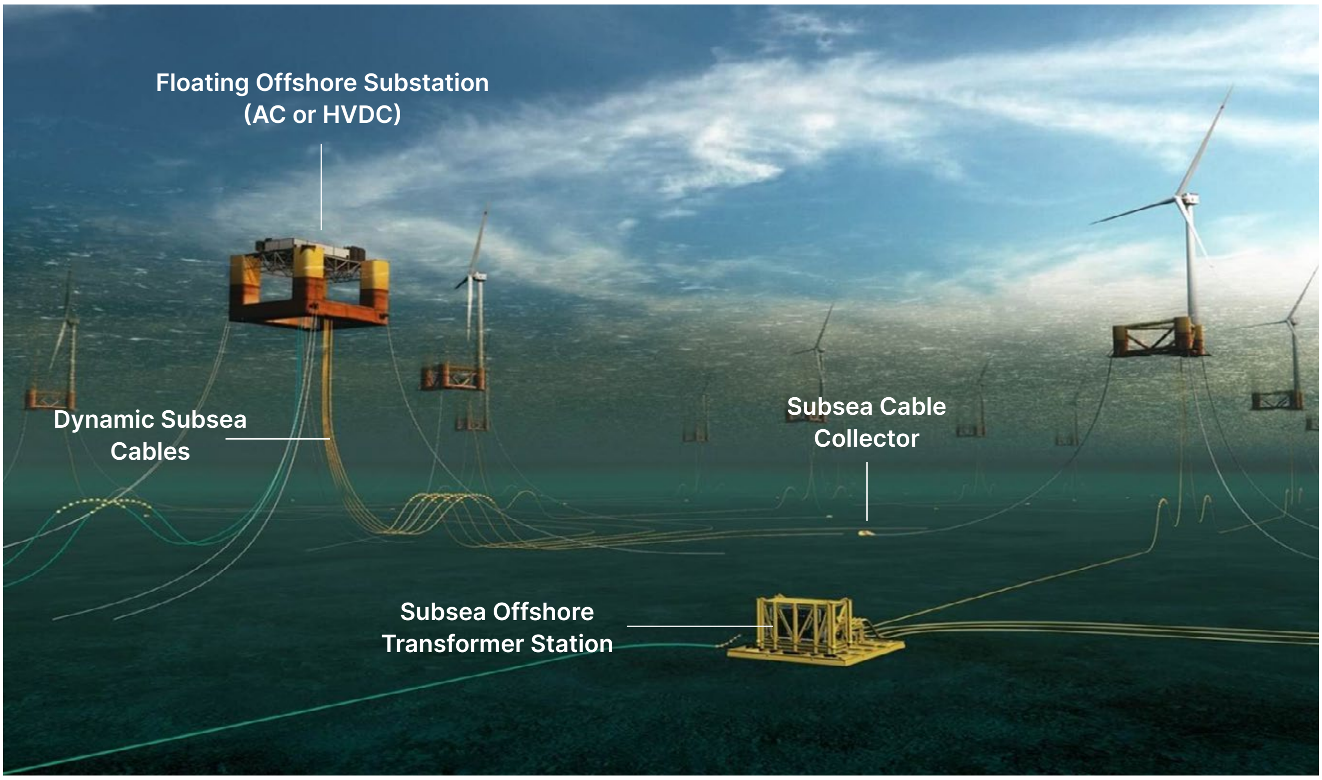


Illustration: Aker Solutions

Figure 1: Overview of evaluated technology areas

1) Definitions, see Chapter 2

Grid connection can constitute a significant portion of the cost (LCOE) for a floating offshore wind farm. It is therefore important to share and discuss the knowledge base and the possible solutions presented in this report. Connection points to the transmission grid, cost-sharing, supplier perspectives, combined vs. individual solutions, etc., are important topics that crucially affect the development of floating offshore wind, overall costs, and the total energy system. The supplier perspective matters, and it has received relatively little attention in a debate about offshore wind that has primarily involved developers, models/criteria for area allocation, subsidies, coexistence with fisheries, and environmental impacts. Sustainable technologies and solutions, as well as capacity in the supplier industry, are essential for successful developments. There is a need for policy instruments, risk mitigation, or other incentives that can encourage suppliers to invest in the long term. This will provide greater possibilities for realizing the necessary technologies and cost reductions.

Grid Configurations

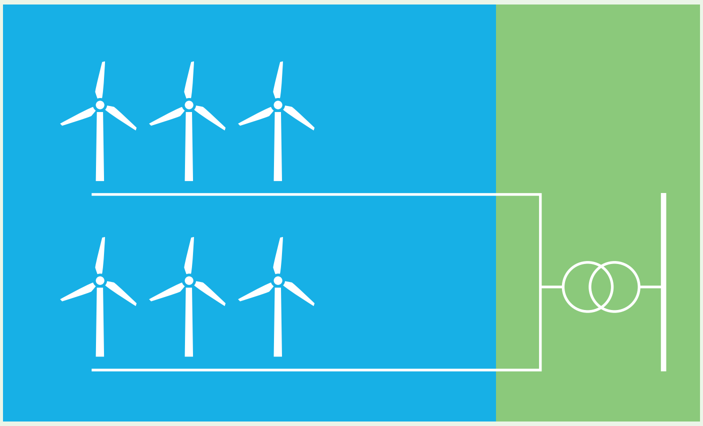
Alternative grid configurations for connecting an offshore wind farm are shown in Figure 2.

If the offshore wind farm is relatively close to land (10–20 km) and with limited capacity (max a few hundred MW), the grid connection can be made without any offshore transformer station. This is shown at the top of the figure. The standard turbine voltage used offshore today is 66 kV. An increase to 132 kV is under development.

For larger distances to land (typically less than 100 km), the wind farm can be connected via HVAC, as shown in the middle. For even larger distances, one must use an HVDC connection, as shown at the bottom of the figure.

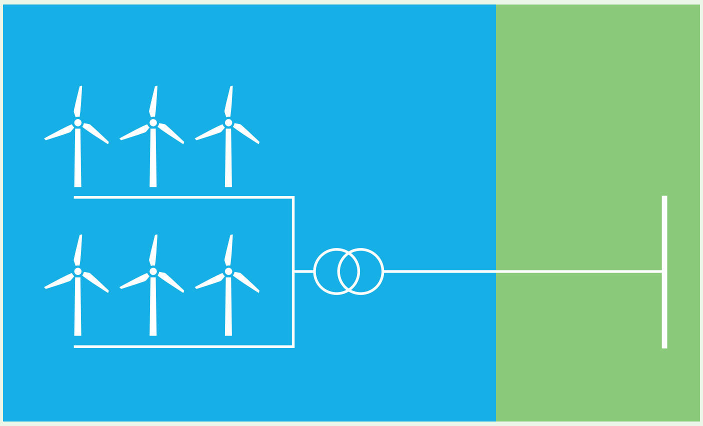
1

Offshore wind farm connected via AC cable directly to land



2

Offshore wind farm connected to an offshore transformer station with AC cable to land



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Offshore wind farm connect-ed to an offshore HVDC converter station and HVDC cable to land

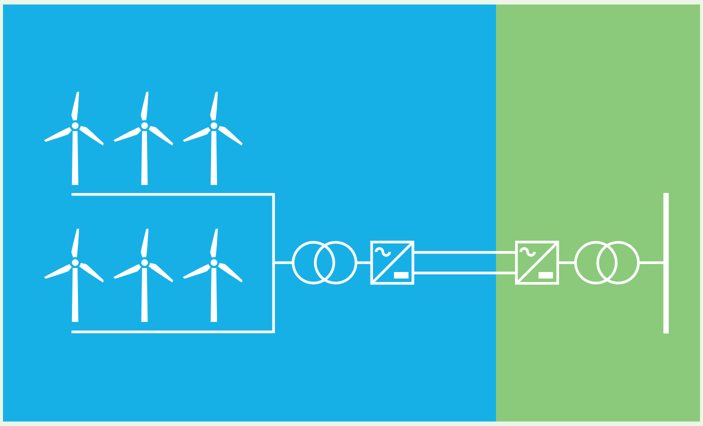

Figure 2: Alternative grid configurations for connecting offshore wind farms

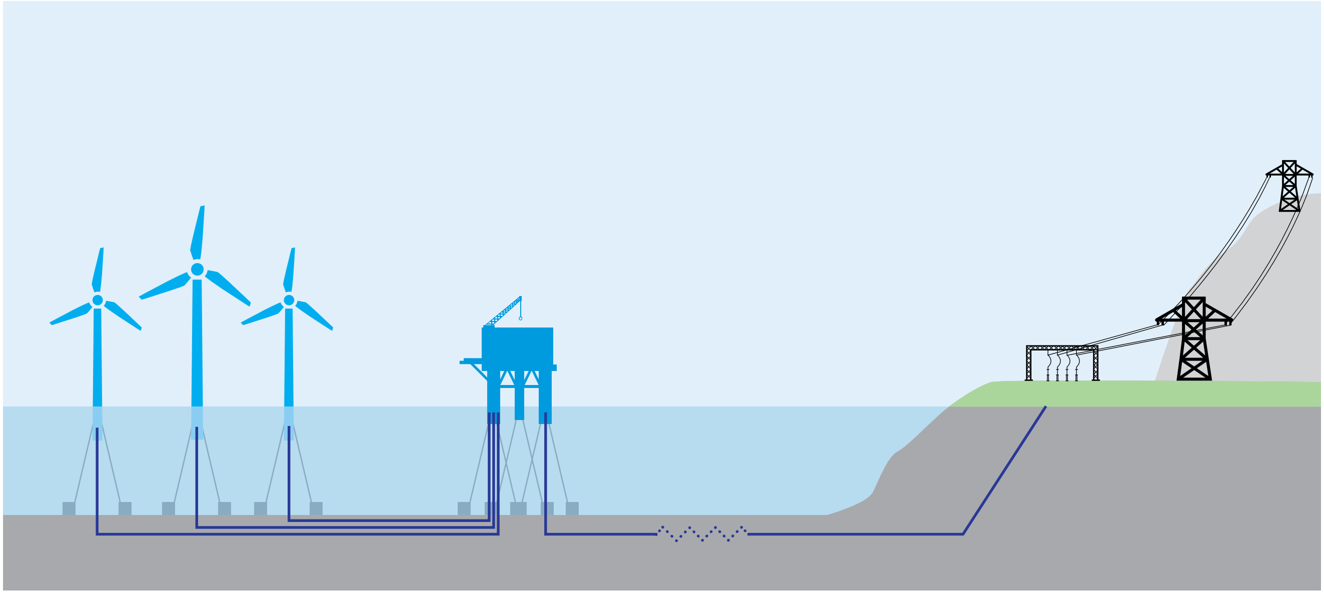

Figure 3: Grid connection of a floating offshore wind farm with a floating offshore substation.

Technology Summary for Floating Offshore Substation

Technological status for the floating hull (structure), marine systems, and mooring is that the design and configuration are largely known and used in the oil and gas industry. For offshore wind, the size of the floater must be adapted to the high-voltage equipment rating, including required area/volume on the topside, simplified ballast systems, mooring systems, and design of unmanned units.

This implies that technology is available to build both smaller floaters for AC projects and larger floaters for the desired ratings for HVDC installations. Gaps and barriers currently lie in the costs. Simplification and cost optimization are needed for offshore wind because the risk profile and profit margins differ from, for example, oil and gas. Direct reuse of solutions from oil and gas may make projects too expensive, yet many of the technical specifications in the NORSOK standards remain relevant.

There is a need to finalize the work on rules and regulations for floating substations. From a cost perspective, it is important to avoid creating special Norwegian requirements or rules that would increase costs.

The electrical systems themselves have mixed status. Some are available and have references from use on oil and gas installations. This includes protection/control systems and AC switchgear up to

132 kV. Suppliers have done general development of components based on typical floater motion data. Components such as transformers and reactors for high ratings always undergo a project-specific design adaptation and check, whether for onshore, fixed offshore, or floating installations. For a given floating project, one must conduct a project-specific mechanical design and check for extreme loads and fatigue.

The same goes for HVDC-converter equipment. HVDC converters are now in operation on bottom-fixed installations, but simulations and testing are needed to confirm that the HVDC components can withstand the mechanical stresses on a floater.

So far, a floating substation pilot has been built in Japan (25 MVA, 22 kV), see Figure 4. Otherwise, the floating wind pilot projects completed to date have not required floating substations.

The best way to drive development and cost optimization is to get started with pilot projects and full-scale projects. This is necessary for industry to fully qualify and verify the technology. Research and development without pilots and full-scale projects is insufficient.

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Photos: Aibel

Figure 4: Floating HVAC station. Left: A general concept from Aibel for 500–1500 MW. Right: The first realized floating substation in the Fukushima floating wind test park in Japan.

Recommendations for Developing Floating Substations:

- Establish specific projects and pilots
- Provide support for R&D in electrical design, mooring systems, and simplified marine systems
- Provide support for work on cost optimization of concepts and systems for unmanned operation
- Provide support for work on developing rules and standards, and ensure they are internationally harmonized

Timeline for Technology Readiness:

- Floating substations with AC technology are ready for the start of project development[2] by 2025
- Floating substations with HVDC technology are assumed to be ready for the start of project development around 2028

Technology Summary for Subsea Transformer and Collector

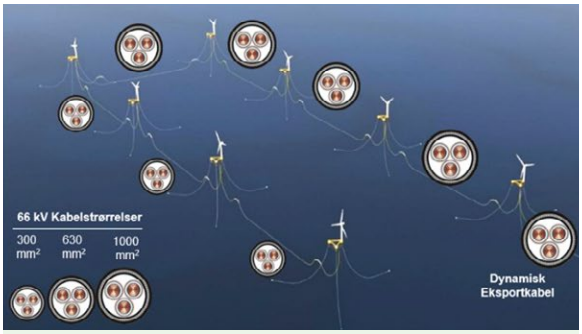
Subsea offshore AC transformer stations and collectors are based on proven technology from the oil and gas industry. There, around 40 subsea transformers have been delivered and operated without failures for the past 25 years, and medium-voltage subsea switchgear technology up to 36 kV has been developed over the last 10 years. This also includes wet-mate connectors up to 52 kV, underwater dry cable terminations up to 145 kV, and installations at water depths of more than 1,500 m.

Where technology gaps are concerned, floating offshore wind initially requires the development of underwater 66 kV switchgear (with protection and control systems) and 66 kV wet connectors for the collector and the turbine side of the subsea transformer. The ability to disconnect individual turbines or subsea cables when a fault arises without shutting down the entire wind farm is important. On the export side of the transformer, a dry cable termination qualified for subsea use at 132 kV (already available) must be scaled up to 220 kV, to match export cables to shore. There are already programs in progress to close these technology gaps, including the «Ocean Grid» project under the Norwegian «Grønn plattform» funding scheme. Some industry players have also started looking at 132 kV wet-mate connectors on the turbine array side. Upscaling to around 400 MVA for subsea transformers is done by drawing on existing subsea design

2) Ready for the start of project development is defined in Chapter 2

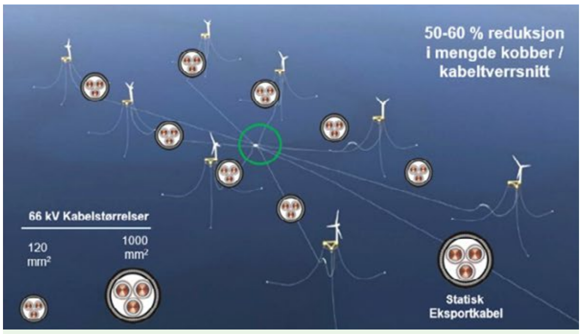
experience from oil and gas projects, along with reusing expertise and facilities from deliveries of large power transformers for onshore and offshore. In the case of collectors, some suppliers have already begun developing subsea 66 kV switchgear with the protection and control systems needed for seabed installation.

Key advantages of placing transformers and collectors with switchgear on the seabed include significantly reduced material usage, associated CO_2 emissions, and cost. This is achieved by halving the number of dynamic cable sections compared to alternatives. If each turbine is connected at a «star node» (collector), rather than linking them in a chain («daisy chain»), the total cross-sections of cable (and copper usage) is also almost halved. In addition, on the 220 kV side of the subsea transformer (and on the collector's export side), the cable can be static instead of dynamic. That can offer an advantage compared to large dynamic export cables. Individual turbines can be disconnected from the system more easily, without affecting or stopping the rest of the turbines for extended periods. Furthermore, the subsea solutions are standardized system architectures that can be relatively easily industrialized—typical ratings up to 400 MVA for each system connecting to shore. That makes it straightforward to expand capacity by copying these systems in parallel, allowing phased development. That can provide a positive impact on project net present value because there is no need to invest in the entire transmission system from Day One.



Chain ("Daisy Chain") Configuration

- Difficult to standardize due to varying cable cross-sections
- The dynamic cables must go down and then back up again — 2× more
- Complex installation with multiple dependencies



Collector with Star-Point Coupling

- All turbines use the smallest cable cross-section – far less copper
- Half as many dynamic cable sections – only goes down
- Static export cable, leading to lower installation cost and risk

Illustration: Aker Solutions

Figure 5: Comparison between daisy-chain and star-point turbine connections.

These subsea solutions are expected to be qualified by around 2025/2026. The goal is to serve a global market, including regions where floating turbines are planned in water depths of up to 1,500 m (for example off California). Provided the development programs stay on track, they will be ready for upcoming offshore wind pilots at around 100 MW (2–7 turbines) within the next 3–5 years (e.g., Goliat Vind), and for larger parks of 0.5–1 GW (or more) toward the end of this decade (e.g., Utsira Nord / Vestavind F).

There is already competition in this market. Companies including ABB together with Aker Solutions, Baker Hughes, SLB OneSubsea, and Siemens Energy each have R&D and operations anchored in Norway. This fosters a substantial competence environment with good conditions for industrial growth, standardization, and export. It also ensures that experience from the oil and gas sector is transferred to renewables—an opportunity for a successful transition in the coming years, especially given that the oil and gas activity level is expected to trend downward in the 2030s.

A key recommendation is that we strive to get these subsea solutions in the water as a full-scale pilot in, for example, Utsira Nord / Vestavind F. Goliat Vind at a smaller scale would likewise be a significant step forward.

A key recommendation is to strive to deploy these subsea solutions as full-scale pilot installations, e.g., in Utsira Nord / Vestavind F. Goliat Vind, at a somewhat smaller scale, could be a useful step along the way. That is because we currently have an opening to verify and build confidence in the technologies. A solution that addresses all of the critical components would be piloting a 400 MVA subsea transformer with 66 kV switchgear (integrated into the transformer module or installed as a separate module) and with 220 kV export voltage.

Technology Summary for Dynamic Array Cables and Export Cables

Dynamic offshore cables are an established technology within certain voltage levels and transmission capacities. Today, 66 kV dynamic cables are installed for smaller floating offshore wind farms, whereas 132 kV dynamic cables have been qualified and have operating experience from electrifying floating oil and gas installations. The technology behind those is especially critical and transferable for both floating offshore wind and cables with higher voltage levels and capacities. Consequently, 132 kV dynamic cables can be considered available technology.

Photo: Adobe Stock

Existing and future voltage levels for array (inter-turbine) cables can thus be covered with current technology. Nevertheless, there is still room for improvement in terms of cost reduction, condition monitoring, and standardization.

Export cables for floating offshore wind are highly mature if the power is exported via a subsea collector or transformer station. However, if power is exported directly from a floating turbine, transformer, or converter station, a dynamic export cable is required. Today, these are limited to the voltage levels mentioned previously (which basically cover existing and future needs if exporting directly from wind turbines). As with bottom-fixed offshore wind, the location and production capacity will often dictate that export via a transformer or converter station is the most cost-effective approach. Dynamic AC and DC export cables at higher voltages are expected to be qualified in 2–5 years.

Pilot projects can play an important role in accelerating the development of new technology. Specifically, higher technical risk allocated to grid connection in pilot projects and support for industrializing the supply chain can be effective policy measures.

New cable technology is largely supported by research and innovation efforts conducted in close collaboration with academia and research institutes. However, technology maturity must be raised in order to ensure market acceptance and earn prioritization among suppliers. Pilot projects can play a critical role in accelerating new technology development. In particular, assigning greater technical risk to grid connection within pilot projects—and providing support for supply chain industrialization—can be effective measures.

Recommendations on Full-Scale Piloting

Status

For the technologies relevant to floating offshore wind grid connections, technical maturity is generally high. Many components will be ready to begin full-scale project development as early as 2025.

1. Technology and concepts are known from the oil and gas sector, such as floating platform substructures, mooring methods, auxiliary systems, etc
2. Relevant electrical engineering (AC/HVDC) is known from onshore installations and from bottom-fixed offshore platforms
3. Subsea installations technology is known from oil and gas, although typically at lower voltages and ratings
4. AC-based grid connections currently have a higher technology readiness than those based on HVDC
5. Some technology development related to floating offshore wind grid connection can also prove beneficial for bottom-fixed solutions

Technology Gaps

There are still some gaps that appear solvable within a reasonable timeframe:

1. Technology must be adapted to marine environments and continuous movement
2. Certain key technologies are not yet qualified to the level needed for full-scale project development, but development and testing are underway. Design and verification cannot be done solely by suppliers; they need support and favorable conditions for development through real projects.
3. Solutions from oil and gas must be simplified and made more cost-effective in terms of both CAPEX (investment) and OPEX (operation and maintenance)
4. Further optimizing technology and processes from a sustainability perspective, including system-level considerations

Measures

The following measures have been identified:

1. Need for standardization of technology and processes at the right level, including scaling industrial capacity and pursuing industrialization.
2. Intensify efforts to identify more opportunities for simplifications and cost reductions regarding both investment and operation/maintenance
3. Facilitate further technology development and testing for certain components to achieve the required maturity level
4. Today's policy instruments must be strengthened to promote technology advancement, support industrialization, and develop supply chains. A report on this subject should be compiled under the Collaborative Forum for Offshore Wind.
5. Accommodate the use of new technology in upcoming licensing rounds so that valuable experience can be gained, leading to important learning and standardization, which in turn drives further cost reductions in floating offshore wind grid connections. Several promising technologies should be tested.
6. It is crucial that the first full-scale offshore wind project(s) be selected for the most rational solutions, in the areas with easiest access, while also providing the greatest benefit for onshore capacity needs. Succeeding with the «first» project yields enormous gains and signals success for future projects.

Risks

Some identified risks:

1. Offshore wind cannot endure unique Norwegian regulations. Simplification of requirements and standards is necessary.
2. Offshore wind should not have distinctly Norwegian technical demands that drive up costs
3. Currently, there is generally high activity in bottom-fixed offshore wind. This poses a risk that floating offshore wind may be deprioritized by suppliers.

Conclusion

There is a need for pilot projects related to floating offshore wind and for testing in full-scale projects to realize new technology.

These pilot projects will foster valuable learning, standardization, and cost reductions.

Photo: Equinor – Hywind Tampen

2

DEFINITIONS

AC	Alternating Current
Cigrè	The International Council on Large Electric Systems
DC	Direct Current
DNV	Det Norske Veritas
FEED	Front End Engineering Design
FIRM	Fiber Rope Moring
R&D	Research and Development
R&T	Research and Technology (an arrangement under the regulatory framework for the Norwegian continental shelf)
GIS	Gas Insulated Switchgear
GW	Gigawatt
GWP	Global Warming Potential – a measure of how much a greenhouse gas warms the atmosphere, expressed in CO_2 equivalents
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IAC	Inter-Array Cable (internal cables between turbines)
IEC	The International Electrotechnical Commission
IPR	Intellectual Property Rights
kV	Kilovolt
LCOE	Levelized Cost Of Energy
MVA	Mega-Volt Ampere (apparent power rating; the maximum MW capacity is generally comparable)
MW	Megawatt
NFR	Norsk Forskningsråd (The Research Council of Norway)
ROV	Remotely Operated Vehicle (underwater robot)
TRL	Technology Readiness Level

<table>
<tr><td>Turbine cables</td><td>High-voltage cables inside each wind turbine (commonly 66 kV)</td></tr>
<tr><td>Internal cable</td><td>High-voltage array cables from/between multiple turbines in a wind farm (commonly 66 kV, also known as Inter-array cables)</td></tr>
<tr><td>Export cable</td><td>High-voltage export cables from the offshore substation/transformer/converter station to shore (typically above 132 kV)</td></tr>
<tr><td>Ready for start of project development:</td><td>Indicates that the technology is sufficiently qualified and the risk is reduced to a point where it can serve as a premise for final project planning. It may require some project-specific adaptations or qualifications, but those are handled within the project scope. Depending on contract type and the amount of technology development built into the project, this readiness typically corresponds to TRL 6 or 7 (see Chapter 8.2).</td></tr>
<tr><td>Substation</td><td>A general term covering both AC transformer stations and HVDC converter stations</td></tr>
<tr><td>Voltage Definitions</td><td>In accordance with IEC standards for AC systems, the following apply:
Um Highest voltage for equipment (The maximum voltage the equipment is designed to withstand continuously under normal operating conditions.)
U Rated voltage (The nominal voltage at which the equipment is designed to operate.)

<table><tr><th>U</th><th>Um</th></tr><tr><td>66 kV</td><td>72,5 kV</td></tr><tr><td>132 kV</td><td>145 kV</td></tr><tr><td>220 kV</td><td>245 kV</td></tr></table></td></tr>
</table>

Photo: Equinor – Arkona Wind Farm

3

BACKGROUND AND MANDATE

3.1 Collaborative Forum

«Samarbeidsforum for havvind»[3] («Collaborative Forum for Offshore Wind») was established by the Minister of Petroleum and Energy, Tina Bru, and has been continued by Minister Terje Aasland. The purpose is to bring together, strengthen, and highlight the offshore wind industry.

A systematic approach through the Collaborative Forum and its working groups aims to raise competence, bolster competitiveness, facilitate progress, secure broad ownership, and clarify issues related to upcoming licensing rounds and projects. It also seeks to foster effective collaboration among offshore wind industry stakeholders and the authorities, promote increased value creation from export of technology and services, build up Norway's own offshore wind resources, and supply renewable power to meet climate and societal needs.

3.2 Composition of the Expert Group

The work was undertaken jointly by Working Group 2 («Industry and Technology Development») and Working Group 3 («Infrastructure and Development of the Offshore Grid») under the Collaborative Forum. These topics are relevant to both groups, especially regarding identifying the need for technology development and pointing to possibilities for cost reductions.

The expert group was formed in the fourth quarter of 2023, by direction of the chairs of Working Group 2 and Working Group 3—namely, Ståle Kyllingstad (Norsk Industri) and Håkon Borgen (Statnett). It was limited to a maximum of nine participants, and no one could participate merely as an observer. All activities had to comply with competition regulations. The group members were drawn from some of the most experienced and central supplier companies, with significant background in both petroleum and offshore wind projects. The group's central position is that offshore wind farms cannot be realized without robust, cost-effective technical grid-connection solutions from the supplier industry. The work was carried out by the expert group itself.

It was decided not to conduct separate consultation rounds or have the text reviewed by developers or other external parties. This was a deliberate choice, both to maintain momentum and to ensure high quality by relying on direct expert assessment within the group. The group's recommendations are thus the sole responsibility of the expert group.

3) https://www.regjeringen.no/no/tema/energi/landingssider/havvind/samarbeidsforum-for-havvind/id3039344/
https://www.norskindustri.no/dette-jobber-vi-med/energi-og-klima/norsk-industri-om-vindkraft/samarbeidsforum-for-havvind/

The Collaborative Forum for Offshore Wind was established in autumn 2021 by the Ministry of Petroleum and Energy, under the leadership of the Minister of Energy. Its objective is to gather, strengthen, and highlight the industry. This systematic approach can raise competence, strengthen competitiveness, and lead to increased value creation—both from exports of technology and services and from the development of Norway's own offshore wind resources. Another key goal is to ensure predictable conditions for activities and coexistence with other established sectors.

