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Offshore Wind Transmission Technologies Assessment

Overview of Existing and Emerging Transmission Technologies

Prepared for:

The California Energy Commission

Submitted by:

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- Invenergy
- Ocean Winds
- RWE

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Executive Summary

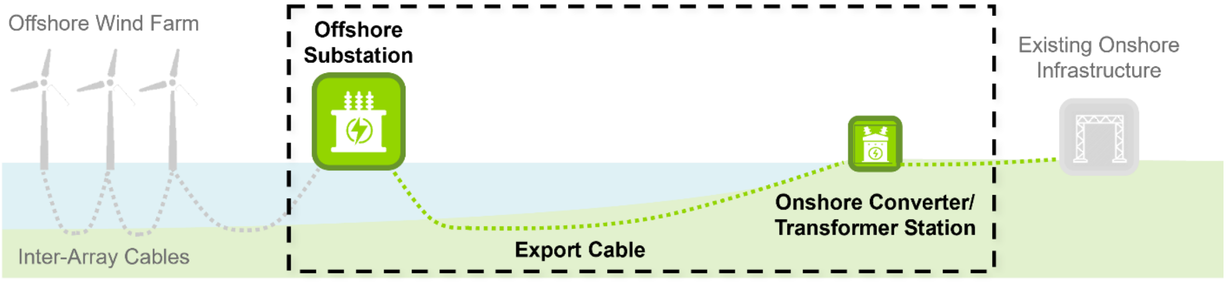
Assembly Bill (AB) 525[1] (Chiu, Chapter 231) directs the California Energy Commission (CEC) to develop a strategic plan for offshore wind energy developments installed off the California coast in federal waters, among other actions to advance offshore wind development towards the state's planning goals of 2,000–5,000 megawatts (MW) of offshore wind by 2030 and aspirational goal of 25,000 MW by 2045.

On December 6–7, 2022, the Bureau of Ocean Energy Management (BOEM) held an offshore wind energy lease sale for five lease areas on the Outer Continental Shelf off Central and Northern California, for a total area of 373,267 acres and potential capacity of up to 8,610 MW. The lease areas are at depths of 700–1,200 meters and at approximate distances from shore of 40–110 kilometers. Fixed platforms will not be economically feasible at the water depths of the wind energy areas in California. Thus, turbine and electrical substation platforms will most likely require floating infrastructure, and as a result, dynamic power cables. However, floating platforms and dynamic cables are still developing technologies that do not yet exist at the scale and capacity needed for large scale offshore wind generation.

Guidehouse was engaged to document the current state and industry experience of existing and emerging technologies for the transmission and interconnection of offshore wind off the coast of California to the onshore grid and examine the development and costs of these technologies. Guidehouse first conducted a secondary review of literature, consisting of publicly available offshore transmission and interconnection studies, offshore wind research papers, information from technology manufacturers, demonstration projects, and wind power deployments. Guidehouse then collected primary data through interviews of offshore wind developers holding California leases and an offshore transmission developer to supplement and enhance the secondary data.

This report informs the transmission and interconnection section of the CEC's offshore wind strategic plan under AB 525. It presents a review of the current state and developments for offshore wind transmission technologies, including high voltage alternating current (HVAC) and high voltage direct current (HVDC) export cables, substations and related electrical components, and offshore substation platforms, as well as meshed grid transmission and interconnection concepts. Figure ES-1 shows the offshore wind transmission technologies within the scope of this report. Offshore wind turbines and platforms, inter-array cables, and existing onshore grid infrastructure are outside the scope of this report.

Figure ES-1. Offshore Wind Transmission Technologies in Scope for This Report



Source: Guidehouse

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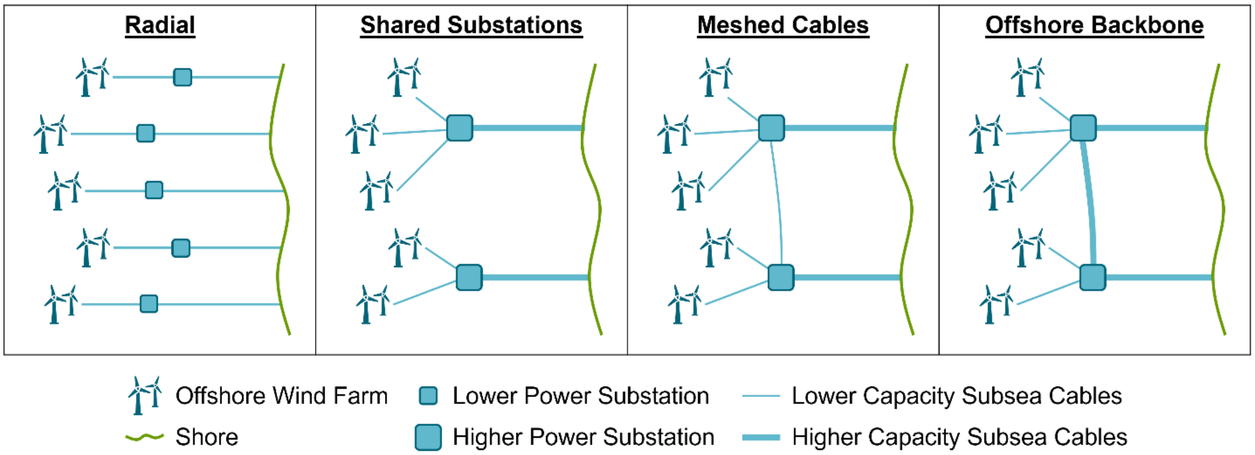
[1] https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220AB525

Existing offshore wind deployments in other regions have primarily used HVAC systems for the transmission of power to shore, although HVDC systems are beginning to be deployed as well. Considering the distance to shore of the California wind energy areas, both HVAC and HVDC transmission systems are viable options for the export of power from offshore wind farms. HVAC transmission technology is highly mature, with more than 20 years of experience in the offshore wind industry. However, HVAC export cables face technical and economic limitations to transmission distance, as they require reactive power compensation for transmission over long distances. HVDC transmission is better suited for long-distance transmission since reactive power losses do not occur. However, HVDC transmission technology has a higher upfront cost and is less mature, especially for offshore applications, and key components such as DC gas-insulated switchgear and DC circuit breakers are still relatively nascent. Literature review shows that there is a breakeven point at 80–100 kilometers, beyond which HVDC is more economical for offshore transmission. In interviews, lessees seemed open to utilizing either HVAC or HVDC and indicated they would need additional information about supply chain and availability of key technologies in each system, as well as long-term transmission plans before making a final decision.

As offshore wind developments expand globally, grid operators have explored concepts for interconnecting multiple wind farms offshore and with the onshore energy system. While most offshore wind farms to date are connected to shore radially, more networked interconnection concepts such as shared substations, meshed grids, and offshore backbones can increase reliability and redundancy, allow for increased offshore wind build-out and interconnection between different regions and markets, and provide onshore grid benefits. These interconnection concepts are illustrated in Figure ES-2. Meshed grids can be achieved for HVAC and HVDC transmission systems, or a combination of both. This report reviews three studies into meshed offshore grids for integration of offshore wind, in New York, New Jersey, and Great Britain.

Figure ES-2. Offshore Wind Offshore Wind Farm Interconnection Concepts



Source: Adapted from WBUR

Through literature review and interviews with developers, the following key technology gaps and pain points were identified for the development of California's first round of offshore wind area development and for long-term offshore wind build-out.

- **Technologies needed to enable transmission and interconnection of large scale floating, deep-water offshore wind farms are still emerging.** These include dynamic and higher capacity export cables and floating substations.
    - **Dynamic cables are not yet available at the level of capacity or voltage rating necessary for California offshore wind.** Dynamic cabling technology exists for lower voltage HVAC applications, and HVDC dynamic cables do not yet exist in any form.
    - **There is limited precedence for floating substations.** Existing offshore wind substations thus far have all been fixed bottom, with the exception of one floating offshore substation that was demonstrated as part of the Fukushima FORWARD project but was decommissioned in 2021.
- **Supply chain constraints and availability of key technologies at scale are top of mind for developers.** Developers expressed confidence in the technological feasibility of offshore wind transmission technologies, but anticipated supply chain challenges as demand for transmission technologies ramps up.
- **Developers identified onshore grid constraints that present challenges to the interconnection of the first round of offshore wind build-out in California.** Specifically, developers singled out transmission constraints in Humboldt and uncertainties around extension or decommissioning of the Diablo Canyon nuclear power plant as barriers to interconnection.
- **Developers strongly encouraged proactive, state-led planning for long-term offshore transmission needs.** Developers were generally in favor of meshed grids as a long-term transmission strategy. However, a meshed system requires collaborative and centralized planning, and developers stressed the need and opportunity for a central transmission solution led by the state, rather than a piecemeal approach as has been the case on the East Coast.

1. Introduction

Assembly Bill (AB) 525[2] (Chiu, Chapter 231) directs the California Energy Commission (CEC) to take multiple actions to advance offshore wind energy developments installed off the California coast in federal waters. This bill requires the CEC to:

- *"Evaluate and quantify the maximum feasible capacity of offshore wind to achieve reliability, ratepayer, employment, and decarbonization benefits and to establish offshore wind planning goals for 2030 and 2045"*

- *"Develop a strategic plan for offshore wind energy developments installed off the California coast in federal waters"*

- *"Work with stakeholders, state, local, and federal agencies, and the offshore wind energy industry to identify suitable sea space for wind energy areas in federal waters sufficient to accommodate the offshore wind planning goals for 2030 and 2045"*

- *"Develop a plan to improve waterfront facilities that could support a range of floating offshore wind energy development activities"*

- *"In consultation with the PUC and Independent System Operator…assess the transmission investments and upgrades necessary to support the offshore wind planning goals"*

- *"Develop and produce a permitting roadmap that describes timeframes and milestones for a permitting process for offshore wind energy facilities and associated electricity and transmission infrastructure off the coast of California"*

- Include information on the *"potential impacts on coastal resources, fisheries, Native American and Indigenous peoples, and national defense, and strategies for addressing those potential impacts, to be included in the strategic plan,"* and

- Prepare *"a preliminary assessment of the economic benefits of offshore wind as they relate to seaport investments and workforce development needs and standards"*

Guidehouse Inc. (Guidehouse) as a subcontractor to Aspen Environmental Group was retained to inform several of these requirements related to transmission and interconnection topics. Specifically, Guidehouse was engaged to document the current state and industry experience of existing and emerging technologies for the transmission and interconnection of offshore wind off the coast of California to the onshore grid and examine the development and costs of these technologies. These technologies include high voltage alternating current (HVAC) and high voltage direct current (HVDC) export cables, substations and related electrical components, and offshore substation platforms, as well as meshed grid transmission and interconnection concepts. Figure 1 shows the offshore wind transmission technologies within the scope of this report, which documents Guidehouse's findings. Offshore wind turbines and platforms, inter-array cables, and existing onshore grid infrastructure are outside the scope of this report.

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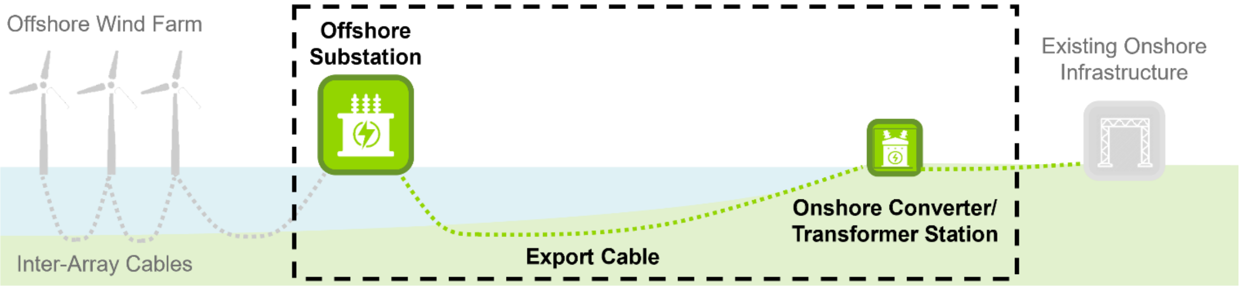
[2] https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220AB525

Figure 1. Offshore Wind Transmission Technologies in Scope for This Report



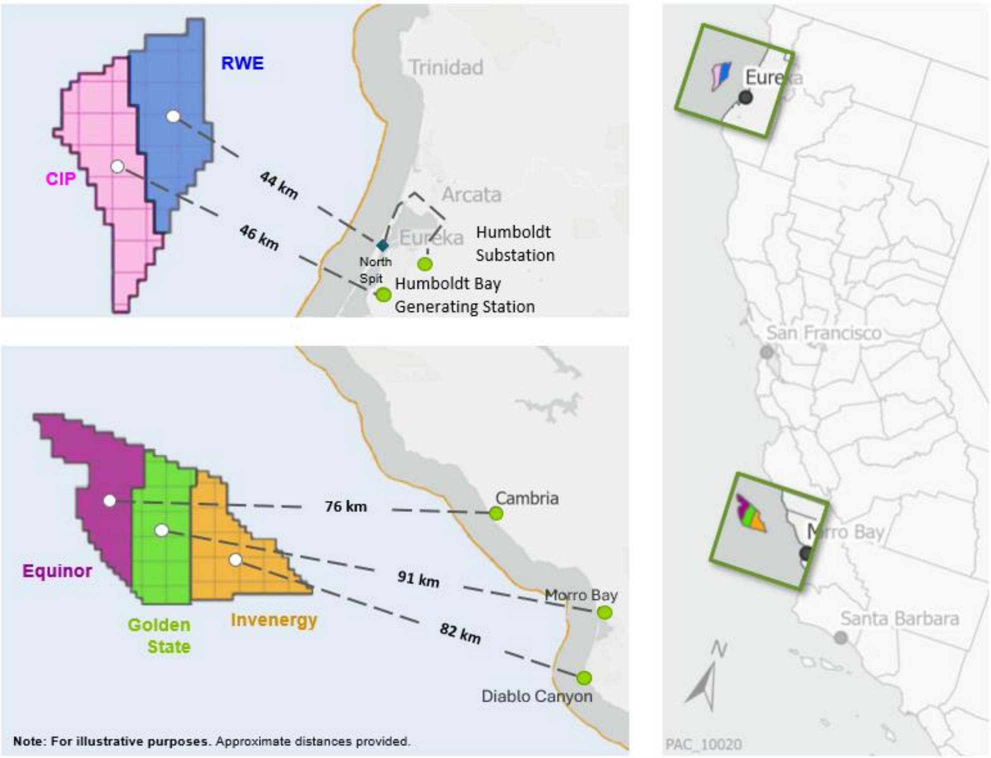
Source: Guidehouse

1.1 Background

In August of 2022, the CEC adopted a report establishing offshore wind goals as required in AB 525. Preliminary findings in the report set planning goals of 2,000–5,000 megawatts (MW) of offshore wind by 2030 and aspirational goal of 25,000 MW by 2045.

On December 6–7, 2022, the Bureau of Ocean Energy Management (BOEM) held an offshore wind energy lease sale for five lease areas on the Outer Continental Shelf off Central and Northern California. The two lease areas in the North Coast center around the city of Eureka and Humboldt Bay, and the three lease areas off the Central Coast center around Morro Bay and the Diablo Canyon Power Plant, for a total area of 373,267 acres and potential capacity of up to 8,610 MW. The lease areas and key information about the provisional winners are shown in Figure 2 and Table 1.

Figure 2. California Lease Areas and Provisional Winners



Source: Adapted from BOEM

Table 1. Key Information about Provisional Winners of the Five California Lease Areas

Provisional Winner	Acres	Potential Capacity (MW)	Average Depth (m)	Average Distance from Shore (km)
RWE Offshore Wind Holdings, LLC	63,338	1,470	723	43 (Eureka)
California North Floating, LLC (CIP)	69,031	1,590	786	47 (Eureka)
Equinor Wind US, LLC	80,062	1,800	1,126	105 (Morro Bay)
Central California Offshore Wind, LLC (Golden State Wind)	80,418	1,905	1,051	91 (Morro Bay)
Invenergy California Offshore, LLC	80,418	1,845	988	77 (Morro Bay)

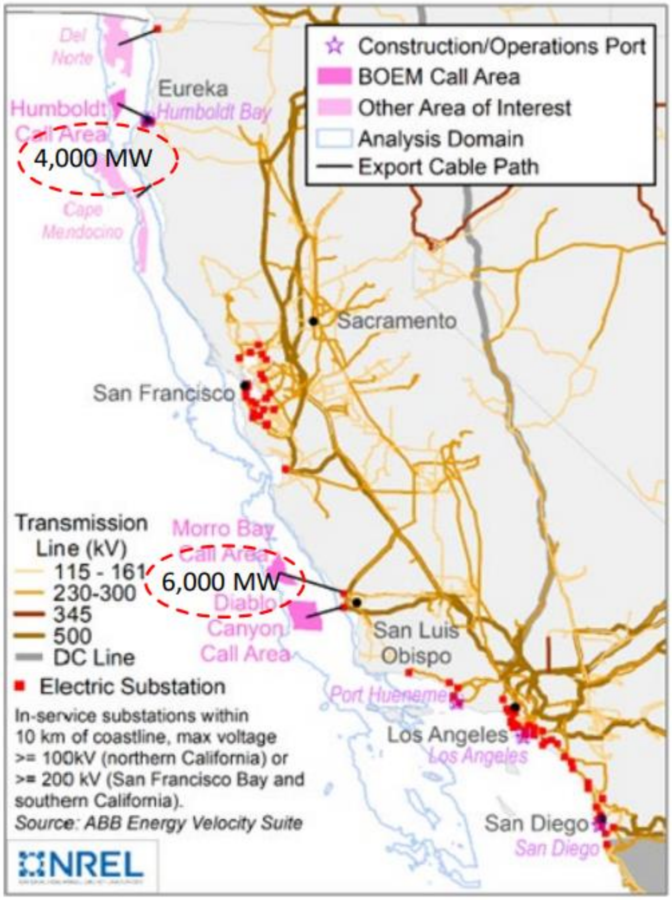
Source: U.S. Department of the Interior and National Renewable Energy Laboratory

Given distances to shore of 40–110 kilometers (km), both HVAC and HVDC are viable options for bulk transmission of power. The range of water depths of 700–1,200 meters (m) creates new technological challenges that offshore wind in the United States has not previously faced. While fixed platforms are sufficient for offshore wind farms on the East Coast, they will not be economically feasible at the water depths of California wind energy areas. Thus, turbine and electrical substation platforms will most likely require floating infrastructure, and as a result, dynamic power cables, both of which are developing technologies that do not yet exist at the scale and capacity needed for large scale offshore wind generation.

Extensive transmission development will be needed to interconnect the offshore wind generation from the recently leased wind energy areas and to reach California’s long-term goal of 25 gigawatts (GW) of offshore wind generation capacity by 2045. Preliminary planning and thought have begun on the necessary transmission infrastructure for offshore wind. The California Independent System Operator’s (California ISO’s) 20-Year Transmission Outlook explores the longer-term grid requirements for interconnecting offshore wind in the Central and North Coast. The 20-year outlook assumes that 6,000 MW of offshore wind resources will be in the Central Coast in the Diablo and Morro Bay areas, and 4,000 MW will be in the North Coast in the Humboldt Bay, Cape Mendocino, and Del Norte areas. These assumptions are shown geographically in Figure 3.

The offshore wind in the Central Coast is assumed to interconnect to the existing Diablo substation and a new Morro Bay substation. Existing interconnection options are less developed in the North Coast. California ISO identified the need for two alternating current (AC) lines connecting the substation at Fern Road and an HVDC line to the Collinsville substation near the Bay Area. Additional transmission would also be required to interconnect the two AC lines and the HVDC system together to the offshore wind farms.

