1c Introduction to HVDC for Offshore Wind

Modules for Maturing HVDC Electric Transmission Knowledge

Primary Author	Xin Fang, Mississippi State University
Email Address:	xfang@ece.msstate.edu
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Prerequisite Competencies:	1. Introduction to HVDC technology 2. HVDC converter types and operations as found in Modules 1a, 1b.
Module Objectives:	1. Identify components of offshore wind power plants 2. Distinguish from AC and DC offshore wind power plants. 3. Identify technologies in HVDC-connected offshore wind power plants

Abstract

In contrast to AC-connected offshore wind power plant integration, high voltage direct current (HVDC) has been increasingly used to connect large-scale offshore wind power plants to the in-land transmission network. The fact that offshore wind power plants are increasingly larger in size and located further away from shore, forced by environmental and social factors, makes it more interesting to connect via HVDC technology.

This module aims to provide a general overview of HVDC-connected offshore wind power plant designs, considering using both AC and DC designs connected to the main grid through HVDC. It focuses on offshore wind power plant overview in Section 2, topology in Section 3, offshore equipment sizing in Section 4, offshore AC/DC transmission economic comparison in Section 5, and Section 6 summarizes the main learning points and concludes. The module focuses on offshore wind power plants topology, offshore equipment limits, offshore transmission options, and economics.

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Acronyms

AC	Alternating current
CSC	Current source converter
DC	Direct current
HVDC	High voltage direct current
IGBT	Insulated gate bipolar transistor
LCC	Line commutated converter
MISO	Midcontinent Independent System Operator
MVAR	Mega-volt-ampere-reactive
PTP	Point to point
SVC	Static var compensator
VSC	Voltage source converter

1c-1 Introduction

Offshore wind power is experiencing unprecedented global expansion, driven by rapid technological advancements, ambitious renewable energy targets, and the superior wind resources available at sea. Offshore wind farms benefit from higher and more consistent wind speeds than their onshore counterparts, resulting in increased energy yield and improved efficiency. As a result, offshore wind projects are growing in scale and being developed at greater distances from shore, necessitating robust and efficient transmission solutions to integrate the generated power into onshore grids.

The transmission of offshore wind power to land presents several technical and economic challenges. The offshore wind power collection grid can be categorized into two main types: **Alternating Current (AC) grids** and **Direct Current (DC) grids**. Traditionally, **High Voltage Alternating Current (HVAC) transmission** has been employed for offshore wind integration due to its well-established infrastructure and cost-effectiveness for short distances. However, as offshore wind farms are built farther from shore—often exceeding 50 km—HVAC transmission becomes less viable due to power losses, reactive power compensation requirements, and increased cable costs.

To overcome these limitations, **High Voltage Direct Current (HVDC) transmission** has emerged as a preferred solution for long-distance offshore wind integration. HVDC technology offers several advantages, including reduced power losses over long distances, the ability to connect asynchronous grids, and enhanced stability in the transmission network. Unlike HVAC systems, HVDC transmission does not suffer from significant reactive power losses in submarine cables, making it particularly suitable for large-scale offshore wind farms located far from shore. **More information about HVDC technology can be found in module 1a "Intro to HVDC technology" and 1b "Application guide for HVDC transmission".**

HVDC technology for offshore wind integration can be broadly classified into two main types: Line-Commutated Converter (LCC)-HVDC Transmission. Also known as classic HVDC, this thyristor-based technology has been used for long-distance power transmission for decades. It offers high efficiency for bulk power transfer but requires a strong onshore AC grid for commutation, making it less suitable for offshore applications where grid strength is limited. Voltage Source Converter (VSC)-HVDC Transmission: A more advanced and flexible solution, VSC-HVDC utilizes insulated-gate bipolar transistors (IGBTs) to enable independent control of active and reactive power. This makes it highly suitable for offshore wind integration, as it can operate without a strong AC grid and allows for black-start capability, modular scalability, and improved system stability. **More information about VSC-HVDC technology can be found in module 2b "VSC-HVDC converter station technologies" and information about the IGBT in converters can be found in module 3c "Operation of thyristors and IGBTs in converters".**

This chapter provides an in-depth exploration of both AC and DC offshore wind power transmission topologies, with a particular emphasis on the role of HVDC technology in offshore wind integration. We will examine the key technical considerations, benefits, and challenges associated with different transmission solutions, offering a comprehensive understanding of the evolving landscape of offshore wind power transmission.

1c-2 Overview of Offshore wind power plants in the USA and the globe

Offshore wind power is a crucial component of the global renewable energy transition. The industry has seen significant growth, particularly in Europe, China, and the United States. Despite rapid development, challenges such as transmission infrastructure, rising costs, and supply chain constraints persist. High-voltage direct current (HVDC) transmission is increasingly adopted in offshore wind projects to efficiently transmit electricity over long distances, reducing losses compared to high-voltage alternating current (HVAC). HVDC is especially critical for large-scale offshore wind farms located far from shore, ensuring grid stability and integration.

1c-2.1 Offshore wind power plants with HVDC in the USA

The offshore wind power has a great potential in the USA. The wind speed is higher and more constant compared to onshore locations, as shown in Figure 1. Therefore, currently there are multiple offshore wind power plants under construction and planning on both the east and west coast. Many of the these under construction and planning offshore wind power plants will connect to onshore electric grid through HVDC.

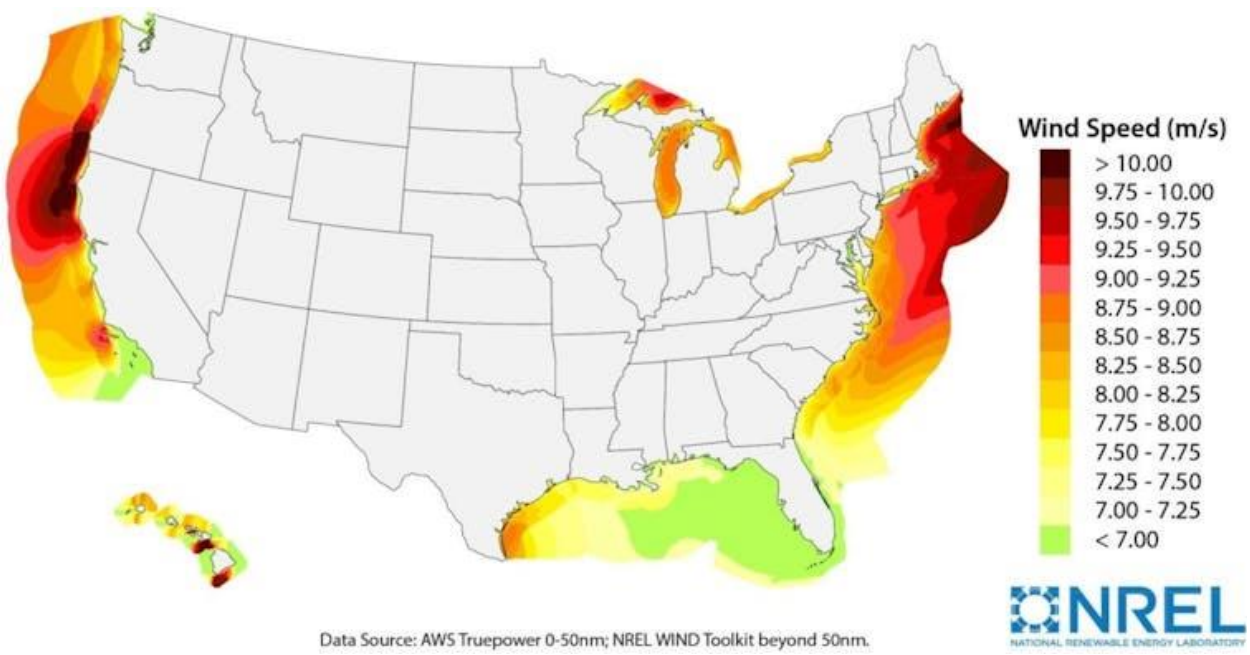

Figure 1. The U.S. Northeast and Northern California have the nation’s strongest offshore winds. (NREL)

Nearly two dozen projects are moving forward in the United States (mainly on the east coast), as shown in Figure 2. Most activity is localized on the East Coast, an ideal location for offshore wind development due to strong winds, shallow waters, and proximity to major population centers. U.S. offshore wind turbines currently use foundations fixed directly to the ocean floor in the shallow waters of the Atlantic Outer Continental Shelf to allow for easier installation. While development has primarily occurred in the Atlantic Ocean, the federal government recently initiated siting processes to expand offshore wind to the Pacific Ocean and the Gulf of Mexico, making offshore wind a national industry.

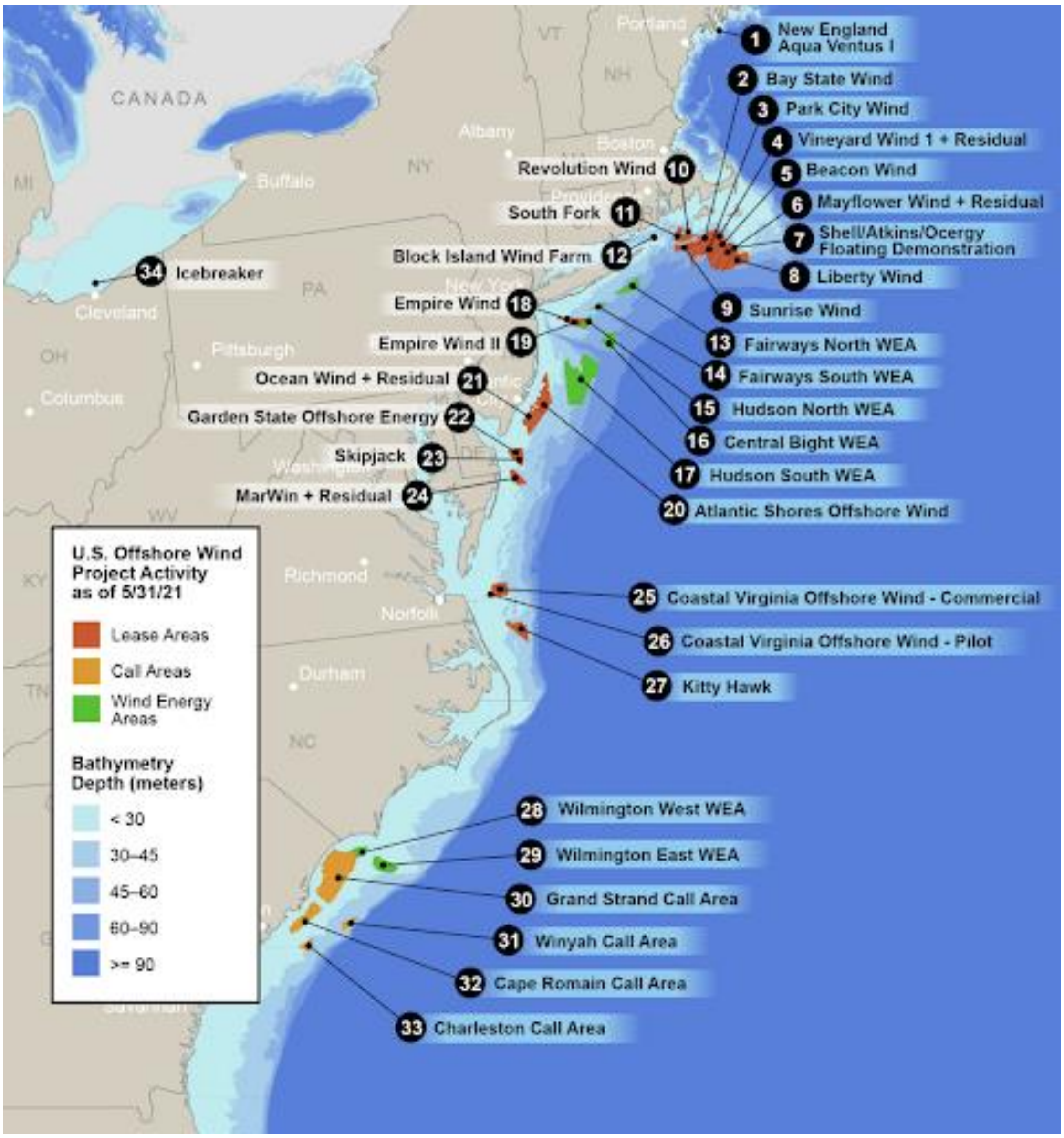

Figure 2 Current planned offshore wind power plants in the USA east coast. (source: National Renewable Energy Laboratory)

East Coast Offshore wind

SouthCoast Wind 1

Capacity: With its proximity to offshore wind energy areas, maritime workforce, and port infrastructure, the SouthCoast region is well suited to grow an offshore wind industry cluster with well-paying jobs, and supply chain and economic development opportunities. The offshore wind lease area, which is located 30 miles south of Martha's Vineyard and 20 miles south of Nantucket has the potential to generate more than 2,400 megawatts (MW) of renewable energy which is enough to power more than one million homes.

SouthCoast Wind will deliver the first 1,200 MW of energy via SouthCoast Wind 1, connecting to the New England regional electric grid at Brayton Point in Somerset, MA. It expects to deliver clean energy from SouthCoast Wind 1 by the end of the 2020s.

SouthCoast Wind is also looking at Brayton Point for interconnection of the second 1,200 MW of electricity generated in the lease area. Falmouth, MA continues to remain an option for this second phase while grid capacity and timing of necessary upgrades are determined.