Figure 6: Collaborative Forum for Offshore Wind

Expert Group Members:

- Truls Normann, Aker Solutions
- Jan Wigaard, Aibel
- Lars Torstveit, Hitachi Energy
- Leif Ingar Stadheim, Siemens Energy
- Audun Johanson, Nexans
- Mikkel Buhl, NKT
- Carl Erik Hillesund, Statnett
- Hans Petter Rebo, Norsk Industri
- Knut Erik Steen, Norsk Industri

Other participants included Bengt Otterås (Statnett), Bente Haaland (Statnett), Runar Rugtvedt (Norsk Industri), and Yngve Børstad (Norsk Industri). Magnus Wold (NVE) joined in an observer capacity.

Lene Mostue, Director of Energi21, took part in several meetings and maintained dialogue with the expert group. Energi21 is Norway's national research and innovation strategy for new, climate-friendly energy technologies. There was also some interaction with other resource persons and organizations during the process. Equinor, represented by Trond Gullichsen and Øyvind Bergvoll, participated in one meeting to present experiences from the Trollvind project, a floating wind initiative that had advanced significantly in project development. Trollvind is located in what is currently referred to as Vestavind B.

The expert group began its work in December 2023 and concluded in December 2024 with the issuance of this report.

3.3 Mandate

Working Group 2 («Industry and Technology Development») and Working Group 3 («Infrastructure and Development of the Offshore Grid») established an expert group to document technologies and potential technology gaps regarding «grid» for floating offshore wind in order to achieve Norway's ambitions through 2040. Key technology areas include:

- Transformer Stations
  - Floating Concepts: Addressing aspects of stability, mooring systems, cable entries, operations, and maintenance
  - Subsea Concepts: Dealing with issues such as water ingress, wet-mate terminations, voltage levels, capacity, and redundancy, including subsea collectors for optimizing the cable system in an offshore wind farm
- HVDC Converter Stations
  - Floating Concepts: Again focusing on stability, mooring systems, cable entries, operations, and maintenance
- Dynamic AC and DC Cables: Addressing higher voltage levels, increased capacity, lifetime, operation/maintenance strategies, monitoring, repair philosophy, and material choices

Technologies specific to floating offshore wind farms (turbines and floaters) are handled under dedicated subgroups in Working Group 2 («Industry Development and Supply Chains» and «Research, Technology Development, and Competence»).

Among the goals of the expert group's work are:

- Greater insight into any technology gaps that need to be closed in order to realize offshore grid connections for floating wind
- Better understanding of capacity in the supply chain
- Proposals for closing any technology gaps in a 2030 and 2040 perspective
- Assessing whether there are technologies or concepts that can yield substantial cost reductions for floating offshore wind
- Helping provide part of the decision-making basis for pivotal technology or concept choices associated with floating wind farm infrastructure and integration with onshore transmission
- Contributing a technical foundation to promote a more realistic discussion and broader knowledge of offshore wind projects
- Suggesting policy instruments, risk relief mechanisms, or other frameworks to support the development of necessary technologies and cost reductions

This report is intended as a contribution to the decision-making process and to enable more informed discussions for both industry and authorities. It outlines key technologies and concepts, stresses the importance of scale and production capacity for cost reduction in floating offshore wind, and underscores the significance of offshore wind's role in the energy system.

It offers a snapshot as of December 2024. Development will continue among both suppliers involved in the expert group and those outside it, so these recommendations represent the group's perspective at that point in time.

Prior to the final publication, preliminary findings were presented in several forums due to the general interest in offshore wind. Notably, these included a Collaborative Forum gathering on September 2 (attended by the Minister of Energy), Statnett's R&D conference on October 29, and the Outlook North conference in Harstad on October 31.

Photo: Adobe Stock

3.4 Offshore Wind Areas

Options for connecting to land with a cable are either direct AC at turbine voltage, stepping up via a floating AC transformer station, stepping up via a subsea AC transformer station, or using a floating HVDC converter station.

In previous work, the Norwegian Water Resources and Energy Directorate (NVE) identified 20 areas intended for offshore wind; 14 of these are suitable for floating wind. They include sites along the western, mid-, and northern Norwegian coasts, as well as «Sønnavind A» just south of Kristiansand. Many of these can be developed with AC connections to shore, though some of the 14 may require HVDC due to greater distances.

A strategic impact assessment of these areas, led by NVE with broad participation[4], was published on November 28, 2024, covering Sørvest F, Vestavind B, and Vestavind F. The deadline to submit the strategic impact assessment for the remaining areas is June 30, 2025.

4) Strategic Impact Assessment of Identified Areas – NVE)

Figure 7: Identified Offshore Wind Areas in Norway

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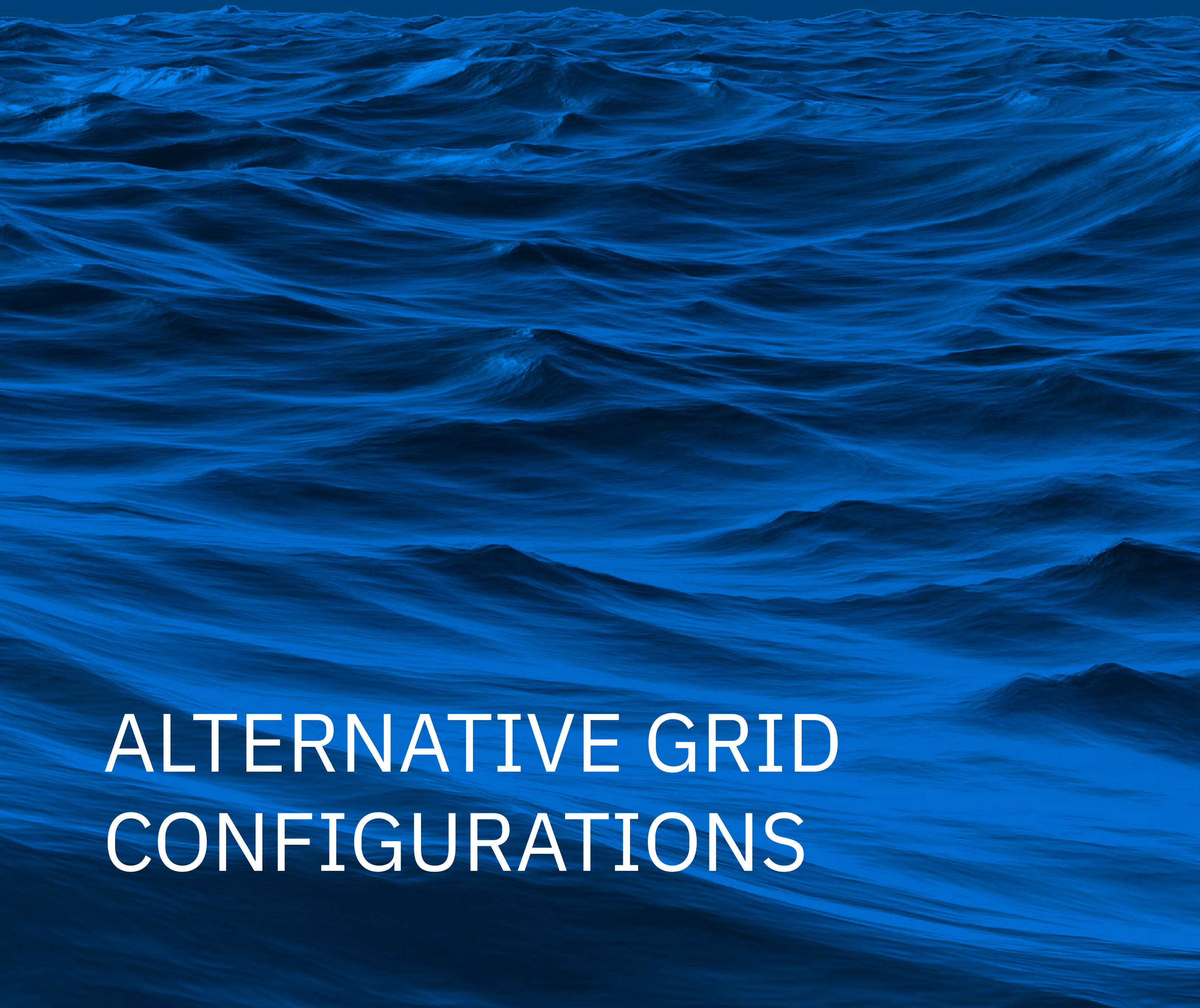


ALTERNATIVE GRID CONFIGURATIONS

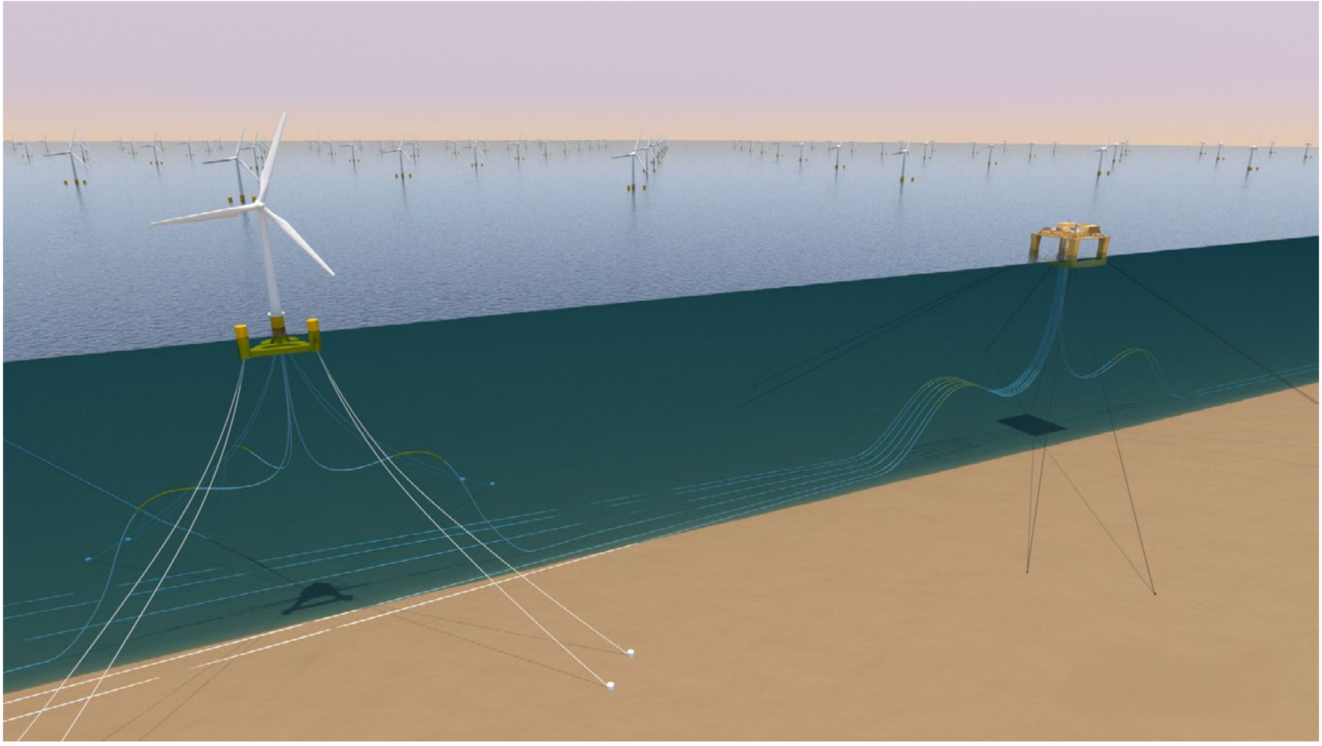


Illustration: Aibel

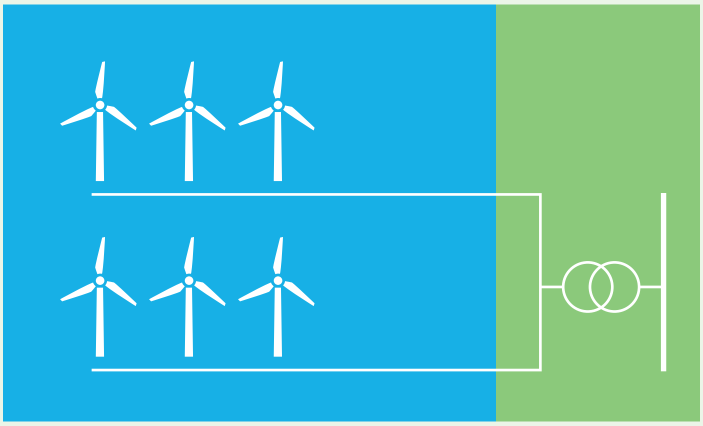
4.1 General

There are two principles for transmitting electrical energy: alternating current (AC or HVAC) and direct current (DC or HVDC). The most common method of transmission is AC. AC can be stepped up or down easily using transformers, making it ideal for both transmission and distribution. AC systems are normally cheaper than DC systems and offer far greater flexibility in distributing energy. If there is a need to isolate or break the grid in the event of faults or other conditions, well-established technology is available. One drawback of AC is the high losses and voltage drop over long distances, especially in cable systems. For long distances and large energy transfers, DC is the best technology. However, DC systems are expensive, particularly because of the need for conversion between AC and DC. Circuit breakers for isolating DC grids in the event of faults are not commercially available at higher voltage levels.

Three typical grid configurations (hereafter called «cases») are described in this report to provide a comprehensive overview and evaluation. All cases apply to floating offshore wind farms with radial connections to land. They essentially differ in terms of distance from the wind farm to the onshore connection point.

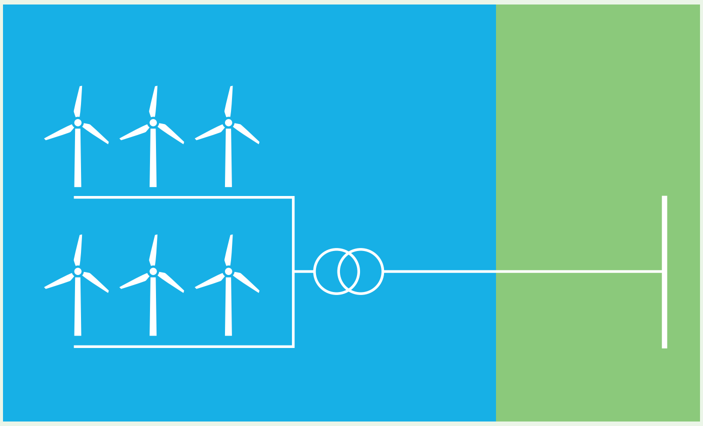
1

Offshore wind farm connected to shore by AC directly



2

Offshore wind farm connected to an offshore transformer station with an AC connection to shore



3

Offshore wind farm connect-ed to an offshore HVDC converter station with an HVDC connection to shore

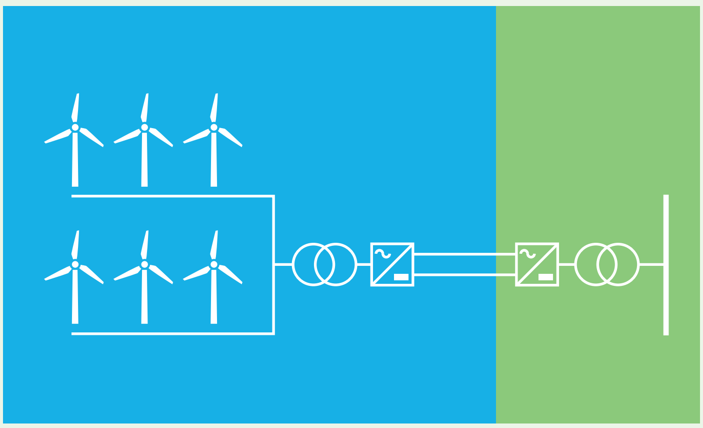


Figure 8: Alternative grid configurations (cases)

The chosen grid solution depends on requirements for transmission capacity, energy-loss considerations, availability of connection points, as well as costs and the maturity of the necessary components.

The chosen grid solution depends on requirements for transmission capacity, energy-loss considerations, availability of connection points, as well as costs and the maturity of the necessary components. Compared to existing bottom-fixed installations, it is primarily these latter aspects that will change for floating wind.

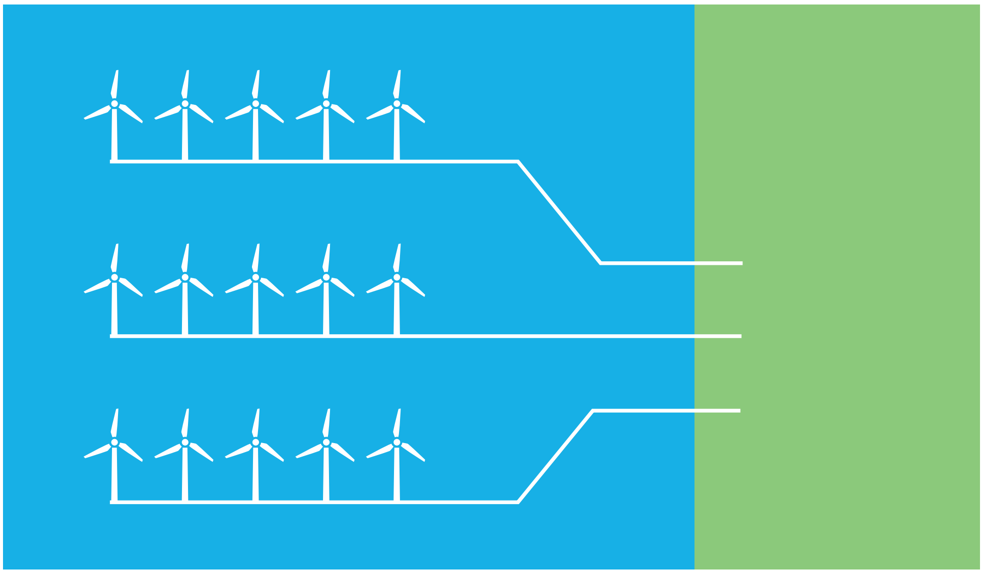
As turbine output increases, the voltage from the turbines (to which the cable system is connected) also rises. There are currently no floating turbines operating at 132 kV, but from an electrical standpoint this is not considered a technical barrier, since 132 kV equipment is, in many cases, also used for 66 kV. However, turbine suppliers note that they do not have a definitive timeline for when 132 kV will become commercially available. It is reasonable to assume that 132 kV will first be introduced for bottom-fixed installations.

Considerations regarding floating wind-turbine substructures and mooring are not part of this report. All cases concern deep water, typically exceeding 70 meters.

For distances of around 100 km or less from the onshore connection point, it is natural to use AC. Whether step-up transformation is needed to minimize transmission losses must be calculated for each individual project, taking into account factors such as the required transmission capacity.

Direct current (HVDC) will be the natural choice for wind farms located more than about 200 km from land. For distances in the range of about 100–200 km, the choice of technology must be evaluated on a case-by-case basis. Note that these numbers for AC and HVDC distance thresholds are very approximate, and every project must conduct extensive calculations to determine the optimal solution.

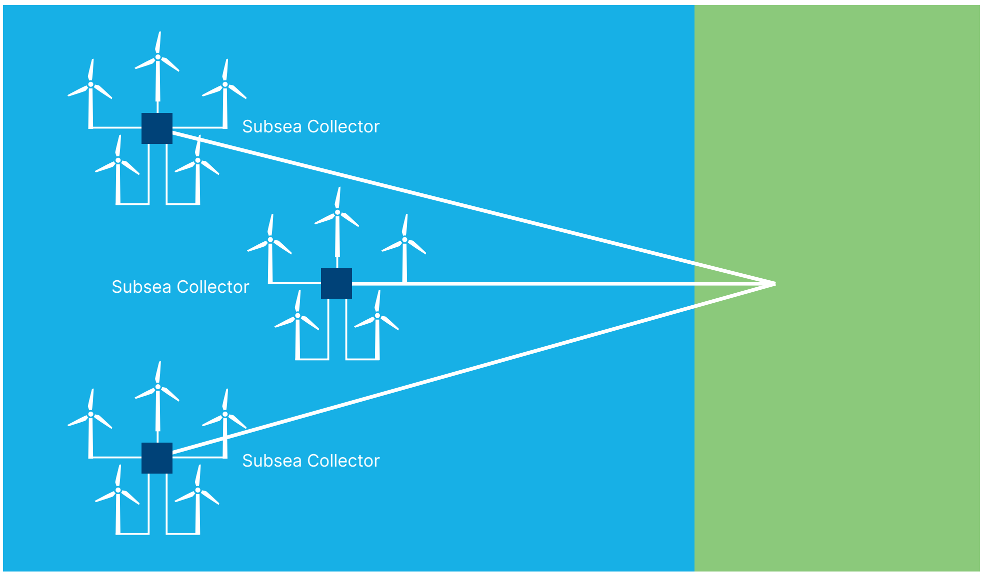
4.2 Wind Farm with AC Connection Directly to Shore



4.2.1 Connection via Cables Directly from Turbines to Shore

Figure 9: Wind farm with a direct cable connection to shore (source: Statnett)

In this configuration, cables run directly to shore from floating turbines. For details on dynamic cables connected to floating turbines, refer to Chapter 5.5.

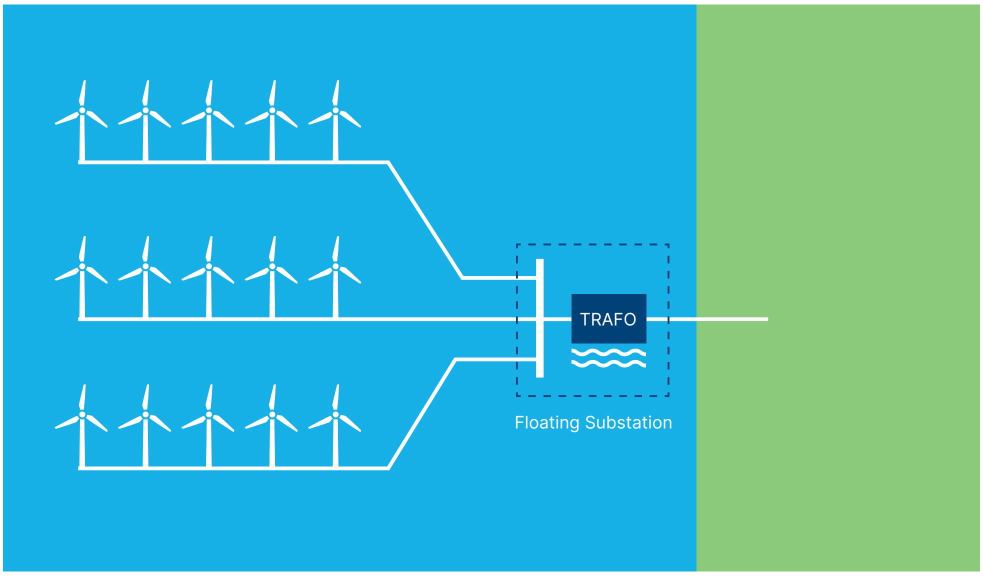


4.2.2 Connection via Collector

Figure 10: Wind farm with a direct cable connection to shore via collectors

In this configuration, cables run directly to shore from a subsea collector rather than from the «last» turbine in the wind-farm area. For details on dynamic cables connected to floating turbines and collectors, see Chapter 5.5. For more details on the collector, see Chapter 5.4. In principle, static cables may be used for the section from the collector to land.

4.3 Wind Farm with Grid Connection via AC Transformer



4.3.1 Floating Transformer Station

Figure 11: Wind farm with grid connection via a floating transformer station

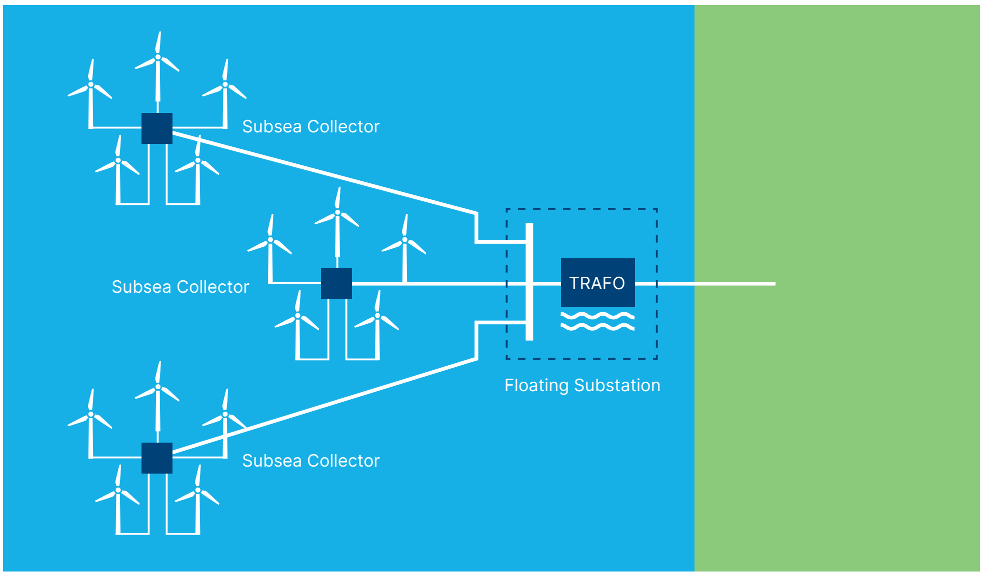


Figure 12: Wind farm with grid connection via a floating transformer station and collectors

In these configurations, the wind turbines (array cables) connect either directly to the floating transformer station or via a subsea collector. From the floating transformer station, cables (export cables) go directly to shore.

For an offshore floating transformer station, dynamic cables are required both for the array cables from the turbines and for the export cables from the platform to shore. For details on dynamic array cables connected to floating turbines and on export cables connected to a floating transformer platform, refer to Chapters 5.5 and 5.6. For more information about the floating offshore platform, see Chapter 5.2.