Figure 3. Offshore Wind Development Location Assumptions in California ISO's 20-Year Transmission Outlook



Source: California ISO

1.2 Report Structure

This report is laid out as follows:

- **Chapter 2** discusses Guidehouse's research methodology of secondary literature review and primary data collection via interviews with offshore wind developers.
- **Chapter 3** discusses existing transmission and interconnection technologies, focusing on export cables, substations, and relevant electrical components for HVAC and HVDC connections. HVAC and HVDC systems are compared based on cost, including perspectives from interviewed offshore wind developers.
- **Chapter 4** discusses emerging transmission and interconnection technologies, focusing on floating and subsea substations, dynamic export cables, and higher capacity export

cables. This chapter also provides an overview of recent studies and activity around meshed grid systems for offshore wind transmission. Insights from interviewed offshore wind developers on emerging technologies are woven throughout.

- **Chapter 5** covers interview insights around transmission planning and supply chain constraints affecting necessary transmission and interconnection technologies, as well as a brief discussion of offshore wind developers' anticipated commercial operation dates and factors affecting those dates.
- **Chapter 6** summarizes the main findings of the report.

2. Research Methodology

Guidehouse conducted research in two phases: secondary literature review focused on the existing and emerging transmission technologies, followed by primary data collection through interviews.

The secondary literature review consisted of examining publicly available offshore transmission and interconnection studies, offshore wind research papers, information from technology manufacturers, demonstration projects, and deployments. In total, 32 secondary sources were reviewed. Among these resources, those that were most useful and most informative for this study are the following:

1. BOEM, Floating Offshore Wind Development Assessment, 2021.
2. DNV GL for New York State Energy Research and Development Authority (NYSERDA), New York Power Grid Study Final Report Appendix D: Offshore Wind Integration Study, 2020.
3. DNV GL for National Grid Electricity System Operator (ESO), Holistic Approach to Offshore Transmission Planning in Great Britain, 2020.
4. DNV GL for European Union, Progress on Meshed HVDC Offshore Transmission Networks (PROMOTioN) Final Report, 2020.
5. National Renewable Energy Laboratory (NREL) for BOEM, Potential Offshore Wind Energy Areas in California: An Assessment of Locations, Technology, and Costs, 2016.
6. The Brattle Group for the New Jersey Board of Public Utilities, New Jersey State Agreement Approach for Offshore Wind Transmission: Evaluation Report, 2022.
7. DNV for Maine Governor's Energy Office, Offshore Wind Transmission Technical Review – Initial Report, 2022.
8. ABS Group for BOEM, Floating Offshore Wind Turbine Development Assessment Final Report and Technical Summary, 2021.

A full list of references can be found in Appendix A. Sources for specific figures and numbers are cited throughout the report in footnotes and captions.

Guidehouse used the literature review to compile an overview of transmission technology as currently known in the public domain. Guidehouse structured this overview into a conversation guide and identified key gaps and areas of uncertainty for which additional information was needed. The conversation guide informed the next phase of the project in which Guidehouse conducted interviews with California offshore wind developers and transmission developers.

In the months of March and April 2023, Guidehouse presented its transmission technology overview to interviewees and facilitated a conversation that primarily aimed to:

- Confirm if findings from literature (some of which may have been dated) were still accurate, then revise or add to the information found via secondary research,

- Seek input on key information gaps that literature did not cover such as technology costs and commercial availability, and
- Seek insights on development timelines and developers' perspective on technology options for offshore wind at the depths and distances from shore seen in California.

In May 2023, Guidehouse conducted interviews with cable and substation manufacturers to gain insight on developing technologies, particularly dynamic export cables and floating offshore substations. These manufacturers requested to remain anonymous.

Insights from interviews with developers and manufacturers are woven throughout the report in Chapters 3, 4, and 5.

3. Existing Transmission Technologies

This chapter focuses on existing offshore wind transmission technologies that are in use in offshore wind projects globally. These technologies include export cables, substations, and reactive power compensation for AC systems. Offshore wind turbines and platforms, inter-array cables, and existing onshore grid infrastructure are outside the scope of this report.

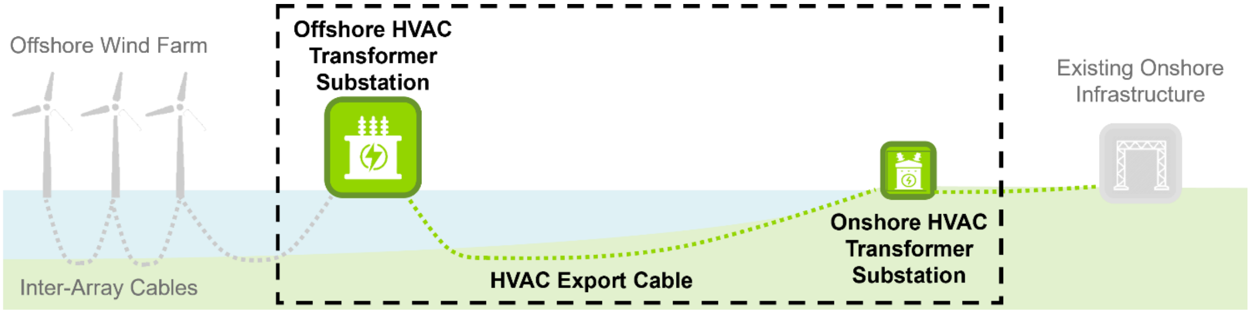
This chapter also includes a discussion of the decision-making considerations when choosing between HVDC or HVAC systems. In some cases, existing transmission technologies cannot adequately be applied to floating offshore wind farms for the level of export needed to support the projected offshore wind generation capacity in California. Emerging transmission technologies and concepts are discussed in Chapter 4 of the report.

Unless otherwise noted, cost figures in this section come from Appendix D of the NYSERDA Power Grid Study (2020)[3] and the New Jersey State Agreement Approach (2022),[4] and cost figures are assumed to be applicable for the year each study was published. The New Jersey State Agreement Approach used NREL's Offshore Renewables Balance-of-System and Installation Tool (ORBIT)[5] to model export cable and substation costs and compiled costs from other studies, including from a National Grid ESO Study. Guidehouse was unable to source the year the National Grid ESO study was published, so costs are assumed to be applicable for the year the New Jersey State Agreement Approach was published (2022).

3.1 HVAC

HVAC transmission technology is highly mature and is currently the most widely used transmission technology for offshore wind farms. Section 3.1 of this report focuses on offshore HVAC transformer substations, reactive power compensation, HVAC export cables, and interconnections to onshore HVAC substations. Figure 4 shows the technologies covered in this section. Reactive power compensation devices are typically integrated within the offshore and onshore substations but can be implemented at a midpoint between the two substations.

Figure 4. HVAC Transmission System for Offshore Wind



Source: Guidehouse

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[3] https://www.nyserda.ny.gov/-/media/Project/Nyserda/Files/Publications/NY-Power-Grid/Appendix-D.pdf

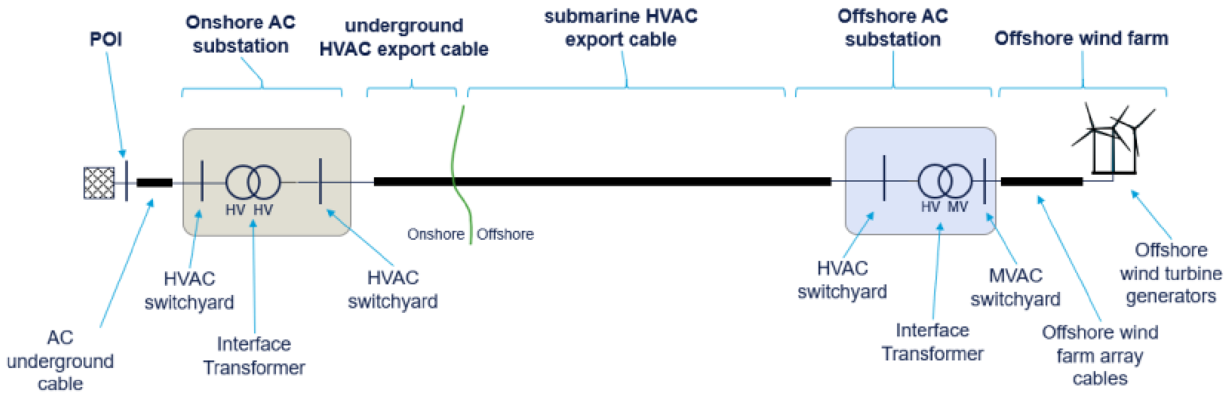
[4] https://www.brattle.com/wp-content/uploads/2022/10/New-Jersey-State-Agreement-Approach-for-Offshore-Wind-Transmission-Evaluation-Report.pdf

[5] https://www.nrel.gov/docs/fy20osti/77081.pdf

3.1.1 Overview of HVAC Technology

Figure 5 illustrates a typical HVAC transmission configuration for an offshore wind project. Individual wind turbines generate power and deliver electricity to the offshore HVAC substation through a series of array cables connected to the wind turbines. The power from the array cables is then aggregated and transformed to high voltage on the offshore substation (OSS). The resulting HVAC power is exported to shore via an export cable that is routed down from the substation platform to the seabed. The export cable terminates on shore at a landing position (landfall) from which it is routed to an onshore substation with sufficient capacity to accept the power from the offshore wind farm. Once at the station, the power can be transformed to serve local load requirements or be routed into the system without transformation to serve load elsewhere. The delivery of power presumes the onshore system has been planned adequately and designed with sufficient capacity to be able to accept the power exported from the offshore platform.

Figure 5. Typical Offshore HVAC Radial Link



Source: DNV

The voltage level of an HVAC power system varies based on several criteria. To transfer more power, higher voltage components are necessary, including export cables and substation equipment. Generally, a higher voltage level results in lower line losses, reducing long-term costs because the system will be more efficient in transferring power. Additionally, using a higher voltage allows more power to be transferred on one cable, reducing the number of cables needed. However, higher voltage transmission systems have higher capital expenditures due to more extensive substation equipment, such as transformers.

Reactive power compensation is required on longer distance HVAC power transmission systems to combat line losses and maintain a smooth voltage profile. Adjustable or switchable power system reactors or capacitors can be installed to maintain stable voltage profiles and ensure an efficient and stable power system. While higher voltage systems can transmit more power, they also require increased reactive power compensation.

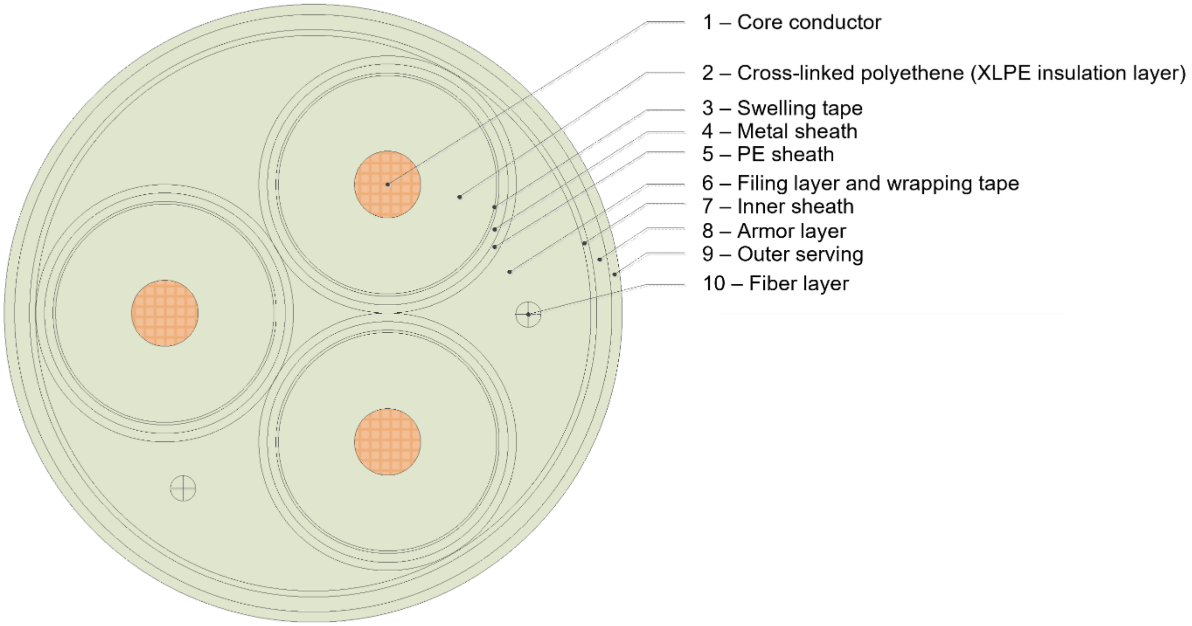
3.1.2 Export Cables

HVAC export cabling technology is the most common transmission technology for offshore wind purposes. Static subsea cables are a mature technology used in numerous commercial offshore wind projects to export energy onshore. While this export cabling technology represents the current status quo, floating wind farms will require dynamic cables. Further, increased transmission capacity necessitates higher voltage cables than are currently available. Existing HVAC export cables are discussed in this section, and emerging technologies are discussed in Section 4.2.

3.1.2.1 Current Status

HVAC subsea export cables are typically three phase cables, where each core is insulated individually, but all three cores share a common armor. The insulation for HVAC subsea export cables is commonly a form of extruded insulation, making use of cross-linked polyethylene (XLPE). Other insulation materials such as mass impregnated paper can be used as well. XLPE provides an attractive insulation technology foundation due to its low relative permittivity, low power loss, and high dielectric strength. Figure 6 illustrates the cross section of a three-core HVAC export cable insulated with XLPE.

Figure 6. Simplified Cross-Section of a Three-Core HVAC Submarine Cable



Source: Journal of Marine Science and Engineering

HVAC subsea export cables are commonly rated between 132 kilovolts (kV) and 245 kV with an export capacity between 300 and 500 MW. However, with improvements in insulation technology, these export cables now exist up to 420 kV and increased capacity is in development to support up to 1 GW of transmission capacity. Nexans, a cable manufacturer, recently opened a high voltage subsea cable plant in Charleston, South Carolina, supplying subsea cables up to 400 kV HVAC.[6]

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[6] https://www.nexans.com/en/newsroom/news/details/2021/11/2021-11-09-pr-nexans-charleston-world-class-facility-positioned-to-serve-rapidly-expanding-us-offshore-wind-market.html

Literature review found that HVAC export cables have a practical maximum length of approximately 80–100 km,[7,8,9] although in one interview, an offshore wind developer cited the use of HVAC export cables up to 125 km. Reactive power compensation can extend the technical maximum transmission length up to 160 km.[10] However, for transmission distances greater than 100 km and capacities greater than 1 GW, HVAC may not be cost effective compared to HVDC transmission. Even with reactive power compensation, there is a technical limit to feasible HVAC cable solutions. At a certain length, depending on multiple factors including subsea conditions, the entire apparent power rating of the cable is consumed by reactive power. These comparisons will be discussed in the following sections (Sections 3.2 and 0).

The major original equipment manufacturers (OEMs) of HVAC subsea export cables include Nexans, NKT, Prysmian, Hellenic, LS Cable & System, and JDR Cable Systems. These OEMs produce HVAC export cables with different maximum voltages, insulation materials, conductor sizes, and suggested transmission lengths.

HVAC export cables are considered very mature and the technology for subsea applications is well understood and commercially available. The market for these cables is well defined, there are standards and certifications in place, and the supply chain is well developed.

3.1.2.2 Costs

The cost of HVAC export cables depends on several factors, including transmission distance, water depth, voltage, and capacity. Table 2 outlines several cost estimates for static HVAC export cables. The NYSERDA study estimated operating expenditures to be about 2.5% of the capital expenditures for subsea export cabling technology. The capital expenditures include procurement cost, installation cost, and project overhead.

Table 2. Static HVAC Export Cable Cost Estimates

Source	Year*	MW Rating	$ Million/km	$/MW	$/MW/km
NYSERDA Power Grid Study	2020	300 MW	$1.55	$8,333	$5,167
NYSERDA Power Grid Study	2020	400 MW	$1.67	$6,750	$4,175
NYSERDA Power Grid Study	2020	500 MW	$1.8	$5,800	$3,600
NREL ORBIT	2022	315 MW	$1.36	$7,109	$3,746
National Grid Study UK	2022	Unspecified	$1.18	-	-

** Costs are assumed to be applicable for the year in which each study was published.*

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[7] https://www.mdpi.com/1996-1073/12/18/3435

[8] https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9420336

[9] https://www.maine.gov/energy/sites/maine.gov.energy/files/inline-files/Maine%20OSW%20DNV%20Offshore%20Wind%20Transmission%20Technical%20Review%20Initial%20Report.pdf

[10] https://www.nkt.com/news-press-releases/nkt-finalizes-the-project-with-the-worlds-longest-hvac-submarine-cable

3.1.3 Substations

The purpose of AC substations is to transform and stabilize voltage and provide grid protection. In an offshore wind system, the offshore HVAC substation collects power from offshore wind turbine generators and transforms the voltage for export to shore. The onshore HVAC substation receives the exported power and transforms the voltage for onshore transmission or distribution to load centers. Both offshore and onshore HVAC substations also house reactive power compensation devices, when necessary.

HVAC substations are designed to provide reliable operation through an arrangement of breakers; operation can continue if a circuit breaker fails to operate, a transmission line is disconnected, or generation becomes unavailable. Standard designs and applications to reduce the severity of unexpected events include automatic protection schemes, balancing generation infeeds with load outfeeds within the breaker configurations, and SCADA (supervisory control and data acquisition) remedial action schemes.

This section addresses offshore platforms and electrical equipment for HVAC substations.

3.1.3.1 Current Status

3.1.3.1.1 Platforms

Currently, deployments of offshore substations have been focused on fixed bottom technologies, although floating offshore substations (which are relatively nascent and are discussed in Section 4.1.1) will be necessary given the water depths off the California coast. Most existing offshore substations operate using an HVAC system.

Fixed bottom foundation types used for offshore substations are typically monopile, jacket, or gravity-based structures and are only functional in water depths less than 60–100 m. The topside, which houses the electrical components of the substation (transformer, switchgear, etc.), is located on top of the substructure. This topside will vary in size and weight and is typically smaller for HVAC technology compared to HVDC (Section 0) because converter technology is not needed. The range of dimensions for a typical HVAC topside is 40–55 m long, 31–35 m wide, and 15–50 m high, and the weight ranges from 2,000–4,000 tons.[11,12,13,14,15] Figure 7 illustrates a typical offshore substation structure.