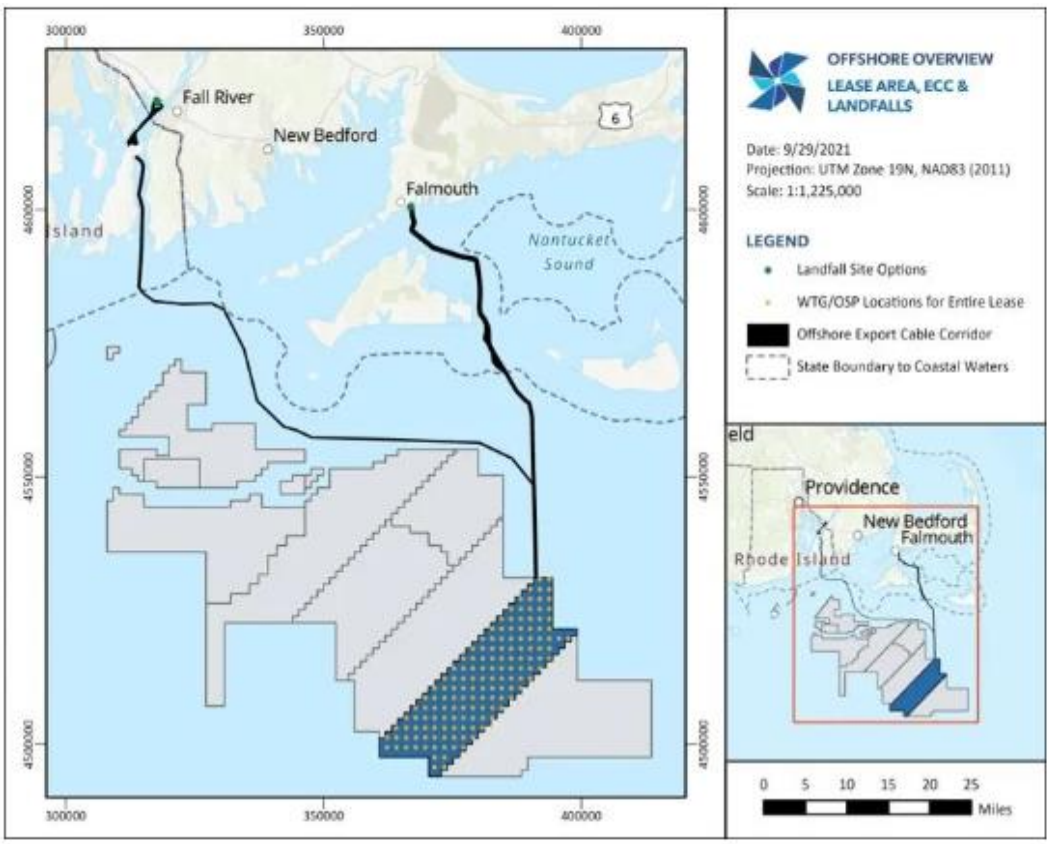

Figure 3. Lease areas of SouthCoast [1]

[1] https://southcoastwind.com/southcoast-wind-1/#:~:text=Onshore%20Underground%20Export%20Cables%20%E2%80%93%20From,deliver%20electricity%20to%20end%20customers.

HVDC Connection: The project is designed to use HVDC transmission to efficiently connect to the New England power grid. ±320 kV direct current, shown in Fig. 3.

The project will use state-of-the-art HVDC technology that minimizes marine cabling, reduces energy losses, and strengthens the New England grid.

The onshore converter station at Brayton Point will be a specialized electrical substation designed to convert the HVDC power from the export cables to HVAC power to enable interconnection to the existing transmission infrastructure.

The converter station will contain equipment necessary to provide power quality conditioning to ensure that the proposed Project's connection meets the technical requirements administered by the regional grid operator, ISO-NE.

Substation/converter station buildings are anticipated to be pre-engineered metal panel buildings or precast concrete buildings, depending on thermal design requirements. A new underground 345-kV transmission line will be constructed entirely within the previously disturbed, industrial site. The underground transmission line will connect the converter station to the existing point of interconnection, the National Grid substation, at Brayton Point in Somerset, Massachusetts.

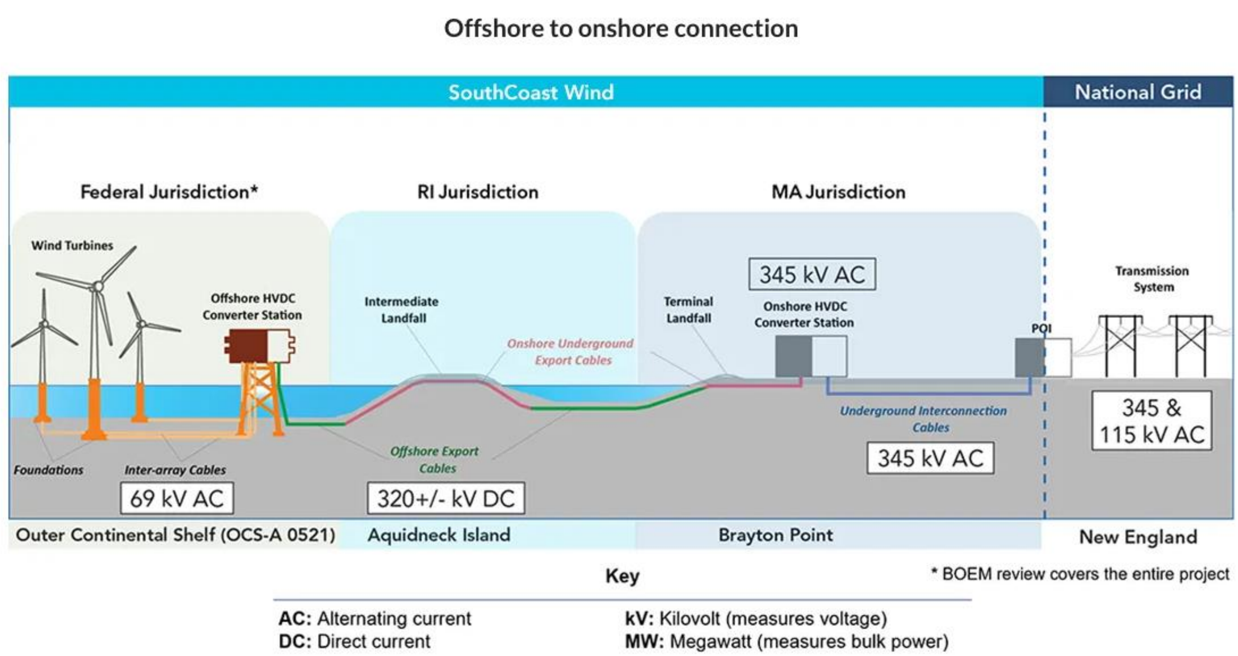

Figure 4. Offshore to onshore connection illustration[1]

Figure 5. Converter station in HVDC[1]

Sunrise Wind (New York)

- **Capacity:** 924 MW
- **HVDC Connection:** This project, developed by Ørsted and Eversource, will be ab **offshore wind project in the U.S. to use HVDC transmission ($\pm$ 320 kV 100 miles submarine cable)**. The HVDC technology enables efficient energy transfer over long distances to the New York grid.
- **Status:** Expected to be operational by 2027
(Ørsted, 2024)

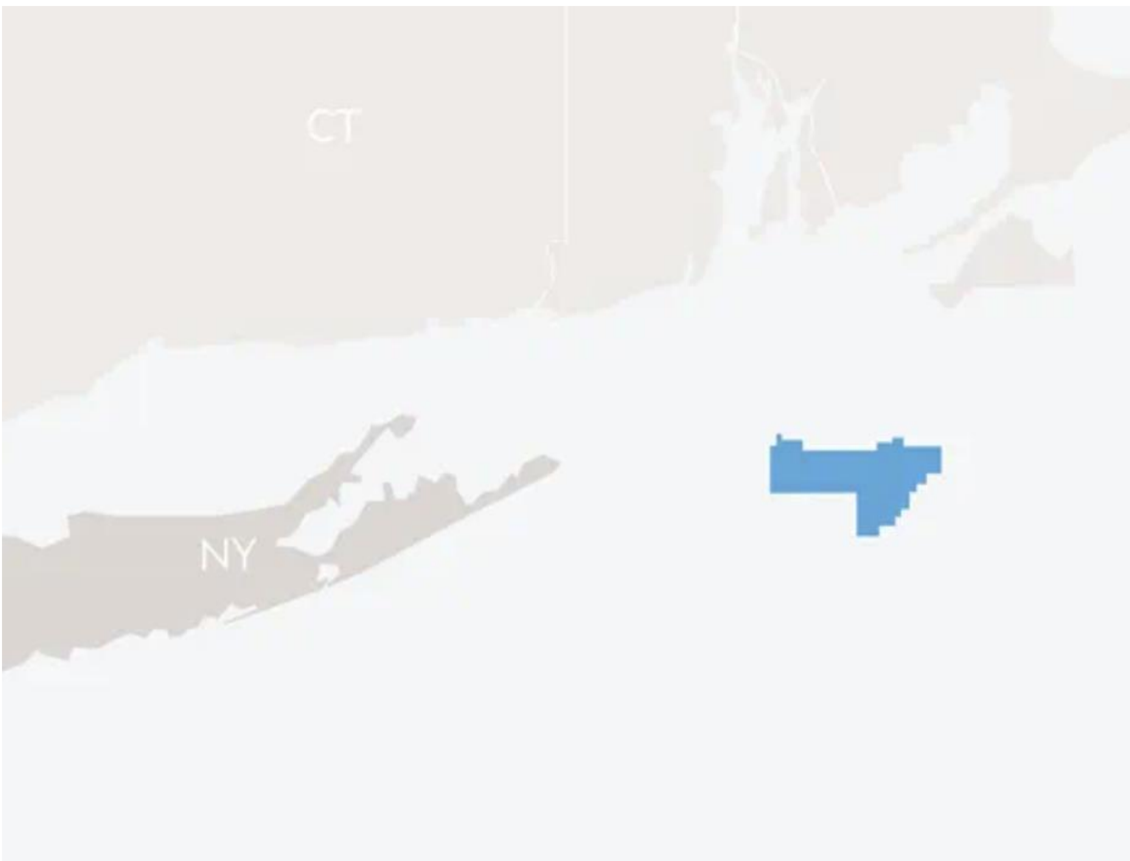

Figure 6. Location of Sunrise Wind NY[2].

[2] https://sunrisewindny.com/about-sunrise-wind

West Coast Floating Offshore Wind (California & Oregon)

As of March 2025, the U.S. West Coast is actively exploring offshore wind energy, focusing on floating wind turbine technology due to the deep waters off California and Oregon. Below is an overview of ongoing and potential offshore wind projects in this region:

California Offshore Wind Projects

In December 2022, the Bureau of Ocean Energy Management (BOEM) auctioned five lease areas off California's coast, marking a significant step toward offshore wind development. The lease areas and their respective developers are:

- Offshore Northern California (OCS-P 0561): RWE Offshore Wind Holdings secured a 63,338-acre lease. RWE Offshore Wind Holdings, LLC subsequently assigned the lease to Canopy Offshore Wind, LLC. RWE has not submitted a Construction and Operations Plan (COP) for BOEM review.

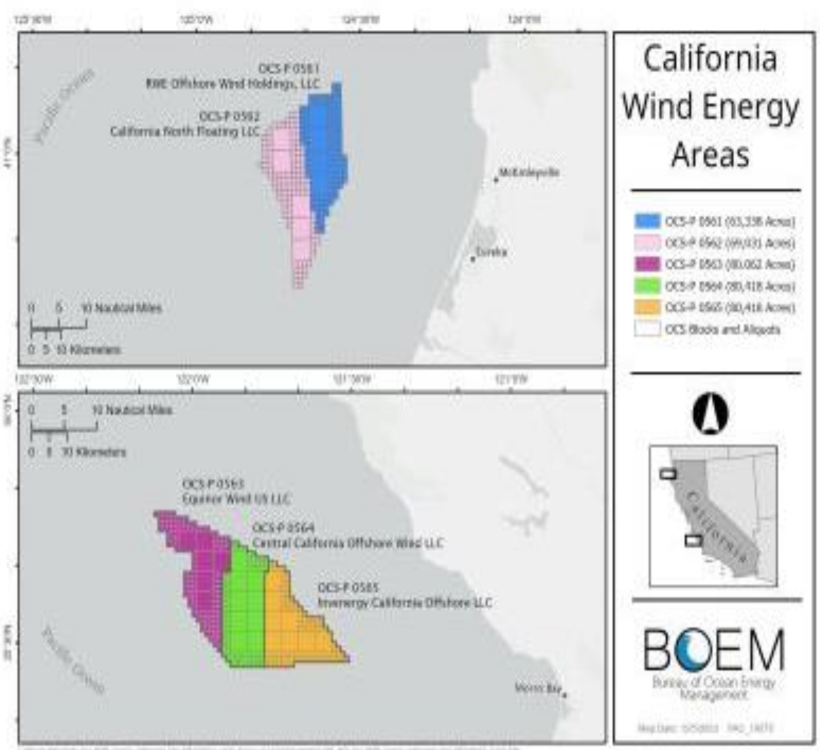

Figure 7. Canopy offshore wind (OCS-P 0561)[3]

[3] https://www.boem.gov/renewable-energy/state-activities/canopy-offshore-wind-llc-ocs-p-0561

- Offshore Northern California (OCS-P 0562): California North Floating obtained a 69,031-acre lease.
- Offshore Central California (OCS-P 0563): Equinor Wind US acquired an 80,062-acre lease.
- Offshore Northern California (OCS-P 0564): Central California Offshore Wind holds an 80,418-acre lease.
- Offshore Northern California (OCS-P 0565): Invenergy California Offshore received an 80,418-acre lease.