4.3.2 Subsea Transformer Station

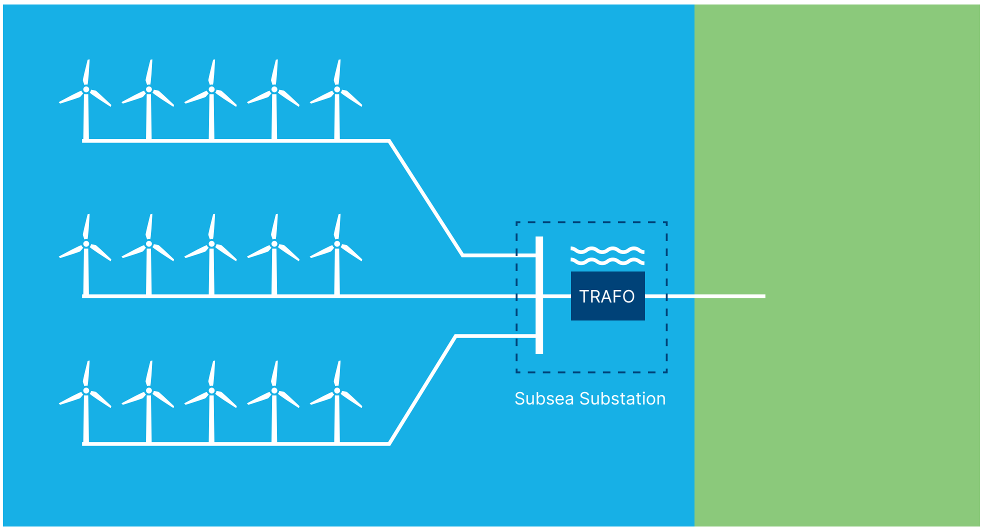


Figure 13: Wind farm with grid connection via a subsea transformer station

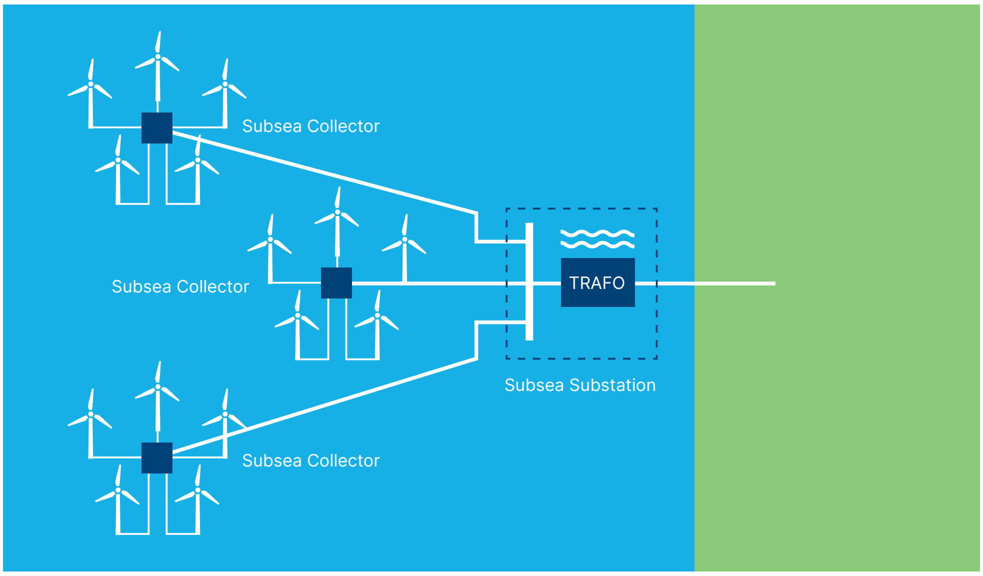


Figure 14: Wind farm with grid connection via a subsea transformer station with collectors

In these configurations, the wind turbines (array cables) connect either directly to a subsea transformer station or via a subsea collector. From the subsea transformer station, cables (export cables) run directly to shore.

A subsea transformer station requires dynamic cables for the array cables from the turbines to the subsea transformer or collector. For details on dynamic array cables connected to floating turbines and collectors, refer to Chapter 5.5. When connecting cables to collectors or to the low-voltage side of the subsea transformer, there must be an option for underwater connection known as a «wet-mate connector.»

For more details on the subsea transformer, see Chapter 5.3. For details on collectors, see Chapter 5.4.

4.4 Wind Farm with Grid Connection Using a Direct-Current Converter (HVDC)

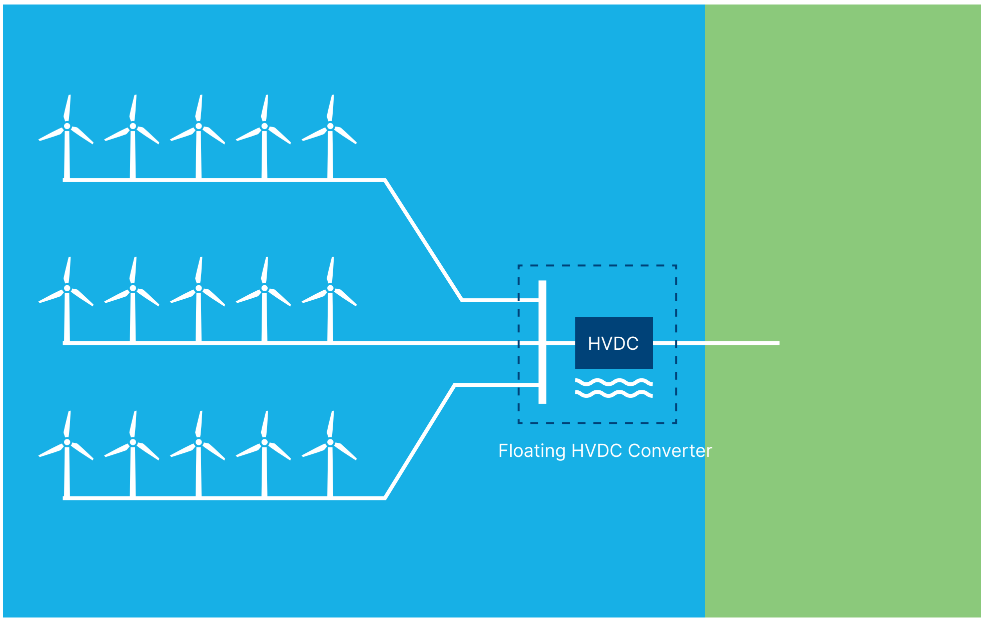


Figure 15: Wind farm with grid connection via a floating HVDC converter

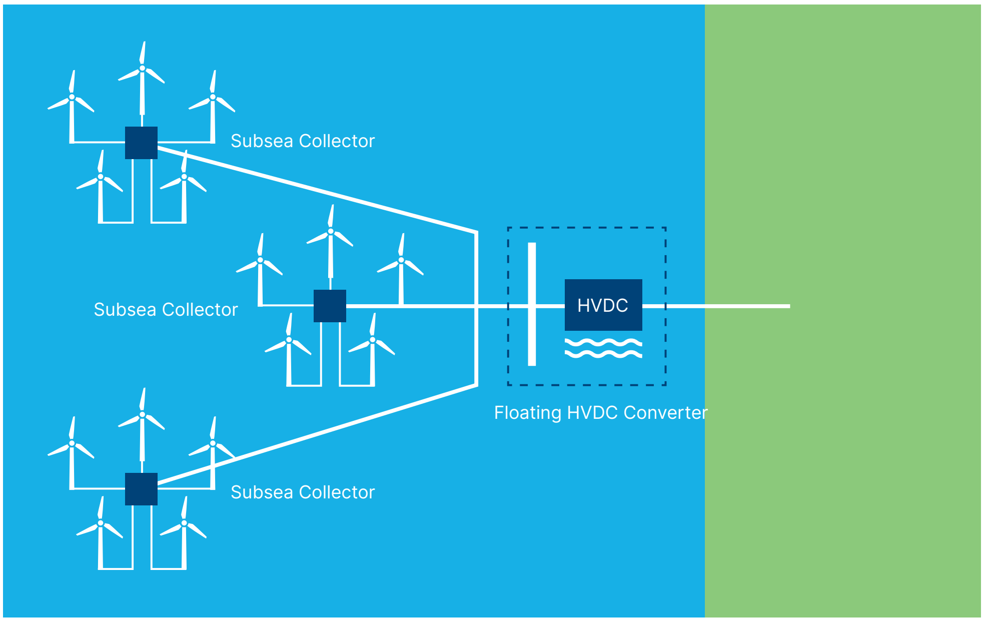


Figure 16: Wind farm with grid connection via a floating HVDC converter and collector

In these configurations, cables from the wind turbines (array cables) run either directly to the floating HVDC converter or via a subsea collector. From the floating HVDC converter station, HVDC cables (export cables) go directly to shore.

Dynamic cables are needed for the array cables from turbines to the collector. For details on dynamic array cables connected to floating turbines and collectors, refer to Chapter 5.5. When connecting cables to collectors, an underwater connection solution known as a «wet-mate connector» is required.

For details on collectors, see Chapter 5.4.

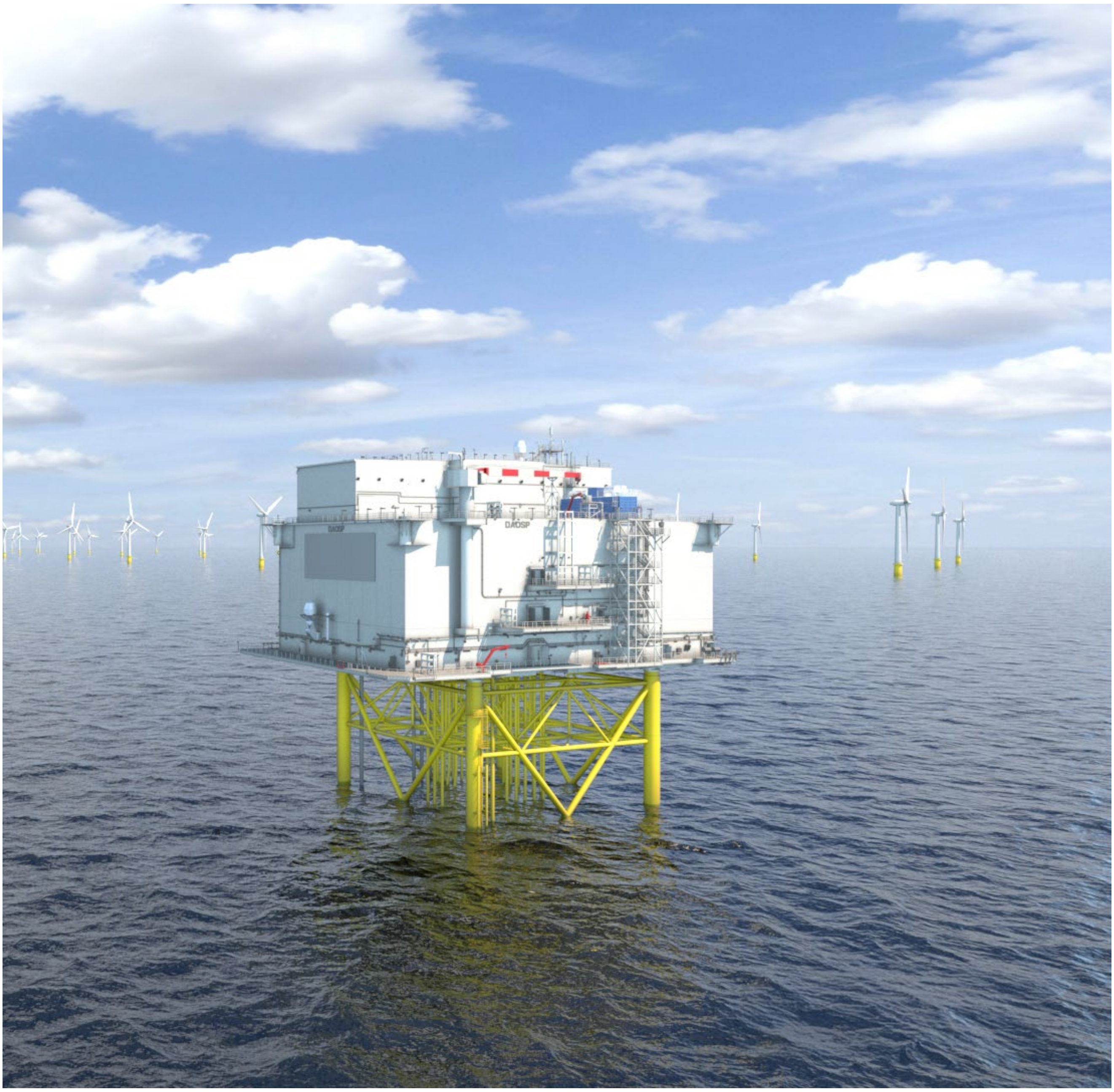


Photo: Aibel

5

TECHNOLOGY EVALUATION

5.1 General

In this chapter, the various technologies related to grid systems for floating offshore wind are evaluated. The main focus is on technology descriptions, technology readiness, technology gaps, and assessments of how such gaps can be closed. Technologies for floating offshore wind are generally considered costly, which makes it important to identify technology gaps and solutions that can reduce expenses. Investment, operating, and maintenance costs are key considerations, as are repairability and repair strategies. Sustainability has been taken into account, but has not been central in this report according to the mandate.

In general, technology development proceeds in several stages, beginning with design and calculations, then moving on to small-scale testing before large-scale testing. An investment decision for a real project is typically made after large-scale testing and verification, at which point the technology is qualified. This is followed by detailed engineering, construction, installation, and testing prior to commissioning. Detailed engineering and implementation generally take 3–5 years from the investment decision to start-up and normal operation.

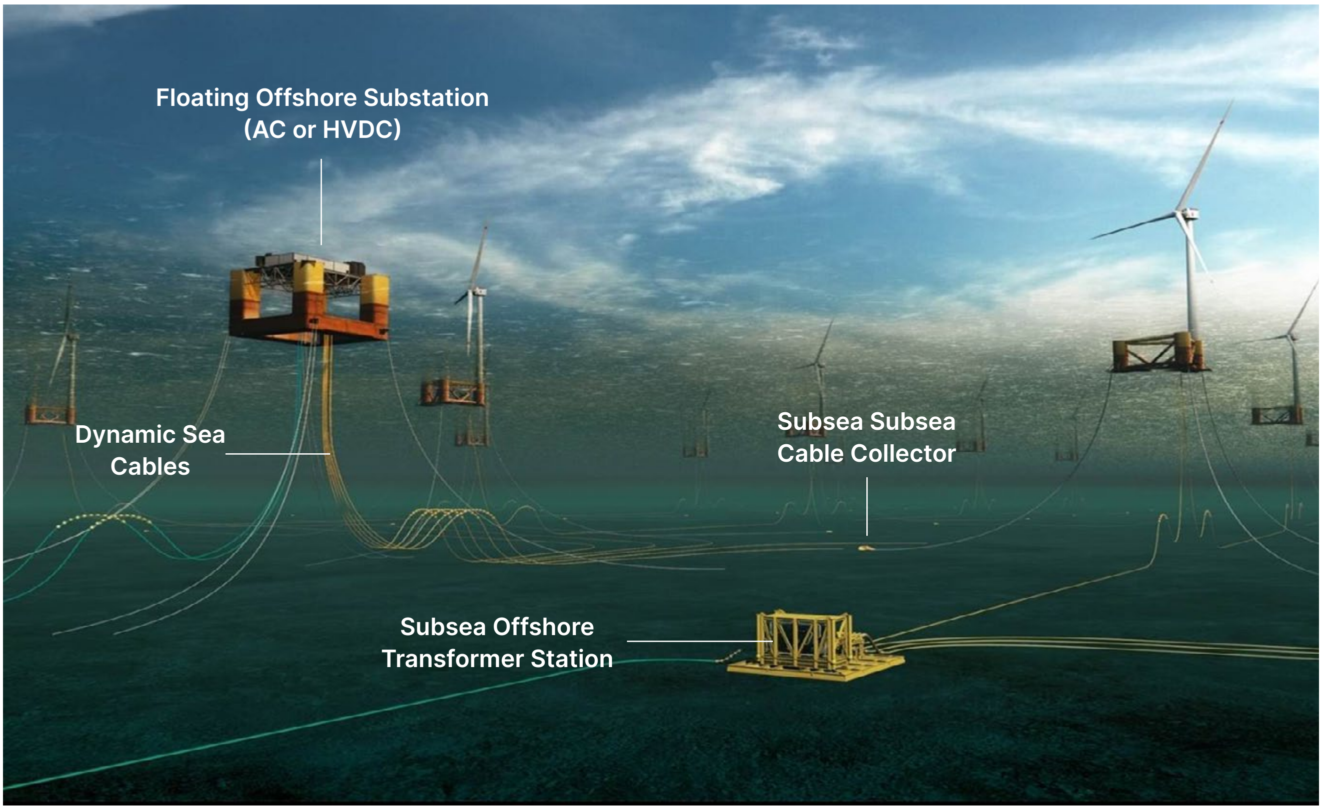


Illustration: Aker Solutions

Figure 17: Overview of evaluated technologies

When we say that a technology is «ready,» we must distinguish whether it is ready for first-time test use in a project or whether it has been built and tested in real-world operation.

To describe a clear status for technology maturity, this report refers to whether the technology is ready for the start of project development.

Capacity in the Industry

The mandate specified that capacity within industry was to be included in the study. However, upon review, this topic was removed from the internal work of the group because it impacts the individual companies' need for confidentiality and could conflict with competition regulations.

Hence, the point regarding capacity in the industry has instead been addressed through an external market analysis carried out by ERM, Brinckmann, and Norwegian Energy Partners (NORWEP). Commissioning clients for the study are Norsk Industri, Fornybar Norge, and Offshore Norge. In very brief summary, the study showed that the Norwegian market is too small to influence the industry's capacity on a global scale. The report also points out where the industry currently faces bottlenecks[5].

Capacity challenges in the supply chain and limited commitment by suppliers—due to uncertainty and risk—can slow technology development, especially in areas with costly industrialization and piloting needs.

5) norskindustri.no/siteassets/dokumenter/bransjer/offshore/2024-global-supply-chain-study---havvind.pdf

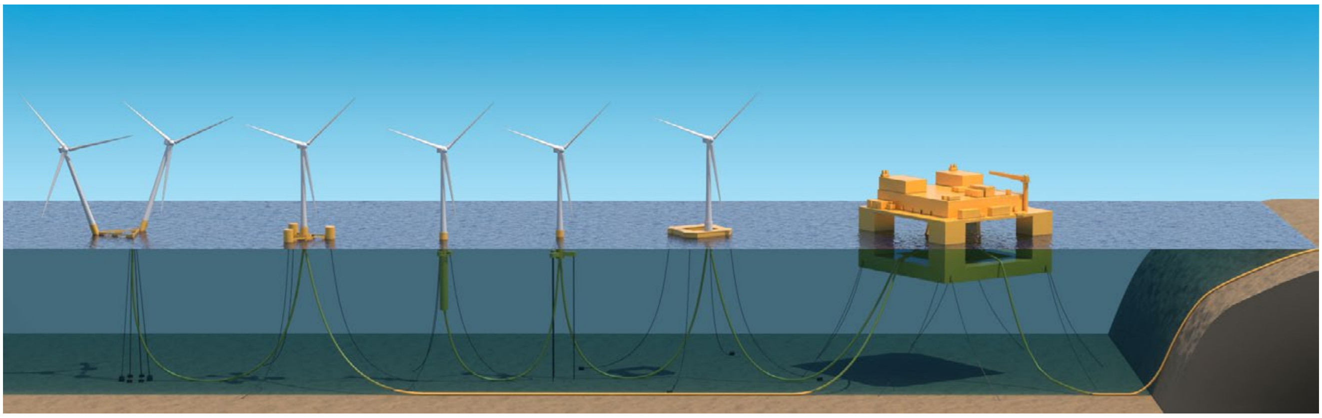


Illustration: Aibel

Figure 18: Floating HVAC substation, schematic drawing for connection with floating turbines and with land.

5.2 Floating Offshore Substations

5.2.1 Technology Description for HVAC Substations

HVAC substations will play a vital role in transmitting electric power from offshore energy sources such as floating wind farms to the onshore grid. The technology in these substations involves several key components, including transformers, switchgear, reactive power compensation, and protection systems that ensure the generated power is transported efficiently over long distances with minimal losses.

For offshore applications, HVAC substations are usually installed on platforms at sea, and their design must be adapted to the challenging marine environment. This includes corrosion-resistant materials, modular designs for simpler installation and maintenance, and protection against fluctuations in temperature, humidity, and mechanical stress from waves and wind.

For floating offshore wind, it is highly advantageous that much of the existing technology from the oil and gas industry can be reused. Nonetheless, further development is needed. This includes simpler and more cost-effective designs, improved subsea transformers and cable terminations, and increased standardization to reduce costs and enhance reliability. HVAC substations have a high degree of technology readiness but require continuous optimization and collaboration between suppliers and designers to address the specific challenges of floating offshore wind installations.

Market Status

Various concepts for floating HVAC stations have been developed over the last 10–15 years. One floating pilot test station has been built in Japan's Fukushima floating wind test site[6]. Apart from that, no floating pilot project has been large enough to require a floating substation. In the typical chain of project development, from feasibility study to conceptual study, FEED, and execution/construction, one Equinor project in South Korea has reached the FEED stage. Planned floating wind farms have received licenses in the UK, though these are designed with floating turbines and bottom-fixed substations at shallow water depths of about 100 m. There are other initiatives and concrete plans for floating wind farms ranging from pilot scale (~200 MW) up to commercial scale (1,000 MW+) in France, Ireland, Taiwan, Japan, and on the U.S. East Coast, but with uncertain timelines.

Technology Status

The technological status for floater hulls (structures) is that their design and layout can and should largely follow standard solutions from the oil and gas industry. Simplifications and certain adaptations are required, for example for ballast systems. The assumption is that the platform will be unmanned.

Different requirements apply to equipment on a floating platform compared to a bottom-fixed one, in order to handle accelerations in all directions and angles. High-voltage equipment rated in the tens of MW and tens of kV has been used on ships and platforms/FPSOs for many years and is well proven and qualified. Work is ongoing at the Offshore Industry Directorate («Havindustritilsynet») and DNV to adapt regulations and requirements for floating substations.

Some attempts have been made to design floater concepts that are more or less fixed in place or so large that they move little more than a bottom-fixed platform. These concepts become extremely costly or are otherwise impractical due to size. For instance, tension-leg platforms are constrained vertically, but have the same horizontal accelerations as other floaters. It is considered not technically feasible to fix horizontal motion with very robust mooring, as it would be cheaper in that case to build a bottom-fixed solution.

6) Floating substation pilot in Japan https://www.fukushima-forward.jp/reference/pdf/study025.pdf

The conclusion is that equipment on a platform must tolerate normal floater movements, and this is fully achievable both technically and economically.

Equipment suppliers have worked on developing and qualifying high-voltage equipment rated in the hundreds of MW and hundreds of kV over the last 5–6 years, and they confirm that they are prepared to deliver the equipment necessary on a floating HVAC substation. For more specific details, refer to Chapter 5.2.3.

Figures 18 and 19 illustrate floating substations that, like floating turbines, require what are called dynamic cables. These are cables and cable arrangements capable of accommodating relative motion between the platform and the seabed. For information on developments in dynamic cables, see Chapters 5.5 and 5.6.

A floating substation also requires a mooring system. Standard mooring systems from the oil and gas industry can function technically for floating substations, though they may be too expensive relative to the revenue potential from wind farms. Several R&D projects have been carried out with funding from the Research Council of Norway (NFR) to develop more cost-optimized solutions using fiber ropes or other alternatives, though no major cost savings have been definitively proven so far. Reference projects include Innovative Mooring Systems and FIRM (Fibre Rope Mooring).

Service Life, Operation, Maintenance, and Repair Philosophy
They are designed for the same service life and operation, maintenance, and repair philosophy as bottom-fixed substations. This is considered sufficiently mature for execution, and no significant gaps have been identified. Standard floating turbines must either be disconnected and towed to shore or rely on a currently nonexistent solution for major offshore maintenance. A floating substation, on the other hand, can undergo all maintenance and any component replacements on-site using known and proven methods involving cranes on service vessels, platform cranes, and floating cranes. For the existing floating substation concepts, access, material handling, evacuation, and replacement philosophies are already integrated into the concept.

5.2.2 Technology Description for HVDC Substations

The same challenges involving cables and equipment apply to floating HVDC substations. Much of the equipment is the same for HVDC as for HVAC and can be considered qualified once HVAC stations have been built and tested. HVDC suppliers are working to qualify the converter equipment itself; this is deemed fully feasible with minor modifications, but its qualification timeline is somewhat longer than that of HVAC equipment.

Aibel, Hitachi Energy, and Nexans are involved in the Grønn Plattform «Ocean Grid» project, which is funded by the Research Council of Norway and Innovation Norway. That project performs fatigue and extreme-load simulations and evaluations for two HVDC concepts based on metocean data from the Snorre field in the Tampen area of the North Sea. The project includes ±320 kV symmetrical monopole solutions with 1.0–1.6 GW capacity for floating converter stations, and ±525 kV bipole solutions with 2–3 GW capacity for floating converter stations. For floating HVDC stations, the specific HVDC equipment still needs additional development and qualification to be used on floaters.

Illustration: Aibel

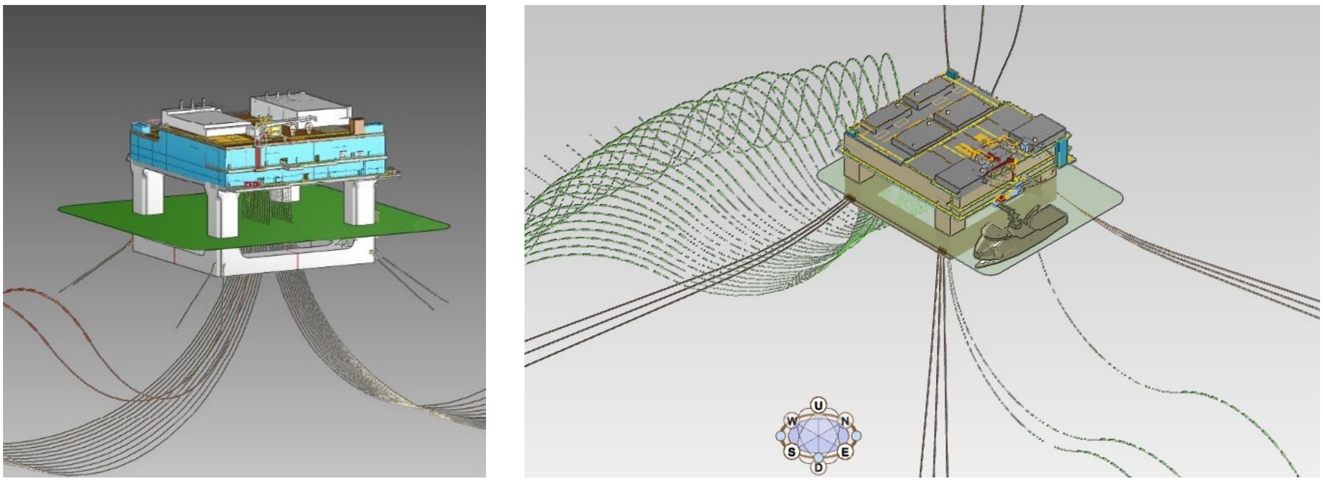


Figure 19: Concept for floating HVDC stations. 1.0–1.5 GW at 320 kV (monopole) on the left, 2–3 GW at 525 kV (bipole) on the right. (Concepts by Aibel for the Equinor/Sintef Ocean Grid R&D project, sub-project on floating HVDC stations).

Similarities and Differences between HVAC and HVDC

- Some of the equipment on HVAC and HVDC substations is identical or of a similar type
- HVDC stations have more equipment on the platform. The converter equipment itself, which converts between AC and DC, requires more deck space.
- HVAC system design and equipment components are interchangeable among suppliers, with possibilities to combine parts from multiple vendors. The system design can be done either by equipment suppliers or by independent parties.
- HVDC system design and equipment components for each station are specific to each supplier and not interchangeable. System design can only be done by the equipment suppliers themselves.
- This affects how contracts are set up and how projects are carried out, being more constrained for HVDC and more flexible for HVAC

Electrical equipment required today is commercially available for use in bottom-fixed projects and has accumulated operational experience spanning more than 10 years in such installations.

5.2.3 Technology Description for HVAC and HVDC Electrical Equipment

Electrical equipment required today is commercially available for use in bottom-fixed projects, and operational experience has been gained over more than 10 years for such installations. Consequently, there is no need to develop components that can handle higher voltages, larger currents, and greater power, etc. The challenge lies in «marinizing» them, or more precisely reinforcing mechanical structures, fixtures, penetrations, etc., so that the equipment can withstand the stresses of being installed on a floater.

For decades, the marine as well as the oil and gas industries have established standards and testing programs to qualify equipment for the industry, either through type tests or project approvals. Some of this can be directly reused for floating offshore wind, such as auxiliary systems (MV and LV), control systems, and telecom systems that already have approvals from maritime classification societies.