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[11] https://www.4coffshore.com/news/hollandse-kust-(noord)-topside-makes-a-stopover-in-ijmuiden-port-nid26429.html

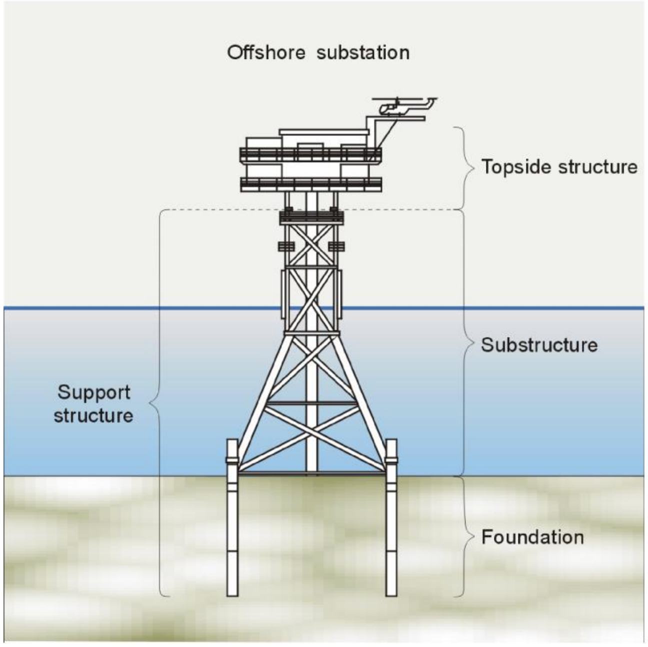
[12] https://www.industryandenergy.eu/renewables/seagreen-offshore-substation-topside-complete/

[13] https://www.nordseeone.com/engineering-construction/offshore-substation.html

[14] https://www.energyglobal.com/wind/08072022/offshore-substation-installed-at-saint-brieuc-wind-farm/

[15] https://renews.biz/80006/deme-installs-hkz-substation-jacket/

Figure 7. Typical Offshore Substation Structure



Source: Electrical Power Engineering Institute

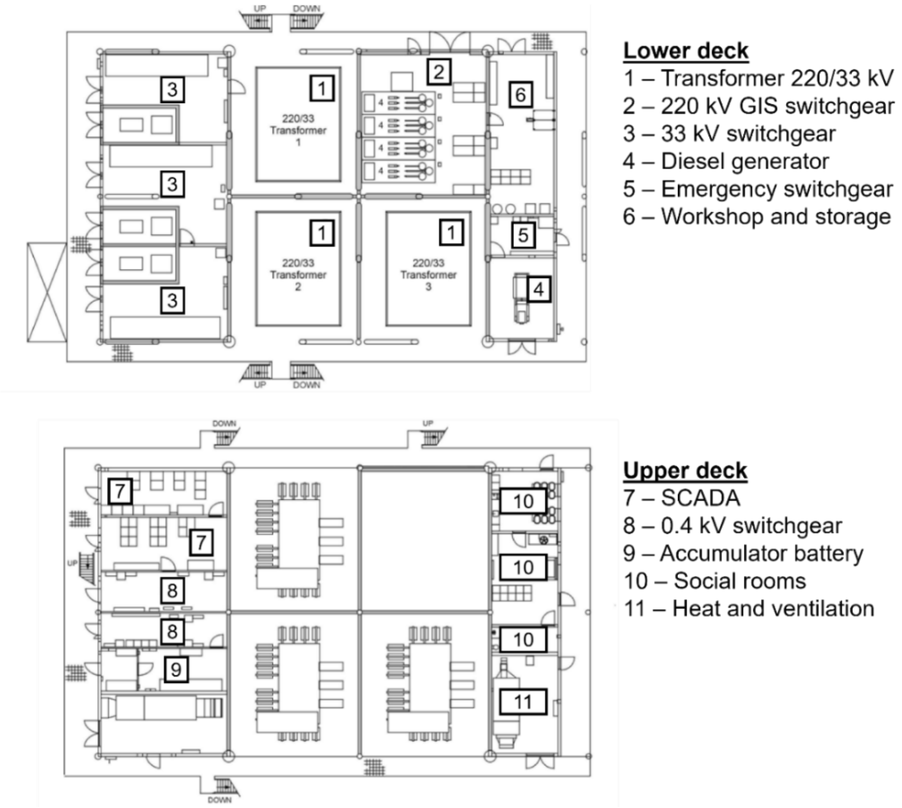
3.1.3.1.2 Electrical Systems

HVAC electrical technology is highly mature and HVAC transformers have been used for offshore wind export for more than 20 years. The offshore HVAC substation electrical systems typically include the following: the array cable systems that connect the turbines to the platform, low voltage level systems that provide operability on the platform itself, and high voltage systems (transformers, switchgear) that support the delivery of wind power to the export cable.

Offshore HVAC substations typically use gas-insulated switchgear (GIS) to minimize topside weight and space. GIS also provides protection and supports longevity of the equipment in the harsh offshore saltwater environment. Offshore substations also include auxiliary components such as cooling systems, fire detection and protection, and lower voltage switchgear, as well as safety, navigational, and other signaling and rescue systems. Components of an offshore HVAC substation are shown in Figure 8.

The onshore HVAC substation receives power via the offshore export cable. The onshore station is meant to flow power seamlessly into the larger power system at the same voltage, or transform the voltage to serve the local distribution system. Onshore HVAC infrastructure encompasses transformers, switchgear (air or gas insulated), station and line protection, reactive compensation devices, harmonic filters, and auxiliary components similar to offshore substations. Reactive compensation components and filters will be addressed in detail in Section 3.1.4.

Figure 8. Example of Offshore HVAC Substation Electrical Layout



Source: Bulletin of the Polish Academy of Sciences

3.1.3.2 Costs

The costs for a fixed HVAC offshore substation depend on a variety of factors: water depth, distance from shore, seabed conditions, transmission capacity, voltage level, supply chain availability, and more. Floating substations do not yet exist (addressed in Section 4.1.1), thus costs in this section apply to fixed HVAC offshore substations. Table 3 outlines HVAC offshore substation cost estimates. These figures include both platform and electrical equipment costs. In discussions with developers, several indicated that these costs may be low compared to what they had heard from suppliers, but they did not provide specific cost figures.

Table 3. HVAC Fixed Offshore Substation Cost Estimates

Source	Year*	MW Rating	$ Million	$/MW
NYSERDA Power Grid Study	2020	800	120	150,000
NREL ORBIT	2022	800	188.1	235,065
National Grid Study UK	2022	1000	143.8	143,753

** Costs are assumed to be applicable for the year in which each study was published.*

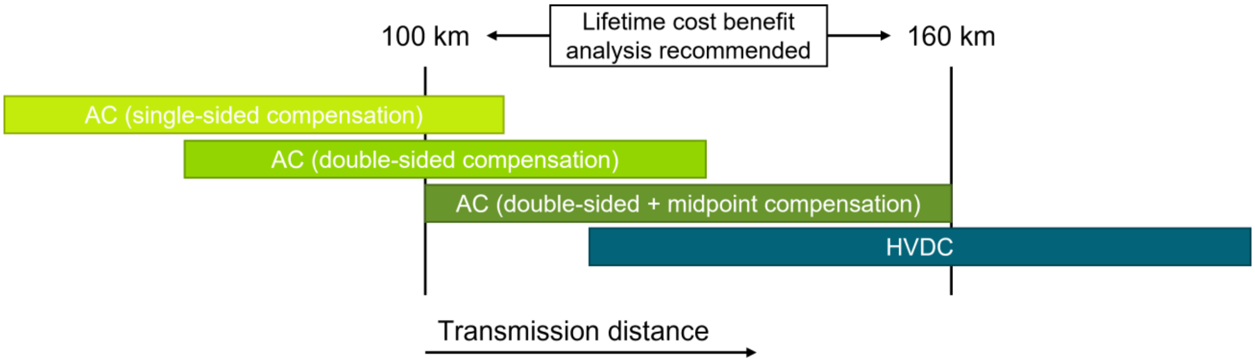
Onshore HVAC substations are an established technology, and many studies did not report costs. The costs for an onshore HVAC substation are expected to be three to four times less than that of offshore HVAC substations.[16]

3.1.4 Reactive Power Compensation

Power transmission over longer distances results in higher cable losses and increased reactive power compensation requirements. By adding appropriate levels of reactive compensation at selected locations, charging current can be reduced, voltage levels will be supported within established thresholds, and overall system losses can be reduced. Compared to onshore overhead lines, subsea cables require reactive power compensation at shorter distances. The active power transmission capability for HVAC systems is limited for lengths greater than 80–100 km in subsea transmission.

Studies can identify the type (reactive or capacitive) of compensation required and where on the line it can be applied to achieve an optimal voltage profile. Increasing amounts of reactive power compensation can extend the transmission distance further: reactive power devices can be placed on one side of the transmission line, on both sides, or on both sides with additional midpoint compensation. The effect of increasing reactive power compensation on transmission distance is shown in Figure 9 and compared to the range at which HVDC transmission is economical.

Figure 9. Practical Transmission Distance for HVAC with Varying Levels of Reactive Power Compensation and HVDC



Source: Adapted from DNV

Reactive power compensation devices may include shunt reactors (fixed or variable), thyristor-based static VAR compensators (SVCs), or static synchronous compensators (STATCOMs).

Shunt reactors are simple on/off devices that provide a means to manage voltage profiles for the transmission system. Fixed shunt reactors are a traditional technology for which the amount of compensation can only be adjusted in discrete steps. Variable shunt reactors provide more controllability by continuously adjusting the compensation according to the load variation via a tap changer, allowing grid operators to optimize reactive power compensation and voltage control.

SVCs use thyristors to produce either reactive power absorption or generation to regulate the voltage of the AC system. STATCOMs are similar to SVCs in that they either absorb or produce

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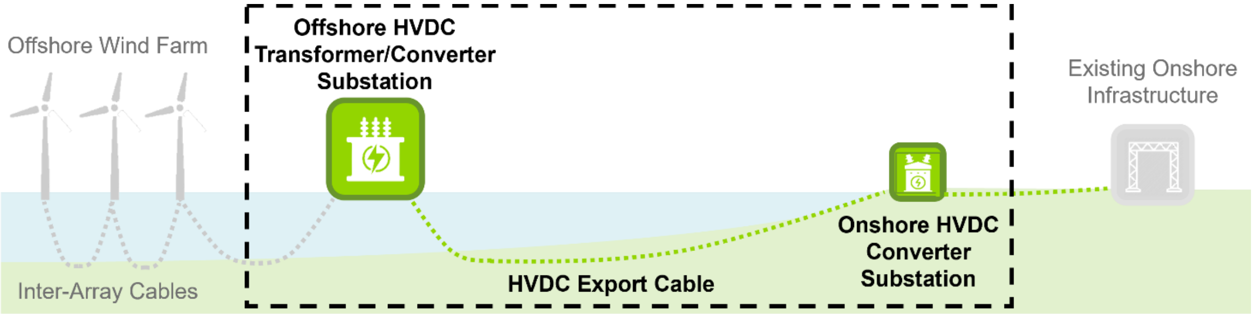
[16] https://guidetoanoffshorewindfarm.com/wind-farm-costs

reactive power, but they use insulated-gate bipolar transducer devices for switching and are much faster in response than SVCs. STATCOMs can also provide damping of low-frequency power oscillations and active harmonic filtering to improve power quality, which is also necessary for HVAC transmission over long distances. Harmonics management can also be achieved using a tuned combination of reactors and capacitors to provide frequency-dependent absorption or damping of harmonic frequencies.

3.2 HVDC

HVDC transmission technology is considered less mature than HVAC systems, especially for offshore applications. This section focuses on HVDC export cables, offshore HVDC converter and transformer substations, and onshore HVDC converter substations. Figure 10 highlights the portion of an HVDC transmission system covered in this report.

Figure 10. HVDC Transmission System for Offshore Wind

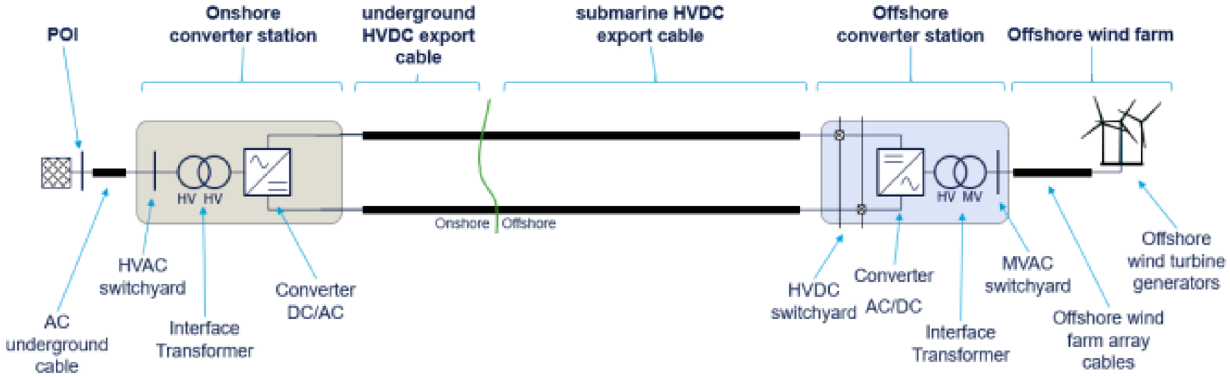


Source: Guidehouse

3.2.1 Overview of HVDC Technology

Until recently, most applications of HVDC have been point-to-point, with power flowing in one direction from a generator source (for example, hydropower) to a converter station where the power is converted to HVAC and potentially stepped down to distribution levels. Unlike HVAC power that can be stepped to other voltage levels using a transformer, HVDC requires a converter station to convert the power to AC before it is used or transformed. A typical HVDC offshore connection is illustrated in Figure 11.

Figure 11. Typical Offshore HVDC Radial Link



Source: DNV

The vast majority of existing offshore wind transmission is HVAC. However, HVDC systems are beginning to play a larger role in recent offshore wind deployments. HVDC is better suited to moving electricity over long distances compared to HVAC. Without the charging current limitations inherent with AC systems, HVDC can transmit more power over far longer distances without the need for reactive compensation. The voltage profiles do not degrade due to reactive losses, and line losses are much lower than with HVAC.

3.2.1.1 HVDC Converter Technologies

There are two main converter technologies used for HVDC transmission: line commutated converters (LCCs) and voltage source converters (VSCs). LCCs are the more conventional, established technology used to convert power from AC to DC or vice versa. While VSCs are a newer technology with less operating experience, they are better suited for the interconnection of remote generation facilities, such as offshore wind farms.

- **LCCs** allow for higher power conversion capacities with lower losses compared to VSC. However, LCCs require a connection to a relatively strong AC network to provide the AC voltage zero crossing for natural commutation (switching) of the converter. Strong AC networks are rare in regions suited for offshore wind, as offshore wind farms are often remote coastal regions. LCC-based HVDC systems are also not capable of reversing the direction of power flow without reversing the voltage polarity, so they cannot energize offshore wind turbine generators on their own.

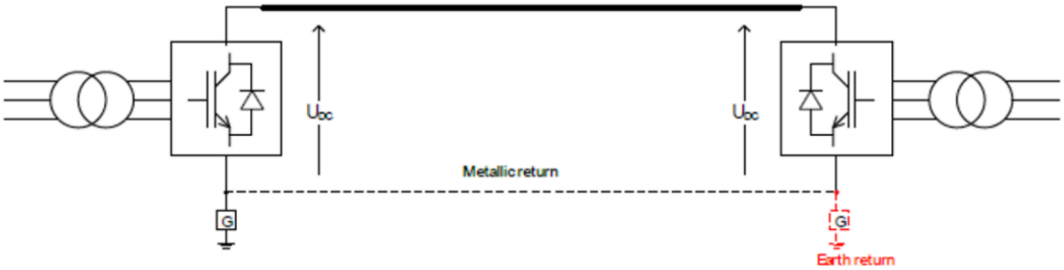
- **VSCs** use high-power insulated-gate bipolar transistors, which can be turned on and off using the gate pulse, so they are fully controllable, self-commutated, and able to generate AC voltages without needing to rely on a strong AC network. VSCs are able to reverse the direction of power flow by changing the direction of current flow, without needing to reverse the voltage polarity. Thus, VSC-based HVDC is capable of energizing offshore wind turbines. VSCs generally do not require filters, as they can switch as many times as needed in a single cycle to reproduce a smooth HVAC voltage with minimal harmonics. Thus, VSC-based HVDC systems are more technically feasible for offshore wind applications and are also more easily integrated into multi-terminal DC systems than LCC-based HVDC.

3.2.1.2 Common Configurations for VSC HVDC Systems

There are three common configurations for VSC HVDC systems:

- **Asymmetric monopole** (Figure 12): a single HVDC cable operating with an earthed return or an optional metallic return path. An earthed return path is typically not used, as it can cause environmental harm. Full transmission is lost during a pole-to-earth fault, which also creates a large fault current that can impact the connected HVAC grids.

Figure 12. VSC Asymmetric Monopole Configuration



Source: DNV

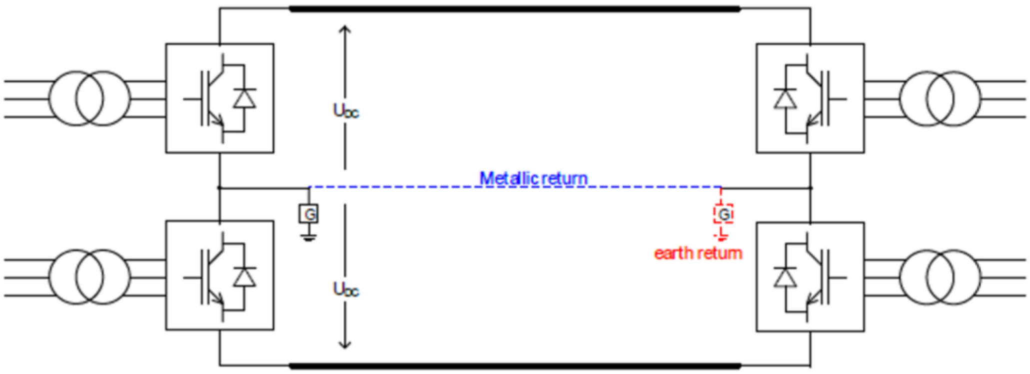
- **Symmetric monopole** (Figure 13): two HVDC cables connecting two converters with the same magnitude but opposite polarity. This configuration is most commonly used in offshore wind export applications. Full transmission is lost during a pole-to-earth fault, but this does not create a large fault current because there is still a healthy pole, so impact to connected HVAC grids is limited. However, the healthy pole does experience an overvoltage, which can stress the components.

Figure 13. VSC Symmetrical Monopole Configuration

Source: DNV

- **Bipole** (Figure 14): two converters connected in series at each terminal, with one between the positive pole and neutral midpoint and the other between the neutral midpoint and negative pole. The midpoints can be connected with a low voltage metallic return conductor, which provides redundancy for either a converter or cable fault by allowing operation as an asymmetric monopole. If no metallic return is used, there is still some redundancy as the system can transmit half of the power as a monopole. In bipole configurations, a pole-to-earth fault creates a large fault current that can impact connected HVAC grids.

Figure 14. VSC Bipole Configuration



Source: DNV

Symmetric monopole and bipole configurations require the use of two HVDC cables, while an asymmetric monopole configuration only requires one HVDC cable with a metallic return.

3.2.1.3 VSC HVDC Converter Technology

Offshore VSC HVDC systems are typically based on modular multi-level converters (MMCs), the latest and most advanced technology for HVDC transmission. MMCs are capable of reversing the direction of power flow, are modular and scalable, and are capable of storing energy internally in the converter, reducing the need for high frequency switching of semiconductor devices.

MMCs can be in either half-bridge or full-bridge configurations, which are compared in Table 4. Half-bridge MMCs are more commonly used for point-to-point or radial connections, as they are more cost efficient and have lower semiconductor losses compared to full-bridge converters. Both half-bridge and full-bridge MMCs can survive AC network faults and can operate continuously under unbalanced conditions. However, half-bridge converters cannot block DC fault currents and require the use of DC circuit breakers (a developing technology, discussed in Section 4.3.1.1) if they are used in a networked system. Full-bridge converters have HVDC fault current blocking capabilities, so they can be used without a DC circuit breaker. However, during the fault clearance period with full-bridge converters, power exchange between converters connected to the affected DC grid would drop to zero. In recent years, mixed submodule MMCs have been presented as an alternative to purely half-bridge or full-bridge configurations, with a combination of half-bridge and full-bridge submodules. The minimum number of full-bridge submodules to provide DC fault blocking capabilities are included, without exposing the system to excessive stresses and losses.