These projects are in the early stages, with developers conducting site assessments and environmental reviews to inform future development plans.

Oregon Offshore Wind Initiatives

Oregon is exploring offshore wind energy, particularly focusing on floating wind turbines. However, local opposition has arisen due to concerns about environmental and cultural impacts. Tribes and fishermen are particularly concerned about harm to sea life and cultural sites. Despite these challenges, the state aims to achieve 100% clean electricity by 2040, necessitating the exploration of new renewable sources.

Challenges and Considerations

The development of offshore wind energy on the West Coast faces unique challenges, including deep ocean waters requiring advanced floating turbine technology, environmental considerations, and the need for collaboration with local communities and stakeholders to address cultural and ecological concerns.

As these projects progress, they will contribute to the diversification of the region's renewable energy portfolio and support state and federal clean energy goals.

Great Lakes Offshore Wind

As of March 2025, there are no operational offshore wind farms in the U.S. Great Lakes region. Despite the significant potential for wind energy generation in these freshwater bodies, various challenges have impeded development.

The National Renewable Energy Laboratory (NREL) estimates that the Great Lakes possess a potential capacity of 160 gigawatts (GW) for fixed-bottom wind turbines. This capacity could increase by an additional 415 GW with the advancement of floating foundation technology. However, several obstacles hinder the realization of this potential:

- Infrastructure Limitations: The St. Lawrence Seaway and Welland Canal locks are too narrow to accommodate the large vessels typically used for offshore turbine installation. Consequently, materials and equipment would need to be transported through these locks or constructed directly on the lakes, complicating logistics.
- Environmental Conditions: The Great Lakes experience icy climates, introducing uncertainties regarding the impact of ice formation on turbine structures. While not insurmountable, these conditions require careful consideration in design and maintenance.
- Regulatory and Environmental Concerns: Projects must address potential impacts on local ecosystems, including bird and bat populations, and navigate a complex regulatory landscape involving multiple state and national jurisdictions.

Several initiatives have been proposed to harness the wind energy potential of the Great Lakes:

- Icebreaker Wind Project: This pilot project aimed to install six fixed-bottom wind turbines on Lake Erie. However, it was put on hold in December 2023 due to various challenges, including environmental concerns and regulatory hurdles.
- Illinois Rust Belt to Green Belt Pilot Program Act: The Illinois House of Representatives passed H.B.2132, aiming to procure at least one new utility-scale offshore wind project with a capacity of at least 150 megawatts (MW) capacity. This initiative reflects a legislative effort to promote regional offshore wind development.
- Great Lakes Offshore Wind Energy Consortium: Several Great Lakes states, including Illinois, Michigan, Minnesota, New York, and Pennsylvania, have signed a bipartisan federal-state memorandum of understanding to support the review and development of offshore wind energy projects in the region.

While the Great Lakes region holds substantial potential for offshore wind energy, realizing this potential requires overcoming significant technical, environmental, and regulatory challenges. Ongoing legislative efforts and consortiums indicate a growing interest in developing this renewable energy resource, but as of now, no projects have reached operational status.

1c-2.2 Offshore wind power plants globally with HVDC

Dogger Bank Wind Farm (United Kingdom)

- **Capacity:** 3,600 MW (Three phases: A, B, C), the world's largest offshore wind power plant
- **HVDC Connection:** This project is the **first large-scale offshore wind farm in the UK to use HVDC transmission**. The world's first **unmanned offshore HVDC substation** was installed in 2023 for Dogger Bank A.
- **Status:** Dogger Bank A expected online in 2024, followed by B and C by 2026. (SSE Renewables, 2024)

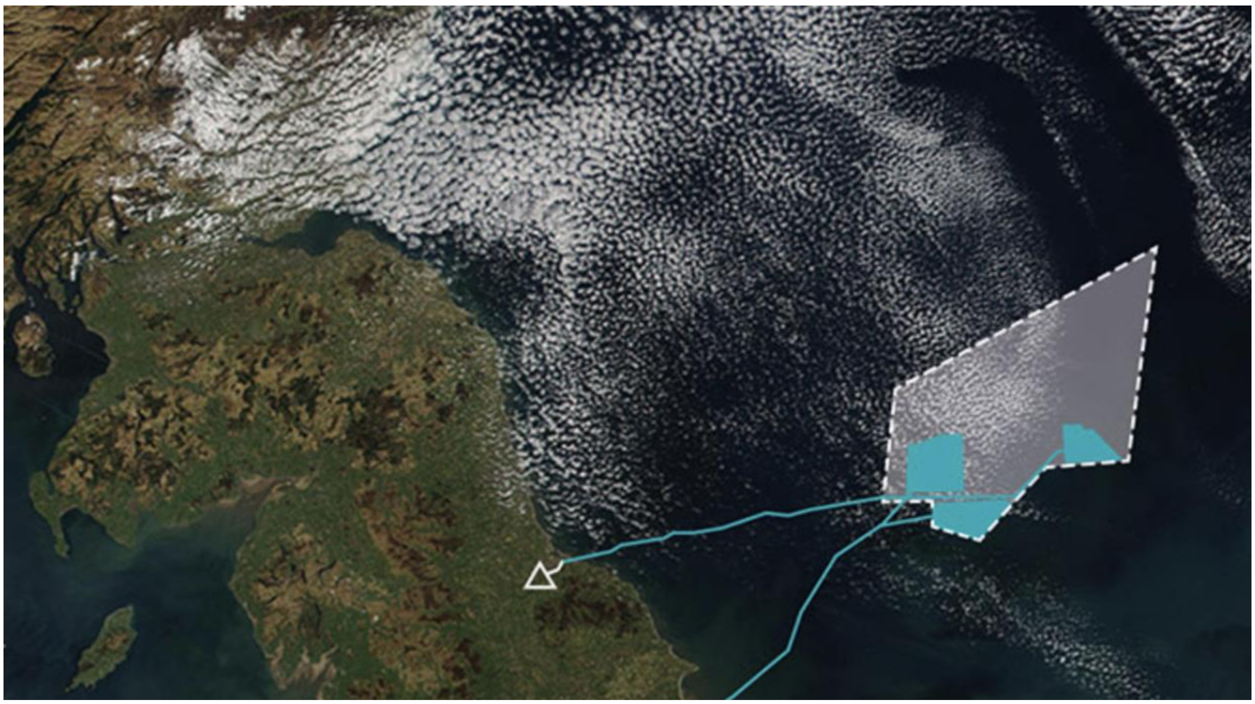

Figure 8. Location of Dogger Bank Wind Power Plants (around 131km from shore at its closest point and has a development area of around 515km^2)[3]

3. https://doggerbank.com/

BorWin2 (Germany)

- **Capacity:** 800 MW
- **HVDC Connection:** BorWin2 is an offshore HVDC link connecting North Sea wind farms to Germany's mainland grid. The system operates at **±300 kV** and transmits electricity over 200 km.
- **Status:** Operational since 2015.
(TenneT, 2024)

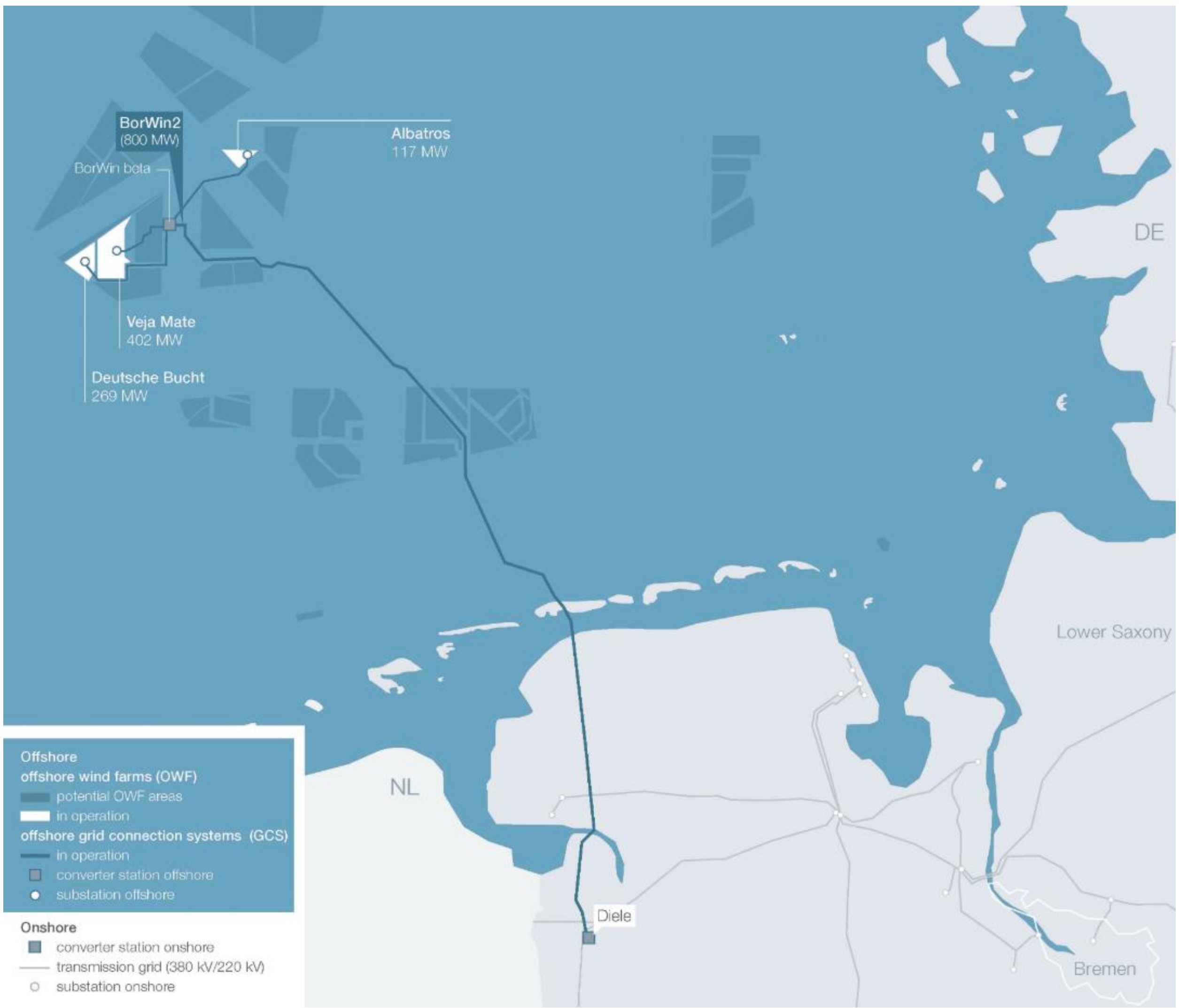

Figure 9. Location of BorWin2[4]

4. https://www.tennet.eu/de-en/projects/borwin2

LionLink (United Kingdom-Netherlands)

- **Capacity:** 1,800 MW
- **HVDC Connection:** A proposed **HVDC interconnector** linking offshore wind farms in the North Sea to the UK and Dutch power grids.
- **Status:** In early development, with statutory consultations expected in 2025. (National Grid, 2024)

Korridor B Project (Germany)

- **Capacity:** 4,000 MW (Two 2 GW HVDC lines)
- **HVDC Connection:** Designed to transport offshore wind power from northern Germany to the industrial heartland, reducing grid congestion.
- **Status:** Planned for completion in the early 2030s. (Hitachi Energy, 2024)

Offshore wind power continues to grow globally, with increasing adoption of **HVDC transmission** for large, remote wind farms. HVDC transmission is becoming essential for large-scale offshore wind projects, particularly for wind farms located **over 100 km from shore**. While the **U.S. is beginning to adopt HVDC** with projects like **Sunrise Wind**, Europe remains a leader with major **HVDC offshore hubs** in the North Sea. As offshore wind expands, **HVDC technology will play a key role** in efficiently integrating renewable energy into national grids.

1c-3 Topologies of Offshore wind power plants with HVDC lines

1c-3.1 Overview of HVDC-connected Offshore Wind Power Plant

AC offshore wind power collection

The use of AC offshore wind power collection networks remains a practical and widely adopted solution, particularly for smaller-scale or nearshore wind farms, where established technology and cost-effectiveness are prioritized. AC systems leverage mature, standardized infrastructure, including transformers and circuit breakers, which simplifies design, installation, and maintenance. For shorter distances (typically under 50–80 km), AC transmission avoids the need for expensive power converters, reducing upfront costs and complexity. The technology also aligns seamlessly with the alternating current generated directly by wind turbines, eliminating the requirement for individual turbine-level AC/DC conversion. This makes AC collection networks inherently simpler for projects with clustered turbines and moderate transmission distances, where resistive and reactive power losses remain manageable through conventional compensation methods.