For heavier electrical equipment like power transformers, shunt reactors, gas-insulated switchgear (GIS), and HVDC converters, GE Vernova, Hitachi Energy, and Siemens Energy are all running qualification programs. These programs assess the mechanical integrity of transformers, GIS systems, HVDC converters, etc., when placed on a floater. Typically, they test for fatigue, extreme loads, accident conditions, varying deflections and deformations, as well as accelerations and

tilting. Historically, electrical equipment at lower voltage levels has been delivered and type-approved for marine and oil/gas installations.
This includes transformers, switchgear, and power-electronics-based converters. DNV and other classification societies type-approve such equipment for ships and oil and gas installations.

There are also specific standards for offshore wind, for example DNV-RU-OU-0512 «Floating wind installations.» At high-voltage transmission levels, there is currently only one voluntary class (HV)[7].

The following systems are covered limited to the hull and its systems, i.e. not including the power transmission and its associated systems, unless the voluntary class notation HV is selected:

- **machinery systems and equipment**
- **electrical systems and equipment**
- **instrumentation and telecommunication systems**
- **fire protection**

The high voltage electrical system, equipment and associated control systems necessary to collect and transform the power from the wind power plants to the offshore transmission system may be covered by the voluntary class notation HV.

In practice, this means that suppliers have experience, and possibly type approvals, for equipment of smaller ratings and lower voltages used on ships and oil and gas installations, but not for the «heavier» equipment required in a transmission system for offshore wind.

As of today, 132 kV HV GIS and transformers in the 50–100 MVA class have been delivered and put into operation on the Troll B and C platforms, Gjøa, and the Goliat platform. The Jansz platform is being outfitted with comparable equipment, as well as power electronics–based converters rated around 20 MVA for compressors and propulsion systems.
This implies that some of the equipment needed for floating offshore wind is already available on the market, while other equipment will have to undergo qualification programs—typically, in the first instance, in the form of data simulations. One challenge is that much of this equipment is so large and heavy that it is neither possible nor practical to test prototypes on a shaking table, as is done in type tests for maritime certifications.

7) https://standards.dnv.com/explorer/document/7A322F7B14014BD793BDCB4C4C1C56CC/7 (login required)

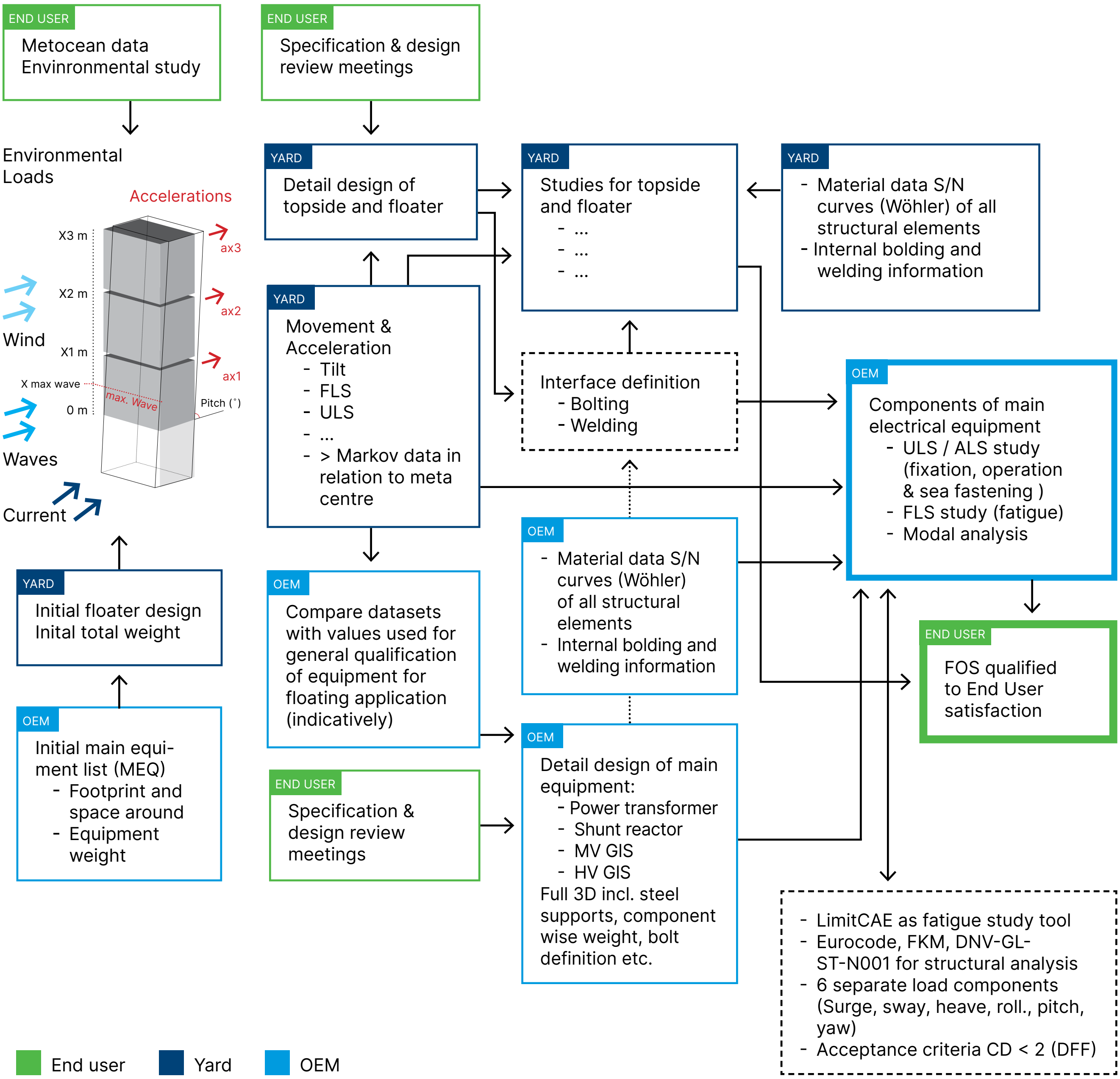


Figure 20: Design and verification process for electrical equipment placed on a floater.

The design and verification process for this equipment cannot be done by an equipment supplier alone. You need data on wind, waves, currents, etc., from the relevant location, as well as data from the platform designer regarding the floater itself, to simulate and verify the solution for a specific project.

Where on the floater the equipment is placed, and what accelerations are relevant at a given point for a given offshore area, must be determined.

One example of such a process:

Risks and Barriers

The market activity for bottom-fixed offshore wind projects and for electrification projects in general is very high. Many suppliers have record-high order books, and lead times on key components are long. There is a risk that floating offshore wind could be deprioritized in favor of other «simpler» projects—both by developers and suppliers.

As an industry, there is a need for coordination and harmonization of standards with criteria and testing/verification requirements. It can become very expensive if all equipment must withstand the accelerations and forces that might arise on a poorly designed floater in extremely rough sea areas.

Instrumentation and subcomponents can be tested separately through physical tests, whereas other equipment must be simulated digitally. Testing larger components in a lab or factory on a shake table is not possible. For instance, testing heavy transformers must therefore be done by other means.

Barriers or points that require industry-wide coordination:
- What can/should be tested and validated through physical tests vs. digital simulations?
- Which standards should be used for testing and simulation, and what test criteria should be set?

Timelines

HVDC converters, with their interconnected power electronics and associated control and cooling systems, are more complex and have more checkpoints than transformers and GIS facilities. Suppliers therefore indicate that floating transformer stations (HVAC) will be commercially ready for the start of project engineering around 2025, whereas floating converter stations (HVDC) are expected to be available for the start of project engineering around 2028.

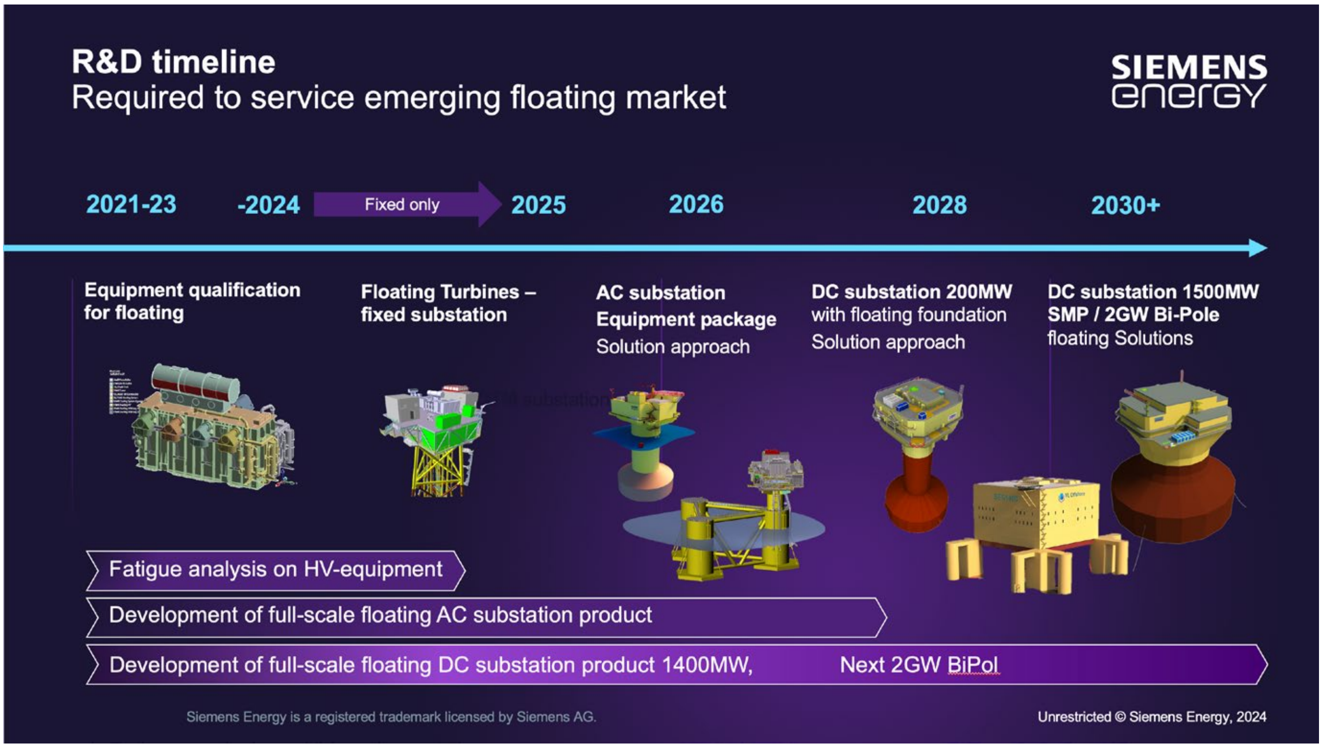


Figure 21: Timeline from Siemens Energy.

Sustainability

Since the 1960s, SF6 gas has been used as an insulating medium for GIS systems and as an arc-quenching medium in circuit breakers. This gas has excellent technical properties, but unfortunately it is also a significant «climate culprit» due to its greenhouse gas emissions impact in the event of leakage, with a GWP of 24,300. One kilogram of SF6 equals 24.3 tons of CO_2 if released into the atmosphere.

Use of SF6 gas is now in the process of being phased out, and SF6-free switchgear is commercially available today at the voltage levels required for floating offshore wind projects. These SF6-free alternatives must also be «marinized» and verified with simulations and tests in much the same way as other electrical equipment. This can be done within the same timeframe as other electrical equipment, provided that a pilot project is launched in which all equipment for the floater is reviewed for the specific project—typically in a FEED study.

5.2.4 Need for Technology Development and Demonstration Projects

Through a full-scale project, there must be room for technology qualification of remaining gaps, as well as potentially uncovering the need for further improvements and technology development.

In order to test and pilot floating substations, areas and projects should be allocated where a floating substation is suitable. This can optionally be made a condition for issuing a wind-power license.

To be able to implement both HVDC and HVAC projects with floating platforms as described above, most of the main components are already in place. However, to take another step forward in closing the identified gaps in installing equipment on a floating platform, it would be most appropriate to carry out a full-scale project. Through a full-scale project, there must be room for technology qualification of remaining gaps, as well as potentially uncovering the need for further improvements and technology development.

In order to test and pilot floating substations, areas and projects should be allocated where a floating substation is suitable. This can optionally be made a condition for issuing a wind-power license. The progress of building a floating substation is currently driven by the ability and willingness to allocate and initiate projects.

There is a certain commercial risk in building the first substations, and risk-mitigating measures will likely be necessary.

Technical requirements and regulations should follow international standards so that one avoids creating special-purpose solutions for Norwegian projects. For instance, floating oil and gas installations on the Norwegian Continental Shelf have unique Norwegian requirements, combining NORSOK standards and regulations from the Norwegian Maritime Authority. This leads to solutions that are not standardized, typically relating to mooring, the number of ballast tanks, ballast systems, surface treatment, steel grades, and so on, which can drive costs upward.

DNV's standard for offshore substations has become the de facto international standard for bottom-fixed wind. DNV has ongoing work, which includes R&D (a Joint Industry Project), to update its offshore substation standard to include floaters. This effort should be supported. There is also work in progress with the Offshore Industry Directorate («Havindustritilsynet») that needs clarification and should naturally be aligned at an international level, referencing internationally recognized standards.

For floating HVDC stations, development and upgrades are needed for the converter equipment itself at foreign suppliers, enabling it to handle the motions of a floater. This must be done by suppliers without direct support, but there should be indirect incentives by ensuring a predictable pipeline of projects. In that way, suppliers will be willing to invest in development; it creates certainty to know there are more projects on the horizon.

Generally, there is a need to reduce the costs of building offshore grids for offshore wind, and an important instrument is running large-scale projects and learning from them. Typical areas where cost reductions may be achievable include introducing unmanned operations, simplified marine systems, and optimized mooring systems—consisting of either smaller amounts of materials or use of cheaper materials and components. The recommended path forward is to combine research and development with execution of projects in which new solutions are tested.

A summary of the recommendations for floating substations:
- Establish pilots and projects
- Continue supporting R&D in anchoring, simplified marine systems, mooring systems, etc.
- Support efforts to lower costs for various concepts and systems for unmanned operations
- Support work on developing regulations and standards, ensuring they are harmonized internationally

5.2.5 HVDC Grids and Interoperability
Work has already been initiated by most suppliers to develop HVDC grids, «multi-terminal – multi-vendor.» This will also introduce and involve onshore switching stations capable of handling system faults, such as fault detection and disconnection (not just point-to-point deliveries). This development is already supported by EU funding in a project called «InterOpera.» It can be assumed that the offshore portion of an HVDC grid will not be significantly affected. This type of development will further expand opportunities to interconnect countries and regions around the North Sea securely and efficiently. Pilot projects for this type of technology have already been selected over the next 5–10 years.

5.3 Subsea Offshore AC Transformer Station

5.3.1 Technology Description

The development of offshore transformer stations as underwater solutions, referred to briefly as subsea substations, originates with subsea transformers used for subsea compression and pumping systems in the oil and gas sector. Companies such as Aker Solutions, ABB/Hitachi, SLB OneSubsea, Baker Hughes, and Siemens Energy, among others, all drawing from Norwegian engineering environments, have played a key role in developing this electrical technology. One example is the Ormen Lange Subsea Compression pilot, which was tested from 2011 to 2015 in Shell's test basin at Nyhamna near Molde. That was the first time a prototype of around 20 MVA and 132/22 kV was tested, designed for 70 MVA[8]. This solution included a 132 kV dry termination from Baker Hughes between the cable and the transformer, also used in Equinor's Åsgard Subsea Compression. Here, multiple subsea transformers with wet and dry connectors up to 52 kV have been in operation since 2015, achieving over 99.9% uptime (equivalent to only about 8 hours of downtime per year, source: Equinor in media 2022[9].

Photo: Aker Solutions

Figure 22: Example of a 400 MVA Subsea Substation with 66 kV input (4 units) and 220 kV output.

8) Offshore magazine, «Ormen Lange pilot test info: 'Norske Shell sanctions Ormen Lange subsea compression tests,' 1 April 2012. [Online]. Available: https://www.offshore-mag.com/subsea/article/16760195/norske-shell-sanctions-ormen-lange-subsea-compression-tests

9) Midtnorsk Næringsnytt MN24, «Equinor statement on uptime for subsea compression with electrical equipment» in the article «Can earn 200 billion on what they thought was impossible,» 6 February 2022. [Online]. Available: https://www.mn24.no/nyheter/i/Xq3nrg/kan-tjene-200-milliarder-paa-det-de-trodde-var-umulig

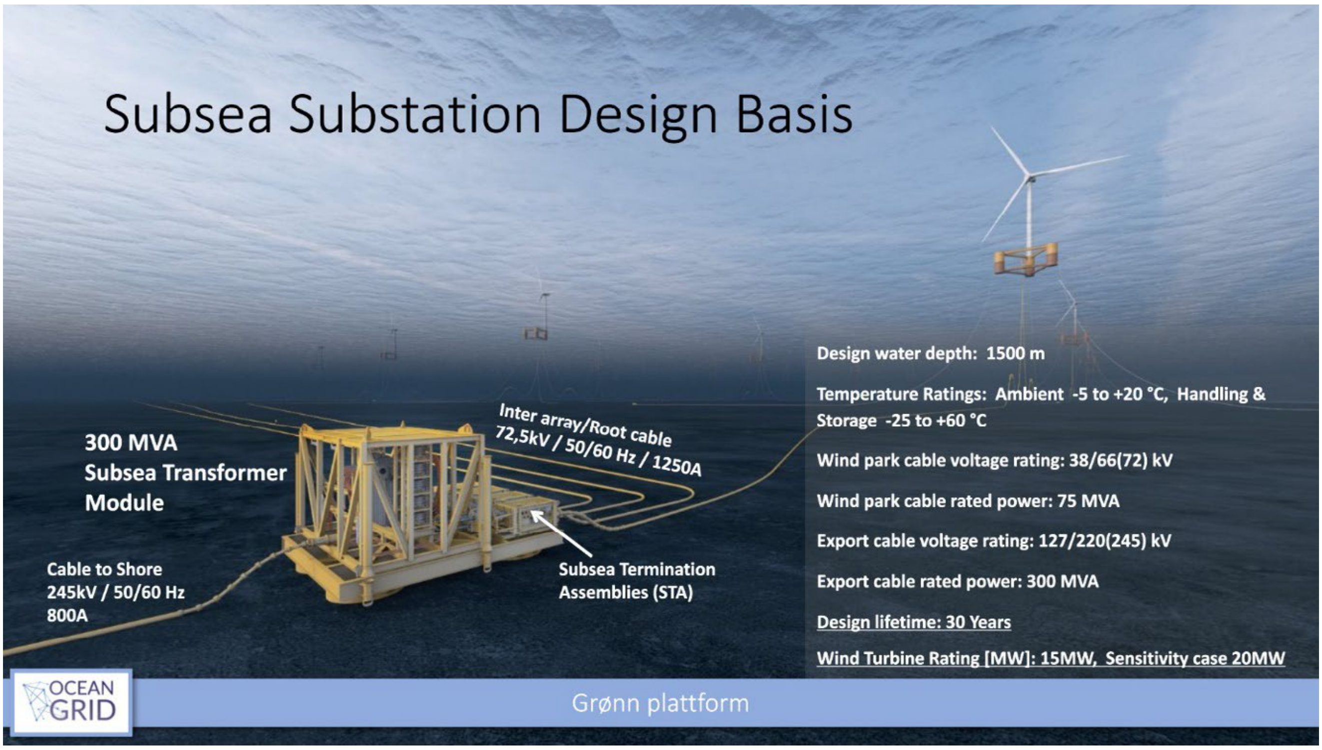


Photo: oceangridproject.no

Figure 23: Example of design basis and technical requirements from OceanGrid/Grønn Plattform.

For example, ABB together with Hitachi Energy have played a pioneering role in technology development both from design studies and testing/prototypes over the last 25 years, and have led the way in delivering around 40 subsea transformers without reported failures. Statistics from Åsgard, as well as multiple underwater pumping systems with products from various suppliers, show that transformers and high-voltage connectors underwater have high reliability.

Over the last 7–8 years, based on experience from oil and gas, similar solutions have gradually been developed for floating and bottom-fixed offshore wind. The same applies for tidal power, for example through HydroQuest Flowatt in France[10]. As of today, several players are developing subsea transformers up to 400 MVA. These are adapted to offshore wind with 66 kV and 132 kV AC cables on the supply side and transmission voltages to shore at 145 kV and 245 kV. Norwegian authorities are, among other things, sponsoring Grønn Plattform / OceanGrid, where ABB and Aker Solutions are developing system topologies and functional requirements for subsea transformer stations under the leadership of Equinor and SINTEF, and others[11].

10) Windstaller Alliance press release, «Windstaller Alliance appointed to HydroQuest Flowatt Tidal FEED,» 2023. [Online]. Available: https://www.windstalleralliance.com/news/windstaller-alliance-appointed-to-tidal-power-feed
11) OceanGrid project, «OceanGrid project,» 2024. [Online]. Available: https://oceangridproject.no

Technological Status / State-of-the-Art
Based on publicly available information, there are currently four players developing underwater offshore AC transformer stations. These are Aker Solutions together with ABB/Hitachi Energy, Baker Hughes (based on conference presentations), SLB OneSubsea[12], and Siemens Energy[13].

Regarding MVA capacity, this is determined by both the current-carrying ability of the cable and its cable termination on the high-voltage export side of the transformer, plus thermal and practical considerations relating to fabrication and installation on the seabed. Although it is technically possible to design a transformer larger than 500 MVA, for instance, there is an advantage to staying below a typical maximum weight of 600 to 900 tons to fit the most common classes of installation vessels. If one goes above this weight, heavier crane vessels become more relevant, which are significantly more expensive and less available.

Several of these players have presented at conferences that they are developing transformers up to 400 MVA, and in that case the weight is expected to typically fall within the abovementioned weight classes. That is also within what transformer factories can handle, logistically speaking, in terms of modular integration and fabrication.

Depending on the power system architecture, it can also be relevant to equip the transformer with circuit breakers, disconnectors, and grounding switches (either integrated in the module or as a separate circuit-breaker module), so that the cables coming in from the wind farm can be isolated in the event of faults, thereby maintaining operation on the other incoming cables / wind turbines. The circuit breakers also allow for pre-testing and voltage testing of the system from shore, as well as enabling phased development of the wind farm.

Table 1 on the next page summarizes the technology status as of Q2 2024 (TRL scale 1–9, EUR 27988 EN). One difference with subsea transformers, compared to those mounted on a platform, is that one

12) A. M. Askeland, «One Subsea: «Subsea Substations - Leveraging Existing Technology to Reduce Costs off Offshore Wind», i Underwater Technology Conference, Bergen, 2023
13) G. Mabey, «Siemens Energy - The Future of Platform Electrification with Subsea Transformers and High Voltage Wet-mate Connectors», i Floating Wind Solutions, Houston, USA, 2024

System Component	Status (December 2024)				Ambition for Offshore Wind			
	Power	Voltage	Water depth	TRL level scale 1–9	Power	Voltage	Water depth	Expected TRL 6/ ready for project
Subsea Transformer[1)]	24 MVA	145 kV (HV side) 52 kV (MV side)	3000 m	TRL 9	400 MVA	245 kV (HV side) 72 kV (MV side)	1500 m	2025–26
Termination / Wet Connector on the MV / IAC Side of the Transformer[2)]	97 MVA	52 kV	3000 m	TRL 6	143 MVA	72.5 kV	1500 m	2025–26
Termination / Dry Connector on the HV / Export Side of the Transformer[3)]	176 MVA	145 kV	3000 m	TRL 9	400 MVA	245 kV	1500 m	2025–26

1) References: Hitachi Ormen Lange (24 MVA), ABB Ormen Lange Pilot (145 kV). Both One Subsea, Aker / ABB, and Siemens have indicated 400 MVA as a goal for offshore wind.
2) Currently: Siemens SpecTRON 45–52 kV / 1250 A. 145 kV is expected to be the next step once the market for floating wind turbines fully transitions from 66 kV to 132 kV. Aker Solutions / Benestad, SCM, Siemens, and Baker Hughes are developing 72.5 kV wet connectors.
3) References: Baker Hughes MECON 145 and MECON 245 (under development together with NTNU and SINTEF in the CROWN project, partially supported by the Research Council of Norway).

Table 1: Technology status for underwater components related to a subsea transformer station.

can install several 400 MVA units successively as the wind farm area is developed. This is feasible because the 400 MVA systems are entirely independent.

This can have a positive effect on net present value, since a bottom-fixed or floating substation is typically designed for the total installed capacity of the entire wind farm right from the start, at the point when the platform is sent offshore. By contrast, multiple subsea transformer units can be installed side by side in step with the capacity/size of the wind farm, also providing inherent system redundancy in line with the number of parallel systems.

Installation

There is considerable experience with installing large, comparable subsea modules exceeding 400 tons from the oil and gas industry (for example, large subsea compressors). This includes subsea transformers with dry cable terminations, as illustrated in the photo in Figure

Photo: Equinor

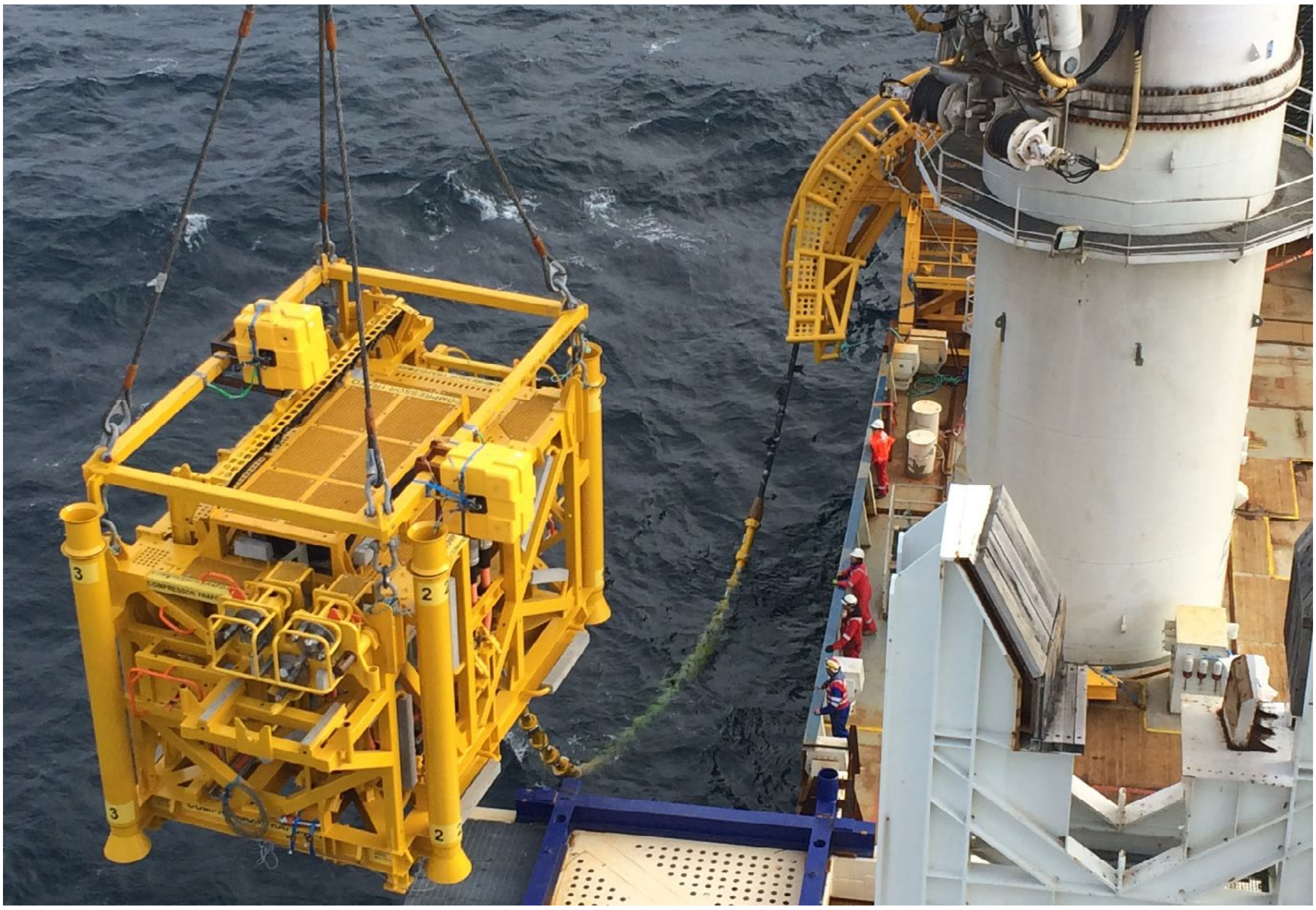


Figure 24: Installation of the Åsgard subsea transformer from Aker Solutions/ABB, 2015. The figure also shows the power cable, which is dry-connected to Baker Hughes' mECON 145 kV cable terminations.