Table 4. Comparison of Half-bridge and Full-bridge MMC for HVDC Transmission

Half-bridge MMC	Full-bridge MMC
• Lower semiconductor losses • Can survive AC network faults (AC fault ride-through) • Cannot block DC fault currents, so requires use of DC circuit breakers in networked applications	• Higher semiconductor losses • Can survive AC network faults (AC fault ride-through) • Can block DC fault currents, but power exchange between affected converters drops to zero during fault clearance period

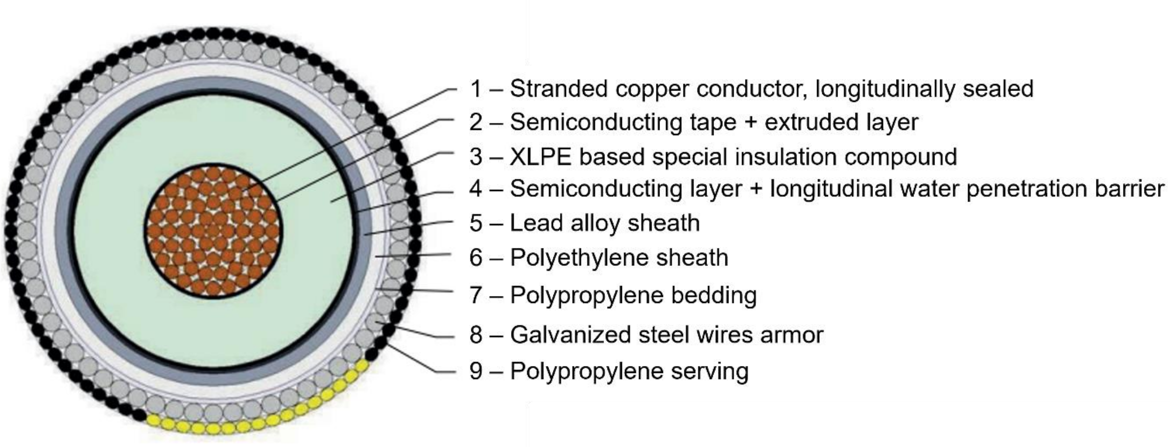
3.2.2 Export Cables

HVDC export cables are becoming a more attractive transmission option as offshore wind farms increase in distance from shore and transmission capacity required. These export cables have only been used in the context of fixed offshore wind farms. Floating offshore wind farms would require dynamic cables, which do not yet exist for HVDC.

3.2.2.1 Current Status

HVDC export cables are a more recent transmission technology in comparison to HVAC. There are several different configurations: asymmetric monopole, symmetric monopole, or bipole systems. These cables are typically single core with extruded XLPE insulation. Mass impregnated paper or paper-polypropylene laminated are also suitable methods of cable insulation for export but are more suspectable to leakage, so XLPE is generally used in offshore applications. Figure 15 illustrates the cross section of an HVDC subsea export cable with extruded XLPE insulation.

Figure 15. HVDC Extruded Cable Cross Section



Source: europacable

Some common configurations for HVDC export cable technology include a 320 kV symmetric monopole with a maximum transmission of 1,300 MW and a 525 kV bipole with a maximum transmission of 2,000 MW.[17,18] These 525 kV cables have the potential to be enable up to 2,600 MW in transmission capacity[19]. These export cables are theoretically unlimited in transmission length, making them an attractive solution for offshore wind farms located further away from shore, although the longest subsea HVDC cable is around 720 km in length.[20] The major OEMs in the HVDC export cable market include Nexans, NKT, Prysmian, Hellenic, LS Cable & System, and ZTT Cable.

HVDC export cables can transfer energy over longer distances in comparison to HVAC technology. Additionally, these cables have a higher active power transfer capacity and stronger voltage regulation. Research indicated that HVDC is the more economic choice for longer transmission distances (past 80–100 km) due to lower cable costs and lower active power losses. However, HVDC export cables require expensive converter technology and larger offshore substations to house electrical equipment. Additionally, technological maturity and supply chain for HVDC export cables is not as developed as HVAC export cables.

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[17] https://www.nyserda.ny.gov/-/media/Project/Nyserda/Files/Publications/NY-Power-Grid/Appendix-D.pdf

[18] https://www.tennet.eu/news/tennet-has-opened-2gw-program-tender-525-kv-dc-offshore-cable-manufacturing-and-installation

[19] https://www.nkt.com/products-solutions/high-voltage-cable-solutions/innovation/525-kv-extruded-hvdc-cable-systems

[20] https://www.eenewseurope.com/en/worlds-longest-subsea-hvdc-link-opens/

3.2.2.2 Costs

The costs for HVDC export cables depend on the same factors as HVAC export cables, although reactive power compensation considerations are not required. Estimates for HVDC export cable costs are shown in Table 5. Based on a 2023 contract with NKT, capital expenditures for a higher rated 525 kV XLPE fixed HVDC subsea cable is estimated to be $1.24 M/km.[21] It is important to note that this contract is for a 1,700 km scope of work covering both on and offshore power, is a recent data point, and may be a fairly competitive bid for NKT. Capital expenditures for HVDC export cables include design, production, and installation costs. As in HVAC cables, the NYSERDA study estimated operating expenditures to be about 2.5% of the capital expenditures for subsea export cabling technology.

Table 5. Static HVDC Export Cable Cost Estimates

Source	Year*	MW Rating	$ Million/km	$/MW	$/MW/km
NYSERDA Power Grid Study	2020	1,000	$1.80	$2,900	$1,800
NYSERDA Power Grid Study	2020	1,300	$1.92	$2,385	$1,476
NREL ORBIT	2022	800	$3.29	$6,600	$4,900
National Grid Study UK	2022	1,000	$2.36	$3,787	$2,360

** Costs are assumed to be applicable for the year in which each study was published.*

3.2.3 Substations

HVDC substations transform the voltage of generated or exported power, convert the power from AC to DC or vice versa, and house components for grid protection such as switchgear and in some cases DC circuit breakers. HVDC substations are also known as converter stations, as one of their main functions is to convert power from AC to DC using a rectifier, or DC to AC using an inverter. The offshore substation collects AC power from wind turbines, steps up the voltage to export levels, and transforms the voltage to DC for export to shore. The onshore substation receives the exported DC power, converts the voltage to AC, and transforms the AC voltage to integrate with the onshore grid.

3.2.3.1 Current Status

3.2.3.1.1 Platforms

Fixed platform technology for HVDC substations is very similar to that of HVAC substations but will need to be larger to accommodate a larger and heavier topside as compared to HVAC. For example, BorWin2, an HVDC offshore substation installed in 2014 with a capacity of 800 MW, has a topside with dimensions of 72.5 m x 51 m x 25 m and a total weight of over 13,000 tons.[22]

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[21] https://www.nkt.com/news-press-releases/nkt-awarded-record-orders-for-worlds-first-525-kv-xlpe-hvdc-submarine-cable-projects-for-offshore-wind

[22] https://e-cigre.org/publication/B4-306_2012-projects-borwin2-and-helwin1---large-scale-multilevel-voltage-sourced-converter-technology-for-bundling-of-offshore-windpower

The larger, heavier topside makes the jacket foundation more attractive for fixed offshore HVDC systems. Additionally, floating offshore HVDC substations are less resilient than HVAC substations because the semiconductor components used for switching in VSC HVDC are highly sensitive to vibrations and movements. Floating offshore substations are discussed in more depth in Section 4.1.1.

Some examples of recent HVDC offshore substations include BorWin3, Dogger Bank and Ijmuiden Ver, which are summarized in Table 6.

Table 6. HVDC Offshore Substation Examples

Name	Voltage Rating	Capacity	Notable Features
BorWin3[23]	320 kV	900 MW	Uses HVDC Light technology Topside weighs 20,000 tons
Dogger Bank[24,25,26]	320 kV	1200 MW	First unmanned HVDC OSS, cutting topside weight by 70% (per MW) compared to previous platforms installed. Topside weighs 7,500 tons
Ijmuiden Ver[27]	525 kV	2000 MW	Industry's first 525 kV OSS Construction of OSS set to begin 2024–2025

3.2.3.1.2 Electrical Systems

HVDC converter stations consist of a converter (AC to DC rectifier offshore, or DC to AC inverter onshore), DC switchgear, and other supporting equipment. Onshore DC switchgear is traditionally air insulated, but air-insulated switchgear requires a relatively large volumetric footprint which is limited on offshore substations. Due to this footprint limitation, offshore HVDC substations are typically designed using gas-insulated switchgear (GIS) instead of air-insulated switchgear.

While GIS is a mature technology for AC applications, DC GIS is still relatively nascent, with recent demonstrations in the Progress on Meshed HVDC Offshore Transmission Networks (PROMOTioN) project. PROMOTioN conducted a long-term test on 320 kV HVDC GIS and

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[23] https://www.petrofac.com/media/news/the-journey-to-offshore-wind/

[24] https://www.oedigital.com/news/503701-dogger-bank-a-sets-sail-giant-offshore-wind-farm-takes-another-step-forward/

[25] https://www.offshorewind.biz/2022/06/30/first-dogger-bank-offshore-substation-topside-arrives-in-norway/

[26] https://doggerbank.com/construction/worlds-first-unmanned-hvdc-offshore-platform-installed-at-worlds-largest-offshore-wind-farm/

[27] https://www.offshorewind.biz/2021/12/06/tennet-issues-cable-link-tender-for-ijmuiden-ver-2-gw-offshore-wind-connections/

produced recommendations on specifications and test procedures. Siemens Energy offers DC GIS with voltages up to 550 kV and currents up to 5 kA.[28] Developers mentioned in interviews that there are sensitivities around GIS because the gas used, sulfur hexafluoride (SF_6), is a potent greenhouse gas. There are some alternatives for SF_6, such as General Electric's g3 GIS[29] or Siemens' 8VN1 Blue GIS.[30] However, GIS using SF_6 alternatives have not been demonstrated for offshore wind.

Onshore HVDC technology is more mature and onshore substations do not face the same space and weight limitations as offshore substations. Similar to offshore HVDC substations, onshore substations house DC switchgear (can be air-insulated), and in some cases DC circuit breakers.

Developers foresee a multitude of obstacles related to offshore HVDC substations and components. These include a limited fleet of installation vessels for heavy HVDC topsides, a limited number of HVDC cable suppliers, and the lack of commercially available DC circuit breakers (which are necessary for meshed or networked HVDC grids, addressed in Section 4.3). One developer cited a 5 to 6 year lead time on DC converter stations for East Coast projects, which is a major factor in defining their commercial operation date. Developers are not confident there is enough market demand to drive commercial availability for HVDC floating technology by the time they would be needed for the first round of California offshore wind projects.

3.2.3.2 Costs

The costs for a fixed HVDC offshore substation depend on similar factors as for a fixed HVAC offshore substation: water depth, distance from shore, transmission capacity, supply chain availability, seabed conditions, and more. Table 7 outlines HVDC offshore and onshore substation cost estimates. These costs include both platform (for offshore) and electrical equipment costs. In discussions with developers, several indicated that these costs may be low compared to what they had heard from suppliers, but they did not provide specific cost figures. One developer stated that they expected onshore substation costs to be higher than offshore substations in the case of a networked offshore DC grid due to the cost of the DC chopper.[31]

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[28] https://www.siemens-energy.com/global/en/offerings/power-transmission/portfolio/gas-insulated-switchgear/dc-gis.html

[29] https://www.gegridsolutions.com/hvmv_equipment/catalog/g3/

[30] https://www.siemens-energy.com/global/en/offerings/references/blue-gas-insulated-switchgear.html

[31] A DC chopper is a device housed in the onshore substation that protects the offshore DC grid from overvoltage during an onshore fault.

Table 7. HVDC Offshore and Onshore Substation Cost Estimates

Source	**Year***	**MW Rating**	**Offshore Substation**		**Onshore Substation**	
			$ Million	**$/MW**	**$ Million**	**$/MW**
NYSERDA Power Grid Study	2020	1,200	$616.3	$513,583	$260.0	$200,000
NREL ORBIT	2022	800	$296.3	$370,368	$192.2	$240,227
National Grid Study UK	2022	1,000	$361.0	$361,015	$242.1	$242,129

** Costs are assumed to be applicable for the year in which each study was published.*

3.3 HVAC vs. HVDC Comparison

Deciding between HVAC and HVDC systems can be a complex and nuanced decision. This section discusses export cable costs considerations, as well as other factors that play a role in this decision for developers.

Literature review found that there is a breakeven distance from shore where HVDC technology becomes more economical than HVAC. This breakeven point occurs due to the limitations of active power transfer as a function of cable length for HVAC export cables and the cost of reactive power compensation. Reactive power equipment required to extend the active power transmission for an HVAC system can incur a significant cost. As previously stated, research shows that this breakeven point lies somewhere between 80 km and 100 km from site to cable landfall. Developers indicated that the breakeven point between HVAC and HVDC export cable systems is project- and site-specific, and that in some cases HVAC was cost effective up to 125 km from site to landfall.

Figure 16 shows the relationship between distance from site to cable landfall and total export system costs (including design, installation, and the technology itself) in millions of dollars, as well as the distance to shore for the five lessee areas within the Humboldt and Morro Bay wind energy areas. These costs come from an NREL report for BOEM, which was published in 2016.[32] While costs may be different in 2023, the graph illustrates the relationship between cost and distance to shore for HVAC and HVDC systems and the breakeven point beyond which HVDC is more economical.

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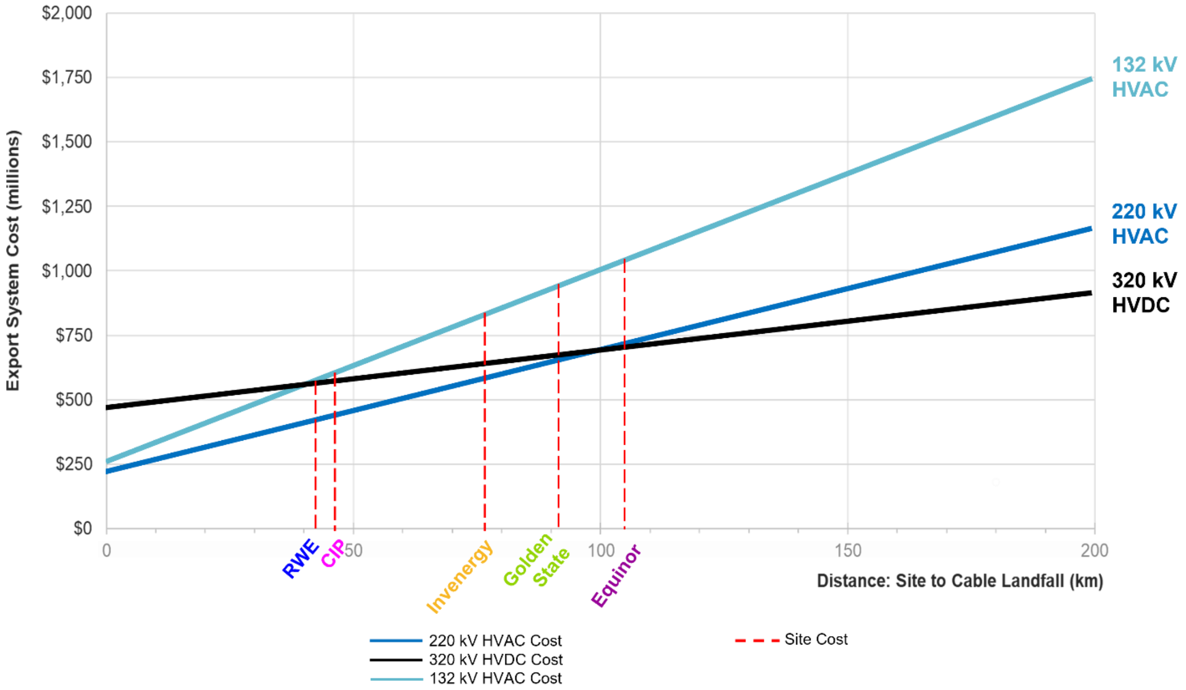
[32] https://www.boem.gov/sites/default/files/environmental-stewardship/Environmental-Studies/Pacific-Region/Studies/BOEM-2016-074.pdf

Figure 16. Comparison of HVAC vs. HVDC Cabling Technology Cost



Source: Adapted from NREL (2016)

This graph illustrates that lessees can consider using HVDC technology over HVAC depending on the distance from their site to the onshore point of interconnection. While distance to landfall is a critical input when deciding between the two technologies, there are other trade-offs that impact the decision. Cost of platform infrastructure and reactive power compensation devices, electrical losses, transmission capacity, space requirements, technological maturity, and supply chain constraints all play a role in evaluating HVAC vs. HVDC export technology for a specific project. Some other considerations may include the available cable corridor space and onshore substation siting constraints for integration with the onshore AC grid.

When asked in interviews, developers were generally open to both HVAC and HVDC solutions for the transmission of power to shore. However, many recognized that HVAC technologies are much more mature than DC and emphasized the maturity of technology as a major driver for their decision. Dynamic HVDC export cables do not yet exist, and static HVDC cables are already difficult to procure due to a limited number of suppliers. One developer even stated HVDC suppliers were “booked out for the next decade.” HVAC cables and equipment are more easily obtained than HVDC, an important consideration when choosing between technologies.

4. Emerging Transmission Technologies and Concepts

Up until this point, offshore wind transmission technology has been applied to fixed bottom offshore wind generation systems for which fixed offshore substation platforms and static export cables have been sufficient. The shift to floating offshore wind will require use of dynamic export cables and alternatives to fixed offshore substation platforms, which are still developing technologies. As offshore wind generation capacity expands globally, higher capacity export cables will be necessary to connect larger wind farms onshore. Existing offshore wind connections have typically been point-to-point, where individual wind farms are connected directly to shore. Grid operators have begun to consider and implement meshed or networked grids, where offshore wind transmission is interconnected.

This section focuses on the most recent technological developments and concepts in relation to floating and subsea substations, dynamic export cables, higher voltage and capacity export cables, and meshed grid systems. The information presented in this section is based on publicly available information, so cutting-edge or proprietary technology may not be captured.

4.1 Substations

In depths past 60 m, fixed platforms are no longer economically feasible due to high material and installation costs. There are deep-water fixed platforms that can potentially be competitive at 100 m of depth, but for depths of 700–1,200 m in the California lease areas, fixed bottom offshore substations are no longer economically or technically feasible[33]. Developers will need to investigate floating offshore substations or subsea substations as potential options for transmitting large amounts of power onshore. Floating and subsea substations are developing technologies and cost data is currently not publicly available.

4.1.1 Floating Offshore Substations

Floating offshore substations will be a critical piece to deep-water offshore wind transmission in depths greater than 60–100 m. The topside of floating offshore substations resembles that of fixed offshore substations, but the platform is floating. Rather than a monopile, jacket, or gravity-based structure, floating offshore substations use designs similar to floating offshore wind turbine platforms or oil and gas substations, illustrated in Figure 17: semi-submersible, spar, tension leg platform, or barge concepts.