AC systems further benefit from compatibility with existing onshore grid infrastructure, minimizing integration challenges. Proven fault management—using widely available AC circuit breakers—ensures reliable isolation of faults without the technical hurdles associated with DC protection. While AC networks face limitations in scalability and efficiency for long-distance transmission, they remain a pragmatic choice for nearshore projects, offering a balance of reliability, lower technical risk, and cost efficiency in scenarios where advanced DC solutions may not yet justify their complexity or expense.

Figure 10 illustrates the layout of an offshore wind farm connected to the onshore grid through High Voltage Direct Current (HVDC) lines, a critical setup in modern offshore wind power generation. Offshore wind power plants (OWPPs) typically consist of a large number of wind turbines, ranging from a few dozen to several hundred, strategically arranged across a designated marine area. These turbines are interconnected through an offshore collection grid, which consolidates the electricity generated by each turbine and channels it to an offshore platform. This platform acts as a central hub, managing the transmission of electricity to the onshore grid.

The layout of wind turbines within the farm is carefully designed based on several key factors. These include the distribution of wind resources, such as prevailing wind directions, which ensure optimal energy capture. Additionally, the cost of cabling and the specific marine environmental conditions—such as seabed characteristics and water depth—also play significant roles in determining turbine placement. These considerations are crucial for maximizing efficiency and minimizing costs.

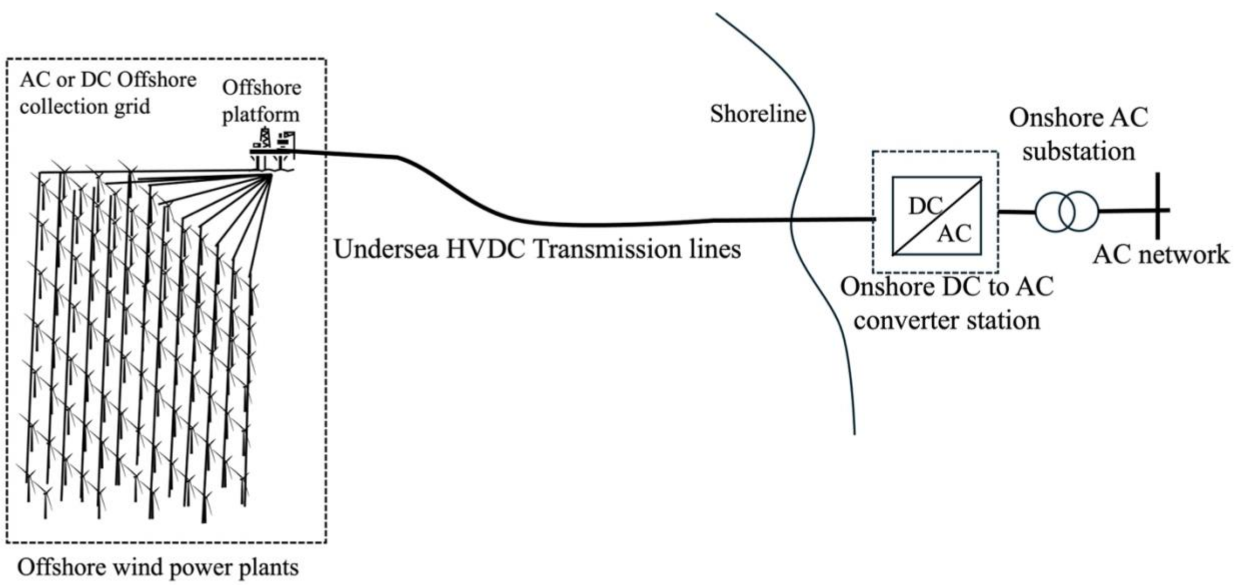

Figure 10: Single-line diagram of offshore wind power plants

The offshore collection grid, responsible for gathering the power generated by individual turbines, can be configured as either an AC (Alternating Current) or DC (Direct Current) system. In an AC collection grid, depicted in Figure *11* and Figure *12*, each wind turbine generates AC power, which is then transmitted to the offshore platform via AC cables. Once the AC power reaches the offshore platform, it is converted to DC power through an AC/DC converter. This DC power is then transmitted to the onshore grid via HVDC lines, which are particularly advantageous for long-distance transmission due to their lower losses compared to AC systems.

The choice between an AC and DC transmission to the onshore grid depends on various factors, including the distance from shore, the size of the wind farm, and the overall design strategy. As offshore wind farms continue to expand in scale and complexity, the integration of HVDC technology is becoming increasingly essential, providing a reliable and efficient means of connecting these vast renewable energy sources to the onshore power grid.

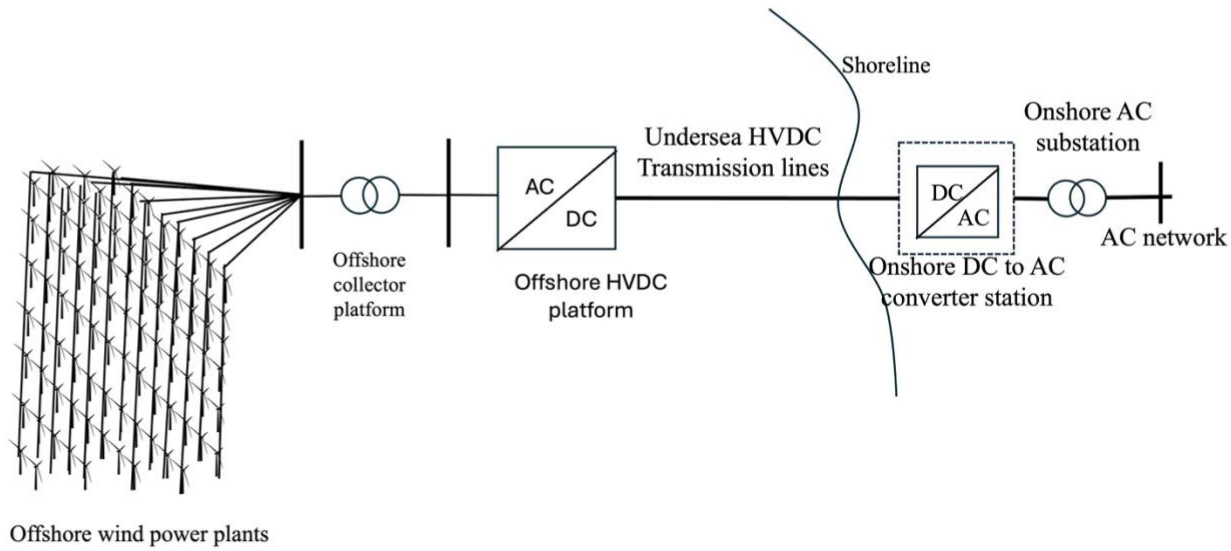

Figure 11. Example of AC connected OWPP with VSC-HVDC lines.

Figure 12. Typical scenario for using HVDC technology to connect offshore wind power to the main AC network [13].

DC offshore wind power collection

Beside the AC offshore wind power collection, there is an increasing discussion about using DC network for the offshore wind power collection. The use of DC offshore wind power collection networks over AC systems is driven by efficiency, cost, and scalability advantages, particularly for large-scale or distant wind farms. DC systems eliminate reactive power losses and cable charging currents inherent in AC networks, significantly reducing energy losses over long distances. This allows for higher voltage operation with thinner cables, lowering material and installation costs. Additionally, DC avoids synchronization challenges between turbines and simplifies integration of variable-speed generators, streamlining system design. By minimizing the need for bulky offshore AC substations and reactive compensation equipment, DC reduces infrastructure costs and platform footprint, critical in space-constrained marine environments.

DC collection also aligns seamlessly with high-voltage DC (HVDC) transmission, the preferred method for long-distance power export to shore. This integration removes intermediate AC/DC conversion stages, cutting losses and costs. While DC requires advanced power electronics and circuit protection, advancements in modular converters and hybrid breakers are addressing these challenges. Overall, DC networks future-proof offshore wind development by enabling scalable, interconnected grids and supporting the transition to larger, more remote projects, where efficiency and cost savings outweigh initial technical hurdles.

Figure *13* and Figure *14* shows an example of an OWPP with DC grids. The power from wind turbines is converted through a local AC/DC and DC/DC converter and then connected to the offshore platform through DC cables. Next, connect to the HVDC lines on the offshore platform.

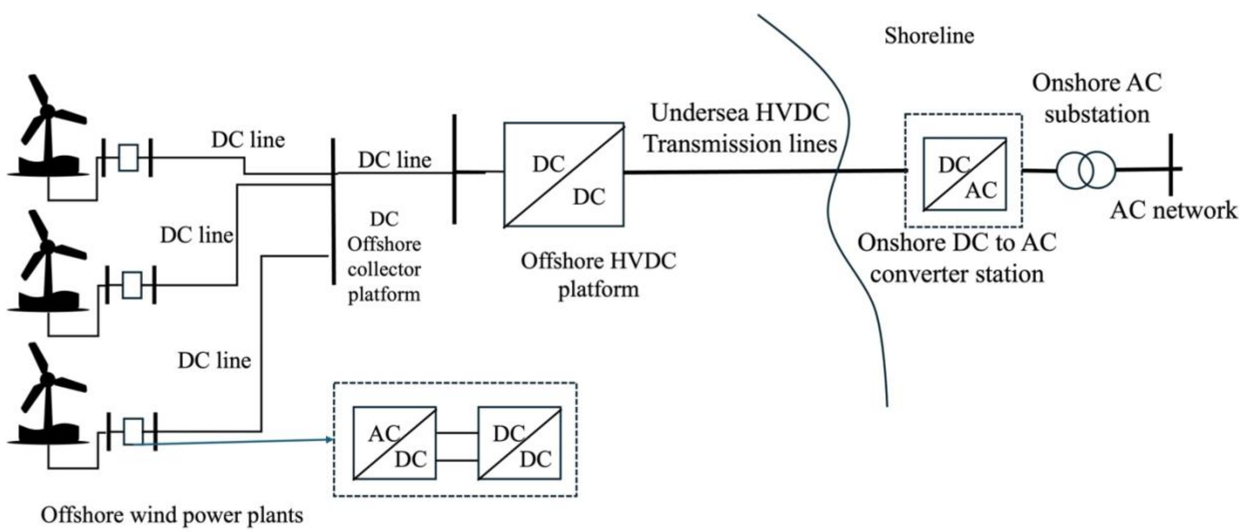

Figure 13. Example of DC connected OWPP with HVDC lines.

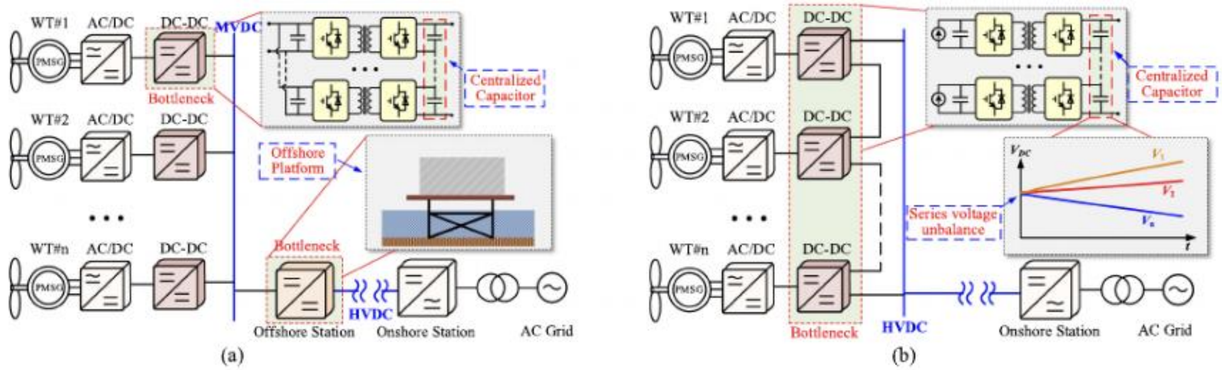

Figure 14. Traditional all-dc offshore wind power networking scheme. (a) Parallel networking scheme (b) Series networking scheme [14]

1c-3.2 Main components in Offshore wind power plants with HVDC

Offshore platforms

Offshore platforms are vital components that ensure the effective connection of the offshore grid to the mainland. These platforms can be categorized into two main types: **collector platforms** and **HVDC platforms**, as illustrated in Figure *15* and Figure 16.

Collector platforms, shown in Figure *15*, serve as intermediate points located between the Offshore Wind Power Plant (OWPP) and the HVDC substation. Their primary function is to gather the medium voltage alternating current (MVAC) inter-array cables from wind turbines and minimize electrical losses by stepping up the voltage from medium to high voltage (HV) just before the power is transmitted to shore.

Figure 15. Alstom's GIS collection substations

The collection substation in Figure *15* were installed on a platform at the Baltic Sea 2 offshore wind site. The platform was placed on a pre-installed jacket and brought out to the installation site where water depths reached 44 meters. The buoyant and self-erecting platform design enabled a high degree of flexibility and independency from crane ships for the transport and installation of the substation. The closed platform layout protects the electrical components from offshore conditions. (Credit: Alstom)

HVDC platforms, shown in Figure 16, on the other hand, are typically situated slightly away from the OWPP to facilitate connections with other OWPPs. These platforms transmit the combined power generated by multiple OWPPs through a single HVDC link. Structurally, these platforms consist of a foundation and a topside.