24 from the Åsgard Subsea Compression project. This also applies at depths greater than 1,000 m, such as Jansz in Australia (under development by Chevron), where multiple large subsea transformers are being designed for 1,500 m water depth. Norwegian companies rank among the world leaders in installation of large underwater modules.

For a transformer with a dry export-cable termination, the installation vessel usually sails to port and first mounts the transformer on the end that is installed first, where each phase is jointed to the cable inside the transformer module. Depending on the distance to shore, the vessel can either lay the entire export cable without multiple joints, or lay a designated overlength of 220 kV cable toward shore, which can then be picked up in the next step and jointed to a cable vessel that lays the remaining cable length to land.

Depending on seabed conditions, the transformer must either be placed on a pre-installed base frame with suction anchors or on a so-called «mudmat» which, if large enough in area, will rest stably on the seabed. These base frames are commonly installed by the same

Photo: Windstaller Alliance

Figure 25: Installation of 66 kV IAC cables and a subsea transformer.

type of vessel in an earlier installation campaign a few months or up to a year or a single installation season beforehand.

Service Life, Operation, and Maintenance

A subsea transformer operates under more ideal conditions than an equivalent transformer offshore or on land. It is not exposed to weather; there is no need to address rust/corrosion in the same way due to different material choices, and transformers underwater are safer. This applies both to the environment and personnel, because they cannot catch fire or explode in an oxygen-free setting.

On the seabed, the ambient temperature is entirely stable, and the hydrostatic pressure reduces the risk of partial discharges, which is an important aging mechanism in high-voltage electrical components. Such discharges typically occur in material irregularities or boundary surfaces in the insulation. In an underwater environment, gas pockets in the insulation are more compressed, thereby reducing the likelihood of partial discharge. This is reinforced by the fact that ABB/Hitachi

Energy, which has delivered over 40 subsea transformers so far, has received no reported failures[14].

Additionally, it is common to install electronics for temperature measurement, leak sensors, and current/voltage measurement in separate, retrievable control modules typically measuring less than 1 m in diameter and 2 m in height, and weighing around a maximum of 3 tons. These are easy to retrieve and replace using the smallest, least expensive installation vessels. In oil and gas, subsea transformers are commonly designed for 30–50 years, and the same timeframe is relevant for offshore wind applications.

5.3.2 Need for Technology Development and Demonstration Projects

Closing the Technology Gap

As mentioned in the technology status introduction and the table in Chapter 5.3.1, the main gaps for a subsea substation up to 400 MVA relate to the following, with a description of progress:

A. 72.5 kV (for 66 kV operating voltage) wet high-voltage connector («wet-mate») with associated penetrator and cable termination

- The Norwegian company Benestad is qualifying its solution through OceanGrid[15], which has been ongoing since 2022 and is expected to achieve TRL6 (ISO scale 1–9) by Q2 2025. So far, testing is proceeding as planned.
- Siemens Energy[16], SCM[17], and Baker Hughes are working on similar programs at the same voltage level, indicating publicly a similar timeframe for completing their qualification programs
- All the solutions under development build on experience from design, testing, and deliveries of penetrators and/or connectors at lower voltages from 11 to 52 kV in the past
- Some suppliers have also started looking at developing 145 kV wet connectors. However, in order to move up to that voltage level, there must be a push from turbine manufacturers to go to that voltage on their wind turbines.

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14) Norwegian Energy Partners, «ABB/Hitachi subsea transformer statistics: 'Subsea substation for offshore wind,' April 2022. [Online]. Available: https://www.norwep.com/technologies-solutions/uvp/subsea-substation

15) Windstaller Alliance press Release, «Windstaller Alliance appointed to HydroQuest Flowatt Tidal FEED,» 2023. [Online]. Available: https://www.windstalleralliance.com/news/windstaller-alliance-appointed-to-tidal-power-feed

16) Midtnorsk Næringsnytt MN24, «Equinor statement on uptime for subsea compression with electrical equipment» in the article «Can earn 200 billion on what they thought was impossible,» 6 February 2022. [Online]. Available: https://www.mn24.no/nyheter/i/Xq3nrg/kan-tjene-200-milliarder-paa-det-de-trodde-var-umulig

17) SCM – Systems et Connectique du Mans, «Solutions for energy – Floating offshore wind,» 2024. [Online]. Available: https://www.scmlemans.com/energy

B. 245 kV (for 220 kV operating voltage) dry high-voltage connector / cable termination

- Baker Hughes is qualifying its mECON245 in IPN Crown[18] in collaboration with the Research Council of Norway and SINTEF, aiming for TRL 6 (ISO scale 1–9) completion by 2025/26
- This solution is based on the existing mECON145 used in the Ormen Lange pilot and Åsgard Subsea Compression projects (already TRL 9)

C. Optional, depending on system design — 72.5 kV subsea circuit breaker for disconnecting incoming wind turbines in case of faults, as well as for test and voltage activation of cable from shore

- Aker Solutions and ABB, in collaboration with customer partners, are developing a subsea circuit breaker system with protection and control electronics and condition monitoring[19]
- The program began in Q1 2024 and is expected to reach TRL6 (ISO scale 1–9) by 2025/26
- The development builds on ABB's Subsea Power JIP from 2013–2020, where 36 kV subsea switchgear was developed to TRL6 (ISO scale 1–9)

Overall progress suggests that subsea substations will become commercially available during 2025, assuming active qualification efforts and that components expected to reach TRL6 in early 2025 move swiftly into testing and piloting.

Overall progress indicates that subsea substations will become commercially available in 2025, given active qualification and that the components expected to reach TRL6 in early 2025 proceed rapidly into testing and piloting.

Plans for larger wind farms of over 0.5–1 GW suggest commissioning schedules in the early 2030s, which means contracts often have to be awarded about 3–4 years earlier i.e., typically from 2027–28 onward.

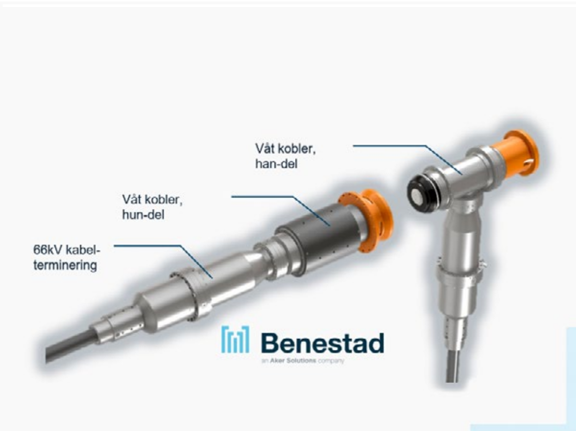
However, one also sees that certain pilot projects for floating wind, such as Goliat Vind (Odfjell Oceanwind with partners Source Galileo and Kansai Electric Power), have plans for pilot developments of up to around 100 MVA earlier than that. The mentioned project indicates the possibility of commissioning as early as 2027–28[20]. Such pilots,

18) The Research Council of Norway, «Forskningsrådet Project Bank – Baker Hughes IpN Crown for mECON245kV,» [Online]. Available: https://prosjektbanken.forskningsradet.no/en/project/FORISS/327921?Kilde=FORISS&distribution=Ar&chart=bar&calcType=funding&Sprak=no&sortBy=date&sortOrder=desc&resultCount=30&offset=0&Fag.3=Elkraft. [Funnet 2022]
19) Aker Solutions, «Aker Solutions to pilot floating-wind-power hub — Subsea collector & 66 kV switchgear,» 2024. [Online]. Available: https://www.akersolutions.com/news/news-archive/2024/aker-solutions-to-pilot-floating-wind-power-hub.
20) Source Galileo, «Odfjell Oceanwind's project overview and plans,» 2024. [Online]. Available: https://goliatvind.no/nb

typically involving between 2 and 7 turbines, will enable, if the projects adopt a subsea transformer as part of the system architecture, the deployment of transformers at the next scale level up from the ~20–25 MVA used in O&G applications. This way, these pilot projects can serve as a springboard for GW-scale wind-farm subsea systems. High-voltage connectors at 66 kV for the IAC cables and 110 kV on the export side to shore could then be tested[21].

This would be a valuable contribution to establishing earlier confidence in system components. However, no operational experience would be gained with the 220 kV transmission voltage required for the GW-class large offshore wind projects, where you need higher voltage for longer and more relevant distances, as well as to reduce power losses.

Photo: Benestad



Benestad 66 kV Subsea Connection System for Offshore Wind

- 66 kV / 1250 A, 50 & 60 HZ
- 143 MW total power, for example covering
  - 7× 20 MW turbines
  - 10× 14 MW turbines
- Planned market readiness in Q2 2025
- 1500 m water depth

Passed TRL 3 (API 17 N, 1–7) / (ISO, 1–9) at Prototype Manufacturing Acceptance Test, Sept. 2024

66 kV wet connectors with 66 kV inter-array turbine cables under high-voltage testing at Aker Solutions' high-voltage lab in Tranby, Norway

Figure 26: The Norwegian company Benestad's 66 kV subsea connection system for offshore wind.

21) Government, «Description of the Goliat Vind project: 'Notification with proposal for project-specific impact assessment program for Goliat-VIND,' 25 October 2023.» [Online]. Available: https://www.regjeringen.no/contentassets/511a51a0645f47738e4e703c7b27b2a3/goliatvind-melding-med-forslag-til-prosjektspesifikt-utredningsprogram_2023-10-25-1520477-l1522652.pdf

Åsgard 2014
MECON DM 145/700

TRL	7
Coltage	76/132 (145) kV
Current	700 A
Water depth	3048 m

For offshore wind at higher voltage rating
MECON DM 145/700

TRL	7
Coltage	127/220 (245) kV
Current	1000 A
Water depth	1000 m

Photos: Baker Hughes

Figure 27: mECON145 (existing solution) and mECON245 (under development).

Risks and Barriers
Risks related to subsea transformer stations mainly concern the jump in rating/size of the transformers, as well as customers' assessments of technical barriers and technology maturity. Differences may exist depending on whether the customer is a renewables developer with subsea experience from oil and gas or one without prior experience in similar subsea solutions. The first pilot projects also likely depend on subsidies (e.g., Enova support, as in the Goliat Vind project) and other economic incentives that represent commercial barriers until volume and scale effects are reached on delivered units. Since pilots not only include subsea equipment but also cables, turbines, installation services, onshore connections, etc., the overall project must be profitable for the developers—similar to offshore wind development in general.

A subsea transformer station usually has more favorable operating conditions on the seabed than at the surface, due to stable ambient temperature, good cooling, hydrostatic pressure (reducing the likelihood of partial discharge), and the elimination of explosion risk (no oxygen/possibility of fire that threatens humans or the environment).

At the same time, the equipment must be oil-filled and pressure-compensated to prevent water ingress, and the number of seals between, for instance, high-voltage (220 kV) and medium-/low-voltage (66 kV) penetrators must be leak-tight. In the flanges for these penetrations, one typically uses metal seals that can be tested with helium leak detectors (part of the FAT—factory acceptance test) to ensure complete watertightness before submerging the equipment on the seabed.

Because subsea transformers have been in operation for more than 25 years now, and no failures have been reported for around 40 installed units, we have operational experience suggesting that the components are reliable and robust. Moving from reference sizes of up to 20–25 MVA in O&G subsea transformer applications to 400 MVA for offshore wind does not fundamentally change the design principles for the structure. One key difference is the size of the equipment (factory handling, transport, etc.). Another key consideration is the pressure compensators to handle a larger volume of transformer oil «breathing» in response to temperature changes associated with MVA rating. One must ensure sufficient transformer-tank surface area so that cooling of the dissipated power losses is adequate (initially with passive cooling, although active oil cooling is also possible). To accomplish this safely, with sufficient design margin, requires experience, calibrated calculation models, and a design developed and tested in appropriate steps for increased MVA rating.

Another risk element is related to installation, especially ensuring that the modules do not become so heavy or large as to be difficult to handle under given weather/wave conditions (there one typically sets a limit for significant wave height, etc.). Because 245 kV wet connectors do not exist at that voltage level today—only dry terminations—the installation also entails handling a large, relatively stiff 245 kV cable in addition to the transformer module. To ensure a safe design, installation expertise/companies should be involved early in the design process.

A potential fault in the transformer or the 245 kV dry cable termination would mean the entire transformer module plus 245 kV cable must be raised and repaired.

On the 66 kV side of the transformer, there are wet connectors for the inter-array cables (IAC). Obviously, it is important that these have undergone a sufficient qualification program (for example, following IEC 61886-1) that ensures robustness in the insulation system and, for instance, that the connectors withstand being mated underwater with sediment and minor sand stirred up by the ROV (remotely operated vehicle) during connection. This forms part of the qualification program for high-voltage connectors, but it is also crucial to ensure sufficient verification so that the subsea substation is not forced to be retrieved and repaired at the surface.

Measurement electronics typically constitute the components with the lowest reliability. To reduce risk, circuit boards, etc., are placed in a retrievable control module. These modules can be replaced by lighter and less costly installation vessels.

Sustainability

A subsea substation can offer significant savings[22] compared to a bottom-fixed or floating substation when measuring total weight or tons per MW. That implies corresponding reductions in CO_2 emissions from materials, logistics, footprint, and fabrication.

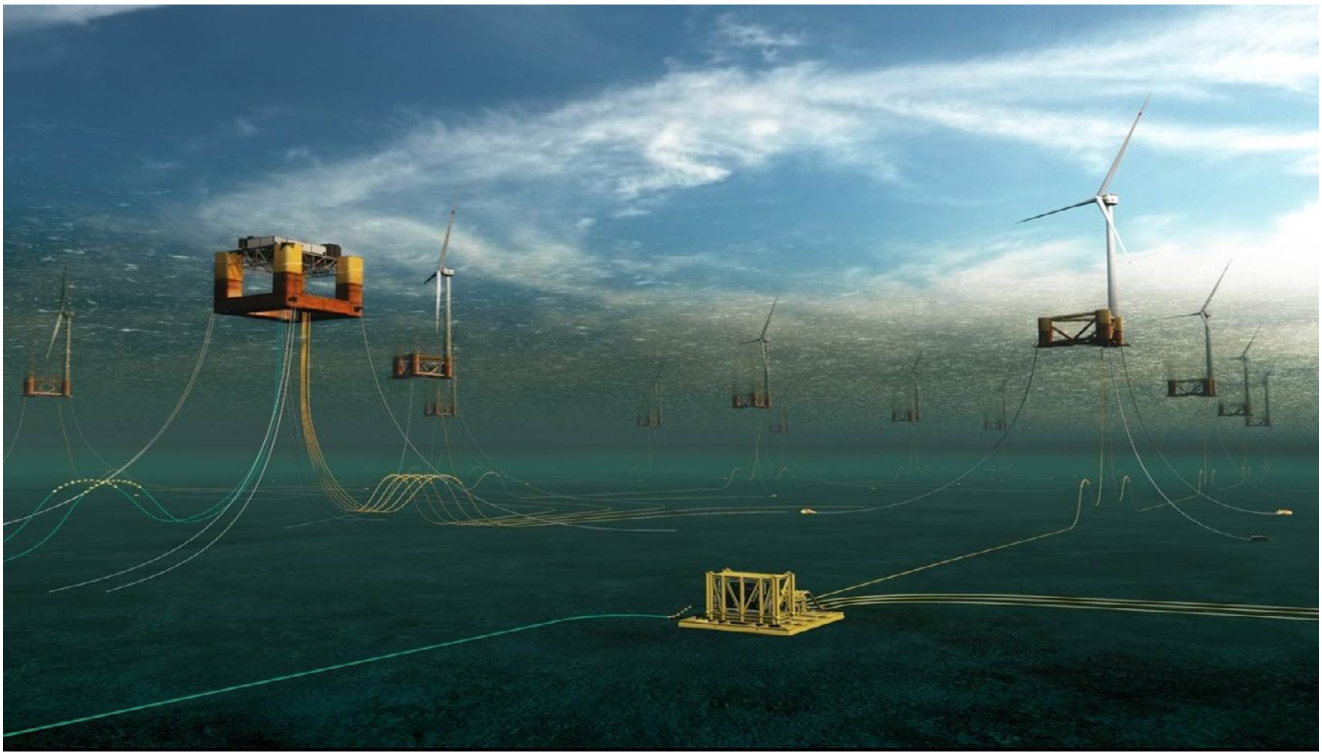


Photo: Aker Solutions

Figure 28: A subsea solution typically requires 80–90% fewer materials and components than, for example, a floating substation, measured in tons per MW. That leads to a substantial reduction in CO_2 emissions.

22) OceanGrid project, «OceanGrid project,» 2024. [Online]. Available: https://oceangridproject.no

Transformers can generally be recycled nearly 100% regarding the transformer tank, iron core, windings, insulation materials, and transformer oil. The same applies, to a large extent, to electronics and instrumentation. A subsea transformer, like a topside transformer, can also have its oil cleaned and reused.

Compared to an alternative topside floating or bottom-fixed substation, subsea transformers require less space on the seabed (a floating platform typically requires up to eight anchor points on the seabed). Additionally, from the oil and gas sector, we have experience indicating that marine life like fish perceive seabed structures as «artificial reefs.»[23] This typically applies in shallower waters where sunlight is available. In relation to fishing—for example, trawling—coexistence can be fostered by burying cables on the seabed and equipping the subsea station with an overtrawlable structure. This design is commonly used in Norway's oil and gas industry.

Underwater transformers are also designed to be placed among the turbines so that spatial usage is minimized and the system does not operate in areas intended for fishing.

Photo: Aker Solutions

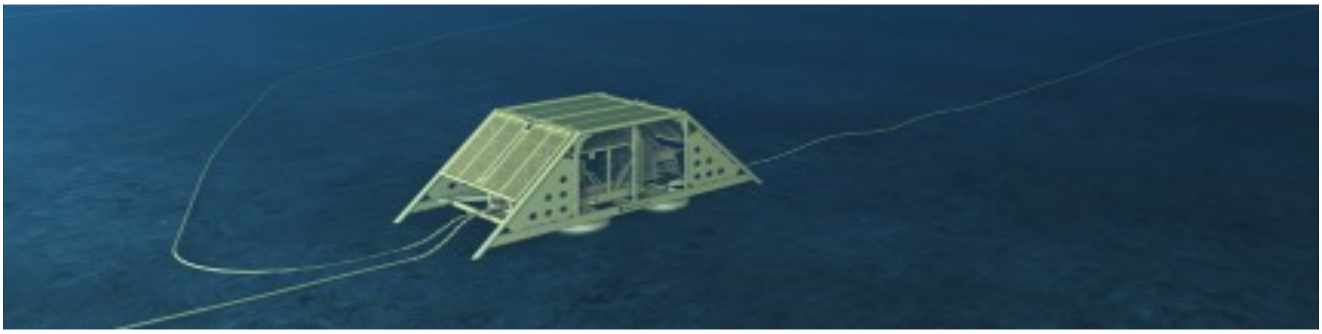


Figure 29: Example of an overtrawlable structure for better coexistence with fishing activity (Image: Aker Solutions)

Subsea substations are also relatively easy to reuse at multiple locations because they are simple to install and swap out, and they can be designed for either 30 or 50 years of service life. The main difference in longevity primarily concerns temperature considerations. To achieve longer lifespans, one typically designs for a slightly lower core temperature which, according to the Arrhenius equation, causes the components to age more slowly.

23) S. D. R. LaraAlvarez, «Marine life near oil and gas installations: 'Ensuring ecosystems when offshore infrastructure is decommissioned,'» 2 June 2022. [Online]. Available: https://www.ramboll.com/no-no/innsikt/kutte-klimagassutslipp-til-nettonull/sikre-okosystemene-nar-infrastruktur-i-havet-avvikles

5.4 Subsea Collector

The main purpose of a subsea collector is to link individual turbines—using identical cables with the smallest feasible cross-sections—into a subsea star node. From there, the aggregate output of all turbines is routed onward, from that star node to an offshore transformer station (which can be on the seabed, on a bottom-fixed or floating AC platform, or an HVDC platform) or directly to land, depending on transmission distances.

One key advantage of this is that each turbine can use an entirely standardized, identical cable of the smallest cross-section, and at the same time, one greatly reduces the number of large cross-section dynamic power cables. For floating offshore wind, a so-called «daisy-chain» topology (i.e., series linking between turbines) typically requires many large, heavy dynamic cables—particularly the cable from the last turbine to the offshore AC transformer, HVDC station, or land, which must be sized for the total MW output from all the turbines in the chain (see Figure 31, left side).

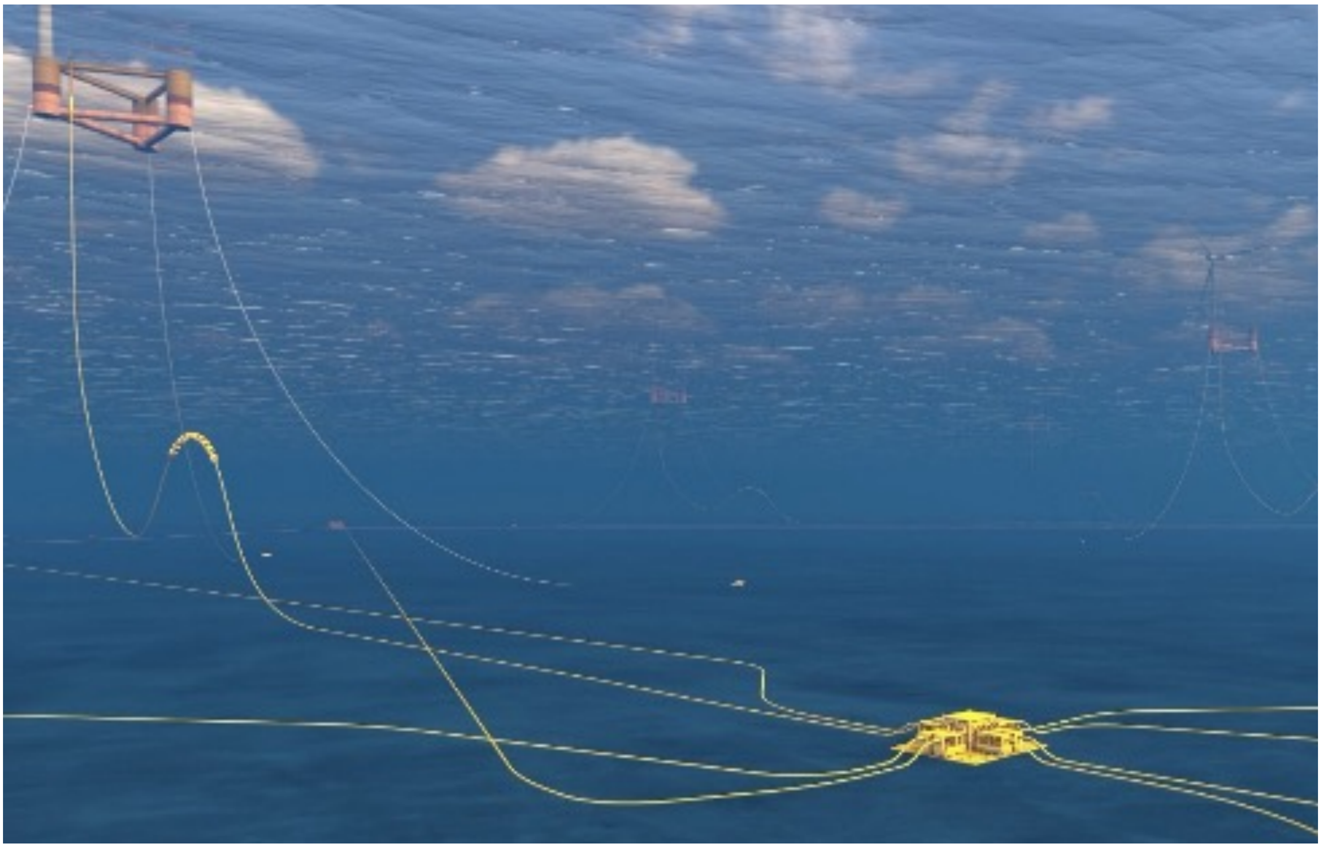
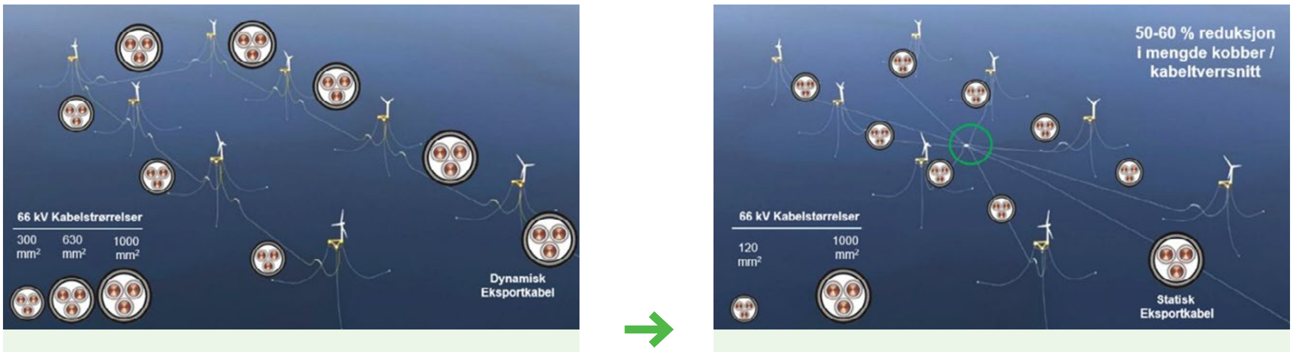


Photo: Aker Solutions

Figure 30: Illustration of a subsea collector with cables from seven turbines, plus a static group cable leaving the collector, which can either go directly to shore or to an offshore transformer station

Illustration: Aker Solutions



«Daisy Chain» Configuration

- Difficult to standardize due to varied cable sizes
- Dynamic cables must go down and back up again – 2× more
- Complex installation with multiple dependencies

Collector with Star-Point Coupling

- All turbines have the smallest cross-section cable – far less copper
- Half as many dynamic cable sections – only down
- Static export cable and lower installation cost and risk

Figure 31: Comparison of daisy-chain vs. star-point turbine connections.