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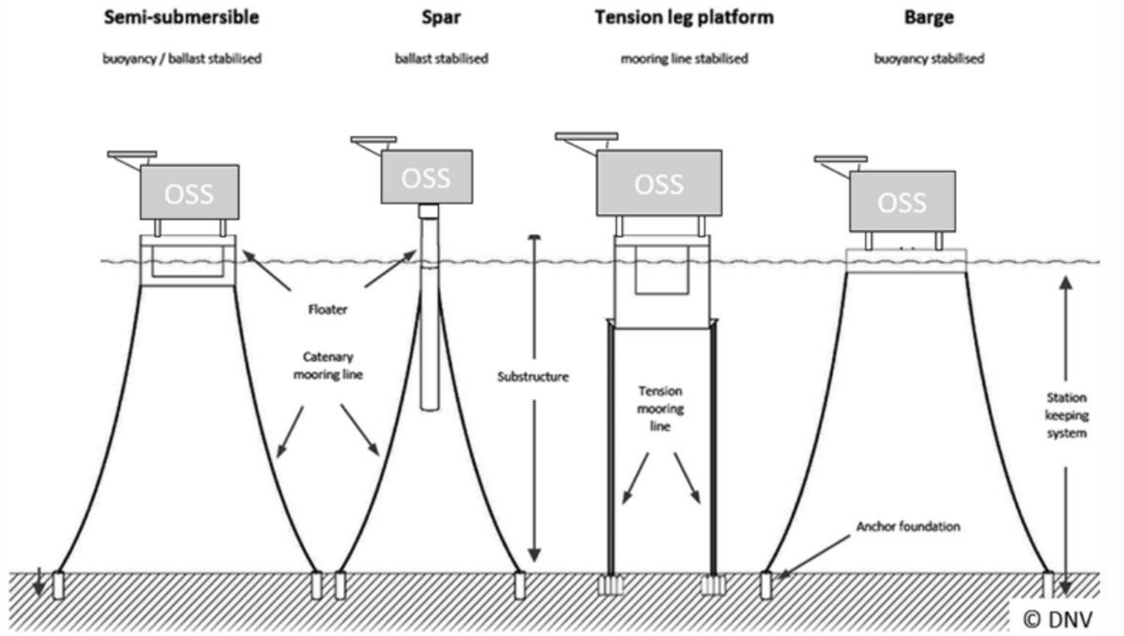
[33] https://www.maine.gov/energy/sites/maine.gov.energy/files/inline-files/Maine%20OSW%20DNV%20Offshore%20Wind%20Transmission%20Technical%20Review%20Initial%20Report.pdf

Figure 17. Floating Substation Platform Concepts



Source: DNV

While these are similar to the floating platforms used for wind turbines, they differ in the fact that the topside would be significantly heavier with a different weight distribution, requiring different platform dimensions. These substation platforms may also build upon floating platform technologies already used in the oil and gas industry. In interviews with developers, some stated they were not concerned about the technological barriers to floating substations and expressed confidence that this technology gap would be overcome by the time they are needed for their projects. They specifically mentioned that floating platforms are a proven technology in the oil and gas industry and the topside can be taken from a fixed offshore substation and combined with a floating platform.

These substations would be connected to both array and export of cables. The export cables attached to the floating offshore substation would need to be dynamic in order to withstand the movement of the platform while simultaneously connecting to the static sea floor. This dynamic cable requirement is a significant technical gap and is further discussed in Section 4.2.1.

Offshore HVDC substations will have a larger topside than offshore HVAC substations (footprint of approximately 66–80 m x 70–80 m)[34], with sensitive electrical equipment. These HVDC topsides will also be significantly heavier than HVAC, due to additional electrical equipment like switchgear and converters. The sensitivity of the electrical equipment housed within the topside will require HVDC substation platforms to adequately protect against accelerations and vibrations from the ocean. In interviews, developers cited concerns that HVDC technology may not be well suited to a floating offshore environment due to the sensitivities of the components in HVDC converter stations. The topsides for HVDC systems will be harder to install than HVAC, due to their size and weight. Semi-submersible platforms offer more stability against ocean movements than barge concepts and are therefore more suitable for hosting HVDC topsides.

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[34] https://www.oedigital.com/news/493140-floating-offshore-wind-attention-turns-subsea-for-power-transport

HVAC topsides are smaller, lighter, and less sensitive in comparison to HVDC, so they are able to use less robust floating platforms such as spar and tension leg platforms. All existing designs and concepts for floating offshore substations are based off AC technologies, although one offshore substation OEM said they estimate that the market will see DC floating offshore substation concepts in one to three years. In an interview, an offshore substation platform OEM stated they are anticipating a need for 21 floating offshore substations globally by 2030. However, the global market for fixed bottom substations is large enough some players may not be motivated to invest in the floating market.

There is only one example of a floating offshore HVAC substation, which was a component of the Fukushima FORWARD project and used an advanced spar platform.[35] With a capacity of 16 MW and an export voltage level of 66 kV, this offshore substation is not comparable to a commercial scale project and was decommissioned in 2021. While the Fukushima offshore substation has been the only floating offshore substation demonstrated, there are numerous designs and initiatives in progress to create scalable floating offshore wind substation platform solutions for both HVAC and HVDC systems.

4.1.1.1 Floating Offshore Substation Designs

While floating offshore substations do not exist commercially, OEMs and other organizations are working on scalable designs to address this technology gap.

Figure 18 provides illustrations for various floating offshore substation designs:

- Top left: Ideol and Atlantique Offshore Energy (AOE) have unveiled a floating offshore substation design, based on Ideol's shallow-draft Damping Pool concept and AOE's electrical offshore substation concept, SeeOs. This universal, modular, and commercial scale floating substation is expected to be installed around the world by 2030.

- Top right: Semco Maritime, ISC Consulting Engineers, and Technip Energies have also unveiled a scalable floating offshore substation design, the FOSS-400. The layout has been designed to follow the shape of a three-column stabilized substructure, building on their expertise in floating turbine platforms and the oil and gas industry. This substation will have 400 MW of transmission capacity, will weigh approximately 6,500–7,500 tons, and is approximately 40–45 m on each side.

- Bottom left: BW Ideol and Hitachi ABB Power Grids have teamed up to develop their own scalable floating substation design, also based off Ideol's shallow-draft floating platforms. Hitachi ABB Power Grids will supply the modular, scalable, and compact substation packages to be installed on top of the shallow-draft platforms.

- Bottom right (reference photo, design not publicly available): Saipem and Siemens Energy are working together to develop the design for a 500 MW HVAC floating substation based on a proven semisubmersible substructure. This concept will be designed to operate in extreme offshore environments and aims to optimize weight, electrical efficiency, and asset longevity.

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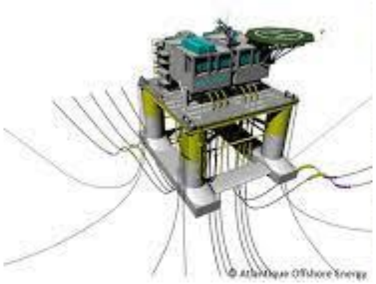
[35] http://www.fukushima-forward.jp/pdf/pamphlet4en.pdf

Figure 18. Examples of Floating Offshore Substation Designs

 Ideol and AOE's (barge) design based on Ideol's shallow-draft Damping Pool concept[36]	 Semco Maritime, ISC Consulting Engineers, and Technip Energies' three-column stabilized substructure design, FOSS-400[37]
 BW Ideol and Hitachi ABB Power Grids based off Ideols' shallow-draft platforms[38]	 General semi-submersible design (Source: Ideol)

OEMs and other organizations continue to work toward developing scalable floating offshore substations designs to address the technology gap. Daewoo Shipbuilding & Marine Engineering in collaboration with Korea Electric Power Technology Company, Petrofac, and others are also working on designs for floating offshore substations for offshore wind transmission.[39,40]

DNV is leading a joint industry project with 30 industry partners to update the DNV-ST-0145[41] standard and accelerate the development of floating offshore substations.[42] This update will

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[36] https://www.bw-ideol.com/sites/default/files/2019-07/2019.06.04%20-PR%20-%20Ideol%20-%20AOE%20-%20FINAL.pdf

[37] https://renews.biz/80006/deme-installs-hkz-substation-jacket/

[38] https://www.oedigital.com/news/488650-bw-ideol-hitachi-abb-power-grids-working-on-floating-substations-for-offshore-wind

[39] https://www.offshorewind.biz/2021/01/20/south-korean-pair-to-develop-offshore-wind-substation/

[40] https://www.petrofac.com/media/news/petrofac-signs-floating-offshore-wind-mou-with-seawind-ocean-technology/

[41] The standard (ST) for the design of offshore substations associated with renewable energy. This ST provides the technical requirements for the certification of electrical offshore substations.

[42] https://www.dnv.com/news/30-partners-join-dnv-to-start-joint-industry-project-for-floating-offshore-wind-substations-222575

make the standard applicable for floating offshore substations as well as address technology gaps for high voltage equipment and export cables and how they tolerate the movements of a floating substructure. Some of the industry partners include ABB, Aibel, Aker Solutions, Equinor, Hitachi Energy, Mitsubishi Electric, Prysmian, RWE, Siemens Energy, Technip Energies, and more.

These floating HVAC and HVDC offshore substations will be critical for the next phase of offshore wind and especially relevant to the projects off the coast of California and in other deep-water areas.

4.1.2 Subsea Substations

Subsea substations are a transmission technology designed for use in the oil and gas industry. In 2019, ABB presented a subsea power system with 100 MW capacity at 3,000 m of depth. Originally developed for the oil and gas industry, ABB recognized the applicability of this technology for floating offshore wind transmission and expanded its existing strategic alliance for seabed solutions with Aker Solutions in 2021 to encompass offshore wind.

Subsequently, Aker Solutions in collaboration with ABB and Benestad, unveiled a design for subsea substations, specifically for floating offshore windfarms. Aker developed the design based on the subsea substation used for the oil and gas industry 20 years ago, scaling the design to bring more power onshore. This substation can collect large amounts of power from floating wind farms and export it at increased voltages. This subsea substation is compact, lightweight, and requires less material compared to alternatives for offshore wind farms. Aker claims their model will lower costs by as much as 30% due to reduced operations and maintenance, lower carbon dioxide emissions, improve energy efficiency, and eliminate personnel safety issues (no manned operations). Developers seemed interested but questioned the technological feasibility of subsea substations.

Aker's subsea substation will come as standardized modules that can be added in parallel as building blocks, eventually supporting several GWs of transmission capacity. The substation can be placed at depths of 1,500 m and has a minimum of 30 years without the need for maintenance, providing significant cost savings. Additionally, this substation design would remove the need for dynamic export cables, addressing an important gap in floating offshore wind transmission technologies (see Section 4.2.1).

Aker's subsea substation will be available for procurement in 2024.[43] Figure 19 is an illustration of Aker's subsea substation design.

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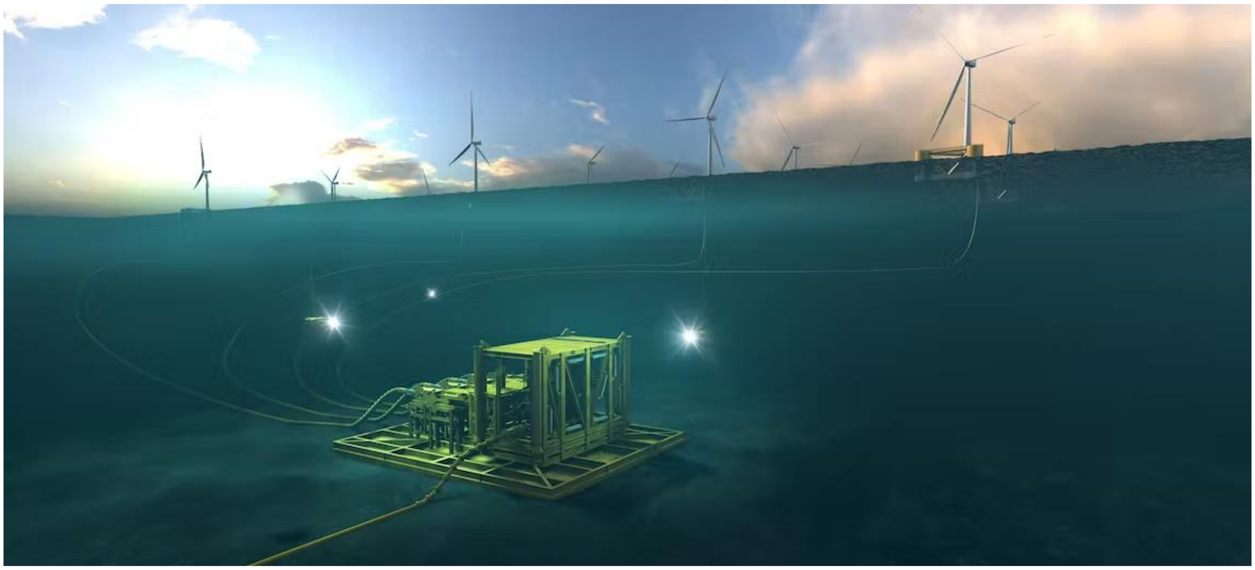
[43] https://www.akersolutions.com/news/news-archive/2022/subsea-substation--unlocking-the-potential-of-floating-offshore-wind/

Figure 19. Offshore Wind Underwater Substation System



Source: Aker Offshore Wind AS

4.2 Export Cables

Export cables are a key component for offshore wind transmission, representing a single point of failure for the entire wind farm. As wind farm capacities and transmission lengths increase, higher voltage cables will be necessary. As water depths increase, dynamic cables will also be necessary. This section discusses the latest information regarding dynamic export cables and higher voltage cables for both AC and DC technologies. These cable technologies are developing and there are no costs publicly available.

4.2.1 Dynamic Export Cables

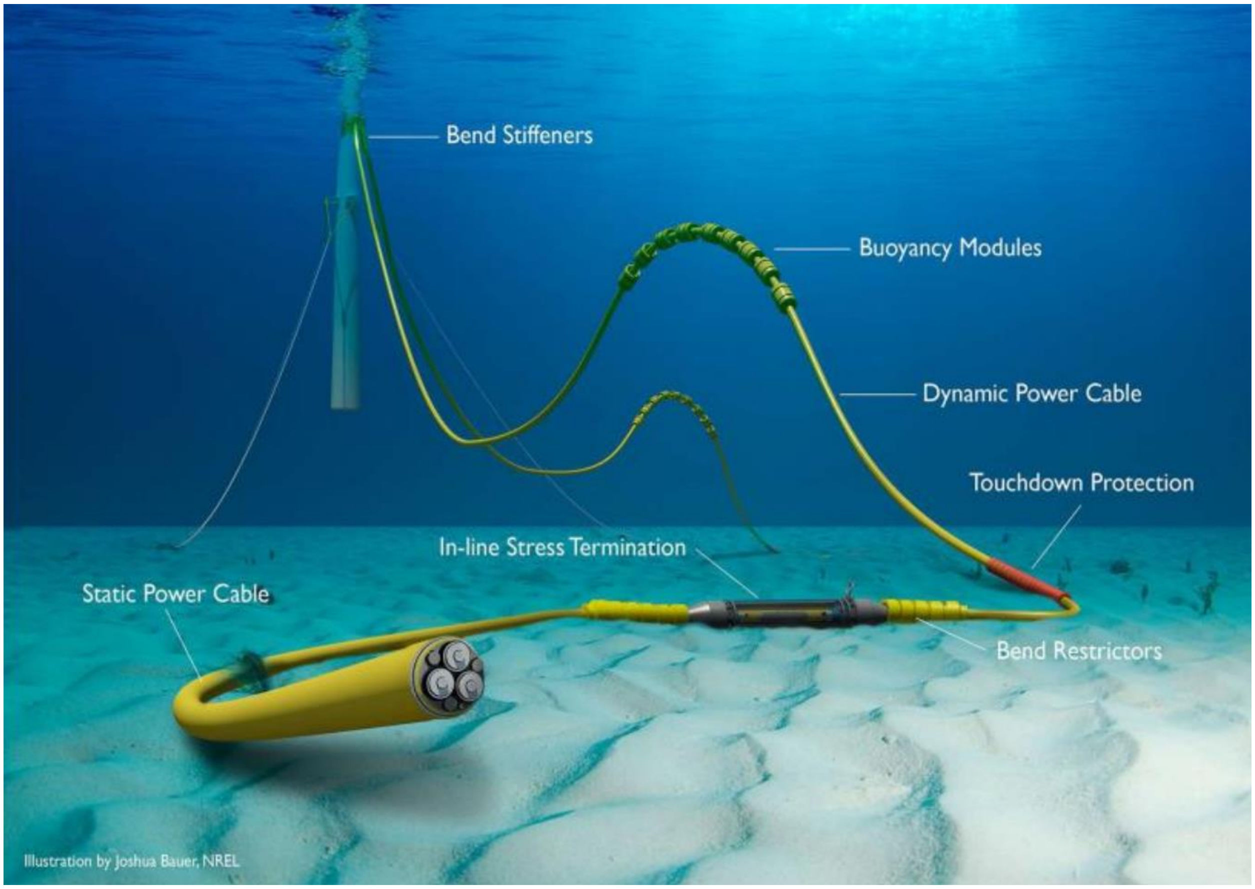
4.2.1.1 Overview

As mentioned throughout the report, dynamic export cables are a critical piece for transmission of power from floating offshore wind farms onshore. Exporting energy from commercial wind farms, which are higher capacity and further from shore, requires high voltage cables. In some areas, these wind farms also require floating structures due to water depth. Water depths, waves, and currents require cables that can withstand movement from the floating offshore substation, as well as the tensile loads and stresses created by the ocean. It is critical that no water penetrates the cable insulation, especially for high voltage export cables which are necessary for increased transmission capacity.

This water barrier is typically a lead sheath in static export cables, but lead is inflexible and cannot bend with dynamic wave movements. Since these lead sheaths are highly susceptible to fatiguing, a metallic corrugated tubular sheath made of copper, aluminum, or stainless steel can be used instead. These dynamic cables may also contain a metallic foil or polymer sandwich, which are suitable barriers for cables many kilometers in length. These cables may also include optical fibers to warn operators if any part of the cable is under extreme stress.

Ancillary equipment like dynamic bend stiffeners, distributed buoyancy modules, abrasion and impact protection, bend restrictors, and subsea connectors all contribute to the structural integrity and stability of the cable, although the necessary equipment will likely be site specific. Lessons can be learned from the oil and gas industry, including knowledge and infrastructure relating to umbilical systems and structural behavior of dynamic cables used for offshore oil and gas platforms. Figure 20 is an illustration of a dynamic power cable and some of the relevant ancillary equipment.

Figure 20. Illustration of Dynamic Power Cable



Source: NREL

Dynamic cable technology is typically used at the termination points where the cable connects to the floating platform and to the seabed, and the rest of the export cable can take advantage of static cable technology. Interviews with developers discussed the importance of the collaboration needed between dynamic cable OEMs and connector suppliers to ensure compatibility and certification of products. Developers also viewed this certification process as a potential slowdown to the procurement process.

In an interview, a cabling manufacturer was not worried about delivering dynamic cable systems (both AC and DC) or scaling these systems to the water depths off the California coast. However, they also mentioned that there has not been strong market demand for dynamic cables historically and anticipated that their dynamic cables could be technologically ready in the next several years. They emphasized that developers must engage early on with OEMs about qualification and timelines for each individual project, as the site-specific conditions are an important factor in the cable system design. The entire process, from the initial concept study to installation, takes an average of eight years.

Overall, dynamic export cables are a bottleneck for floating offshore wind transmission technology, especially as dynamic cables with higher export capacities are still under development.

4.2.1.2 HVAC

While high voltage dynamic export cables are currently not available commercially, all existing dynamic cables are AC. AC power cables are available at array-level voltages of 33 kV and 66 kV, which do not have enough transmission capacity for commercial scale offshore wind farms. There are several floating offshore wind farms that demonstrate the use of dynamic AC array cables as well as dynamic export cables at 115 kV and 123 kV used for oil and gas purposes.

There are power-from-shore dynamic cables that are used for floating oil and gas platforms. The Gjöa project, located in Norway, includes the world's first power-from-shore dynamic AC cable. The Goliat project features a longer and more powerful dynamic AC cable, using a corrugated copper sheath instead of lead. While used in the context of oil and gas, these cables provide a basis for manufacturers to build on in the process of developing commercial scale dynamic export cables. Table 1Table 8 provides details about these two dynamic cables and further illustrates the relatively low export capacity and power compared to what is needed for offshore wind export.