The topside of the platform houses essential equipment needed to operate the substation, including the HVDC converter, transformers, switchgear, backup diesel generators, ventilation coolers, and winches for hoisting subsea cables. The topside also includes facilities for personnel, such as living quarters, a crawler crane, a helipad, a boat landing, safety gear, and a meteorological mast. When designing the topside, factors like water depth and the size of the wind power plant are crucial considerations. Typically, a platform's topside can weigh around 2,000 tones, span an area of 800 square meters, and stand 25 meters above sea level. Large wind power plants may require more than one offshore platform.

Figure 16. Siemens Energy HVDC offshore wind converter station[5]

5. https://www.windpowerengineering.com/hvdc-transmission-comes-to-u-s-offshore-wind/

Foundation structures

Foundation structures, shown in Figure 17, for offshore platforms include several types: monopiles (similar to those used for wind turbines), hybrid or gravity-based foundations (consisting of a concrete caisson with a steel leg structure), and jacket constructions. The jacket structure, which has been extensively used in the offshore oil and gas industry, is a robust option for future offshore platforms. It typically features three or four main legs, depending on seabed conditions and platform weight, supported by piles at each corner of the foundation. Additionally, the jacket structure incorporates J-tubes to guide the inter-array cables from the offshore collection grid to the platform. This steel framework is not just a structural support for the topside; it is also engineered to withstand various challenges such as wave impacts, corrosion, and sea currents.

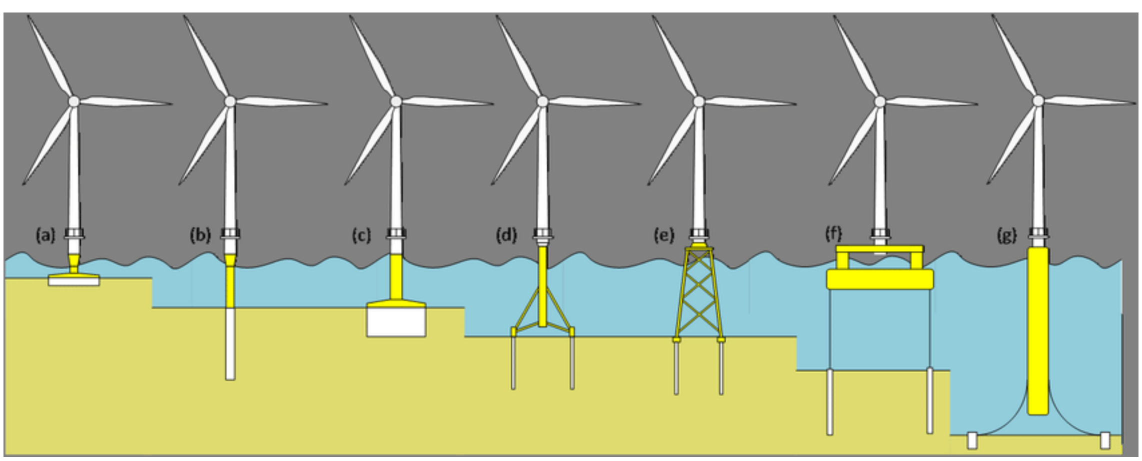

Figure 17. Support structures for offshore wind turbines. (a) Gravity based foundation, (b) monopile, (c) suction caisson, (d) tripod, (e) jacket, (f) tension leg platform and (g) ballast stabilised spar buoy (Houlsby and Byrne, private communication).

Given the massive size of these platforms and the challenges of constructing them at sea, they are entirely assembled on land and then transported to their offshore locations. When determining their placement, it is important to choose sites that allow for easy future access and do not interfere with inter-array or export cables.

DC circuit breakers

DC circuit breakers (DCCBs) are critical components in offshore wind power plants integrated with high-voltage direct current (HVDC) transmission systems, enabling safe and reliable operation of large-scale, far-from-shore wind farms. Unlike traditional AC grids, HVDC networks lack natural current zero-crossings, making fault interruption inherently challenging. DCCBs address this by rapidly isolating faults—such as short circuits in submarine cables or converter stations—to prevent cascading failures and ensure grid stability. Their role becomes indispensable in multi-terminal HVDC configurations, where interconnected wind farms and transmission links require selective fault clearance to maintain partial operation during disturbances.

Modern offshore wind projects increasingly adopt hybrid or solid-state DCCBs, which combine mechanical switches with power electronics to interrupt high DC currents within milliseconds. These breakers mitigate the risks of excessive thermal stress and voltage surges, protecting costly offshore infrastructure like converters and cables. As offshore wind farms expand and evolve into meshed DC grids, advancements in DCCB technology—such as modular designs and adaptive protection schemes—are overcoming historical limitations, including high costs and energy dissipation during interruption. By enabling efficient fault management, DCCBs underpin the transition to resilient, scalable HVDC networks, ensuring offshore wind remains a cornerstone of global renewable energy systems.

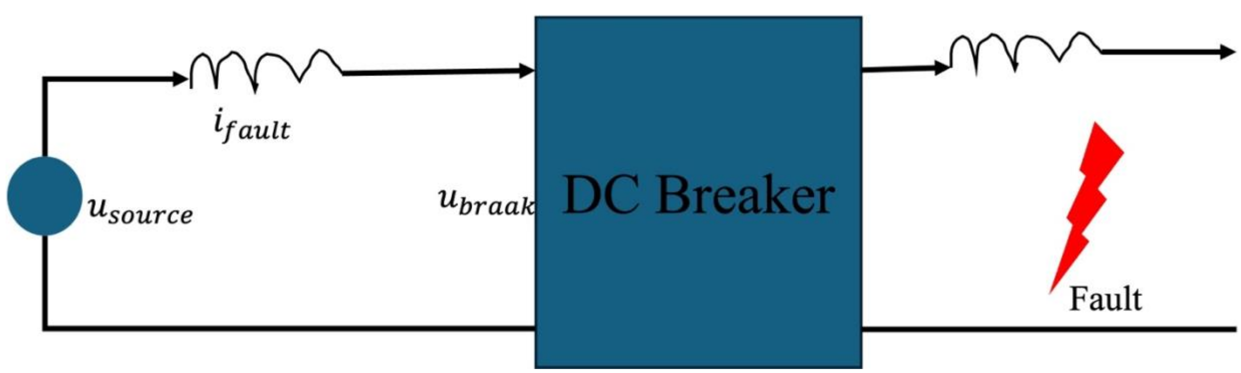

Figure 18. DC breaker in HVDC grid

Figure 19 PCS-8300 HV DC Circuit Breaker[6]

6. https://www.nrec.com/en/index.php/product/productInfo/350.html

National Grid's Offshore Design Example

A practical example of an OWPP connected via HVDC is provided by National Grid's reference design [1]. This design, referred to as HVDC1000, demonstrates the electrical system that connects the main onshore grid to an offshore substation platform built to operate an AC OWPP with an HVDC transmission link. The detailed single-line scheme is shown in Figure 20.

In the HVDC1000 design, three offshore platforms are utilized: one hosting a VSC converter and two 520-MVA substations, along with one onshore VSC converter station platform. The radial feeders from the wind turbine array are connected directly to one of the two 520 MVA AC intermediate collector platforms. The arrangement of these AC offshore platforms mirrors that of the AC900 scheme, with the notable exception that no shunt reactor is required. To enhance reliability, two 320 MVA tertiary transformers are installed on each platform. Both platforms are connected directly to the solid bus of the VSC offshore platform using 3-core AC submarine cables rated at 220 kV. Similarly, the onshore and offshore VSC station platforms are linked by two 300-kV submarine dipole cables. Finally, the HVDC VSC converts the 300-kV DC voltage into 400-kV AC for integration into the main onshore grid, with the primary winding of the autotransformer solidly earthed.

This DC technology-based design is theoretically more cost-effective than any AC scheme when dealing with large power ratings (over 1000 MW) and locations that are far from shore.

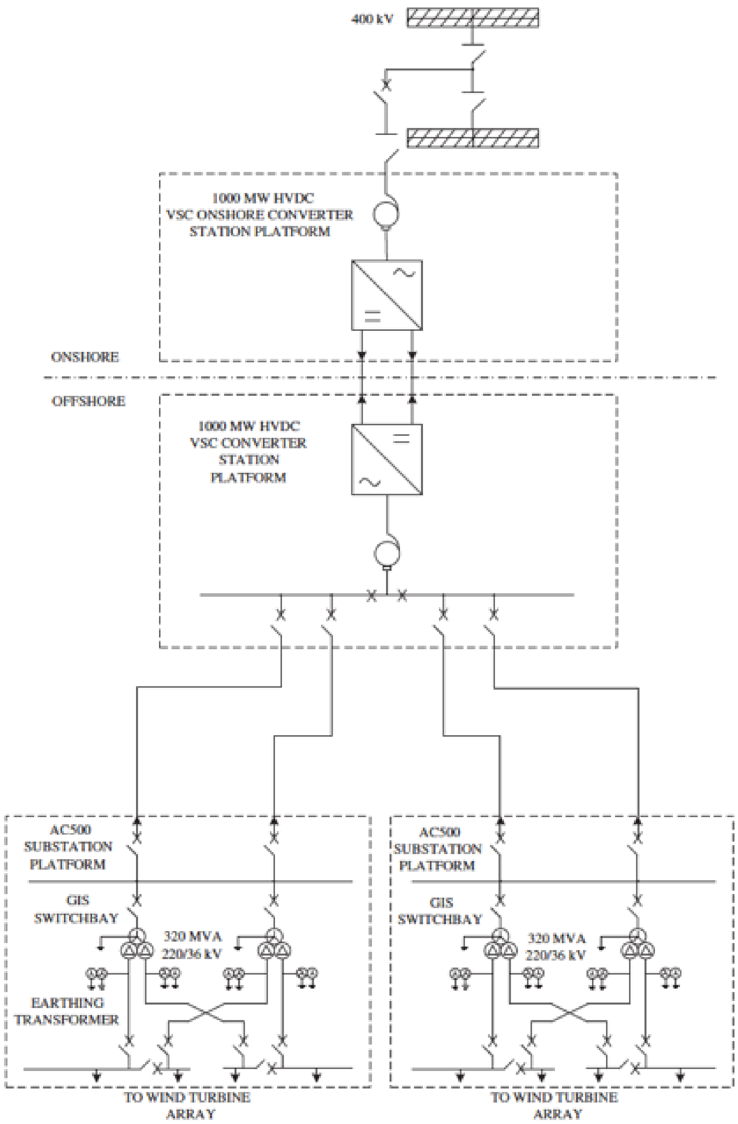

Figure 20. Single-line diagram based on the HVDC1000 scheme proposal based on National Grid's reference offshore design arrangements [1].

1c-3.3 AC collected Offshore Wind Power Plant Topologies

There are several kinds of topologies used for AC and DC OWPP for their offshore collection grids. For AC OWPP, there are mainly three different possible connection designs know as radial, ring, and star [3-7].

Radial: The radial connection system is the most common utilized configuration for offshore wind power plants due to its simplicity and cost-effectiveness. In this system, wind turbines are connected in a string configuration, where multiple turbines are linked to a single feeder, as shown in Figure *21*.. The maximum number of turbines that can be connected is determined by the cable ampacity and the rated power of the generators. Despite its popularity, the radial system does have reliability concerns. A failure in the cable connecting the first turbine to the feeder's hub can result in a complete loss of power from all downstream turbines in the string, highlighting a significant vulnerability in this otherwise economical setup [3-6].

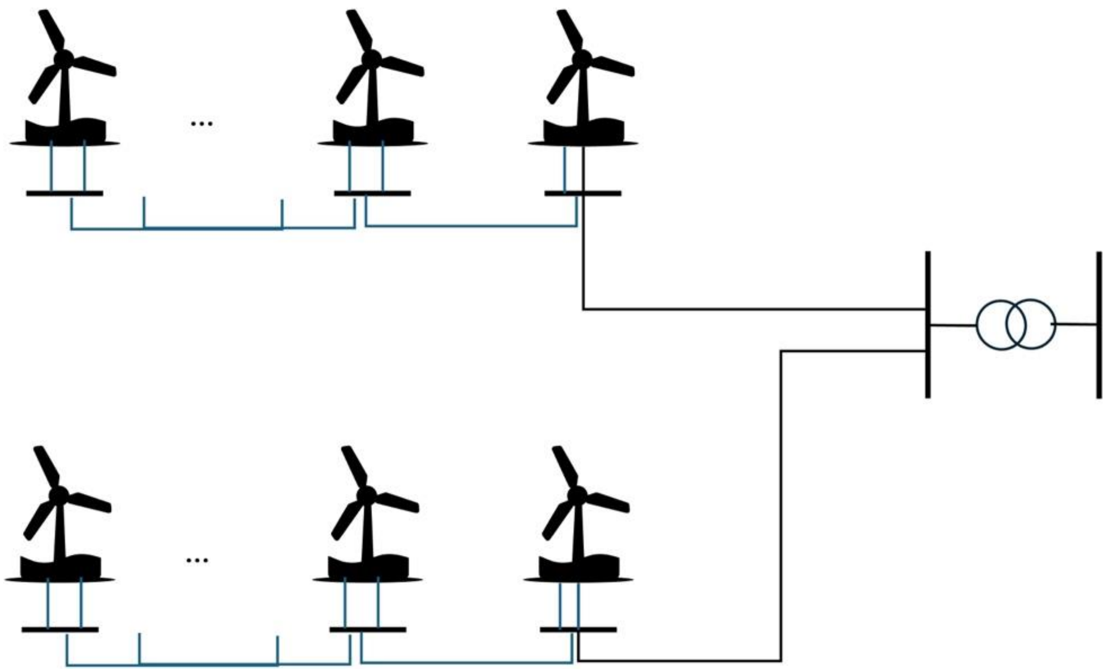

Figure 21. Radial collection configuration.