With a star-point configuration, the number of dynamic cable connections from each turbine is also reduced—simply because the cable only hangs down once rather than returning to the surface again (as is the case with a daisy-chain solution among turbines). Moreover, the time and complexity required for offshore installation operations are reduced, which directly impacts total costs. These factors, along with the fact that the group cable for all turbines in the star configuration lies static on the seabed (see Figure 31, right side), are advantageous for system reliability, something that also benefits the insurance perspective.

Today, it is mostly the same companies developing subsea transformer stations that also, in conferences, press releases, etc., present their work on this collector technology. These include Aker Solutions (together with ABB), Baker Hughes, SLB OneSubsea, Siemens[24] and the French firm SCM[25].

A subsea collector can also be equipped with circuit breakers, so that

24) A. M. Askeland, «One Subsea: «Subsea Substations - Leveraging Existing Technology to Reduce Costs off Offshore Wind»,» i Underwater Technology Conference, Bergen, 2023
25) Norwegian Energy Partners, «ABB/Hitachi subsea transformatorstatistikk: "Subsea substation for offshore wind",» April 2022. [Internett] Available: https://www.norwep.com/technologies-solutions/uvp/subsea-substation

not all turbines connecting into the collector are forced offline if a cable from one of the turbines fails. Baker Hughes, Siemens, and ABB have developed subsea circuit breakers up to 24 kV and 36 kV over the last 10–15 years for power-distribution solutions used in subsea pumping and compression in oil & gas. Thus, the basis for scaling up to 66 kV (and beyond) for offshore wind is in place among multiple players.

5.4.1 Technology Description

Figure 31 shows how the turbines connect in a star arrangement, with the collector having a static export cable resting on the seabed, rather than a dynamic cable descending from the last turbine as in a daisy-chain configuration. This reduces the risk associated with fatigue and lifetime.

Regarding details of the solutions from different parties developing collectors, not all information is publicly available. However, Aker Solutions issued a press release in January 2024 stating that they had won an early-phase design study (FEED) to implement a 66 kV subsea collector at the METCentre test site for offshore wind turbines, located 10 km off the coast of Karmøy in Norway. According to the release, the ambition is to have the technology ready by 2026, i.e., at TRL 6 on the ISO scale (1–9). The press release states that this would help reduce the total cost of a 1 GW wind farm by about 10%, which amounts to savings in the billions (NOK) compared to conventional system architecture that relies, for instance, on daisy-chaining the turbines.

The collector unit is planned to incorporate high-voltage wet connectors at 66 kV from the Norwegian technology company Benestad (owned by Aker Solutions), along with circuit-breaker and protection technology from Aker Solutions' subsea alliance partner ABB. Installations are planned by Windstaller, an alliance between Aker Solutions, DeepOcean, and Solstad Offshore. This is an example of collaboration among major Norwegian technology players.

A subsea collector can be designed either without any particular intelligence or functionality—i.e., simply as a busbar system that routes incoming cables from the turbines together and then passes current onward via an export cable—or it can be equipped with breaker switchgear having circuit breakers and protection, as well as measuring equipment. In both cases, the unit is relatively small with moderate weight, making installation simple (thus, the installation descriptions for subsea transformer stations in Section 5.3 also apply here).

As for standardization and the number of turbines each collector can serve, it is primarily the wet high-voltage connectors that determine total MW capacity per collector unit.

Example:
- Wet connector (66 kV, 1250 A) equates to about 143 MW per static export cable
- For 14 MW turbines, a collector unit can cover and gather power from approx. 10 turbines
- For 20 MW turbines, a collector unit can cover and gather power from about 7 turbines
- If, in a floating wind power system, there are two offshore transformers totaling 800 MVA (whether subsea or on a platform), typically you would need four to five 80–100 MVA collectors for each 400 MVA transformer

A subsea collector likely has relatively high reliability and a long service life, even if it includes subsea circuit breakers. This is because circuit breakers generally have long lifetimes and are used relatively infrequently (though they can be tested regularly during operation). It could also be set to fail in the closed position, in other words functioning like a collector without a breaker. Since the sales volume potential is relatively large, there is a basis for a maintenance philosophy in which the supplier could rent out standard spare units to customers in the event a unit fails. Beyond that, the unit requires little or no maintenance on the seabed, forming the foundation for a fairly low-cost operations and maintenance strategy.

5.4.2 Need for Technology Development and Demonstration Projects

Early-phase design study (FEED) for implementing a 66 kV subsea collector at the METCentre test site for offshore wind turbines off Karmøy in Norway is an important step in developing the collector.

Technology development for collectors is, in many respects, comparable to that of subsea transformer stations, without the transformer itself. This makes development somewhat simpler. As mentioned above, the key developments mainly concern 66 kV subsea breaker switchgear, wet connectors, and a subsea control module with protection functionality.

Early-phase design study (FEED) for implementing a 66 kV subsea collector at the METCentre test site for offshore wind turbines off the coast of Karmøy in Norway is an important step in collector development.

If METCentre choose to to implement an underwater module with a subsea collector, such a pilot could be operational by about 2026/2027.

5.5 Dynamic Array Cables

5.5.1 Technology Description

Dynamic cables must be designed to withstand continuous mechanical loads over their entire service life. These arise from a combination of platform movement, wave action, and currents, potentially degrading the cable's functional properties. Failure modes can be purely mechanical, electrical, chemical, or a combination. Dynamic cables must be viewed as complete systems, including ancillary equipment such as bend stiffeners, buoyancy elements, seabed anchors, termi-

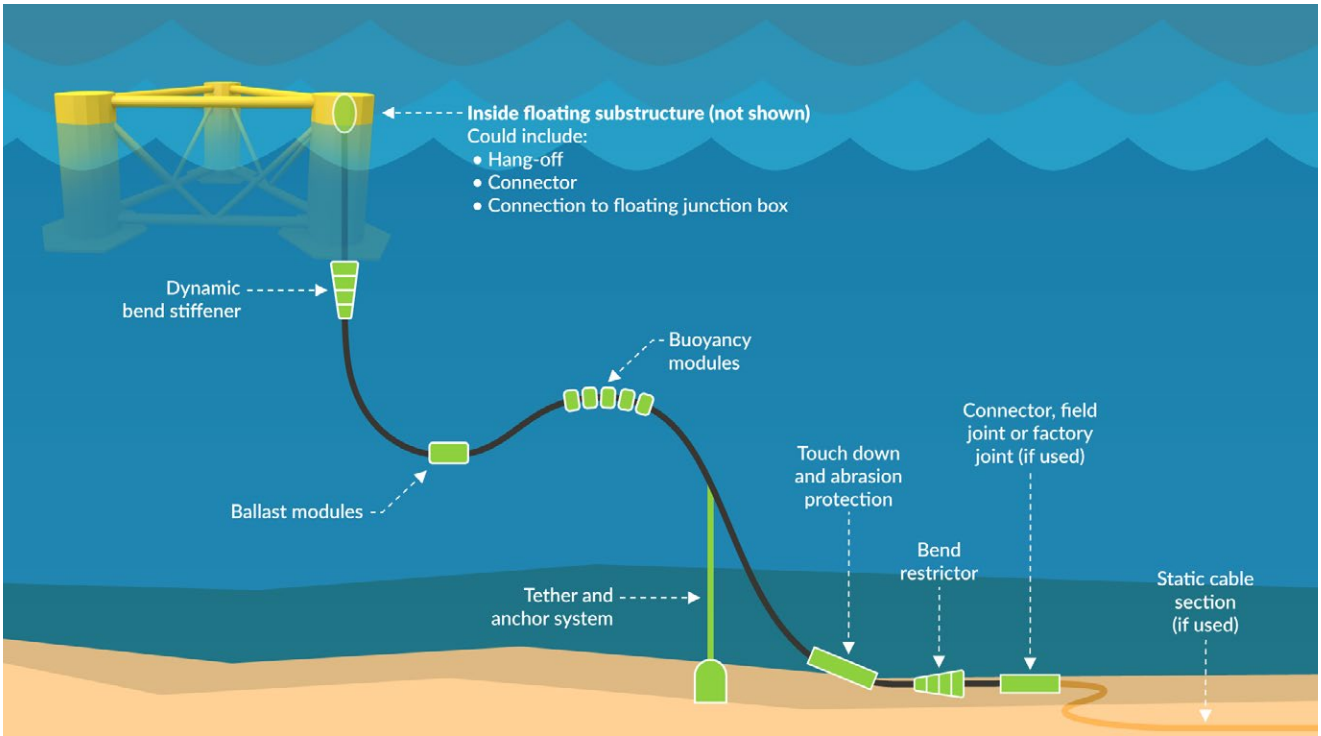


Figure 32: Overview of equipment components in a dynamic cable system (https://guidetofloatingoffshorewind.com)

Photo: NKT

Figure 33: Pull-in head and bend stiffeners during installation for electrification purposes (www.NKT.com).

nations, and joints. The installation method likewise forms an essential part of the overall package. Furthermore, interactions with the floater and its mooring are crucial inputs to cable design.

The design of the cable system requires standard electrical system design, much like static cables, along with mechanical considerations known from dynamic riser deliveries in the oil and gas sector. Unlike risers, submarine cables are often more mechanically complex and present more potential failure scenarios due to material characteristics. Generally, this demands more engineering up front and as part of the cable supply. This ensures the cable design, dynamic configuration, and associated equipment achieve the specified service life.

«In summary, a dynamic cable delivery includes cable and equipment design supported by mechanical and electro-thermal analyses. In particular, long-term global and local mechanical analysis using experimentally derived material and component data is uniquely critical for dynamic cables, compared with static cables. Material fatigue is of particular importance and subject to extensive development. Finally, full-scale cable systems are manufactured and subjected to mechanical and electrical type testing, including flex tests per existing industry standards (Cigré TB490, TB623, and IEC62067).»

5.5.2 Availability and Reference Projects

Currently, the 145 kV voltage level is considered available for dynamic array and export cables. Greater water depth is not typically a limiting factor, whereas shallow water and/or challenging environmental conditions may impose restrictions.

Voltage level and water depth are key technology parameters that can be constrained by both available technology and vendor-specific qualification status, as well as project-specific boundary conditions. Today, the 72 kV dynamic cables for floating wind are considered available and an industry standard, with the following reference projects in operation[26,27]:

- 2023 Provence Grand Large (Prysmian). 24 MW. 100 m water depth.
- 2023 Hywind Tampen (JDR). 88 MW. 300 m water depth.
- 2024 Gruissan/EOLMed (Prysmian). 30 MW. 90 m water depth.

The 72 kV cable designs in operation today use a «wet design,» meaning they do not have a metallic water barrier around each phase that ensures a dry insulation system[28]. Qualification of wet cable systems up to 145 kV is in progress.

Dynamic cables up to 145 kV are today qualified and/or in operation for electrification purposes[29,30,31]:

- 2010 Gjøa power-from-shore (NKT). 115 kV AC, 40 MW. 360 m water depth.
- 2015 Goliat (NKT). 123 kV AC, 75 MW. 400 m water depth.
- 2023 Troll West (NKT). 145 kV AC, 160 MW. 330 m water depth.
- 2025 Jansz (Nexans). 145 kV AC, 100 MW. 1,500 m water depth.
- 2025 Njord (NKT). 145 kV AC. 330 m water depth.

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26) JDR wins contract for first floating offshore wind project to power oil and gas platforms - JDR Cables, providing the vital connection
27) Dynamic Cables Pre-termination phase completed for Provence Grand Large floating offshore wind farm | Prysmian
28) Traditional high-voltage cables today use an extruded lead sheath as a water barrier. Lead generally does not tolerate the mechanical stresses seen by a dynamic cable
29) Dynamic high voltage cables – from the world's first to future applications | NKT
30) Dynamic cables: Unlocking offshore wind development (nexans.com)
31) Nexans - Nexans' groundbreaking deep-water high voltage dynamic cable selected for Jansz-Io Compression project, paving the way for future offshore innovation

Illustrations: Nexans, NKT

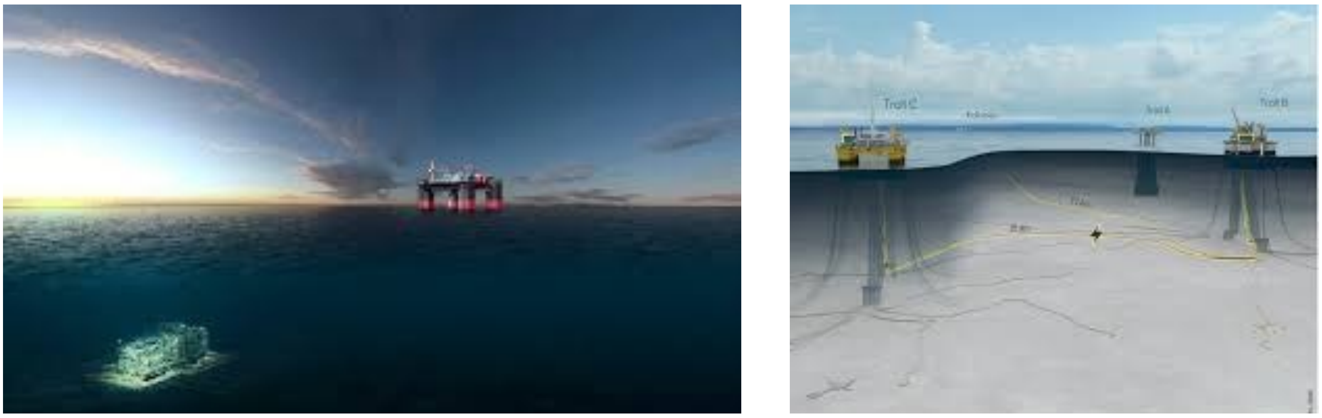


Figure 34: Oil and gas installations electrified with dynamic 145 kV cable technology.

The technology used for these projects can be extended to floating wind, including array cables. These cables currently are «dry-design,» with a water barrier (lead-free). Depending on design and component choices, increased water depth can raise challenges for dynamic submarine cables. Often, however, shallow water and/or demanding environmental conditions limit cable design and/or the design of equipment, mooring, or floaters.

Recommendations from Cigré are often used as industry standards and describe required qualification testing for submarine cables, including dynamic cables. However, the standard for the latter is new and could be considered immature. Thus, in practice, development and qualification of submarine cables for higher voltages (>145 kV) depend heavily on expertise and experimental work outside existing standards.

5.5.3 Need for Technology Development

Costs can be reduced, and reliability can be improved. Today, dynamic array-cable technology is relatively mature, but there are several specific areas for further development:

- 145 kV Voltage Level
  Establishing a 145 kV voltage level for array cables enables larger wind turbines and a more optimized wind-farm layout. It would also allow for smaller conductor cross-sections, reducing cost and environmental impact. Additionally, a 145 kV array cable setup would provide a better starting point for direct-to-shore connections (without needing a subsea or floating transformer). Realizing 145 kV array cables could initially leverage existing dry designs (see above), though wet cable designs will also be important in future cost-reduction efforts.

- Replacing Copper with Aluminum
  Aluminium is significantly more cost-effective than copper (and more sustainable in terms of material scarcity). However, aluminum has different mechanical and physical properties, requiring a degree of development and/or qualification work to implement.

- Monitoring and Lifetime Considerations
  Monitoring methods for static submarine and onshore cables are well established. By contrast, unique failure scenarios and monitoring methods for dynamic submarine cables are not well developed. Innovations here could reduce the risk of unforeseen failures and facilitate extended service life.

- Installation Methods
  Reducing installation time, as well as lowering vessel and personnel requirements, can cut costs, environmental impact, and improve safety for floating offshore wind. Methods connect directly to qualified and/or demonstrated technology for electrical and mechanical terminations, with associated equipment like pull-in heads or T-connectors.

- Qualification Norms and Standards
  Current standards—such as Cigré, IEC, or DNV—are immature or under development. As solutions mature, it will be beneficial to standardize testing and qualification methods. Traditional oil and gas standards in use today for floating wind do not necessarily match the needed reliability profile. Floating offshore wind likely requires optimization aimed at cost-effectiveness while meeting reliability expectations[32].

Technology gaps can be addressed through various channels—R&D projects, cross-value-chain collaborations, and qualification efforts at individual cable suppliers.

These technology gaps can be addressed through various channels—R&D projects, cross-value-chain collaborations, and qualification efforts at individual cable suppliers. Weak or incomplete norms and standards, combined with the introduction of new materials and components, may also make full-scale demonstration projects crucial to ensure realistic environmental and test conditions, as well as credibility for new cost- and eco-efficient solutions in floating wind.

32) Optimizing mooring and dynamic cable design requirements for floating wind - new joint industry project launched (dnv.com)

5.5.4 Risks and Barriers

Bottlenecks in the value chain, new suppliers, and demanding technology may cause the floating offshore wind market to be deprioritized and/or increase failure risk.

Cable supply is a bottleneck in the value chain today, with significant lead times. There is also a major distinction between typical medium-/internal cabling vs. export cables, where the larger and more experienced cable suppliers focus on the latter. Dynamic cables—especially high-voltage cables—are niche products associated with higher technical risk and, in many cases, limited or no experience among many cable vendors, as well as potential investment needs in the supply chain.

Inexperienced suppliers will increase the risk of error, which in turn can reduce reliability and inflate estimated costs. Among the bigger, more established suppliers (Nexans, NKT, Prysmian, and LS), technical risk likely must be minimized if floating offshore wind is to be prioritized.

Public policy tools and particularly pilot programs—for both manufacturing technology and deliveries—can help ensure that floating offshore wind gets supply-chain priority.

5.5.5 Operation, Maintenance, and Sustainability

Cable systems are largely maintenance-free, but mishandling, trawling, or manufacturing flaws may necessitate replacement cable lengths and repair joints, requiring marine operations. Vessel availability can then be a limiting factor.

Like other offshore components, submarine cables play a crucial role in sustainability. This especially concerns seabed impacts during installation and material use, from a life-cycle perspective. Metals usage is particularly relevant, but one must also consider operations. Electrical losses during operation—i.e., choosing larger conductor cross-sections for reduced losses—are part of the equation. Today, life-cycle assessments are standard practice in most cable deliveries. Technology development generally helps cut material use and/or electrical losses.

5.6 Dynamic Export Cables

5.6.1 Technology Description

Dynamic export cables differ significant from array cables in terms of transmission capacity and the associated technical challenges.

Where dynamic array cables in the medium term are mostly limited to a 145 kV voltage level, export cables must handle transmission capacities generally requiring 145 kV and up. Nevertheless, they must meet the same technical demands for continuous mechanical loading. Given the consequences of failure, reliability requirements may be higher here than for array cables. The higher voltage level, combined with reliability requirements and cable lengths, may favor a dry cable design at 145 kV and is likely a necessity at higher voltage levels (AC and HVDC).

Figure 35: (Left) Static three-phase AC export cable (www.Nexans.com); (Right) Installing an export cable from a bottom-fixed structure (www.nexans.com)

Export cables must be viewed as a system, where associated equipment is included alongside the cable. As with array cables, export cables typically run over longer distances, making factory- and repair joints crucial. Export cables likely include a transition joint between the dynamic and static portions, where the static cable is often comparable to standard export cables for bottom-fixed wind, but with sufficient mechanical tension capacity for deeper water.

Compared with array cables, stricter requirements often apply under standards regarding longitudinal water blocking in case of faults and water ingress.

For many years, replacing lead in water barriers (to achieve a dry cable design) has been a high R&D priority: High-voltage (static) submarine cables depend on a dry insulation system, traditionally requiring a water barrier. The materials and processes (extruded lead sheaths) have proven highly robust in a static context, but typically do not survive permanent dynamic suspension between a floater and the seabed, because of mechanical loads. This has traditionally been the biggest technological leap for dynamic submarine cables, limiting the maximum voltage level. If or when a solution for this is established, it is likely that dynamic export cables—either partially or wholly—can follow the same electrical qualification path currently in place (and under development) for static submarine cables:

- 420 kV AC up to 1 GW
- 525 kV DC up to 2 GW

The existing qualified static cable cross-sections described above represent a major technological jump from 145 kV dry designs. Important intermediate steps and immediate technology priorities include:

- 245 kV AC up to 400 MW
- 320 kV DC up to 1.2 GW

As described, dynamic export cables can be more challenging to realize due to mechanical loads, imposing constraints on dynamic configurations and the interaction with floater design. Development is even more dependent on collaboration among floater, cable, and mooring suppliers than is the case for array cables.

5.6.2 Availability and Reference Projects

Currently, a 145 kV voltage level is considered available for dynamic export cables. Technology developed for existing 145 kV dynamic cables is assumed scalable for higher transmission capacities (i.e., export cables) and is expected to be qualified within 2–3 years. As with array cables, existing dynamic cables for electrification in oil and gas are a critical foundation, especially:

- 2010 Gjøa power from shore (NKT). 115 kV AC, 40 MW, 360 m water depth.
- 2015 Goliat (NKT). 123 kV AC, 75 MW, 400 m water depth.
- 2023 Troll West (NKT). 145 kV AC, 160 MW, 330 m water depth.
- 2025 Jansz (Nexans). 145 kV AC, 100 MW, 1,500 m water depth.

These projects employ a water barrier (not lead) that can likely be extended to dynamic export cables for both AC and DC. Depending on design and component choices, greater water depth may raise challenges for dynamic cables, but frequently shallow water and/or demanding environmental conditions form the limiting factors around cable design or mooring, equipment, or floater design.

Approximate timelines for technology qualification for the described grid-connection architectures (Case 1–3) are listed in the table below.

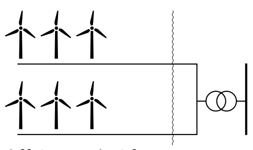
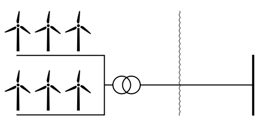
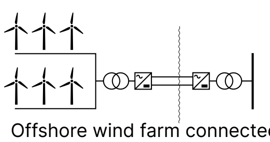
<table>
<tr><th></th><th>2024</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029</th></tr>
<tr><td>
Offshore wind farm connected by AC cable directly to shore</td><td>HVAC (dry) dynamic cable technology for 72–145 kV AC is available today</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>
Offshore wind farm connected to an offshore transformer station with AC cable to shore</td><td colspan="3">HVAC dynamic cable technology for 245 kV AC (~400 MW) is currently under qualification in accordance with normal industry standards.</td><td></td><td></td><td></td></tr>
<tr><td>
Offshore wind farm connected via an offshore HVDC link to shore</td><td></td><td></td><td colspan="4">Cable technology for 320 kV DC (~1 GW) is assumed to be qualified by one or more cable suppliers in the 2026–2028 timeframe.</td></tr>
</table>

Table 2: Roadmap for technology development for the described grid-connection architectures (Case 1–3)

Recommendations from Cigré are frequently used as industry standards and specify necessary qualification testing for submarine cables, including dynamic cables. However, these standards for dynamic cables are new and can be considered immature. In practice, then, the development and qualification of submarine cables above 132 kV relies heavily on expertise and experimental work outside existing standards.

5.6.3 Need for Technology Development

The main focus today is qualifying and verifying dynamic export cables at the needed transmission voltage levels. Just as critical is optimizing overall export solutions, including cost-optimization of both cables and floaters.

Dynamic export cable technology is relatively mature for grid connections up to 132 kV. There is definite potential for expanding voltage and transmission capacity. This primarily involves floating transformers and converter stations, as described in Section 5.2. Moreover, there are multiple aspects that can be strengthened or scaled up to achieve broader cost reductions:

- >245 kV AC Voltage / >400 MW Transmission Capacity
  Establishing a voltage level for export cables above 132 kV, initially 245 kV AC. Such cable designs will presumably remain «dry».

- Dynamic DC Export Cables >1 GW Transmission Capacity
  Establishing DC export cables. Initially, 320 kV is a requirement for floating converter stations. Such cable designs will presumably remain «dry».

- Replacing Lead for Static Export Cables
  Dry dynamic cable designs for both AC and DC will likely track technology development for generally eliminating the lead sheath used today. This could yield substantial environmental and cost benefits for cables.

- Monitoring and Lifetime Considerations
  Monitoring solutions and tools for static submarine and onshore cables are well established today, but specialized failure scenarios and monitoring for dynamic cables remain underdeveloped. Advances could reduce the risk of unexpected failures and bolster lifetime analyses.

- **Qualification Norms and Standards**
  Existing standards such as Cigré, IEC, or DNV are immature and in development. As solutions mature, standardizing testing and qualification methods will become sensible. Traditional oil and gas standards currently central to floating wind do not necessarily ensure the right reliability level. In addition, reliability requirements for export cables likely differ from those for array cables.

These technology gaps can be addressed on multiple levels: R&D projects, cross-industry collaborations, and qualification programs at each cable supplier. With weak norms and qualification standards and new materials and components being introduced, full-scale demonstration projects may be essential for achieving realistic environmental and test conditions, as well as credibility for new cost- and environmentally efficient solutions in floating wind.

5.6.4 Risks and Barriers

Bottlenecks in the value chain, new suppliers, and demanding technology can cause floating offshore wind to be deprioritized as a market segment or raise the risk of errors.

Cable deliveries are a bottleneck in the value chain today, with significant lead times. There is also a key distinction between delivering typical array cables and export cables, where the larger, more experienced cable vendors mostly focus on the latter. Dynamic cables—especially high-voltage cables—are niche products associated with increased technical risk, limited or no experience among many cable manufacturers, and possible supply-chain investment needs.

Inexperienced suppliers can increase the risk of errors, which in turn can reduce perceived reliability and thus estimated costs. For the larger, more established suppliers, technical risk must likely be minimized in order for floating offshore wind deliveries to be prioritized. Policy instruments—and especially pilot programs covering both production technology and product delivery—can help secure priority for floating offshore wind deliveries.

5.6.5 Operation, Maintenance, and Sustainability

Vessels for operation and maintenance can be a bottleneck. Technology development for floating offshore wind can have a positive sustainability impact for both floating and bottom-fixed wind.

As with array cables, the O&M aspects for export cables are similar, but capacity and competence availability are more challenging. Compared with array cabling, there is likely more scope for sustainability improvements, especially focusing on replacing the lead sheath.

5.7 Other Technologies, Systems, or Processes that Could Save Cost

5.7.1 General

In the preceding chapters, we have examined technologies and concluded that they generally exhibit high technology readiness but would benefit from full-scale demonstration projects to facilitate full implementation. That is necessary to unlock the potential for more cost-effective solutions in the longer term.

However, there are several technologies that could further enhance cost-effectiveness in both development and in operation and maintenance. Some of these technologies may lie well in the future, while others are more mature and could be included, for example, in a floating offshore AC or HVDC platform.

Beyond the examples shown below, it is recommended that a broader screening effort be undertaken to see whether there are other solutions that can provide cost-effective outcomes, both in the short and long term, and which measures should be pursued. Factors to be evaluated include smarter grid solutions, material technology, production processes, logistics, installation, operation, maintenance, repair, and disposal. Sustainability is important in these considerations.

Beyond the examples shown below, it is recommended that a broader screening effort be undertaken to see whether there are other solutions that can provide cost-effective outcomes, both in the short and long term, and which measures should be pursued. Factors to be evaluated include smarter grid solutions, material technology, production processes, logistics, installation, operation, maintenance, repair, and disposal. Sustainability is important in these considerations.