Table 8. Dynamic HVAC Export Cables in Oil and Gas

Project	Year	Location	Distance to Shore	Water Depth	Power Capacity	Power Cable	References
Gjöa	2010	Norway	100 km	380 m	40 MW	ABB 115 kV	(ABB, 2010)
Goliat	2013	Norway	105 km	400 m	75 MW	ABB 123 kV	(ABB, 2013)

Source: BOEM

In the Hywind Scotland Wind Farm, Nexans provided a 33 kV, 30 km dynamic cable to transmit energy from the 30 MW wind farm. The Fukushima FORWARD project also used HVAC dynamic cables, rated at 66 kV and designed by Furukawa Electric. There are additional projects, such as WindFloat Atlantic and Kincardine Floating Offshore Wind Farm, that also demonstrate the use of lower rated (33 kV and 66 kV) dynamic cables.

Manufacturers and other key players in the floating offshore wind space are focused on developing higher voltage dynamic cables. Industry players in the United Kingdom are looking at 132 kV array cables as a transmission option, which may even provide the option to bypass an offshore substation if the project is within 20–50 km from shore. JDR states that if they started working on 132 kV array cables now, they could deliver these cables by 2025.[44]

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[44] https://www.oedigital.com/news/500147-fow-players-target-132kv-dynamic-cables

Phase II of the Carbon Trust's Floating Wind joint industry project launched to address the lack of high voltage dynamic export cables. Their goal is to support the design, initial testing, and development of dynamic cables ranging from 130 kV to 250 kV. Five OEMs were selected to develop and test their designs for product qualification and future manufacturing (Aker, Furukawa Electric, Hellenic, JDR, and ZTT).[45] This joint industry project works toward ensuring the necessary technology is viable in the next 5 to 10 years for commercial scale floating offshore wind farms. In an interview, one cable manufacturer noted that they have a 220 kV dynamic HVAC cable in the qualification phase, which will be ready to install by 2027. Manufacturers also noted that individual project timelines are highly dependent on the existing back-log at the time the project is awarded.

4.2.1.3 HVDC

Currently, HVDC dynamic export cables do not exist in any form. Insights from developers indicated the landscape for dynamic cables using HVDC technology is significantly further behind HVAC. The supply chain is limited to a few key players in HVDC technology, and the market signal is not yet there for manufacturers to begin focusing on this product offering. While developers do recognize these as issues, they do not see major roadblocks for the development of this technology. Developers expressed that California has the opportunity to be the first signal to the market that HVDC dynamic cables will be needed at a commercial scale. In an interview, a cable manufacturer stated they are now working on a 150 kV HVDC dynamic cable, which can be stepped up to 320 kV. While they stated that their dynamic HVDC cable technology could be technologically ready by 2028, they also emphasized that this timeline is highly dependent on market demand, wind developers' timelines, and developers' willingness to engage with OEMs for the qualification of dynamic cable systems for their projects. As with dynamic HVAC cables, the actual installation time will depend on the existing project back-log and the overall market supply and demand. In interviews, both OEMs and developers noted that the supply chain for dynamic HVDC cables is already booked out for several years, and that lead times will continue to grow as OEMs book larger and larger contracts.

Literature review and insights from developers indicated that 2035 is an appropriate estimate for the commercial availability of HVDC dynamic export cables, which is beyond most of the developers' anticipated commercial operation dates. However, developers also noted that market demand could drive commercial availability to an earlier date. Until then, floating offshore wind will likely focus on the use of HVAC technology for transmission.

4.2.2 Higher Voltage and Higher Capacity Export Cables

In addition to dynamic export cables, higher voltage export cables are also in development to support the increasingly large offshore wind transmission requirements and distances from shore.

4.2.2.1 HVAC

For HVAC technology, the highest voltage export cable in existence is 420 kV. The world's first 420 kV submarine three core HVAC cable was built by ABB and used in Denmark to transmit power across the Little Belt strait in the Baltic Sea. Since then, other HVAC export cables rated at 420 kV have been used to transmit power for similar purposes but have never been

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[45] https://www.carbontrust.com/our-work-and-impact/impact-stories/floating-wind-joint-industry-programme-jip/floating-wind-jip-phase-ii

demonstrated in the context of offshore wind. However, Nexans has a 420 kV HVAC export cable using XLPE insulation as a product offering in their Integrated Cable Solutions for Offshore Wind Development catalog.[46] In an interview, an OEM stated they are in the process of pre-qualification testing for a static, subsea 420 kV HVAC export cable to be used for offshore wind farms. However, OEMs have not yet seen demand for this high of a voltage rating. Thus, while OEMs may have the technological capabilities to produce this level of HVAC export cable, they have yet to be demonstrated in a commercial offshore wind project.

4.2.2.2 HVDC

HVDC export cables are a more efficient transmission option that can achieve higher capacities compared to HVAC, because the cables do not experience losses from reactive power generation. OEMs are currently working on increasing the transmission capacity of their cables, and a developer stated in an interview that Prysmian is working to increase the rated power of their HVDC export cables to 1,500 MW.

Although 525 kV XLPE subsea HVDC export cables exist, they have not yet been used in a commercial offshore wind project. These cables have passed the performance qualification and type tests for German corridor projects, putting them in the demonstration phase. Referenced in Section 3.2.2.2, NKT, in collaboration with Prysmian, signed a contract in 2023 for the world's first 525 kV XLPE HVDC export cable connections in the Netherlands and Germany. Offshore cable laying is set to start in 2026, with the completion of the three 2 GW offshore wind projects projected between 2028 and 2030.

OEMs are also in the pre-qualification process for producing higher voltage HVDC cables. NKT claims to have a 640 kV HVDC subsea cable in development, stating an increase of maximum power transmission by 20% and a reduced cable weight per installed MW.[47] This higher voltage provides transmission with lower energy losses and is estimated to be commercially ready by 2030. However, this level of export cable has not been demonstrated at a commercial scale, and an interview with an OEM reinforced that manufacturers have not yet seen demand for this high of a voltage rating for HVDC cables.

4.3 Meshed Grid Systems

Most offshore wind farms to date are connected to shore radially, using point-to-point transmission lines that export power directly from the offshore substation to the onshore substation. These systems are typically HVAC, although more recently radial HVDC topologies have also been used. As offshore wind continues to expand globally, meshed grid systems and other networked offshore connection concepts have been explored to better integrate multiple offshore wind farms in the onshore energy system, allow for increased offshore wind build-out and interconnection between regions and markets, and provide reliability and redundancy, among other onshore grid benefits. Policy direction can facilitate the development of meshed interconnection strategies. These strategies would reduce financial risk for new offshore wind development, increase overall system reliability, and enable the offshore wind market to grow.

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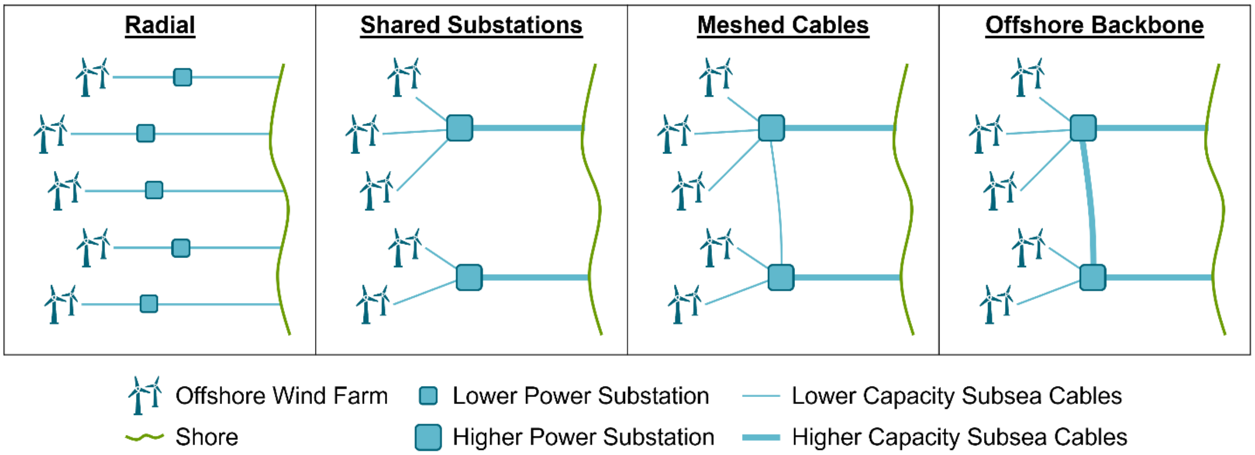
[46] https://www.nexans.com/en/dam/jcr:717293e8-cb52-4dba-81f3-fd5370159a7b/Nexans%20Offshore%20Wind%20Farm%20WEB.pdf

[47] https://www.nkt.com/products-solutions/high-voltage-cable-solutions/innovation/640-kv-extruded-hvdc-cable-systems

Figure 21 shows four offshore wind farm interconnection concepts, increasing in degree of connectivity from radial, to shared substations, to meshed cables, to a complete offshore backbone with high-capacity cables connecting offshore substations. The offshore substations can be HVAC or HVDC, and meshing can be achieved for either type of system, or a combination of both. Many of the meshed grid concepts that have been investigated thus far, including the Meshed Ready concept in New York, are meshed on the AC side of transmission, and use HVDC export cables to bring the power to shore.

Figure 21. Offshore Wind Farm Interconnection Concepts



Source: Adapted from WBUR

Both meshed AC with DC export to shore and fully meshed DC systems provide added resilience and load-serving capability from the use of shared substations. However, meshing on the AC side faces the same limitations for transmission distance and cable corridor capacity as HVAC export cables, and meshed DC systems face technology readiness bottlenecks for floating substations, dynamic cables, and DC circuit breakers (addressed in Section 4.3.1.1).

Meshed grid systems have been studied in New York and New Jersey, as well as in Great Britain and the European Union. California ISO also is evaluating preliminary concepts for connecting offshore substations from California’s North Coast area to a substation in the Bay Area with an offshore HVDC link to provide additional transmission capacity to load centers. This section discusses the benefits and challenges facing meshed grid systems and dives into case studies from New York, New Jersey, and Great Britain.

4.3.1 Benefits and Challenges

While radial lines are simple and cost effective in the short term, they limit the long-term offshore wind build-out potential, as each wind farm is individually connected to shore, crowding cable corridors. Using shared substations helps avoid crowding cable corridors, but both radial and shared substation configurations offer little resilience in the case of a cable failure, as the failure of a single cable can put an entire wind farm offline, or multiple wind farms in the case of an export cable failing in a shared substation configuration.

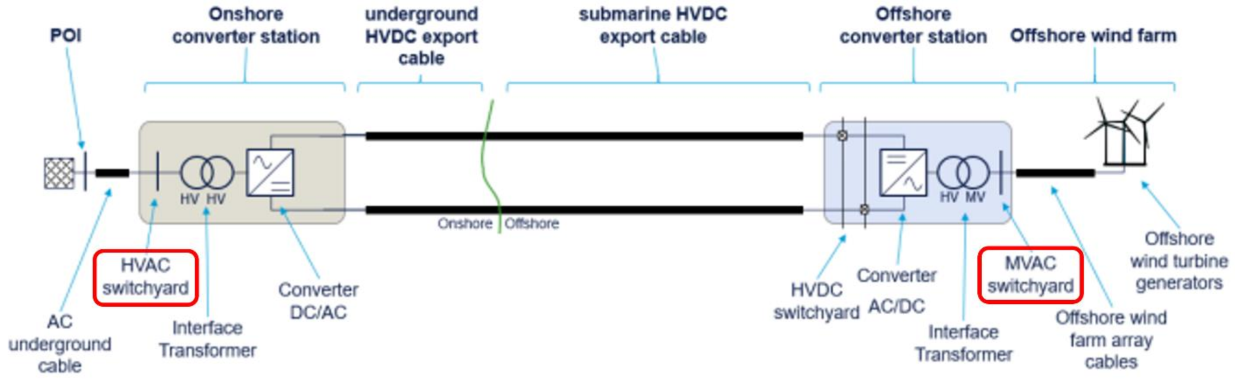
Meshed and backbone systems provide more resilience and redundancy in the offshore transmission system, allowing for power to be evacuated via connected offshore substations in the case of an export cable failure or other fault. Use of high-capacity DC export cables can maximize the potential of cable corridors and allow for continued expansion of offshore wind generation capacity. However, meshed systems require a higher upfront investment, strong policies on transmission development, and coordination among offshore wind and transmission developers. Additionally, many supporting systems and technologies for meshed grid systems are still in development, including vendor- and technology-neutral requirements to allow for compatibility and interoperability between technologies, standardized communication protocols and a DC grid code, DC grid protection and fault clearing strategies, and HVDC circuit breakers.

4.3.1.1 HVDC Circuit Breakers

HVDC circuit breakers are a key emerging technology that will be necessary for meshed DC grids and multi-terminal DC links. Protection of an HVDC grid is fundamentally different than that of an HVAC grid. Since the reactance of HVDC cables is negligible, a fault at any point in an HVDC grid will cause widespread voltage collapse if the fault is not cleared in a timely manner. Because there is no natural zero current crossing to break the fault current, one needs to be introduced as part of the protection scheme.

Existing point-to-point HVDC connections do not have protection schemes in place, so any HVDC fault takes out the entire HVDC link and the fault is isolated by the HVAC breakers on each side of the converters. A point-to-point HVDC system with AC switchyards on either side of the converters is illustrated in Figure 22. As the offshore grid develops and interconnections on the HVDC side are needed, this approach would allow for unacceptable loss of power and availability of transfer capacity.

Figure 22. Point-to-point HVDC Connection, AC Switchyards Highlighted



Source: DNV

Implementing a DC grid protection scheme requires use of a combination of DC circuit breakers, full-bridge converters, or other fault current limiters. Full-bridge converters can control the voltage down to zero to isolate a fault but cannot act as a circuit breaker. DC circuit breakers are switching devices that interrupt the flow of normal and abnormal direct current. Because DC transmission does not have natural zero current crossings like AC, DC circuit breakers are necessary to allow healthy branches of an HVDC system to remain in service after a fault in the larger system. While DC circuit breakers are a relatively new technology that differs from their AC counterparts, they have been demonstrated in 2020 in the PROMOTioN project. The Zhoushan multi-terminal VSC HVDC project in China was the first to use DC circuit breakers, at 200 kV.[48] However, DC circuit breakers have not yet been used at transmission levels in Europe

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[48] https://ieeexplore.ieee.org/document/7779770

and are not yet commercially available. The lack of availability of DC circuit breakers and their large size are two major challenges for meshed grids and offshore DC applications.

4.3.1.2 Compatibility and Interoperability

The compatibility interoperability of different technologies from different vendors within a meshed grid system is a major hurdle for meshed grids. Compatibility relates to the ability of two or more systems or components to perform their required functions while sharing the same environment, and interoperability refers to the ability for these systems or components to exchange and use meaningful information. Compatibility and interoperability are necessary between two different technologies, such as converters and HVDC circuit breakers, as well as on a larger scale between equipment from different vendors, and between grid systems with different operators.

Standardization will be necessary to achieve compatibility and interoperability. Grid system operators and vendors must align on common, technology-neutral performance requirements and adopt common communication protocols and standards for electrical equipment.

The PROMOTioN project helped advance standardization for an HVDC meshed grid by developing technology-neutral testing procedures for HVDC GIS and HVDC circuit breakers, integrating protection systems from multiple vendors, demonstrating different DC grid configurations, and developing recommendations for a DC grid code. The project identified defining technology neutral requirements for events such as DC fault ride through as a major challenge to achieving compatibility and interoperability.

4.3.2 Case Studies

This section reviews three studies into meshed offshore grids for integration of offshore wind: New York, New Jersey, and Great Britain. These case studies highlight the importance of coordination among state energy agencies and grid system operators for the planning and development of meshed transmission systems for offshore wind.

4.3.2.1 New York: Offshore Wind Integration Study

The New York Offshore Wind Integration Study[49] was initiated by NYSERDA and the New York Department of Public Service to investigate potential long-term offshore wind transmission solutions. The study considered radial and backbone HVAC concepts, as well as HVDC in symmetric monopole and bipole configurations.

The study found that networked connection concepts (shared substations, meshed, or backbone) are economically justifiable if they encompass at least three offshore wind projects with a minimum aggregate rating of 3 GW. While uncertainty around availability of wind energy areas makes it difficult to move from radial to networked connections, the study found that the meshed concept was the most flexible considering wind energy area uncertainty. Additionally, upfront preparations and investments (e.g., over-sizing cables and converters, and additional breaker positions) can overcome challenges with wind energy area uncertainty.

Radial, meshed, and backbone connection concepts were short-listed for further analysis. Radial and meshed concepts had a lower levelized transmission cost of energy than backbone,

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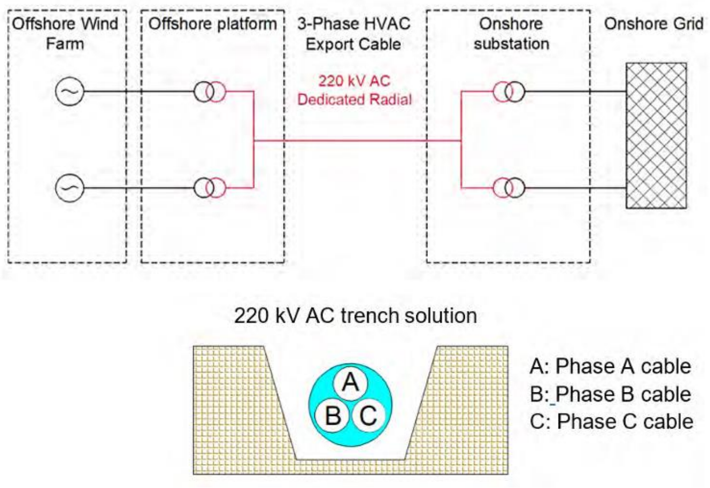
[49] https://www.nyserda.ny.gov/-/media/Project/Nyserda/Files/Publications/NY-Power-Grid/Appendix-D.pdf

and meshed concepts had the highest availability and operational benefits among the three concepts.

Specifications for the configurations that were considered are shown in

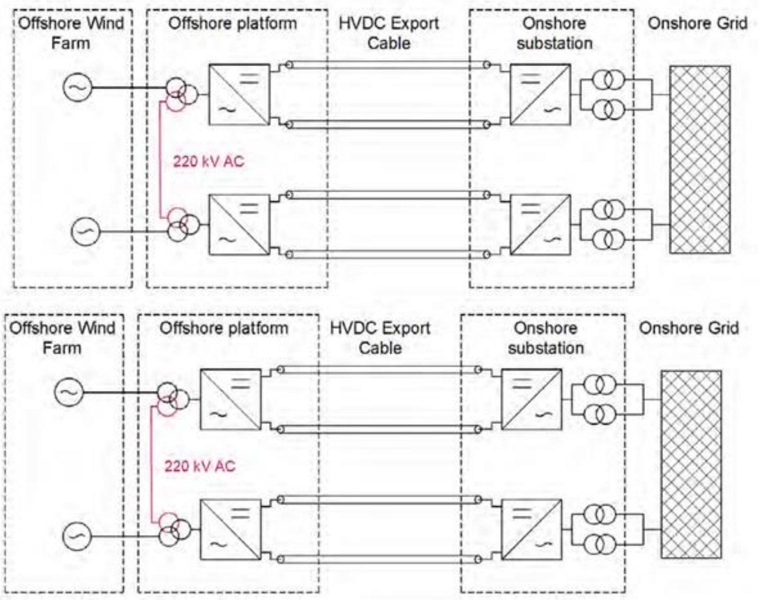
Table 9. The study considered 70 miles (112 km) was as viable distance threshold for HVAC technology; for distances greater than 70 miles, HVDC technology was considered as an alternative.