Ring: The ring collection system (shown in Figure 22) represents an enhanced design for offshore wind power plants, offering improved reliability compared to the radial system. This design incorporates redundant cables that create alternative pathways for power flow, thereby mitigating the impact of any single cable failure. Different configurations of the ring system, such as single-sided, double-sided, and multi-ring designs, provide varying levels of redundancy [8]. For instance, in a single-sided configuration, a cable connects the outermost turbine directly to the collector hub, while a double-sided ring connects two feeders with an additional cable. However, this increased reliability comes at a cost, as some cables need to be oversized to accommodate bidirectional power flow in the event of a failure, adding to the overall expense of the system.

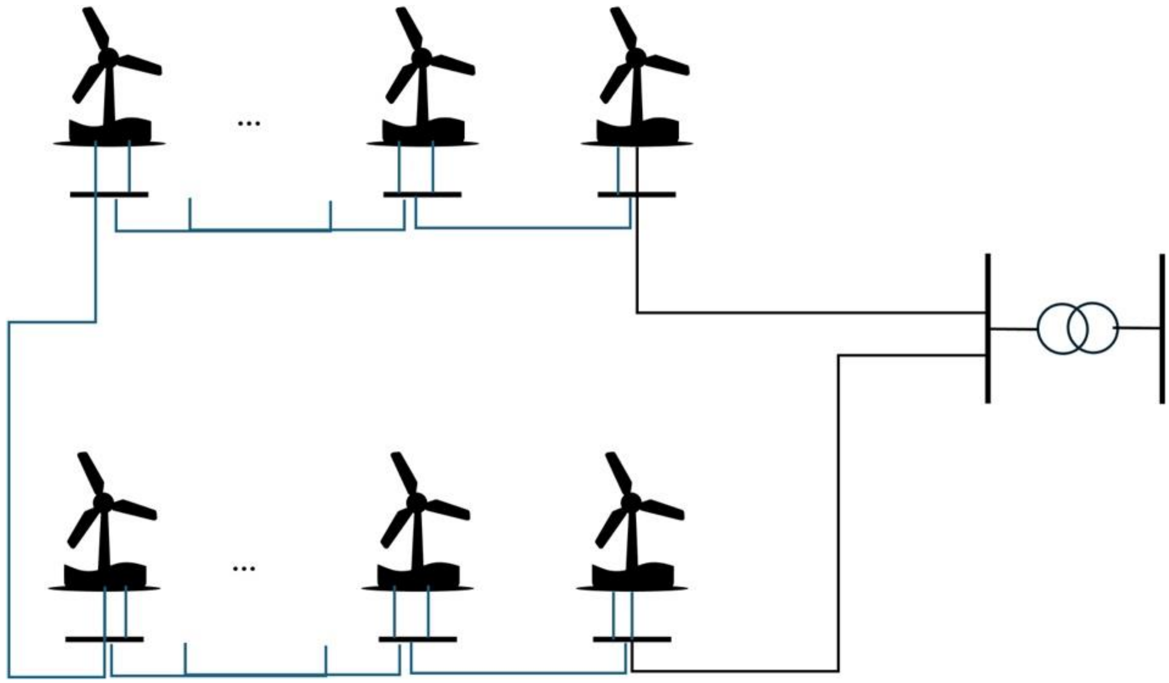

Figure 22. Ring collection configuration.

Star: The star collection system (as shown in Figure 23) is designed to optimize the cable ratings between wind turbines and the central collector point in offshore wind power plants. Typically, the collector point is strategically positioned at the center of the wind turbine array, minimizing the distance between each turbine and the collector. This topology enhances the system's reliability, as a cable failure impacts only the turbine directly connected to it, rather than the entire string of turbines. However, this improved reliability comes with trade-offs. The longer cable lengths required in a star configuration, combined with the use of lower voltage ratings, lead to increased cable losses and higher overall costs compared to other wind power plant designs. Despite these drawbacks, the star configuration remains a viable option for enhancing the reliability of offshore wind farms [9].

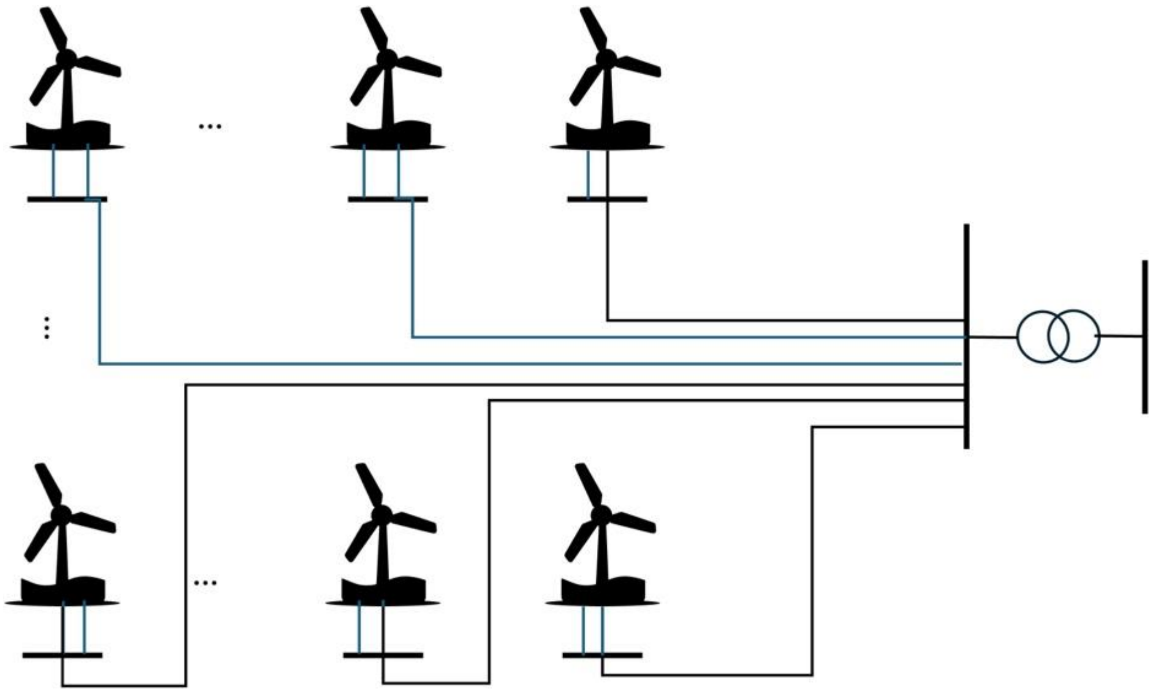

Figure 23. Star collection configuration

1c-3.4 DC collected Offshore Wind Power Plant Topologies

For DC OWPP, there are three typical topologies: parallel topology, series topology, and hybrid topology.

Parallel Topology

In the parallel, or shunt, topology, wind turbines are electrically connected in parallel, as depicted in Figure 24. This configuration ensures that the output voltage of each wind turbine remains constant, while the current flowing through the inter-array cables is determined by the number of turbines connected. The total power delivered by each feeder is expressed as:

$$P_{feeder} = V_{wt} \sum i_{wt}$$

This topology closely resembles the conventional AC system, making it a logical first step for the development of DC Offshore Wind Power Plants (OWPPs). Various design alternatives for OWPPs based on the shunt topology are possible, with the four most common configurations described below:

- Configuration (a): In this setup, all DC cables are connected directly to the offshore HVDC converter platform. Each wind turbine's output voltage is stepped up by a DC/DC power converter, allowing the power to be transmitted at medium voltage DC.

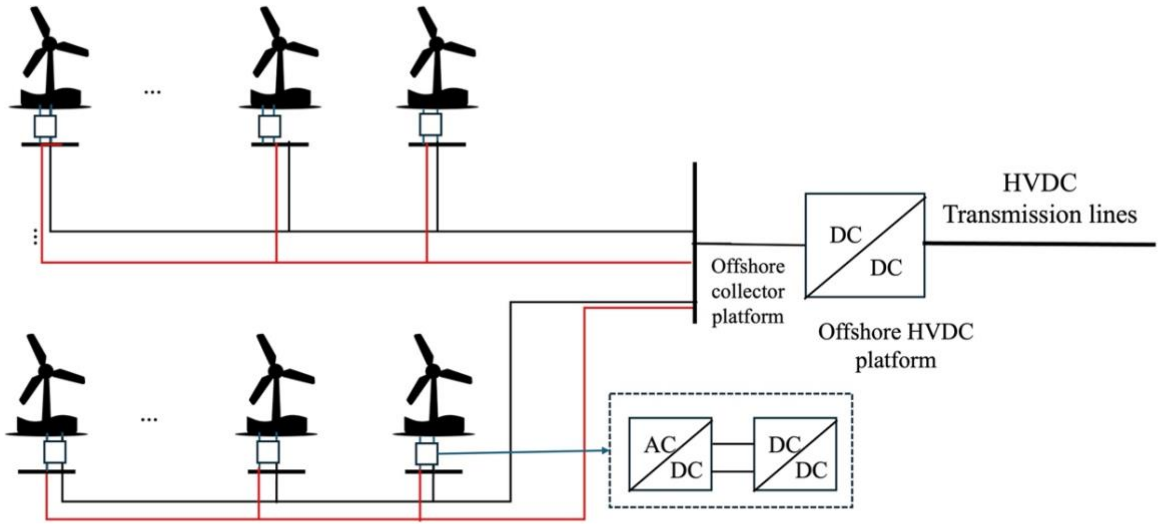

Figure 24. Configuration (a) of DC OWPP

- Configuration (b): Similar to the previous design, this configuration (shown in Figure 25) involves gathering all inter-array cables into an offshore collector platform. Wind turbines connect to this platform via the inter-array cables, and an export cable links the collector platform to the HVDC offshore platform. The voltage is stepped up using a DC/DC converter, and power is delivered to the onshore grid through an HVDC transmission link.

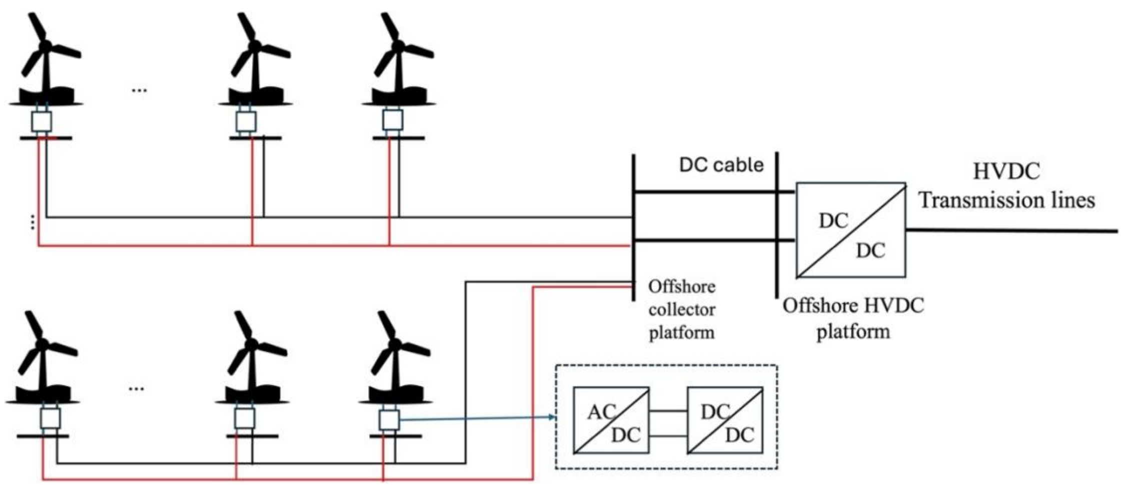

Figure 25. Configuration (b) of DC OWPP

- Configuration (c): To minimize export cable losses, this design proposes installing a DC/DC power converter on an intermediate offshore platform (Figure 26). As a result, the output voltage is stepped up twice—once at the wind turbine level and again at the collector platform.

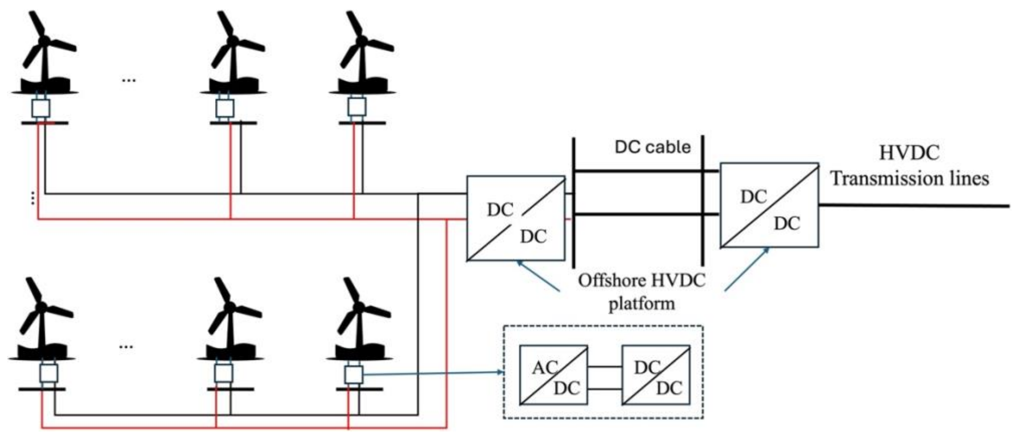

Figure 26. Configuration (c) of DC OWPP

- Configuration (d): This arrangement (Figure 27) installs one DC/DC power converter per feeder on an intermediate collector platform, aiming to enhance system reliability. Consequently, the intermediate offshore platform must be larger than those in other topologies considered.