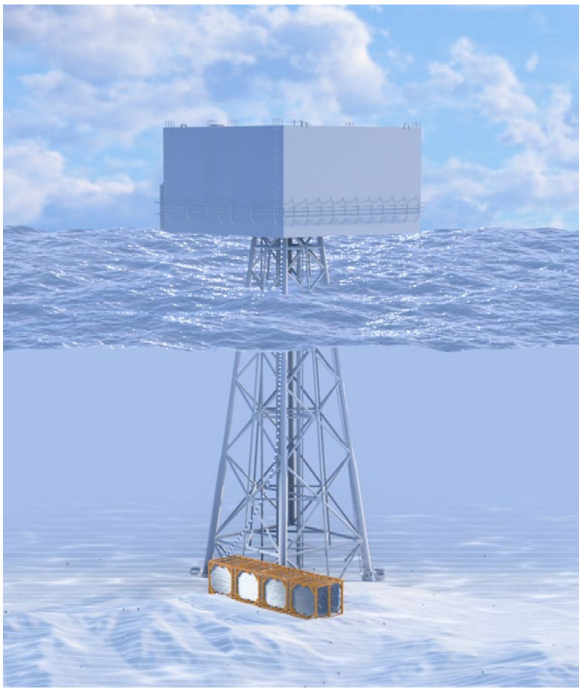
5.7.2 Subsea Cooling Systems

Auxiliary systems on platforms represent a relatively large share of weight and space usage. This is particularly true for HVDC installations, which traditionally require substantial cooling systems that use seawater pumped onboard. Alternatively, air cooling can be employed, commonly used for HVDC installations on land. Both conventional seawater cooling and air cooling require fairly large space and high weight. Implicitly, that means high topside costs, and the cooling systems themselves are expensive and require considerable maintenance.

One possibility under consideration is to move the cooling module(s) down to the seabed or attach them to the substructure. There would be different solutions depending on water depth, bottom-fixed or floating technology, etc. In that case, the cooling loop would be a closed system with an inhibitor—glycol, for instance. Heat exchangers for the electrical equipment, among other things, would remain topside, and pump(s) would circulate the coolant from the subsea coolers.

At present, no large-scale system using this technology is installed on, for example, existing offshore AC transformer stations or HVDC stations. However, similar systems exist on a smaller scale and have been in service for many years. The Åsgard field in the North Sea has had such a system in operation since 2015, and the Jansz subsea compression project[33], which is under development, is also planned to use one. Future Technology[34] is a Norwegian firm in this space, and in addition to the cooling system itself, they have developed advanced software to optimize the cooling system. This may reduce both investment costs and operation/maintenance relative to traditional water and air cooling solutions.

Illustration: SLB OneSubsea



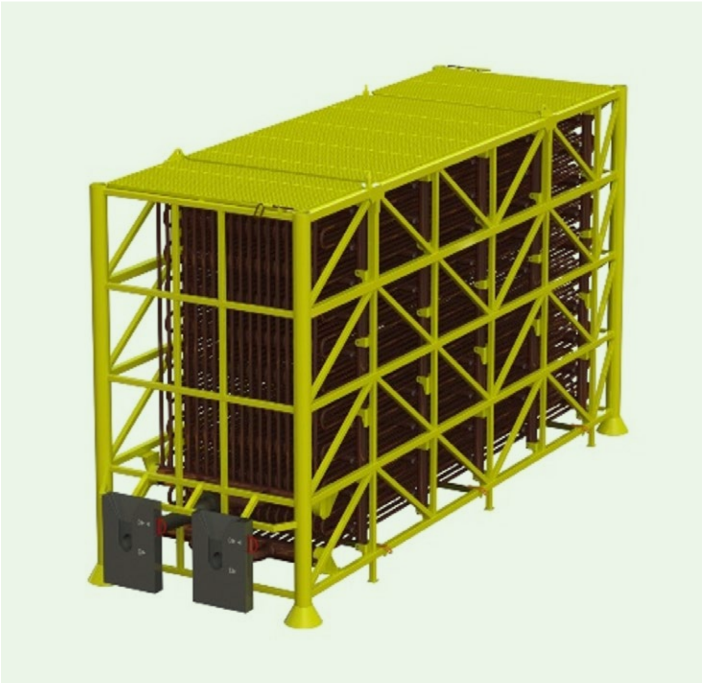


Illustration: Future Technology

Figure 36: Subsea cooling unit.

33) Aker Solutions Awarded Subsea Gas Compression Contract | Aker Solutions
34) Subsea Cooling — Future Technology

In general, it is recommended that both bottom-fixed and floating substations (AC and HVDC) explore optimization opportunities in auxiliary systems. It appears the technology is relatively mature, but some technology qualification remains, and operation and maintenance are central. Marine growth, among other issues, is important to address.

In general, it is recommended that both bottom-fixed and floating substations (AC and HVDC) explore optimization opportunities in auxiliary systems.

Overall, for both bottom-fixed and floating substations (AC and HVDC), a thorough analysis should be conducted to identify where it might be possible to reduce investment costs and operation/maintenance costs.

5.7.3 Subsea Transformer for HVDC Converters

It may be feasible to use underwater transformers for large offshore HVDC systems (HVDC transformers that supply AC to DC converters). A challenge when building large offshore HVDC platforms is that equipment weight and footprint on deck approach a practical maximum, driving costs up. One general advantage of the underwater transformer concept is that much volume and weight can be shifted to the seabed, resulting in a lighter and more compact topside. Additionally, it enables more effective and reliable cooling.

Illustration: TenneT

Figure 37: Illustration of TenneT's offshore 2 GW HVDC platform

In June 2024, TenneT[35] announced that it is inviting industry to bid on a technical/economic feasibility study for developing so-called VSC-HVDC transformers[36]. The same reliability advantages realized by subsea components for AC transmission and system simplification could, in principle, apply. With subsea transformers (potentially in combination with subsea collectors and high-voltage breakers on the seabed), the power from the turbines could be fed directly into underwater transformers, and from there straight to the rectifier system on the HVDC platform. A major challenge here is the transformer's power electronics, which would be very difficult to place in a subsea configuration. Whether that can be done in a practical manner or not, it is likely that an HVDC transformer on a platform would be more straightforward than a subsea solution.

Large-scale HVDC infrastructure construction with standardized platforms could, by adopting a subsea concept, lead to a significant volume of large (typically 500 MVA+) underwater power transformers, thereby driving down unit costs for the transformer technology itself and opening the field to more players and greater competition. The same suppliers that offer subsea transformers for AC could typically also address these HVDC subsea applications.

It is important to emphasize, however, that this is technology relatively far into the future. An HVDC transformer is much more complicated than an AC transformer, making the complexity of installing it on the seabed greater than for AC transformers.

It is, however, crucial to reiterate that this is technology relatively far into the future. An HVDC transformer is substantially more complex than an AC transformer, thus placing more complexity on a subsea configuration. At present, assigning a date for when an HVDC transformer might be commercially available for subsea installation is difficult. It is also worth noting that an offshore subsea HVDC transformer would initially be most relevant to bottom-fixed installations.

35) TSO, also a leading European builder and operator of renewable power systems
36) https://www.offshorewind.biz/2024/07/04/tennet-develops-subsea-transformer-concept-launches-feasibility-study-tender

Illustration: Aker Solutions

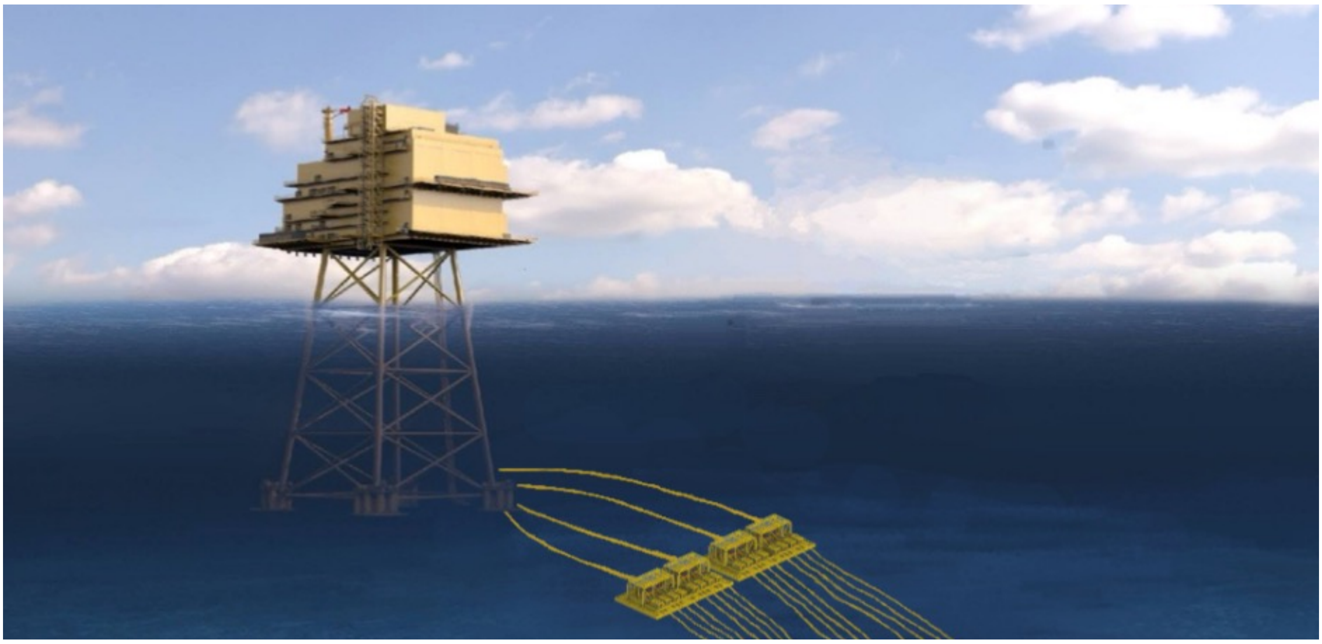


Figure 38: Illustration of an offshore converter station for HVDC in combination with a subsea HVDC transformer.

5.7.4 Low-Frequency Transmission System

Alternating current in long cables means the cables act like large capacitors, due to the capacitance between the cable conductors and ground/environment. Using 50 Hz (the typical frequency worldwide) leads to significant reactive power losses that restrict efficient energy transmission. Employing direct current removes this effect, as the current does not vary with frequency, making it possible to transmit energy over much longer distances without the capacitive losses.

However, one can employ a lower frequency than 50 Hz and still gain better transmission properties, while preserving the advantages of AC. For instance, by lowering the frequency to 16 2/3[37] Hz a cable-based AC system can transmit substantially more energy over longer distances than the same system at 50 Hz[38].

Studies have shown how such a system, effectively a hybrid of AC and HVDC, can yield significantly higher transmission capacities over longer distances. A typical 50 Hz system might have losses around 160 kW/km, whereas a 16 2/3 Hz system might be about 80 kW/km, and an HVDC system around 60 kW/km. These references assume

37) 16 2/3 Hz is a frequency that is widely used, for example in railway systems (16 2/3 Hz arises from dividing 50 by 3).
38) (PDF) Low Frequency AC Transmission on Large Scale Offshore Wind Power Plants - Achieving the Best from Two Worlds? (13th WindIntegration Workshop, Berlin 2014, paper_WIW14-1085)

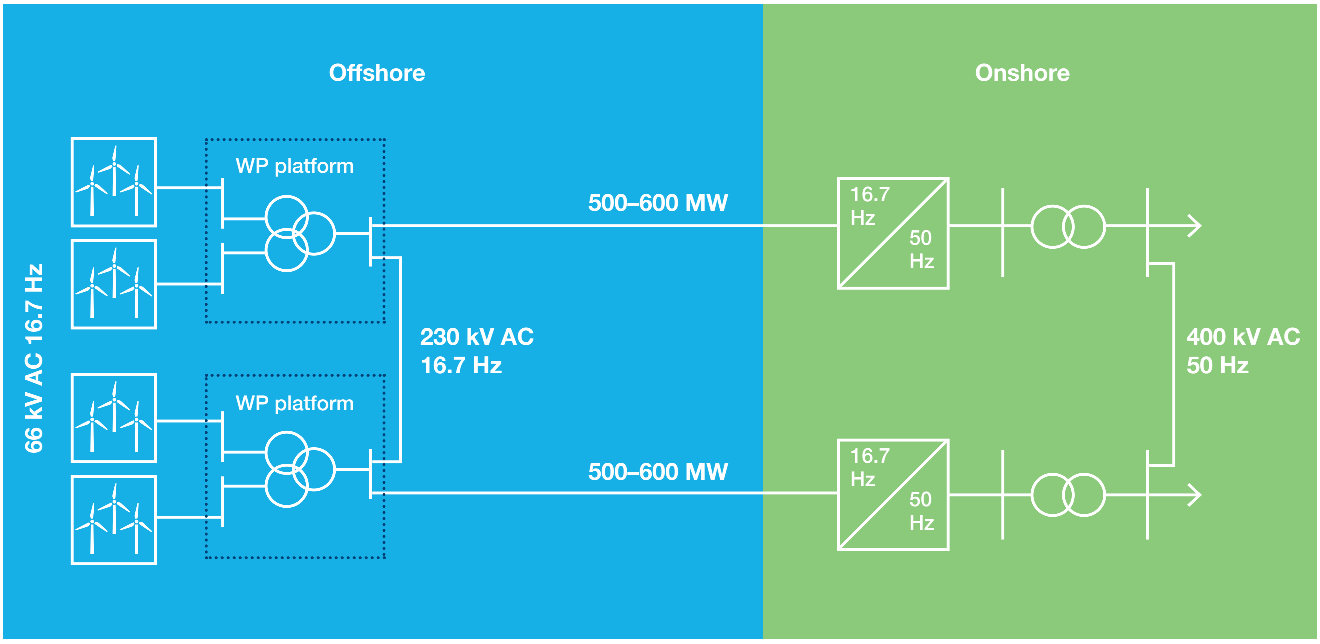


Figure 39: Low-frequency AC system schematic (reference: J-Cable 2015-B2.1 «AC Transmission Systems for Large and Remote Offshore Wind Farms»)[34].

an AC voltage of 230 kV. Typically, 230 kV with no compensation can transfer roughly 500 MW over ~200 km, whereas a 50 Hz system would require compensation at both ends to transmit about 250 MW over the same 200 km[35].

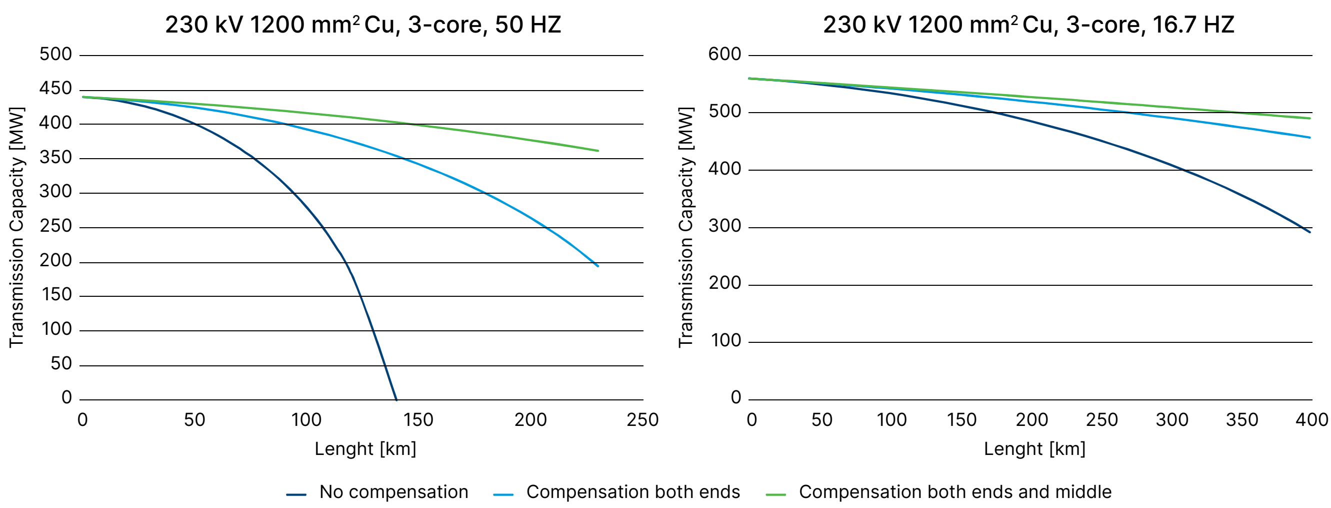


Figure 40: Comparison of transmission capacities for 50 Hz and 16 2/3 Hz. (Reference: J-Cable 2015-B2.1 «AC Transmission Systems for Large and Remote Offshore Wind Farms»)[36].

34, 35) Jicable'15 Home-page J-Cable2015-B2.1 «AC Transmission Systems for Large and Remote Offshore Wind Farms.» (login required)
36) (PDF) Low Frequency AC Transmission on Large Scale Offshore Wind Power Plants - Achieving the Best from Two Worlds? (13th Wind Integration Workshop, Berlin 2014, paper_WIW14-1085)

It is not straightforward to change the frequency to, for example, 16 2/3 Hz. The following conditions must be taken into account:

- Turbines must operate with an output frequency of 16 2/3 Hz at the high-voltage cable outlet (typically 66 kV). This means that transformers for stepping up to 66 kV within the turbines become much larger and heavier (about 2–3 times the size of a 50 Hz transformer).
- A transformer for stepping up from 66 kV to, for instance, 220 kV will also have greater weight and volume (about 2–3 times a 50 Hz transformer)
- An onshore converter station will be required to convert 16 2/3 Hz to 50 Hz before the system can connect to the onshore transmission grid. It is worth noting that, unlike a traditional HVDC transmission, no offshore converter station is needed here.

No projects to date have utilized this approach to achieve higher transmission capacity over longer distances for submarine cables. Nonetheless, it is a mature technology, and this system can be competitive for distances from shore that fall into the borderline range where HVDC would otherwise be required instead of AC.

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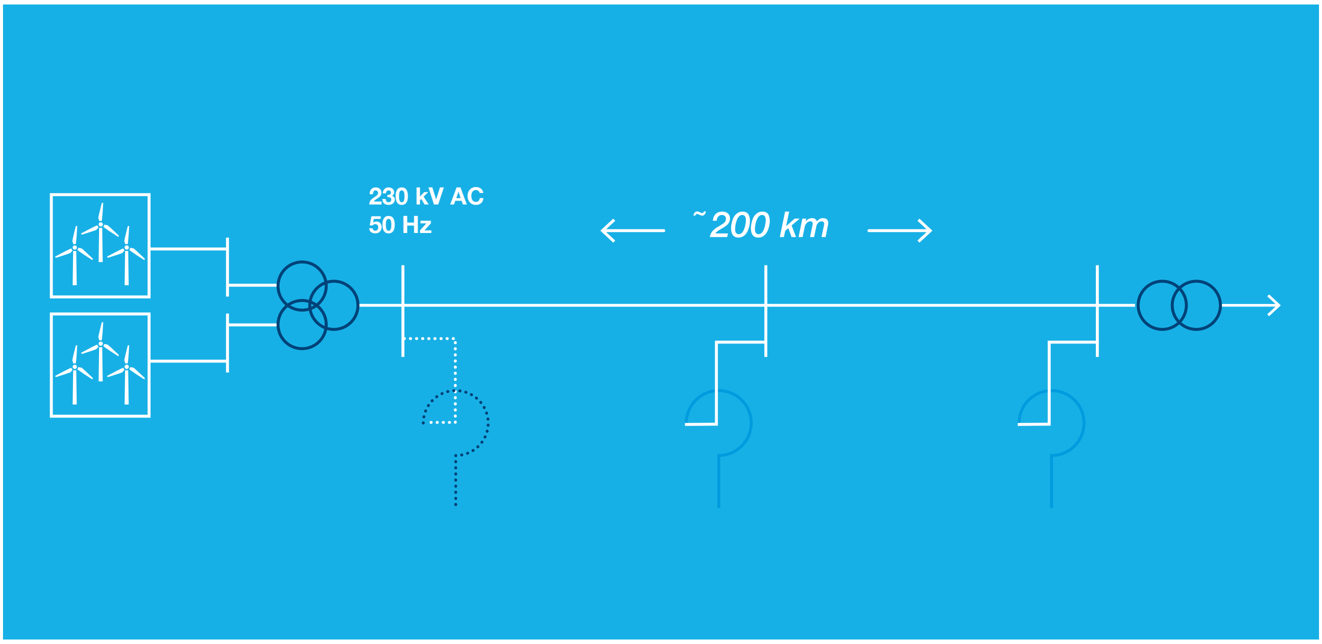

Figure 41: Example of reactive compensation at both ends plus midpoint. (Reference: J-cable2015-B2.1 «AC Transmission Systems for Large and Remote Offshore Wind Farms»)[37].

37) (PDF) Low Frequency AC Transmission on Large Scale Offshore Wind Power Plants - Achieving the Best from Two Worlds? (13th Wind Integration Workshop, Berlin 2014, paper_WIW14-1085)

5.7.5 Subsea Reactive Compensation for AC Systems

Reactive compensation at one or both ends of a submarine cable is a well-known technique for increasing transmission capacities and lengths. Midpoint compensation is also commonly used on land, where such an arrangement is easier to implement. If midpoint compensation is to be used offshore, the reactor(s) must necessarily be installed either on a platform or as a subsea installation.

For offshore grids in deep water, a subsea reactor could be competitive by enabling better utilization of AC cable connections, while also potentially offering a more cost-effective solution than placing a reactor on a floating platform.

For offshore grids in deep water, a subsea reactor could be competitive by enabling better utilization of the AC cable connection, while also potentially being more cost-effective compared to placing a reactor on a floating platform.

It is not known whether subsea reactors exist today. However, the technology is largely similar to that of subsea transformers, except that both incoming and outgoing cables will be at the same voltage level (primarily 230 kV or higher). That means a wet-mate solution at this voltage level still lies some way in the future. It should therefore be investigated whether it is possible to attach cables to the reactor before submerging it, using bend stiffeners adapted to the reactor design, cable type, and installation method.

It is assumed that this system will be mature enough for commercial project deployment at a later point than the subsea transformer.

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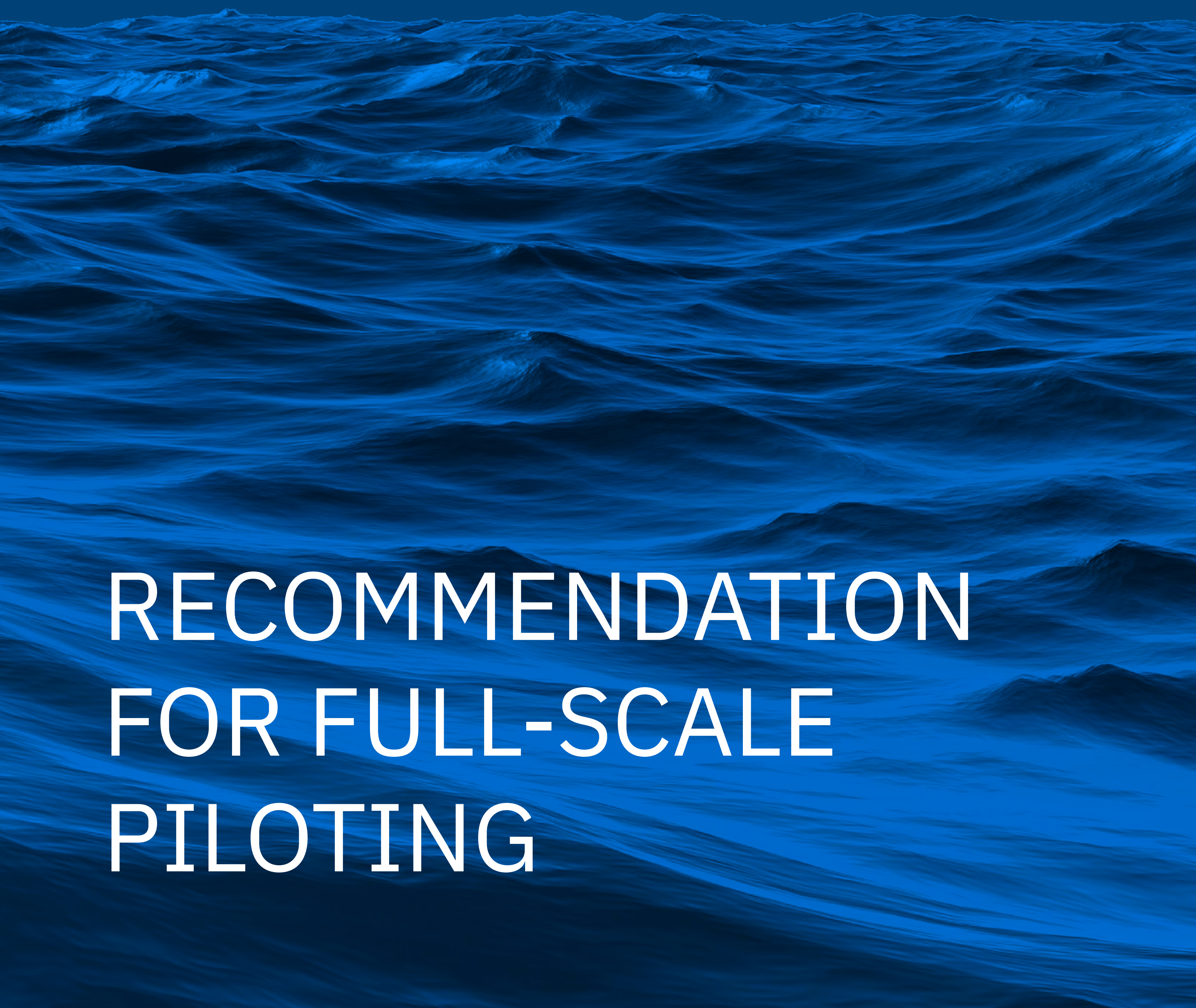

RECOMMENDATION FOR FULL-SCALE PILOTING

In the preceding chapters, the status, relevant gaps, and proposals for closing those gaps—technologies needed to realize offshore grid connections—have been described. It shows when the various technologies may be ready to begin project development, and it gives a general overview of how costs can be reduced.

Almost all identified areas along the Norwegian coast that have been designated as potential offshore wind sites—except for those in the southwest—have deep waters and thus will require floating offshore wind technology. It is reasonable to assume that the areas closest to shore will be announced first, and that these areas will be linked to land via an AC connection.

In Chapter 5, both AC and HVDC technologies for floating offshore wind are analyzed. In general, AC technology has the highest maturity and can be ready for use earlier than HVDC technology.

The simplest form of connecting a wind farm is by cable, with no transformer between the wind farm and shore. Turbines delivered today have an output voltage of 66 kV, which can mean a very large number of parallel cables. This situation might improve somewhat if turbine voltage is raised to 132 kV, which the industry believes is coming in the relatively near future. For offshore wind farms located near shore, typically around 20–30 km, running directly from turbines to shore at the same voltage as the turbine often proves the most cost-effective. For farms located farther out, it may quickly become necessary to step up the voltage. It should be considered to choose 'alternative' technologies, described with high maturity, for earlier qualification of forward-looking technology even for projects where it would initially be sufficient with direct connection without stepping up the voltage.

In the summary, and as a basis for recommendations, we assume technology in which the turbine voltage is stepped up to a higher voltage before the power is exported to the onshore grid.

For an AC grid configuration where turbine voltage is stepped up to a higher voltage, the conclusion is that, in principle, all components have a high degree of maturity and are basically ready for the start of project development—provided a typical 220 kV voltage is used for export cables.

In Chapter 5, both an AC transformer placed on a floating platform and one placed in a subsea structure have been evaluated. Whichever proves most suitable is subject to extensive engineering and optimization, taking multiple conditions into account. It is also important that requirements for availability and redundancy be considered, in addition to investment and O&M costs. Repair strategies and repair times also come into play here.