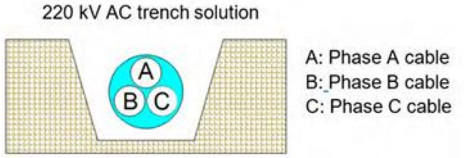
Table 9. Configurations Considered in New York Offshore Wind Integration Study

Configuration	Illustration
220 kV HVAC Dedicated Radial • Three-phase HVAC cable system rated at 220 kV with maximum transfer capacity of 450 MW requiring multi-parallel HVAC circuits for higher power transfers • Maximum cable conductor cross section: 1,600 mm^2 • Number of offshore trenches for one three-phase cable system: 1	

220 kV HVAC Backbone

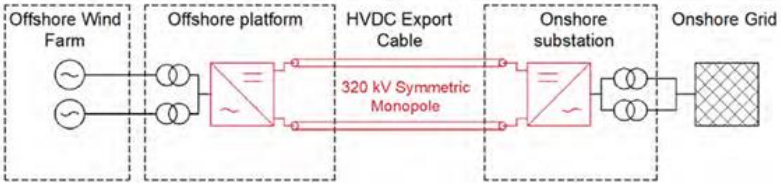
- Same specifications as 220 kV HVAC Dedicated Radial configuration

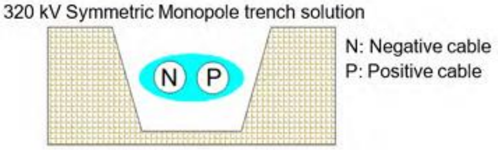




320 kV Symmetric Monopole HVDC

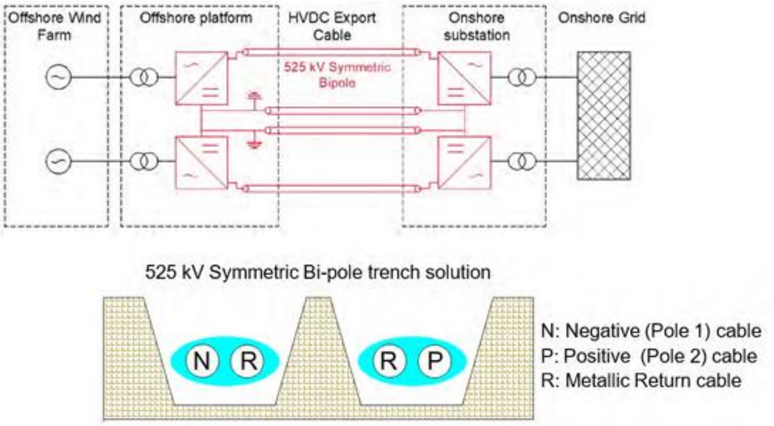
- Voltage level: +/- 320 kV
- Maximum transmission power: 1,300 MW
- Maximum cable conductor cross section: 2,500 mm^2
- Maximum cable system length in proposed connection designs: 168 miles
- Number of offshore trenches: 1





525 kV Symmetric Bipole HVDC

- Voltage level: +/- 525 kV
- Maximum transmission power: 1,700 MW
- Maximum cable conductor cross section: 2,500 mm^2
- Maximum cable system length in proposed connection concepts: 106 miles
- Number of offshore trenches: 2, one cable per trench



Source: NYSERDA

The 220 kV HVAC Backbone configuration illustrates a concept where the offshore platforms are meshed on the AC side of transmission, and HVDC export cables are used to transport power to shore. One advantage of the 220 kV HVAC Backbone configuration is that the need for costly HVDC circuit breakers (required in a full HVDC backbone) can be partially eliminated.

The 320 kV HVDC option was considered at the maximum allowed contingency level of 1,310 MW. The 525 kV HVDC topology was considered for ratings greater than 1,400 MW. While there is no precedent for the use of 525 kV symmetric bipole HVDC technology for export of offshore energy to the onshore grid, the study assumed the technology would be available for implementation by 2030.

4.3.2.2 New Jersey: State Agreement Approach for Offshore Wind Transmission

The State Agreement Approach[50] was initiated by the New Jersey Board of Public Utilities (NJBPU) at the direction of the New Jersey Legislature and the New Jersey Governor's Energy Master Plan to identify the necessary transmission solutions to support New Jersey's long-term offshore wind capacity goal. The NJBPU asked the Pennsylvania-New Jersey-Maryland Interconnection (PJM) to incorporate the state's offshore wind goals into the regional transmission planning process, creating the State Agreement Approach, a competitive transmission solicitation process. The State Agreement Approach solicited four types of proposals for offshore wind transmission solutions:

- Option 1a: proposals for required upgrades to the existing PJM grid to interconnect additional offshore wind generation reliably
- Option 1b: proposals for new onshore transmission facilities that would extend the existing PJM grid toward the shore

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[50] https://www.brattle.com/wp-content/uploads/2022/10/New-Jersey-State-Agreement-Approach-for-Offshore-Wind-Transmission-Evaluation-Report.pdf

- Option 2: proposals for new transmission facilities, from the onshore transmission facilities to the offshore wind generation projects in the wind lease areas
- Option 3: proposals for transmission links between offshore substations of Option 2 transmission links

Option 3 encompassed meshed offshore transmission concepts, where offshore substations were interconnected to create a networked offshore grid. While the State Agreement Approach was one of the most developed studies into networked offshore grids, it ultimately did not recommend procuring any Option 2 or 3 transmission facilities, due to limited benefits and higher costs and risks.

4.3.2.3 Great Britain: Holistic Approach to Offshore Transmission Planning

The Holistic Approach to Offshore Transmission Planning in Great Britain[51] identified four HVAC and four HVDC offshore network designs and assessed their suitability for achieving the United Kingdom's long-term offshore wind generation goal. The topologies considered in the study are summarized in Table 10. Topologies Considered in Great Britain's Holistic Approach to Offshore Transmission PlanningTable 10.

The study found that the benefits of the integrated offshore designs include:

- Reduced transmission losses in the onshore network, reduced impact of onshore contingencies,
- Improved dynamic performance and voltage control,
- Reduced offshore cabling and other required transmission infrastructure,
- Supply chain efficiencies via standardization of offshore designs, and
- Benefits to local coastal communities by minimizing congestion of projects landing onshore.

The study also identified barriers to implementing integrated offshore designs, including uncertainty around grid code application to an offshore transmission network and technology maturity for higher capacity cables, converters, and DC circuit breakers.

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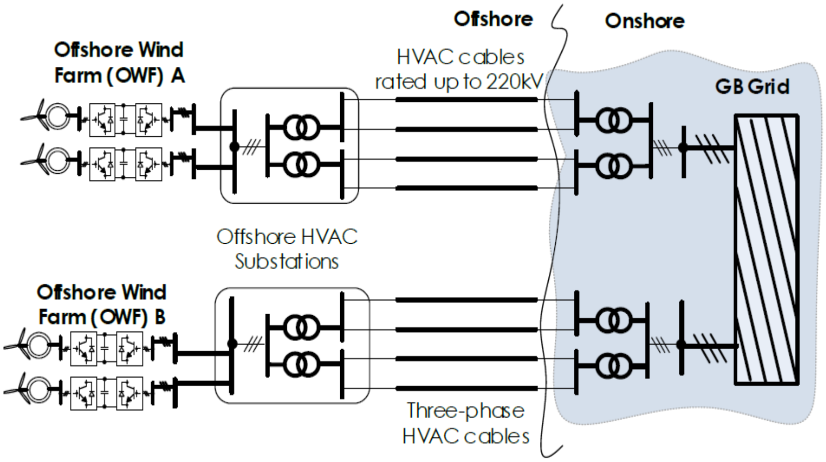
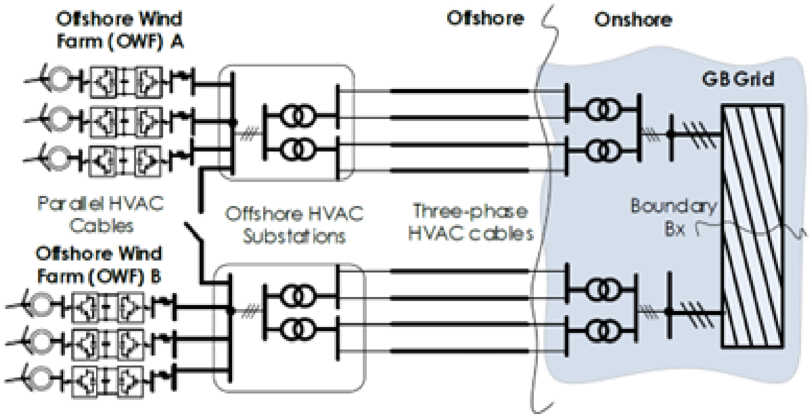
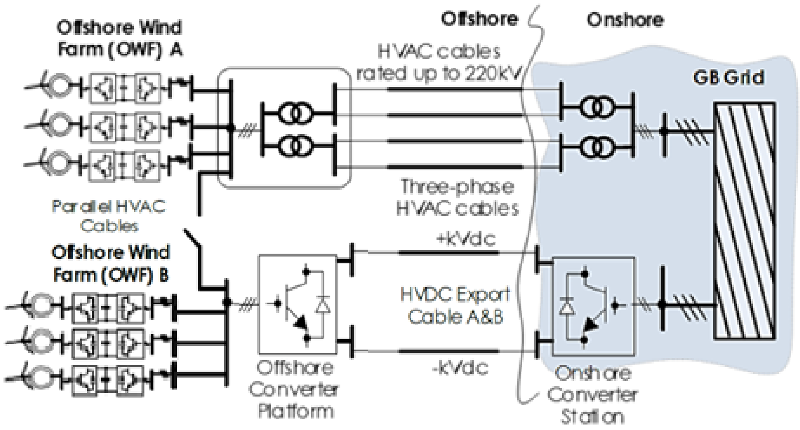
[51] https://www.nationalgrideso.com/document/177221/download

Table 10. Topologies Considered in Great Britain's Holistic Approach to Offshore Transmission Planning

Topology Description	Schematic
Radial HVAC • Established, business as usual approach, used as comparison to other designs	
More integrated HVAC • Parallel HVAC cables connect the wind farms to allow power to be gathered from multiple wind farms and distributed among them • Relatively well established design, selected by many developers to date • Limited in max power transmission capability and distance, but can be enhanced with endpoint or midpoint compensation	

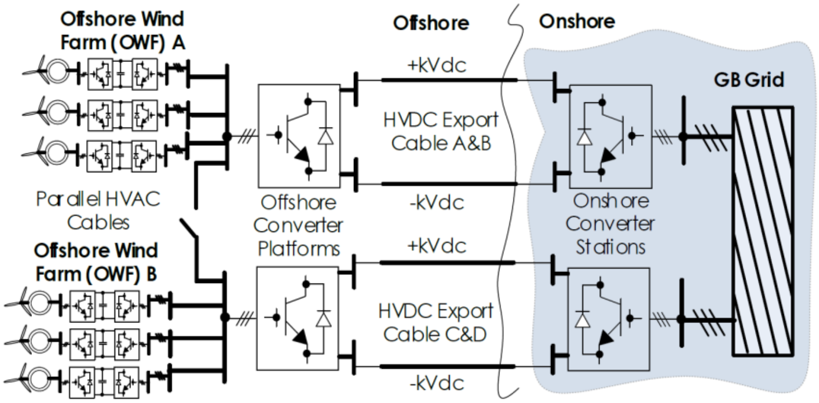
HVAC with parallel HVDC

- Combination of HVAC and HVDC export to shore for different locations
- Allows for expansion of offshore development where the current infrastructure cannot adequately handle new development
- Allows for more distant and higher capacity offshore connections for the HVDC circuit, but distance and capacity limits remain for the HVAC connection



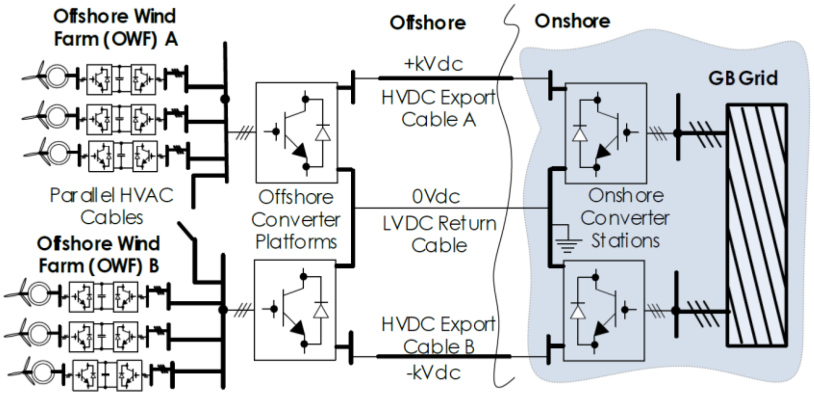
Point-to-point symmetrical monopole HVDC link

- No technical limits to distance from shore, and allows for higher wind farm capacity
- Can be developed point-to-point or with interconnection of offshore HVDC substations on the AC side with traditional HVAC technology
- International experience in Germany



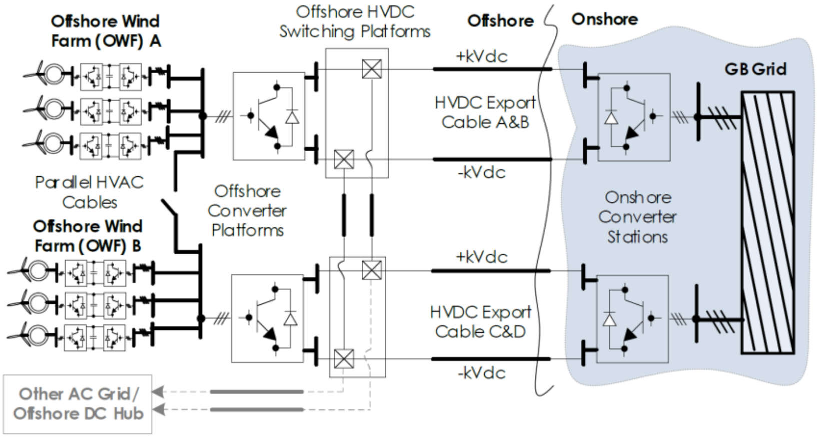
Point-to-point bipole HVDC link with return cable

- Bipole configuration requires less offshore and onshore cabling than other networked designs considered, which can mean lower costs
- HVDC system provides more flexibility for onshore landing points and can manage faults with HVAC and LVDC switching arrangements (does not rely on DC circuit breakers)



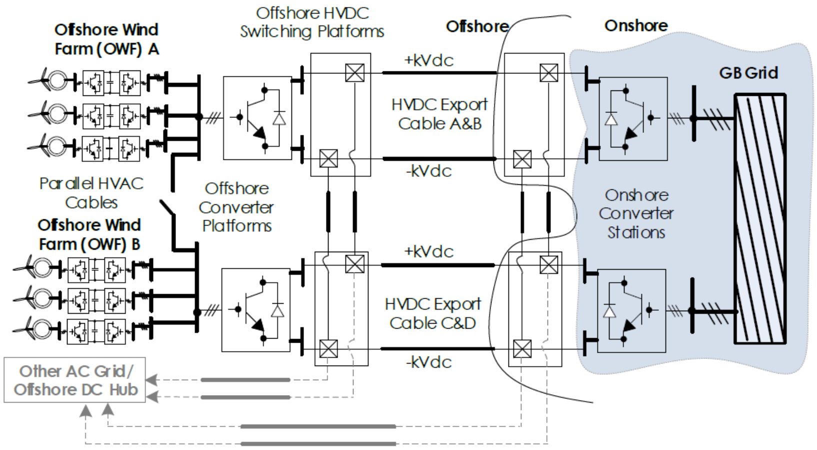
Radial multi-terminal HVDC system

- Could represent integrated solutions with other interconnectors or European networks
- Use of offshore HVDC switching platforms facilitates multi-terminal DC interconnection, but may result in higher costs for offshore transmission assets compared to other designs
- Would require use of DC circuit breakers offshore, which has not yet been demonstrated anywhere



Meshed multi-terminal HVDC system

- Series of offshore HVDC substations, connected via a meshed HVDC cable arrangement to onshore converter stations
- Similar to an onshore integrated HVAC grid, but offshore with HVDC assets
- Provides flexibility offshore and limits the impact that offshore network maintenance has on individual offshore connections
- Onshore and offshore HVDC switching substations add additional cost compared to other designs
- Has the most complex transmission system control operation



Source: National Grid ESO

5. Interview Insights

The following interview insights come from offshore wind developers holding California lease areas and a transmission developer. Overall, developers expressed confidence in the technological feasibility of offshore wind transmission technologies, but expressed concern around supply chain constraints and the availability of technologies at the scale needed. They also universally urged proactive, state-led, strategic planning for long-term offshore transmission needs.

Insights about specific technologies are included within Chapters 3 and 4. This chapter aggregates interviewees' perspectives around transmission planning, supply chain, and anticipated commercial operation dates.

5.1 Transmission Planning

5.1.1 Onshore Grid Constraints

Multiple developers singled out transmission constraints in Humboldt as a barrier to the interconnection of wind farms and stressed that transmission upgrades in the Humboldt region need to begin as soon as possible to enable the delivery of the first offshore wind projects in the North Coast by mid-2030. One developer expressed the belief that options for new wind energy areas would most likely lie in the North Coast, and they signaled the need to start looking into shared transmission or meshed grids for larger volumes of offshore wind generation in the North Coast.

In the Central Coast, developers were concerned about the uncertainty of the extension or decommissioning of the Diablo Canyon nuclear power plant. If Diablo Canyon stays online beyond 2030, developers anticipated additional costs for onshore network upgrades to accommodate offshore wind interconnection.

5.1.2 Long-term Transmission Planning and Meshed Grids

Developers strongly encouraged the state to proactively plan for a long-term transmission solution to accommodate the state's ambitious goal of 25 GW of offshore wind by 2045. They stressed the need (and opportunity) for a central transmission solution led by the state, rather than a piecemeal approach as has been the case on the East Coast. Developers urged the creation of clear policy goals for long-term offshore wind build-out with intermediate capacity increments as well as strategic transmission planning to meet these goals, both ideally backed by statute.

Most developers were in favor of meshed grids and expressed that if projects were expected to connect to a meshed offshore grid or shared substations, the technical specifications needed to be clear in the procurement process and additional costs needed to be priced in. However, they were generally uncertain about cost allocation for the build-out of a meshed offshore grid, as well as compensation structures and revenue allocation for the power they generate. The transmission developer's perspective was that the regulatory scheme for offshore transmission and generation owners could be analogous to onshore, where generation is separated from transmission and the dispatch of power is coordinated by independent grid operators. Developers also expressed concern around needing to size cables and equipment to plan for contingencies and the addition of new projects in a meshed grid system.

Developers recognized the importance of coordination among each other for long-term transmission, including meshed grids, and many stated that they were beginning to have conversations with other lease holders around general planning needs. Some suggested a third-party organization to facilitate coordination among developers and oversee subsea infrastructure development, or a joint industry project to consider topologies for meshed grids and compatibility of control schemes and communications.

Another important consideration for transmission planning is the availability of cable corridors and onshore points of interconnection. Transmission developers urged the use of higher capacity DC export cables rather than lower capacity AC cables (350–400 MW) to maximize the long-term connection potential given limited cable corridors and points of interconnection, and developers expressed interest in collaboration among each other for cable corridors, landfall, and installation logistics.

Developers also expressed uncertainty around the rules for the placement of offshore substations, stating that there is no express prohibition or right in BOEM language to place an offshore platform in the middle of a lease area, on the edge, or midway between the lease area and shore.

Lastly, the transmission developer expressed a preference for full DC meshing, rather than creating a meshed grid on the AC side of the offshore transmission system as in New York. While meshing on the AC side provides redundancy and reliability benefits, the offshore transmission system would still face limits to transmission distance and intermediate platforms for reactive power compensation may be necessary between substations.