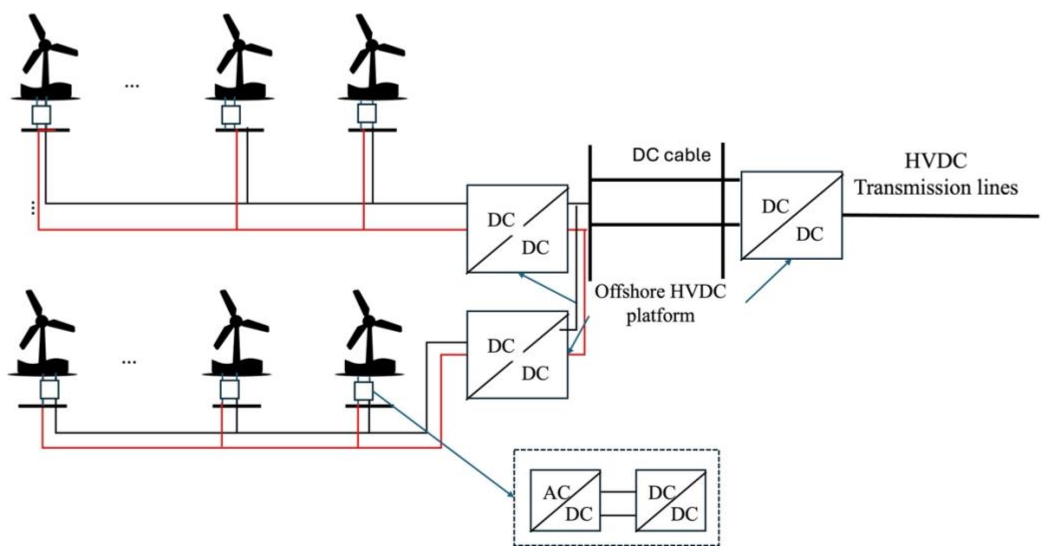

Figure 27. Configuration (d) of DC OWPP

Series Topology

In the series topology, wind turbines are connected in series, as illustrated in Figure 28. Here, the current through each turbine is kept constant, while the output voltage increases with each additional turbine in the series. The power delivered by each feeder can be expressed as:

$$P_{feeder} = V_{wt} \sum i_{wt}$$

While this topology has potential, it introduces some challenges, including the need to modify the control system to regulate voltage instead of current, as is typical in conventional setups. Additionally, some electrical components in the wind farm must be oversized to handle the maximum power of the entire wind farm, which can lead to inefficiencies.

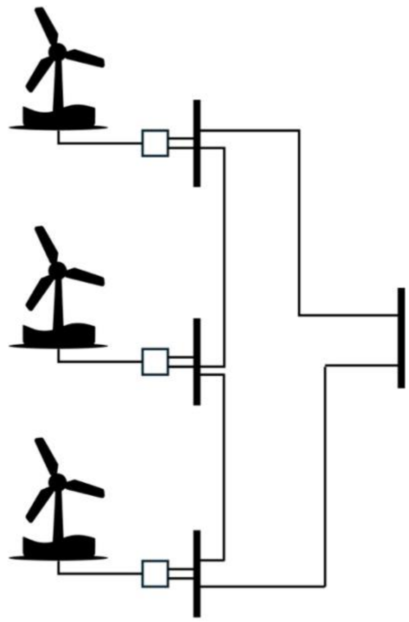

Figure 28. Series collection for DC OWPP

Hybrid Topology

The hybrid topology combines elements of both parallel and series configurations. In this design, a small number of wind turbines are connected in series, with these series-connected feeders then linked in parallel. Figure 29 presents a potential design for the hybrid topology. If only one feeder is used, it essentially represents a series topology, where all wind turbines are connected in series.

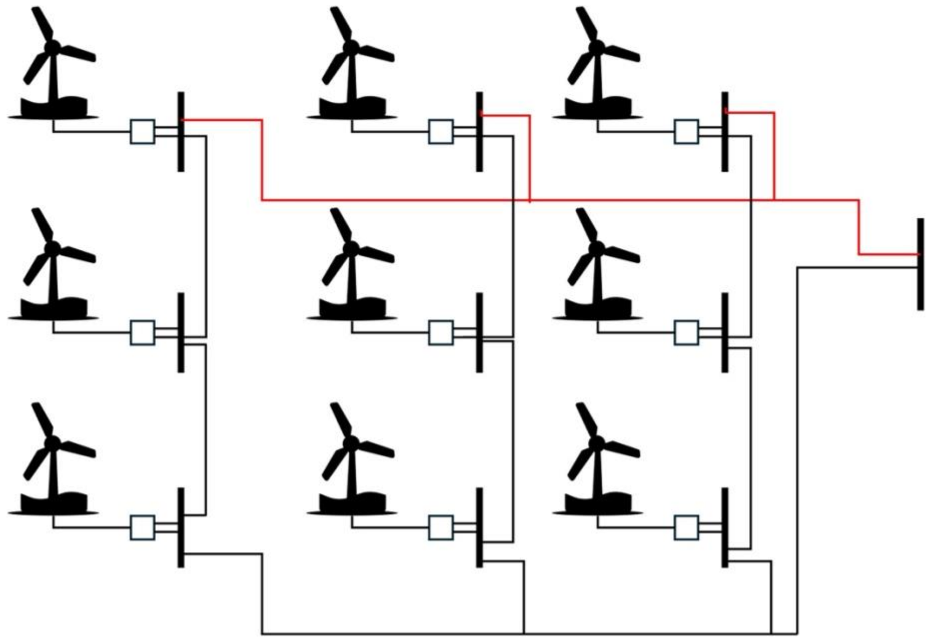

Figure 29. Hybrid collection of DC OWPP

However, similar to the series topology, the hybrid configuration requires careful control of voltage while maintaining constant current. Additionally, some electrical components must be oversized due to the series connection, although this oversizing is less significant than in a purely series-connected system.

1c-4 Offshore equipment limits

1c-4.1 Power Ratings for HVDC Technology

High Voltage Direct Current (HVDC) technology plays a crucial role in the transmission of electricity over long distances, particularly in the context of offshore wind power plants (OWPP). HVDC systems are favored for their ability to efficiently transmit large amounts of power with minimal losses, making them ideal for connecting remote offshore wind farms to the onshore grid. The ratings for HVDC systems vary based on the specific technology and application. For instance, modern HVDC systems utilizing Voltage Source Converters (VSC) can achieve voltage ratings up to 525 kV DC with power transmission capabilities exceeding 2500 MW per system. These high ratings are essential for accommodating the growing scale of offshore wind projects and ensuring reliable, long-distance transmission to onshore grids. The development of XLPE (cross-linked polyethylene) cables has further enhanced HVDC technology, providing robust insulation that supports higher voltage ratings and improved efficiency. As the demand for renewable energy continues to rise, advancements in HVDC technology will be critical in expanding the capacity and reach of offshore wind power generation.

Overhead lines are not a viable option for connecting offshore wind power plants (OWPP) to the onshore grid. Table 1highlights the limitations of current offshore transmission systems, which generally have lower ratings than their onshore counterparts. For onshore applications, mass-impregnated cables can support up to 500 kV and 2500 MW per system in submarine installations. However, due to the challenges of installing three single-core cables in close proximity underwater, three-core cables are often used instead. These three-core cables have a limited cross-section, restricting their capacity to a maximum of 275 kV and 400 MVA per system for submarine AC cables. With the adoption of Voltage Source Converter (VSC) technology, systems with voltages up to 320 kV and ratings exceeding 1200 MW per system are now being implemented. Additionally, XLPE cable systems with a voltage rating of 525 kV DC and a single circuit rating of over 2500 MW have been announced. The actual ratings of these cable systems depend on specific placement and usage conditions, leading to case-dependent performance variations [2].

Table 1 Limits of Offshore Transmission Systems

System	Voltage rating	Power rating
DC submarine cable mass-impregnated	Up to ±500 kV	Up to 2500 MW per system
DC submarine cable extruded	Up to ±525 kV	Up to ±2650 MW per system
AC submarine cable	Up to 275 kV	Up to 400 MVA per three-phase cable
Offshore DC converters (VSC)	Up to ±320 kV	Up to 1200 MW per converter

1c-4.2 Current Ratings for HVDC Technology

Current ratings for High Voltage Direct Current (HVDC) technology are pivotal in determining the efficiency and capacity of power transmission, especially in the context of large-scale renewable energy projects like offshore wind farms. The current rating of an HVDC system refers to the maximum current that can be safely carried by the transmission line, which directly impacts the overall power capacity of the system.

Modern HVDC systems, particularly those employing Voltage Source Converter (VSC) technology, are designed to handle high current ratings, often exceeding 2000 A per circuit. This high current capability is essential for transmitting large amounts of power over long distances, making HVDC technology a preferred choice for connecting distant offshore wind farms to onshore grids. The development of advanced cable technologies, such as XLPE (cross-linked polyethylene) cables, has further enabled these high current ratings by providing superior insulation and thermal performance, thereby reducing losses and enhancing the reliability of HVDC systems.

As offshore wind projects continue to grow in scale, the ability to transmit high currents efficiently becomes increasingly important. The continuous improvement in HVDC current ratings will be critical in meeting the rising demand for renewable energy and ensuring the stability and efficiency of power transmission systems.

In Figure *30*, the current ratings for HVDC systems are presented, covering both Line Commutated Converter (LCC) and Voltage Source Converter (VSC) systems, as well as various transmission mediums such as overhead lines, XLPE cables, and mass-impregnated cables. Overhead lines are predominantly used with LCC HVDC systems, especially outside Europe, while only one VSC-HVDC system with overhead lines, the Caprivi link between Zambia and Namibia, currently exists. The figure highlights that the voltage limits of cables are a significant constraint on the development of high-power VSC HVDC systems. While higher voltage ratings (up to 500 kV) for DC XLPE cables are being developed, mass-impregnated cables can handle even higher voltages but are more challenging to install, more expensive, and harder to maintain. The indicated power ratings are approximate, as they are influenced by installation methods and environmental conditions. Specifically for cables, system ratings are affected by factors such as the type of burial (e.g., direct burial, sea burial, tunnel) and the material used (e.g., copper or aluminum). Oil-filled cables, on the other hand, are not suitable for long-distance transmission due to the need for regular oil refilling [10].

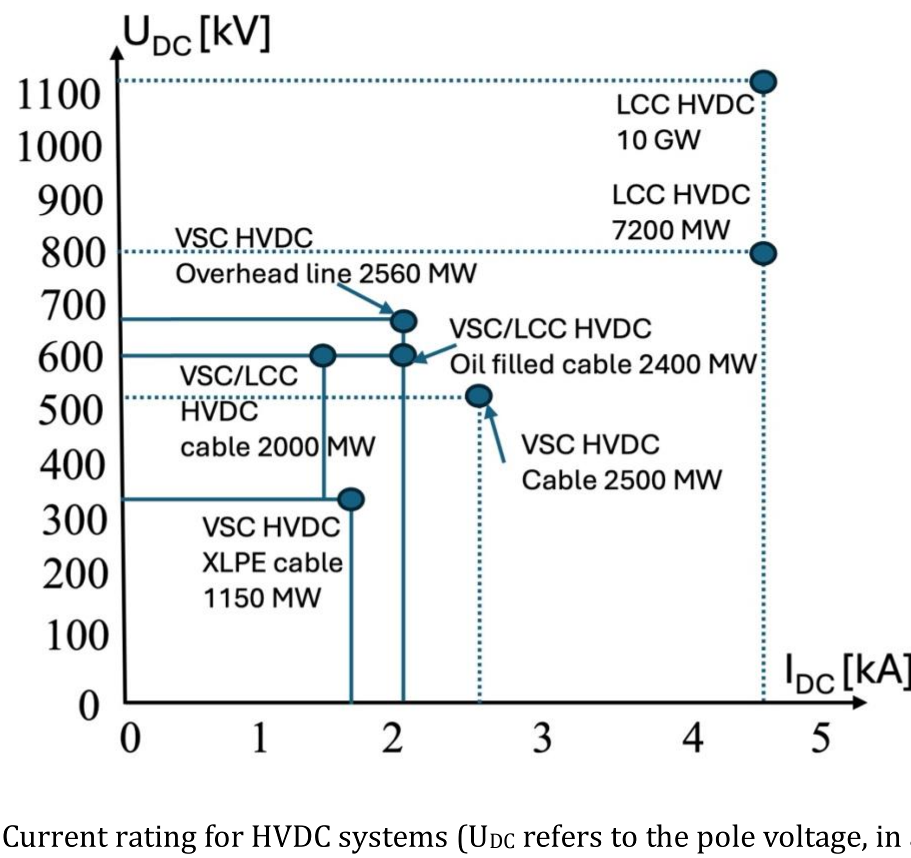

Figure 30 Current rating for HVDC systems (U_{DC} refers to the pole voltage, in a bipolar or symmetrical monopole setup, P=2 $\cdot$ $U_{DC} \cdot I_{DC}$) [10]

1c-5 Offshore AC/DC transmission economic comparison

Classic HVDC is an excellent technology for transmitting large amount of electricity. For example, a 2000 km-long line rated at 800 kV and 6000 MW, HVDC loses the electricity by about 5% but HVAC by about 10% and HVDC needs just two power lines versus three lines for an AC link of equivalent power and length.