In Chapter 5, both an AC transformer placed on a floating platform and a transformer placed subsea have been evaluated. Determining which is the most appropriate solution involves extensive engineering and optimization, factoring in numerous conditions. It is also crucial that availability and redundancy requirements be taken into account, along with investment, operations, and maintenance costs. Repair strategies and repair times likewise matter.

Many project-specific factors must be considered before a project can determine the most optimal grid-configuration solution. Typical considerations are distance to shore, depth, seabed conditions, and onshore grid-connection issues (both electrical and geographical), among others.

Transformer Station on a Floating Platform

For a transformer station on a floating platform, the significant gaps identified mainly concern the electrical equipment's ability to withstand the accelerations caused by waves, wind, and currents. Nevertheless, the industry views these gaps as manageable, and the technology is effectively ready to be implemented in a full-scale pilot project. For a transformer station on a floating platform, there is in principle no real limit on the transformer capacity (or capacities) up to about 1500 MW. Also, a floating transformer station can potentially include an optimized arrangement of circuit breakers and disconnectors, depending on the desired flexibility and redundancy.

Dynamic Cables

It is essential for 220 kV dynamic cables to be available in order for a floating transformer station to be realized. Today, 132 kV dynamic cables for deep water with high transfer capacity are already available from the leading suppliers of high-voltage submarine cables in Europe. Work is underway to qualify 220 kV dynamic cables, and the industry reports that qualification will be completed shortly, making them ready for the start of project development as soon as 2025. Like a floating transformer station, 220 kV dynamic cables are ready to be implemented in a full-scale pilot project. In addition, there are several cost-saving elements that might be relevant for pilot implementation.

Subsea Transformer
In the offshore oil and gas industry, equipment has been moved down to the seabed for decades, in part to save costs. Therefore, suppliers have made efforts to develop subsea solutions for transformers at 66 kV / 220 kV voltage levels and with capacities around 400 MVA, matching the scale required for renewable projects—typically offshore wind in deep water. The technology is considered relatively mature, but some qualification remains, for instance related to 66 kV wet-type terminations and passive cooling of higher-capacity transformers. Some further development is needed before a subsea transformer can be combined with breakers (disconnectors and circuit breakers). The first projects will most likely proceed without breakers, although availability and repair times must be taken into account. In other words, the technology gaps that remain are solvable, and substantial technology development and testing is already in progress to ensure readiness. Subsea transformers rated 66 kV / 220 kV at 400 MVA are considered feasible for implementation in a full-scale pilot project as early as 2025.

Subsea kollektorer
Offshore wind farms are traditionally connected in a so-called «da-isy chain» configuration, where turbines are linked in series, with the cable cross-section increasing in proportion to how many turbines are connected, and the cable's transfer capacity requirement goes up. In this configuration, each turbine foundation must accommodate both inbound and outbound cables, and multiple cable types with different cross-sections are needed. Rethinking it—connecting all turbines in a star formation such that all cables gather at one point—would use only the smallest cable cross-sections. One cable type is used from turbine to gathering point and one out from that gathering point to a transformer station or shore. Each turbine thus needs just a single cable hookup.

It is envisioned that a collector solution may yield cost savings compa-red to a «daisy chain,» particularly if the collector is placed subsea rather than on a dedicated platform or the like. Similar to the subsea transformer, the collector can likely be implemented in a full-scale pilot project by 2025.

Other potential initiatives that can lead to cost savings
In the report, we also consider other potential initiatives that can lead to cost savings. We do not go into detail here, but point to them as examples of technologies, systems, or processes that may have an impact. It is recommended to conduct a more extensive screening to identify whether, and how, such measures might help, either in the short or longer term.

The working group «Research, Innovation, and Education» under the Collaborative Forum for Offshore Wind produced a report on R&D / innovation and education.
This extensive work focuses strongly on research, innovation, and education, with recommended measures in those areas, though not as much on technology readiness and cost reductions. Nonetheless, some relevant points merit mention here.

There is a need for research and development in both floating and bottom-fixed offshore wind technology. Emphasis should be on technology fields where Norway already has strong research environments and an industry able to apply findings for projects in Norway and internationally.

There is a need for research and development in both floating and bottom-fixed offshore wind technology. Emphasis should be on technology fields where Norway already has strong research environments and an industry able to apply findings for projects in Norway and internationally.

- Key goals for research and innovation efforts include cost reductions, scaling up industrial capacity, competitive solutions, and efficient, safe, eco-friendly, and equitable development and operation of offshore wind farms as a central part of a sustainable future energy system. Furthermore, new materials should be developed that can deliver greater structural lifespans, reduced maintenance, and are recyclable.
- New cable technology and subsea technology must be developed for connecting large floating offshore wind farms, plus cost-reducing solutions with HVDC or other technology for power transmission from large offshore wind farms located far out to sea. The technology must be robust and environmentally friendly. There is a need for industrialization and standardization, with technology enabling efficient manufacturing, assembly, and installation at large volumes, but also new thinking and innovation in conceptual approaches, on both the component and system levels.
- Industrialization will be essential for achieving major cost reductions. Industrializing floating offshore wind means developing the methods, technology, and infrastructure needed for mass production and installation, given that production and assembly processes differ significantly from those for bottom-fixed wind.

- Shipyard and port capacity must be increased so as to facilitate scaling production from just a few floaters per year to series production. Production and assembly should be streamlined by greater use of automation, robotics, new or improved joining methods, and standardized components.

Criteria and Conditions for Area Allocation
There has been much debate and differing practices across countries concerning the model and conditions for allocating offshore wind areas to developers. Topics like two-sided Contracts for Difference (CfD), investment grants, considerations of state-aid, auction principles, qualitative criteria, and weighting have been widely discussed.

To enable a build-out that includes vital elements of technology development, the financing structure should allow a combination of CfD risk relief and Enova funding, or a model in which part of the project is financed separately as a technology project. Several of the solutions outlined in this report may be suitable for such a combined financing approach.

For the upcoming tender for Utsira (Vestavind F), it should be explored whether parts of the project's CAPEX that involve technology development might be financed separately through other support schemes.

The group recommends that a report be produced examining both the legal aspects of combining support schemes and how these might be handled in a licensing round, and that an overview of relevant national and EU-level support programs for floating offshore wind be compiled. It is recommended that this should be done in management of the Collaborative Forum for Offshore Wind.

It must be legally clarified under both Norwegian law and relevant competition bodies in the EU how such a combined financing solution can be structured. Additionally, one should map which support schemes exist through EU programs. Innovation Norway or the Research Council of Norway could provide an overview. More practical experience is also forthcoming on how national and EU funds can be combined.

The group recommends that a report be developed addressing both the legal aspects of combined support schemes and how to handle these in a licensing process, as well as a catalog of relevant national and EU-level support programs for floating offshore wind. It is recommended that this be carried out under the Collaborative Forum for Offshore Wind.

Nevertheless, we do point to ways in which technology could help reduce costs more generally, offering a basis for comparison. Below are some findings indicating certain cost-reduction elements, without quantifying amounts. The expert group believes there could be significant savings if the correct and recommended measures are implemented.

Typically, there are two aspects related to cost-reduction measures:

(1) What can be done in the short term, prior to «the first project.»

(2) The assumption that lessons learned from the first—or first few—projects could yield major savings through standardization, supplier development, and a higher degree of industrialization.

Cost Reduction

The group's mandate includes *assessing whether improvements, technologies, concepts, or other factors might substantially reduce costs* for floating offshore wind, as well as the policy instruments, risk relief, or other schemes that could facilitate the necessary technologies and cost reductions. It also requires an evaluation of supplier capacity. In line with established guidelines, commercial and sensitive information such as pricing, production capacity, transportation, and markets were not shared in this work.

Nevertheless, we do point to ways in which technology could help reduce costs more generally, offering a basis for comparison. Below are some findings indicating certain cost-reduction elements, without quantifying amounts. The expert group believes there could be significant savings if the correct and recommended measures are implemented.

Typically, there are two aspects related to cost-reduction measures;

(1) What can be done in the short term, prior to «the first project.» and
(2) The assumption that lessons learned from the first, or first few, projects could give major savings through standardization, supplier development, and a higher degree of industrialization.

The overall picture for cost reductions emerges when investment, O&M costs, and service life are included and evaluated in context. Below is a list of some key points from the perspective of an AC grid:

A. Adapt requirements and regulations for the offshore renewables industry
B. Standardize unmanned platforms and associated logistics for operation and maintenance. Emphasize collaboration between the grid operator and wind farms if applicable.
C. Evaluate risk-based approaches for the necessity of redundant high-voltage systems, as well as needs for protection and breakers
D. Further development and design optimization (lean design) of AC platforms, reducing both investment and operating costs
E. Optimize anchoring / mooring systems for the platform
F. Optimize auxiliary systems
G. Optimize the electrical equipment to handle motions due to waves, wind, and currents
H. For AC-platform grid configurations, raising the wind-farm's internal voltage from 66 kV to 132 kV could yield significant savings

I. In cases where subsea transformers are technically feasible, there may be significant savings compared to floating platforms. The wind-farm's internal voltage would remain at 66 kV due to wet-mate connections. The capacity of each transformer unit would tentatively be limited to around 400 or 500 MW. If more capacity is required, multiple independent systems could be connected in parallel. The cost of installing a subsea transformer station is thought to be lower compared to a platform. A subsea transformer design, in principle, offers less redundancy and flexibility than a platform design (depending on the protection/breaker arrangement). Export cables from a subsea transformer could be a static type (230 kV).
J. Subsea transformer stations likely reduce O&M costs relative to a floating platform
K. Subsea collectors appear cost-effective. Because they rely on wet-mate connections, collectors will be restricted to 66 kV for quite some time, initially without breakers.
L. Developing 230 kV (or possibly higher) dynamic cables would yield substantial savings for export cables from a floating transformer station

The expert group believes that, besides the points listed above, the largest cost-effectiveness benefit lies in establishing a full-scale pilot project. Subsequent projects could make use of lessons learned, enabling standardization and sharper focus on technology advancement, supplier development, and increased industrialization.

Summary

Status

Relevant technology potentially used for grid connections to floating offshore wind generally exhibits high technological maturity. Many components will be ready for full-scale project development as early as 2025.

1. Related technologies are known from oil and gas, typically including floating platform substructures / topsides, mooring methods, auxiliary systems, etc.
2. Related electrical technology (AC and HVDC) is known from onshore installations and bottom-fixed platforms
3. Related subsea-installation technology is known from oil and gas, however at lower voltages and ratings
4. Grid connections based on AC technology have higher technological maturity than those based on HVDC
5. Some technology developments for floating offshore wind grid connections can also be economically beneficial for bottom-fixed solutions

Technology Gaps

It is still some technology gaps that could presumably be closed in a reasonable timeframe:

1. Technology must be adapted to marine environments and continuous motion
2. Some key technologies are still not fully qualified for large-scale project development. Work and testing are ongoing. Design and verification cannot be done by suppliers alone; they require support and conducive frameworks via real projects.
3. Solutions developed for oil and gas need to be simplified and made more cost-effective in terms of both capital expenses and O&M costs
4. Optimize technology and processes from a sustainability perspective, also at the system level

Measures

A few measures have been identified:

1. A need to standardize technology and processes to the right level, including scaling up industrial capacity and industrialization
2. Intensify efforts to identify further opportunities for simplification and cost reduction regarding both investment and O&M
3. Facilitate further technology development and testing of certain components to achieve the necessary technology maturity level
4. The current policy instruments must be strengthened to further encourage technology development and support industrialization and supplier growth. A report should be produced to examine this, managed by the Collaborative Forum for Offshore Wind.
5. Upcoming licensing rounds must be arranged so that new technology can be used, allowing valuable lessons to be gained, leading to important learning and standardization, which in turn lowers costs further for floating offshore wind grid connections. Several promising technologies should be tested.
6. It is essential that the first full-scale offshore wind project(s) be selected with a focus on the most rational solutions and in easily accessible areas, while also serving the greatest onshore capacity needs. Succeeding with the «first» project will give major benefits and improvements and set a strong example for future developments.

Risks

Certain risks have been identified:

1. Offshore wind cannot withstand uniquely Norwegian requirements. Simplification of rules and standards is necessary.
2. Offshore wind should not have distinct Norwegian technical demands that inflate costs
3. There is generally high activity in bottom-fixed offshore wind, risking that floating offshore wind may be deprioritized by suppliers

Conclusion

A need exists for pilot projects related to floating offshore wind, along with testing in full-scale projects for implementing new technology.

These pilot projects will foster vital learning and standardization, as well as cost reductions.

Photo: Engineered Solutions/Unsplash

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CITATIONS / REFERENCES

In general, references are given as footnotes throughout the document. Below is a list of some general references that are not directly linked to the text in the document:

General References
Grønn plattform Ocean Grid: https://oceangridproject.no/research/floating-hvdc-platform

References Floating Offshore Substations
Hitachi Energy: https://www.hitachienergy.com/markets/renewable-energy/oceaniq#what-is-oceaniq

Relevant Cigré publications: (login required)

ID: 11147 B3 SUBSTATIONS AND ELECTRICAL INSTALLATIONS - Full Papers
Topics: B3 PS1 - Challenges and New Solutions in T&D Substation Design and Construction for Energy Transition
Keywords: Floating, HVAC, HVDC, Offshore Wind, Primary Equipment, Substations
Offshore floating HVAC and HVDC substations – Experiences in design of selected primary equipment
Douglas RAMSAY, Mark GEARY, Thomas HAMMER, Thorsten STEINHOFF, Matthias STEUER, Stephan VOSS, Joerg HAFERMAAS, Yana SHATEROVA

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Topics: B3 PS1 - Challenges and New Solutions in T&D Substation Design and Construction for Energy Transition
Keywords: USA West Coast, Offshore Substation (OSS), Floating Offshore Substation (FOSS), Finite Element Analysis (FEA), Wave Basin, Model Test
Conceptual Design of Semi-submersible Floating Offshore HVAC Substation Solution
Hongbiao SONG, Zhaoxiang TANG, Yang OUYANG, Robert LUESCHER, Tobias STIRL, Hana ASSEFA

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Topics: B3 PS1 - Challenges and New Solutions in T&D Substation Design and Construction for Energy Transition
Keywords: Floating Offshore Substation, FOSS, GIS, Simulation, Vibrations, Experimental Correlation, GIS for offshore and floating applications
Marcel STOECKLI, Yang OUYANG, Lukas TREIER, Bernhard SPICHIGER, Robert LUESCHER, Hongbiao SONG

ID: 10259 A2 POWER TRANSFORMERS AND REACTORS - Full Papers
Topics: A2 PS1 - Design of Resilient Transformers
Keywords: Powers transformers, floating offshore, applications, technology, potential failure
Stresses on Power Transformers in Floating Offshore Applications
Triomphant NGNEGUEU, Max GILLET, Vivekkumar CHAUBEY, Rupesh DARIPA, Oguzkan SENTURK, Tobias STIRL, Jian ZHANG, Hongbiao SONG

References Dynamic Cables
Relevant Cigré publications: (login required)

ID: 10955 B1 Insulated cables - Full Papers

Topics: B1 PS1 – Learning from experiences
Keywords: Floating wind farms, Subsea HV XLPE cables, Dynamic cables, Wet aging, Time-to-failure testing, Water treeing
Model Test
Time to Failure of Model HV XLPE Cables in Salt Water at High Electrical AC Stress and Temperature Sverre Hvidsten, Karl Magnus Bengtsson, Elise Olsen

Iversen, Øyvind, and Johanson Audun. «High Voltage Cables – A Technology Step.» Paper presented at the Offshore Technology Conference, Houston, Texas, USA, May 2022. doi: https://doi.org/10.4043/32084-MS

Photo: Equinor – Hywind Tampen turbin

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APPENDIX

8.1 The Policy Instrument Framework

Norway, as well as other individual nations and the EU, provides a business-oriented policy instrument framework that offers programs such as loans, grants, guarantees, and various competence measures. The purpose is to support industry in important development within R&D, establishment, growth, scaling, and exports. In Norway, it has been decided to develop an R&D strategy covering the entire energy sector, which will become operational at the start of 2025, replacing Energi21 and OG21. It is tentatively called «Energi2050.»

It is well known that the biggest financial risk often occurs during the scaling-up phase and during the final qualification of a solution or system. Substantial costs arise in developing and verifying technology at large scale, making risk relief or direct support crucial for realizing potential demonstration or pilot projects. At the same time, such solutions can be entirely necessary for reducing costs and achieving technological leaps that advance the sector.

The conditions for costly technology piloting are vital for maturing the supply chain, while the current support level in Norway is low compared to other research and development. Industry finds that in some areas, there may be discrepancies in the use or interpretation of European state-aid rules between Norway and other countries. The table below describes the programs as the Expert Group understands them.

Activity		Support Rate (Large Enterprises)
TRL 5 - 8 Experimental development	Investment Support – Floating offshore wind farms	< 100% (Provided an exception from state-aid rules. For example, Enova's program «competition for support for small-scale commercial floating offshore wind projects»)
	Pilot testing of individual components and investment support for new production technology	< 25 %
TRL < 5 Industrial research	Research and development	< 50 %

Table 3: Investment Support Related to Different Levels of Technological Maturity

Collaboration in projects can in some cases boost the maximum support rate by 15%. For instance, the government's Grønn Plattform has helped facilitate such projects, often focusing on piloting. Continuation and strengthening of this scheme can be an important piece in the policy instrument framework.

Many critical components related to the grid that are included in this study currently stand around TRL 6 in maturity. Meanwhile, the cost of further maturation is high and the support rate is low if the development is not part of a complete investment backed by an end user. The possibility of standalone piloting is seen as an important opportunity, especially for suppliers. This should be reinforced in the policy instrument framework. It is recommended to examine the scope for action and develop models that address this gap. This must be weighed against how support schemes are practiced in European countries and the U.S., to ensure a competitive industry that attracts activity and develops technologies for deployment—thus providing a competitive advantage. Regardless, it is crucial that existing schemes for investment support emphasize the integration of important and scalable pilot components in the final installation (which is presumably already allowed within the existing scope).

Working Group 2 in the Collaborative Forum has, in earlier work, described the policy instrument framework and technology development to which it refers. For instance:

«Norway has substantial technical expertise from the oil and gas industry that can be directly transferred to the offshore wind industry. This applies, for instance, to bottom-fixed and floating structures, mooring systems, static and dynamic cables, and marine operations. Norwegian industry also has deep experience in carrying out major, complex development projects where authorities, operators, and developers work closely together from early-phase to project execution. In recent years, there has also been significant experience gained in partnership models in the Norwegian oil and gas industry. We believe this is an advantage we can build on, especially in floating offshore wind, which has a prototype character and a partially untested supply chain. Developers and subcontractors work together as a team from early phase into project execution, thus avoiding silo thinking and sub-optimization—an advantage when developing innovative and cost-effective solutions specifically needed in floating offshore wind.»

Norwegian Research Council, Innovation Norway, Norwegian Energy Partners, Eksfin, and Enova all have relevant programs and schemes. Eksfin offers guarantee arrangements; Innovation Norway has financed over 200 projects; and NORWEP engages in targeted sales dialogues between Norwegian industry and international clients. However, for many companies, it is time-consuming to prepare applications, response times can be long, and there may be challenges around ownership and usage rights to technology (IPR), among other issues.

Enova has long played a role in wind power. Its focus is now on technology development for offshore wind, especially for floating solutions. Enova's stance is that by targeting technology development and demonstration, solutions can be matured more quickly and costs can go down. The overarching goal of the policy instruments is to help reduce LCOE for floating offshore wind so that solutions can eventually become commercially viable without support.

Norwegian players are well-positioned to deliver technology and products to a growing international offshore wind market, but several technology areas require further refinement and maturation so that offshore wind concepts can stand firmly as energy suppliers at competitive prices.

Norwegian players are well-positioned to deliver technology and products to a growing international market in offshore wind, but several technology areas require further refinement and maturation so that offshore wind concepts can stand firmly as energy suppliers at competitive prices:

- Wind turbine (WTG)
- Floating foundation
- Mooring
- Power cable
- Storage technologies
- Automation technologies including digitization (digital twins)
- Vessels (access and service)
- Installation and service methods
- Port areas (transport and logistics)

Enova Offers Support Through Two Different Mechanisms:

Havvind 2035
This is an ongoing support program that encompasses pilot projects, investment projects for projects, and feasibility studies, with no specific application deadlines. The program is anchored in the general block exemptions for state aid, meaning the maximum support for investment projects is €30 million (and 45% of approved costs), while the maximum support for pilot projects is €25 million (the support ratio depends on project content and participating partners). Feasibility studies and pre-projects can receive up to NOK 10 million in support (50% of approved costs).

Projects must be linked to a specific investment and related to new technology. Commercial business development and related positioning for future market opportunities fall outside Enova's scope.

Investment support can be applied for in projects that demonstrate a complete power-generating installation delivering electricity and that has a full service life. Pilot support can be granted for testing individual components without any requirement of energy delivery from the project, but with more emphasis on demonstrating a likely contribution to reducing future LCOE.

The program is open to commercial actors, public-sector players, or consortia. In a consortium, all participants must be co-financing, active partners. The applicant (project lead) will always be the project's responsible party when entering into a contract with Enova. The applicant (project lead) can be:

- A well-established company registered in the Norwegian business register that has economic activity in Norway
- A Norwegian public entity
- A research organization, if the application is submitted on behalf of a consortium with at least one Norwegian-established business or public entity, and if other participants in the consortium (companies and/or public-sector entities) provide at least 50% of the project's financing

The applicant and any project partners must meet all requirements to receive state aid.
Examples of potential support recipients include:

- For a typical pre-project, the project lead would be the company that will carry out the investment in any subsequent investment project
- For an investment project, the applicant must be the company responsible for carrying out the investment and meeting the project objectives
- For a pilot project, the applicant can be a supplier, an end user, or a research organization
- In the case of consortia, all participants receiving support must be registered in the Norwegian business register

More information is available here: https://www.enova.no/bedrift/industri-og-anlegg/havvind-2035

Competition for Support for Small-Scale Commercial Floating Offshore Wind Projects
In this support program, funding is available for commercial floating offshore wind projects with a need for more than €30 million in support. The program has specified application deadlines, and the maximum support per project is NOK 2 billion. In principle, one could apply for 100% support, but the projects compete with each other, and cost-effectiveness (for Enova) is the deciding factor in the ranking (70% weighting on cost-effectiveness, 30% on innovation height and application area).

There is a requirement that the planned operational date come within five years of Enova's decision. The project:

- Must demonstrate cost-effective concepts in floating offshore wind energy production.
- Must have a full service life, subject to a maximum support of NOK 2 billion, meaning full-scale parks do not fall within this program.

Research and Development Contracts (R&T)[38]
A great deal of the research, technology development, and qualification of technologies and systems on a larger scale on the Norwegian shelf in the oil and gas industry has been carried out under what are called R&T arrangements. This arrangement is part of the regulations for the Norwegian shelf, meaning that licenses pay a fixed percentage of Exploration, Capex, or Opex which the operator may use for research benefiting the Norwegian shelf. Funding is in line with the Accounting Agreement on the Norwegian shelf, Article 2.2.2 – Research and Development. It includes describing and strongly prioritizing R&D from an operator that has been granted a license, supporting major investments in education, research, and innovation. This has provided competitiveness for Norwegian industry and optimized project development and operation.

Working Group 2 – R&D and «Education»
A major effort is underway in research, development, and innovation as part of one of the three subgroups in Working Group 2. The group includes participants from universities, developers, and suppliers, among others. Reference is made to the report presented in a webinar on 14 March 2024[39].

In the Grønn Plattform project «OceanGrid» about offshore grids, three work packages are highlighted for technology development related specifically to the grid connection of floating offshore wind: lead-free cable with Nexans, subsea switching equipment with Aker Solutions and Benestad, and floating HVDC with Aibel and Hitachi Energy. This also produces recommendations concerning important technology and knowledge requirements.

Through the Collaborative Forum for Offshore Wind, the theme group «Research, Technology and Competence Development» has observed a growing need to map competence requirements for offshore wind in order to meet the challenges arising from the ambition of allocating new areas for 30 GW of offshore wind by 2040.

Such a competence mapping will form the foundation for a national offshore wind effort, where industry defines the need and academia can respond with curricula spanning everything from vocational training to research.

38) R&T Contracts (Research and Technology Contracts) related to research, development, and innovation. This scheme stimulates collaboration between industry and public actors, often with the goal of developing new products, services, or solutions.
39) https://www.norskindustri.no/dette-jobber-vi-med/energi-og-klima/norsk-industri-om-vindkraft/samarbeidsforum-for-havvind

To meet this need, Norsk Industri and others have initiated a project building on the work done under «Leveransemodeller for Havvind,» which included an overview of the Norwegian competence landscape. It showed that there are particular shortages in secondary-level education and technical colleges, especially in technical fields. The project will further explore this data and examine how we can strengthen Norway's technical communities, as well as how this might align with international competence requirements.

The project «VindKOMP»[40] started in autumn 2023, with financial backing from the Ministry of Energy, Norsk Industri, Fornybar Norge, Offshore Norge, and several larger industry partners. VindkOmp is to be led by the Nasjonalt kompetansesenter for Havvind (National Offshore Wind Competence Center), with in-kind support from industry and academia. VindkOmp is therefore proposed to be split into 3 phases:

Phase 1: Needs Mapping
Through in-depth interviews and workshops with companies across the value chain (technical, finance, legal, social science), we aim to map industry needs in the short and longer term. This study will identify the demand for workers with both shorter and longer educations, as well as the specific competence areas that will be in demand.

Phase 2: GAP Analysis and Recommendations for Academia
Here, we aim to analyze the results from Phase 1 and compare them to the existing array of educational programs. Through discussions with academia, new shorter and longer learning modules could be introduced, including continuing education in the industry and specialized modules in technical colleges and higher education.

Phase 3: Plan for Competence Development Related to Exports and Indirect Jobs
In this phase, we will take results from the first two phases and produce targeted strategic measures to fill the gap between supply and demand of offshore wind-relevant skills. The goal is that everyone knows how they contribute to building and retaining a robust workforce prepared for the offshore wind industry's challenges and opportunities.

40) VindKOMP Norsk Industri

The first partial report from VindkOmp was released in October 2024 and can be read on the Nasjonalt kompetansesenter for Havvind website (https://www.havvind.no/tema/vindkomp)

8.2 The TRL Scale

Technology Readiness Levels (TRLs) represent a method for estimating a technology's maturity. Using TRLs enables consistent and coherent discussions about technical maturity across various types of technology. A technology's maturity is determined via a Technology Readiness Assessment, examining program concepts, technology requirements, and demonstrated technological capabilities.

TRL 1	Basic research: Fundamental principles are observed and reported.
TRL 2	Applied research: Technology concept and/or application are formulated.
TRL 3	Critical function, proof of concept established: Key functions are tested, and the concept is proven.
TRL 4	Laboratory testing of prototype components or process: Individual components are tested under controlled conditions.
TRL 5	Lab testing of integrated system: Several components are integrated and tested together in a lab environment.
TRL 6	Prototype system verified: A prototype system is tested in a relevant environment.
TRL 7	Demonstration of integrated pilot system: A fully integrated system is demonstrated in an operational environment.
TRL 8	System incorporated in commercial design: The technology is developed and integrated into commercial products.
TRL 9	System ready for full-scale implementation: The technology is fully developed and ready for large-scale use.
This scale is often used in research, development, and innovation projects to measure progress and maturity. More information can be found in «EU, Technology Readiness Level. Guidance principles for renewable energy technologies,» Technology readiness level - Publications Office of the EU	

Table 4: Generic TRL scale

Design: Bly.as