5.2 Supply Chain Constraints

Developers anticipated challenges with supply chain for transmission technologies as demand ramps up. For many technologies, such as dynamic cables and DC circuit breakers, the long-term offshore wind goal set by California is a major market signal to OEMs to begin ramping up production.

Developers also pointed out that the current global economic environment is constraining supply chains and driving increased costs. As demand for floating offshore wind transmission technologies increases, developers anticipate continued difficulties in predicting costs and obtaining necessary components. Developers also saw bottlenecks in ramping up port infrastructure, dry docks and manufacturing, and standardization of processes for floating offshore wind development.

5.3 Commercial Operation Dates

Expected commercial operation dates for both the Central and North Coasts ranged from 2030 to 2035 and beyond. Developers anticipated a commercial operation date closer to 2030 for projects on the Central Coast, due to the existing interconnection at Diablo Canyon. The commercial operation date for North Coast projects is heavily dependent on timing to build and upgrade onshore transmission lines in the Humboldt area.

6. Conclusion

This report reviewed the current state and development of key technologies for the transmission and interconnection of offshore wind farms to the onshore grid in California. These technologies include HVAC and HVDC export cables, HVAC and HVDC substation power equipment, and offshore substation platforms. Several offshore wind farm interconnection concepts, such as meshed grid systems, were also reviewed, with case studies from New York, New Jersey, and Great Britain. Lastly, this report summarized important insights obtained from interviews with offshore wind developers holding California lease areas, as well as other stakeholders.

While currently available technology has met the needs of existing wind farms, offshore wind farms in California will require emerging solutions to accommodate deep waters and export larger volumes of power in an efficient manner. Considering the distance to shore of the California wind energy areas, both HVAC and HVDC transmission systems are viable options for the export of power from offshore wind farms. Existing technologies for export cables include static, subsea cables rated up to 420 kV HVAC with 300-500 MW of transmission capacity or up to 525 kV HVDC with up to 2600 MW transmission capacity. HVAC export cables face technical and economical limitations to transmission distance, as they require reactive power compensation for transmission over long distances. While HVDC export cables do not face technical limits for transmission distance, HVDC transmission systems have a higher upfront cost and key components, such as DC gas-insulated switchgear and DC circuit breakers, are still being developed.

There are many considerations that go into deciding between HVAC or HVDC transmission systems for offshore wind farms. Cost of infrastructure (including cables, substations, and other necessary equipment), electrical losses, transmission capacity, space requirements, technological maturity, supply chain status, and cable corridor space all impact the choice between HVAC or HVDC. While HVDC systems have a higher upfront cost, literature review shows there is a breakeven point at 80–100 km, beyond which HVDC is more economical. This breakeven point occurs due to higher line losses experienced by HVAC export cables and the need for reactive power compensation equipment for transmission over longer distances. In interviews, lessees seemed open to utilizing either HVAC or HVDC and indicated they would need additional information about supply chain and availability of key technologies in each system, as well as long-term transmission plans before making a final decision.

Offshore substations house the electrical components necessary for high voltage transmission of power from the wind farm to shore. An offshore HVAC substation collects power from offshore wind farms, transforms the voltage for export to shore, and can house reactive power compensation components if necessary. An offshore HVDC substation serves the same function, but also converts the transformed HVAC power to HVDC before the power is exported. HVDC substations can also house DC gas-insulated switchgear and, in the future, DC circuit breakers for meshed grid applications. Because of the additional equipment, offshore HVDC substations are typically larger and heavier than their HVAC counterparts. While floating platforms will be necessary for offshore substations at the water depths of California wind energy areas, existing deployed offshore substation platforms are all fixed bottom platforms. One floating offshore substation was demonstrated as part of the Fukushima FORWARD project but was decommissioned in 2021. Onshore substations house similar components as their offshore counterparts but have less restrictive space and weight limitations.

Developments to existing export cable and substation technology will be necessary to enable higher capacity, deep-water, floating wind farms. OEMs and other key players in the industry are working towards building higher voltage cables to support the increasing capacity requirements of offshore wind farms, as well as dynamic export cables to enable transmission from floating substations. These dynamic cables must flex with the movement of the ocean while remaining insulated from water. Manufacturers are currently working on solutions to address this technological gap and to create a less fatigable export cable. While dynamic cabling technology does exist at lower voltages for HVAC, HVAC dynamic cables are not yet available at the higher capacities and voltages that will be needed in California. Additionally, dynamic cables do not exist in any form for HVDC, which is a critical technological gap for offshore wind transmission in California's deep waters. Developers cited a lack of market signal as contributing to this existing gap and expect that dynamic HVDC cables would be commercially available by 2035, which is outside of the range of most of their estimated commercial operation dates.

There have also been developments in progress regarding offshore substations for deep-water applications. Floating offshore substations are the main technology that OEMs are focusing on to enable floating offshore wind farms in deep waters. The platforms of these substations build on concepts from the oil and gas industry as well as floating wind turbine platforms. Several OEMs have created designs that include spar, barge, and tension leg platform concepts, but these are not currently commercially available. Another developing option is subsea substations, which aggregate the wind turbine array cables and transform the voltage on the sea floor, then export power to shore using static export cables, eliminating the requirement for dynamic export cables. These substations are under development by Aker Solutions, which claims that their technology will be available for procurement by 2024. However, subsea substations have not yet been demonstrated in offshore wind applications.

As offshore wind developments expand globally, grid operators have explored concepts for interconnecting multiple wind farms offshore and with the onshore power system. While most offshore wind farms to date are connected to shore radially, more networked interconnection concepts such as shared substations, meshed grids, and offshore backbones can increase reliability and redundancy, allow for increased offshore wind build-out and interconnection between different regions and markets, and provide other onshore grid benefits. Meshed grids can be achieved for HVAC and HVDC transmission systems, or a combination of both. However, meshed AC systems face limitations for transmission distance and cable corridor capacity, and meshed DC systems face technology readiness bottlenecks for dynamic cables, DC gas-insulated switchgear, and DC circuit breakers. This report reviewed three studies into meshed offshore grids for integration of offshore wind, in New York, New Jersey, and Great Britain. In interviews, developers were generally in favor of meshed grids as a long-term transmission strategy but emphasized that the process must be state led.

As California works to meet its planning goal of 2,000–5,000 MW of offshore wind by 2030 and aspirational goal of 25,000 MW by 2045, there is an urgent need for continued research and development and subsequent commercialization of key technologies. Through literature review and interviews with developers, several technology gaps and pain points were identified that will affect the development of California's first round of long-term offshore wind generation build-out. High capacity, floating offshore wind farms in waters as deep as off the California coast will require dynamic export cables and floating substations, neither of which have been demonstrated at the level of capacity anticipated for the first round of offshore wind farms in California. While developers were confident in the technological feasibility of offshore wind transmission technologies, they expressed concern around supply chain constraints and the availability of technologies at the scale needed.

For the first round of offshore wind build-out, developers identified transmission constraints in Humboldt and uncertainties around the extension or decommissioning of the Diablo Canyon nuclear power plant as major hurdles to interconnection with the onshore grid. Developers strongly encouraged proactive, state-led planning for long-term offshore transmission needs. Coordination among the CEC, the California ISO, and offshore wind and transmission developers, as well as policy support, will be critical to efficient and effective development of transmission development to accommodate California’s long-term offshore wind capacity ambitions.

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Appendix B. Glossary

B.1 General Transmission

Circuit Breaker

A circuit breaker is a device designed to protect electrical devices and individuals from overcurrent conditions and refers to a mechanical switching device capable of making, carrying, and breaking currents under normal and abnormal circuit conditions, such as those of short-circuit. Circuit breakers are automatically operated in case of a fault. The technology for AC and DC circuit breakers differs, and the two cannot be used interchangeably. DC circuit breakers for high voltage DC transmission are a new technology that is still in the development phase.

Harmonic Filter

Harmonic frequencies of currents and voltages in a power system are caused by non-linear loads, such as rectifiers. Harmonics and harmonic distortion can result in poor power quality and cause damage to equipment. Harmonic filters are resonant circuits that shunt or block harmonic currents in power systems. The filters are designed to ensure harmonic currents flow between the load and the filters, rather than reaching the power source or other components.

High Voltage Alternating Current

High voltage alternating current (HVAC) uses an alternating current for power transmission. An alternating current is the flow of electrical charge that periodically reverses direction and continuously changes magnitude with respect to time. These voltages can be changed in a simple manner with the use of transformers and substations.

High Voltage Direct Current

High voltage direct current (HVDC) uses a direct current for power transmission. A direct current is the flow of electric charge that maintains a single direction flow, from positive pole to negative pole, without any change in magnitude for a specific load. This is optimal for longer distance transmission but requires a converter to convert current from alternating to direct and vice versa.

Line Commutated Converter

Line commutated converters (LCCs) are the conventional, mature and well-established technology used to convert electric power from AC to DC or vice versa. LCCs require connection to a strong grid with sufficient short circuit power and a synchronous voltage source in order to operate and avoid commutation faults.

Metallic Return

A high voltage DC power transmission system sometimes utilizes a metallic return conductor for carrying return current between converters at opposite ends of the system. The return conductor is connected to earth ground at one end of the system and is otherwise insulated from earth ground so that its opposite end is floating with respect to DC. High voltage DC applications typically use dedicated metallic return cables, separate from the high voltage DC cables (i.e., not bundled).

Modular Multi-level Converter

Modular multi-level converters (MMCs) are the latest and most advanced technology used for HVDC transmission. In offshore HVDC grids, MMC is becoming the preferred power electronic converter for converting between AC and DC as it presents several benefits: (i) the ability to reverse the power flow without reversing the polarity of the DC voltages by DC current reversal; (ii) modularity and scalability features, making it advantageous compared to other VSC topologies; (iii) its inherent capability of storing energy internally in the converter. This can benefit the system in which it is connected and enables the drastic reduction of operating losses of the converter stations by avoiding the need for high frequency switching of the semi-conductor devices. MMC differentiates further into the Half Bridge type and Full Bridge type MMC.

Power System Capacitor

A capacitor is a device that stores energy within an electric field. When used in AC power transmission, capacitors provide reactive power and voltage support to increase system load capacity, reduce losses, and improve power factor.

Power System Reactor

A reactor is a device that provides reactive power compensation to minimize voltage spikes and unwanted current and voltage effects during load variations or short circuits within an AC power system.

Reactive Power

In AC power grid systems, total power produced is a combination of real and reactive power. Real power is the useful component of the electricity produced which powers loads such as lights, motors, etc. Reactive power is a result of the electrical characteristics of the network and does not contribute to actual work. Several methods of reactive power compensation (see below) have been developed to reduce the amount of reactive power in the system.

Reactive Power Compensation

Reactive power compensation is the management of reactive power to improve the performance (or power factor) of alternating current power systems. In general, reactive power compensation is related to load and voltage support and uses devices such as reactors and capacitors.

Shunt Reactor

Shunt reactors are used in high voltage transmission systems to control and stabilize voltage profiles to maintain optimal performance. Depending on the voltage requirement needs, shunt reactors can be adjusted to provide reactive power compensation to maintain voltage within prescribed limits.

Static VAR Compensator

A static VAR compensators (SVC) is a device that provides reactive power support. SVCs use thyristors to produce either reactive power absorption or generation to regulate voltage during steady state conditions and provide dynamic, fast response reactive power following system contingencies. SVCs can also reduce losses, mitigate active power oscillations, and prevent voltage excursions outside of prescribed operating limits during a loss of load or generation.

Synchronous Static Compensator

A static synchronous compensator (STATCOM) is a fast-acting device capable of providing or absorbing reactive current and thereby regulating the voltage at the point of connection to a power grid. STATCOMs are voltage source converter-based devices that provide variable reactive power in response to voltage variations. STATCOMs are similar to static VAR compensators but faster and can function with limited need for harmonic filters.

Voltage Source Converter

Voltage source converters (VSCs) are self-commutated converters that can connect HVAC and HVDC systems. Because VSCs are capable of self-commutation, they are able to generate AC voltages without the need to rely on an AC system, allowing for independent rapid control of both active and reactive power and black start capability.

B.2 Cables

Array Cables

Array cables, or inter-array cables, are subsea power cables connecting offshore wind turbines to the offshore substation.

Cable Corridor

A cable corridor is a designated area from shore to a wind farm that export cables may be placed. Cable corridors require permitting, and corridors are typically scoped based on environmental and regulatory factors. Developers may be required to offer several options for cable corridors, including a preferred option.

Cable Insulation Types

- **Cross Linked Polyethylene (XLPE):** Extruded cables are insulated using cross-linked polyethylene (XLPE). With improvements in material science, XLPE has achieved a high dielectric strength, low dielectric constant, high insulation resistance and good mechanical properties, making it an excellent insulation medium for subsea power transmission.

- **Polypropylene Laminated Paper (PPL):** Polypropylene laminated paper insulation consists of one layer of polypropylene sandwiched between two Kraft paper layers.

- **Mass Impregnated Paper:** Mass impregnated cables are a very consolidated and traditional technology mainly deployed for subsea applications. These cables are composed of a very high viscosity impregnating compound which does not cause leakage in the event of cable damage or failure.

Dynamic Power Cables

Dynamic power cables are an essential subsea power transmission component designed to withstand extreme dynamic load and cyclic fatigue damage from waves and vibrations.

Dynamic Power Cables Ancillary Equipment

- **Metallic Corrugated Tubular Sheath:** A metallic corrugated tubular sheath is an alternative to the lead sheath of a static subsea export cable. This sheath has favorable fatigue and corrosion properties.

- **Metallic Foil or Polymer Sandwich:** A metallic foil or polymer sandwich is an alternative to the lead sheath of a static subsea export cable. The barrier is thick enough to provide reliable protection, but not so thick that it resists the movement of the cable.

- **Dynamic Bend Stiffener:** Dynamic bend stiffeners provide a pre-defined stiffness to a cable or umbilical at its point of connection to a rigid structure or other system component. Its primary function is to limit design life bending stresses in the line at its most vulnerable point, thus removing the potential for damage at the line connection as a result of over bending.

- **Distributed Buoyancy Modules:** A distributed buoyancy module is a two-piece construction that is designed to attach to a dynamic cable to reduce the submerged weight during installation. Assemblies are produced in various sizes and lengths to suit the project specific uplift requirement.

- **Bend Restrictors:** Bend restrictors are applied to ensure the bending radius of the cable will not exceed the minimum bending radius defined by the manufacturer. Bend stiffeners are especially designed and manufactured for use in dynamic applications to prevent failure as a result of cyclic loading.

- **Subsea Connector:** Underwater connectors, also known as wet-mate connectors, subsea connectors, or marine connectors, are designed to be mated or unmated in wet environments and capable of withstanding the most extreme environments, from corrosive seawater and pressure to vibration and shock.

Export Cables

Export cables transfer power from offshore wind farms to connect to an onshore grid network, typically via intermediate AC substations or DC converter stations.

Static Submarine Power Cable

A static submarine power cable is a transmission cable which carries electric power below the surface of the water. These cables are often buried and are fixed from end to end.

B.3 Substations

Auxiliary Systems

Substations require auxiliary systems such as cooling systems, fire detection and protection, low and medium voltage switchgear, and safety, navigational, and other signaling and rescue systems. Supervisory control and data acquisition (SCADA) and automatic protection schemes are also part of a substation’s auxiliary systems.

DC Chopper

A DC chopper protects the DC network from overvoltage and allows the HVDC system to ride through HVAC system faults. When moving to integrated HVDC grids, it will also rebalance poles to allow continued operation of the HVDC grid after clearing a HVDC fault. For a fault in the onshore HVAC grid in a point-to-point connected offshore wind farm, a DC chopper acts as a firewall by absorbing the excess power generated by the wind farm that cannot be transmitted to the onshore grid during the fault.

Offshore Substation Foundation or Platform

An offshore substation foundation or platform is the substructure that the topside is placed on top of. A fixed offshore substation foundation will likely be a monopile, jacket, or gravity-based structure. A floating offshore substation platform may follow a semi-submersible, spar, barge, or tension-leg platform concept.

- **Monopile Structure:** A monopile structure is a fixed foundation consisting of a single, generally large-diameter, structural element that supports the entire load of a large above-surface structure.
- **Jacket-based:** A jacket-based foundation is a fixed foundation with a lattice-frame structure that supports offshore wind structures.
- **Gravity-based:** A gravity-based foundation is a fixed foundation with a very heavy displacement structure, usually made of concrete. The gravity base, which applies vertical pressure to the area below, stands on the seabed.
- **Semi-submersible:** A semi-submersible platform design is a multi-legged floating structure with a large deck**.**
- **Spar:** A spar platform is a cylindrical, partially submerged floating offshore platform, similar to a very large buoy.
- **Barge:** A barge platform is extended from semi-submersible concept. It is a concrete or steel floating hull with shallow draft to support the structure on top.
- **Tension-Leg Platform:** A tension-leg platform is a floating substructure that is vertically moored to the seafloor by tendons.

Substation

A substation is a part of an electrical generation, transmission, and distribution system that transform voltage from high to low, or vice versa, and perform other functions. In the context of transmission from offshore wind farms, substations can be high voltage alternating current (HVAC) or high voltage direct current (HVDC), and there are offshore and onshore substations. Offshore substations can be fixed, floating, or subsea.

	Offshore	**Onshore**
HVAC	An **offshore HVAC substation** collects power generated by an offshore wind farm and transforms it to a higher voltage for transport to the onshore grid connection.	An **onshore HVAC substation** receives high voltage AC power from the offshore substation and transforms it to integrate with the onshore transmission or distribution grid.
HVDC	An **offshore HVDC substation**, also known as an **offshore HVDC converter station**, collects power generated by an offshore wind farm, transforms it to a higher voltage, and converts it to direct current for transport to the onshore grid connection.	An **onshore HVDC substation**, also known as an **onshore HVDC converter station**, receives high voltage DC power from the offshore substation, converts the current to AC, and transforms it to integrate with the onshore transmission or distribution grid.

Switchgear

Switchgear defines equipment installed on the power system which fulfills the need to safely and securely allow the flow of power. Switchgear plays roles in controlling the operation of the power system, protecting assets from damage during unexpected events, and isolating parts of the system prior to reconnecting them during maintenance or unplanned outages. Unlike circuit breakers, which are automatically operated in case of a fault, switchgear is controlled by an operator.

Switchgear can be air-insulated or gas-insulated. **Air-insulated switchgear** (AIS) uses air as its insulating medium between phases and requires more space than **gas-insulated switchgear** (GIS), as air is a worse insulator than SF_6, the gas typically used in gas-insulated switchgear.

Switchyard

A switchyard is a substation that operates at a single level of voltage, without transformers.

Topside

The topside of an offshore substation is a large steel structure placed on top of the foundation. This structure contains the electrical and auxiliary equipment and control systems. The size of the topside and the electrical equipment it contains will differ for HVAC and HVDC systems.

B.4 Meshed Grids

Meshed Offshore Transmission Grid

In a meshed or networked offshore transmission grid, energy generators are connected to each other via offshore transmission infrastructure (shared collector substations, connected by high voltage cables) and are connected to multiple connection points onshore.

Meshed Offshore Transmission Grid Concepts

- **Radial Connection:** A point-to-point connection between a single wind farm and a single onshore connection point.

- **Shared Substations:** Multiple wind farms connecting into a single offshore substation.

- **Meshed Cables:** Multiple wind farms connecting to a single offshore substation, which is then connected to other offshore substations which are each connected to shore.

- **Offshore Backbone:** Multiple wind farms connecting to a single offshore substation, which is connected to other offshore substations using high capacity cables, reducing the number of onshore connection points needed.

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