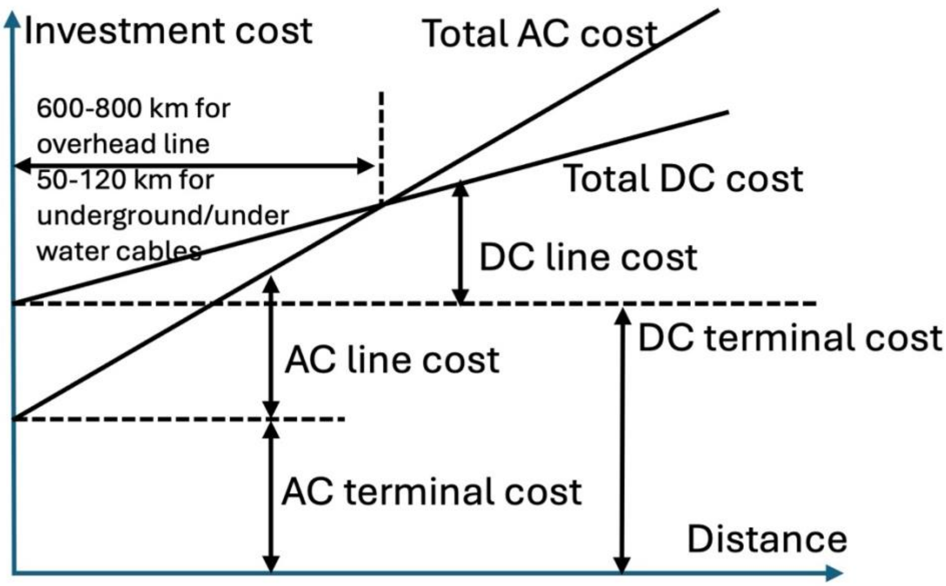

Figure 31 HVDC vs. HVAC cost.

The comparison of the investment cost of HVDC verse HVAC is shown in Figure 31. The cost-benefit of DC over AC transmission is apparent over long distances, typically more than 600km for overhead lines and more than 50km for underground of underwater cables.

The breakeven length between HVAC and HVDC transmission depends on the transmission system length and the rating of the transmission system. There is a significant difference between the breakeven lengths between offshore and onshore transmission system, as overhead lines are not suitable for offshore transmission.

In the case of AC transmission, charging current compensation can only be provided from two sides of the cable, which limits the transmission distance for AC systems. In the case of HVDC offshore transmission, a distinction should be made between transmission systems connecting two onshore substations and transmission systems connecting an offshore substation with an onshore substation.

In the first scenario, LCC converter stations, which can operate at voltages up to ±500 kV, are utilized. However, for connecting offshore substations, such as those in wind farm clusters, only VSC converters are suitable, with current voltage ratings at ±320 kV. One advantage of VSC converters is their compatibility with extruded HV cables, which are more cost-effective than mass-impregnated HV cables. Figure 31 illustrates the breakeven distance for the submarine connection between two onshore substations. In this example, a 1500-MW (MVA) transmission system with an AC transmission voltage of 245 kV is considered. The figure shows that the breakeven point occurs at the distance around 50-120 km.

Figure 31 examines the connection of an offshore substation to the shore. This study considers the investments required for offshore substations. For DC transmission, a voltage of ±320 kV is used, necessitating a higher number of conductors (two systems instead of one) compared to the AC option. The increased number of conductors, coupled with the higher costs of converters, shifts the breakeven point to the AC system's active power transmission capacity limit.

1c-5.1 DC Transmission Losses

In the case of DC overhead lines, the phenomenon known as the skin effect does not occur because the transmission frequency is 0 Hz. This is a significant advantage over AC transmission, where the skin effect causes current to concentrate near the surface of conductors, leading to increased resistance and losses. For underground or submarine DC cables, the situation is similarly advantageous; the cable capacitance is only charged once when the cable is initially energized. This means that, unlike AC cables, which require a continuous charging current due to the alternating nature of the voltage, DC cables only require a brief charging current when voltage is first applied.

The losses in Line Commutated Converter (LCC)-HVDC systems are composed of several components, including losses in the converter transformers, thyristor valves, DC smoothing reactors, AC filters, and auxiliary systems. A detailed breakdown of these losses is provided in Table 2, which reveals that 23–34% of the total converter losses are independent of the load. State-of-the-art LCC converters typically have total losses in the range of 0.65–0.75% of the rated power when operating at full load. To calculate losses under partial load conditions, the load-dependent losses can be scaled according to the square of the utilization factor.

Table 2. Typical breakdown of LCC HVDC Converter Station Losses [11]

Item	Total Losses in %
Converter transformers	
No-load losses	12-14
Load losses	27-39
Thyristor valves	32-35
DC smoothing reactors	4-6
AC filters	7-11
Auxiliary losses	4-9

1c-5.2 VSC-HVDC Losses

Voltage Source Converter (VSC)-HVDC systems also experience losses, which primarily originate from four key components: the valves, the converter transformers, the phase reactors, and the auxiliary equipment. Table 3 provides a detailed breakdown of these losses. Notably, advancements in VSC-HVDC technology, particularly the adoption of multilevel converter topologies, have significantly reduced converter station losses from 1.9% to approximately 1% at full load over recent years. Additionally, the no-load losses for VSC-HVDC converter stations are relatively low, typically around 0.2%.

Understanding the sources and behavior of these losses is crucial for optimizing the design and operation of HVDC systems, particularly as they become increasingly integral to the efficient transmission of electricity over long distances, such as in offshore wind power applications.

Table 3. Typical breakdown of VSC-HVDC Converter Station Losses [12]

Item	Total Losses in %
Converter transformers	13
Semiconductors	70
Phase reactors	8
Auxiliary losses	9

1c-6 Summary and conclusions

Due to technological advances and better wind conditions at sea, offshore wind power plants (OWPP) are rapidly expanding. As wind farms grow larger and are located farther from shore, integrating their power into the onshore grid becomes crucial. High-voltage Direct Current (HVDC) is increasingly favored for connecting offshore wind farms to the onshore grid over long distances due to its lower electrical losses and higher efficiency.

Two main types of collection grids are used. AC (Alternating Current) collection grids: Wind turbines generate AC power, which is transmitted to an offshore platform and then converted to DC for transmission to shore. DC (Direct Current) collection grids: Wind turbines convert power to DC locally, which is transmitted directly via DC cables to the offshore platform and then to shore using HVDC lines.

There are Offshore Platforms in OWPP. Collector Platforms: Gather medium-voltage AC from turbines and step up the voltage to reduce losses before transmission. HVDC Platforms: Convert and transmit combined power from multiple wind farms to the onshore grid via HVDC links.

There are several topologies of OWPP. AC Topologies include Radial, Ring, Star; and DC Topologies include Parallel, Series, Hybrid.

HVDC becomes more cost-effective than HVAC over longer distances (typically beyond 50–120 km offshore) due to lower losses and fewer required conductors.

Offshore transmission systems have lower voltage and power ratings due to submarine cable constraints, but advancements are increasing these limits. No skin effect in DC lines reduces resistance and losses; DC cables require charging current only once. Losses occur in transformers, valves, and auxiliary systems, but technological improvements are reducing these inefficiencies.

The integration of HVDC technology and the selection of appropriate topologies are essential for efficient and reliable offshore wind power transmission to onshore grids, supporting the continued growth of renewable energy sources.

Quiz Questions

1. **True or False:** HVDC transmission is preferred over HVAC for offshore wind farms located more than 50 km from shore due to lower transmission losses.

   (Answer: True)

2. **True or False:** Line Commutated Converter (LCC) HVDC technology is more suitable for offshore wind applications than Voltage Source Converter (VSC) HVDC.

   (Answer: False, VSC-HVDC is preferred due to better control and black-start capability)

3. **True or False:** Offshore HVDC platforms only serve as transmission hubs and do not perform any voltage conversion.

   (Answer: False, HVDC platforms contain converters that step up or step down voltage for efficient transmission)

4. **Which of the following is a major advantage of using HVDC over HVAC for offshore wind transmission?**
   A) Lower installation cost
   B) Reduced transmission losses over long distances
   C) Simpler converter station design
   D) Lower maintenance requirements

   (Answer: B - Reduced transmission losses over long distances)

5. **Which type of HVDC converter is more commonly used in offshore wind projects?**
   A) Line Commutated Converter (LCC)
   B) Voltage Source Converter (VSC)
   C) Load Commutated Inverter (LCI)
   D) Thyristor-Based Rectifier

   (Answer: B - Voltage Source Converter (VSC))

6. **What is a key limitation of using HVDC transmission for offshore wind farms?**
   A) Higher power losses than HVAC
   B) Limited availability of HVDC cables
   C) Higher initial investment cost compared to HVAC
   D) Incompatibility with modern wind turbines

   (Answer: C - Higher initial investment cost compared to HVAC)

7. **Which of the following offshore wind farms uses HVDC technology?**
   A) Vineyard Wind 1 (Massachusetts)
   B) Sunrise Wind (New York)
   C) Block Island Wind Farm (Rhode Island)
   D) Empire Wind 1 (New York)

   (Answer: B - Sunrise Wind (New York))

8. **What is the main function of an offshore HVDC converter station in a wind farm?**
   A) To store excess energy generated by wind turbines
   B) To convert AC power from turbines to DC for efficient long-distance transmission
   C) To directly distribute power to nearby coastal cities
   D) To replace the need for wind turbine inverters

   (Answer: B - To convert AC power from turbines to DC for efficient long-distance transmission)

Reference

[1] “Offshore development information statement, 2010 annual review. Appendix 1,” National Grid, Technical Report.

[2] A. Gustafsson, M. Saltzer, A. Farkas, H. Ghorbani, T. Quist, and M. Jeroense, “The new 525 kV extruded HVDC cable system—World’s most powerful extruded cable system,” ABB, Technical. Report., Aug. 2014, ABB White Paper.

[3] S. Lumbreras and A. Ramos, “Offshore wind farm electrical design: A Review,” Wind Energy, vol. 16, no. 3, pp. 459–473, 2013.

[4] T. H. Hansen, “Offshore wind farm layouts. Performance comparison for a 540 MW offshore wind farm,” Master’s thesis, Norwegian University of Science and Technology. Department of Electric Power Engineering, July 2009.

[5] P. K. Steimer, O. Apeldoorn, L. Dalessandro, R. Grinberg, and S. Ebner, “Efficient medium voltage power collection windparks.” Copenhagen, Denmark: EWEA, 16–19 April 2012.

[6] A. Sannino, H. Breder, and E. K. Nielsen, “Reliability of collection grids for large offshore wind parks,” in 9th International Conference on Probabilistic Methods Applied to Power Systems, KTH, Stockholm, Sweden, June 11–15 2006.

[7] T. Ackermann, Wind Power in Power Systems. Hoboken, NJ: Wiley, 2005.

[8] J. Pierik, M. Damen, P. Bauer, and S. de Haan, “Steady state electrical design, power performance and economic modeling of offshore wind farms,” EPE Journal, vol. 16, pp. 44–49, 2006.

[9] M. A. Parker and O. Anaya-Lara, “Cost and losses associated with offshore wind farm collection networks which centralise the turbine power electronic converters,” IET Renewable Power Generation, vol. 7, no. 4, pp. 390–400, 2013.

[10] D. Van Hertem and M. Ghandhari, “Multi-terminal VSC HVDC for the European Super Grid: Obstacles,” Renewable and Sustainable Energy Reviews, vol. 14, no. 9, pp. 3156–3163, 2010.

[11] “IEEE recommended practice for determination of power losses in high-voltage direct-current (HVDC) converter stations,” IEEE Std1158-1991, p. 1, 1992.

[12] H. Pang, G. Tang, and Z. He, “Evaluation of losses in VSC–HVDC transmission system,” in Power and Energy Society General Meeting-----Conversion and Delivery of Electrical Energy in the 21st Century,2008 IEEE, July 2008, pp. 1–6.

[13] Koondhar, M.A.; Kaloi, G.S.; Saand, A.S.; Chandio, S.; Ko, W.; Park, S.; Choi, H.-J.; El-Sehiemy, R.A. Critical Technical Issues with a Voltage-Source-Converter-Based High Voltage Direct Current Transmission System for the Onshore Integration of Offshore Wind Farms. *Sustainability* 2023, *15*, 13526. https://doi.org/10.3390/su151813526

[14] F. An, B. Zhao, B. Cui and R. Bai, "Multi-Functional DC Collector for Future All-DC Offshore Wind Power System: Concept, Scheme, and Implement," in *IEEE Transactions on Industrial Electronics*, vol. 69, no. 8, pp. 8134-8145, Aug. 2022, doi: 10.1109/TIE.2021.3109539.