HVDC LEARN

Modules for Maturing HVDC Electric Transmission Knowledge

Funded by the US Department of Energy (DOE)
within the Office of Energy Efficiency & Renewable Energy (EERE)

HVDC-Learn Short Course

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Module 1c: Introduction to HVDC for Offshore Wind

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Outline

- Overview of wind power resources
- Topology of wind power plants with HVDC
- Equipment limits of wind power plants with HVDC
- AC/DC transmission economic comparison

Overview of onshore wind power resources

Most U.S. wind electricity generation capacity is in the middle of the country

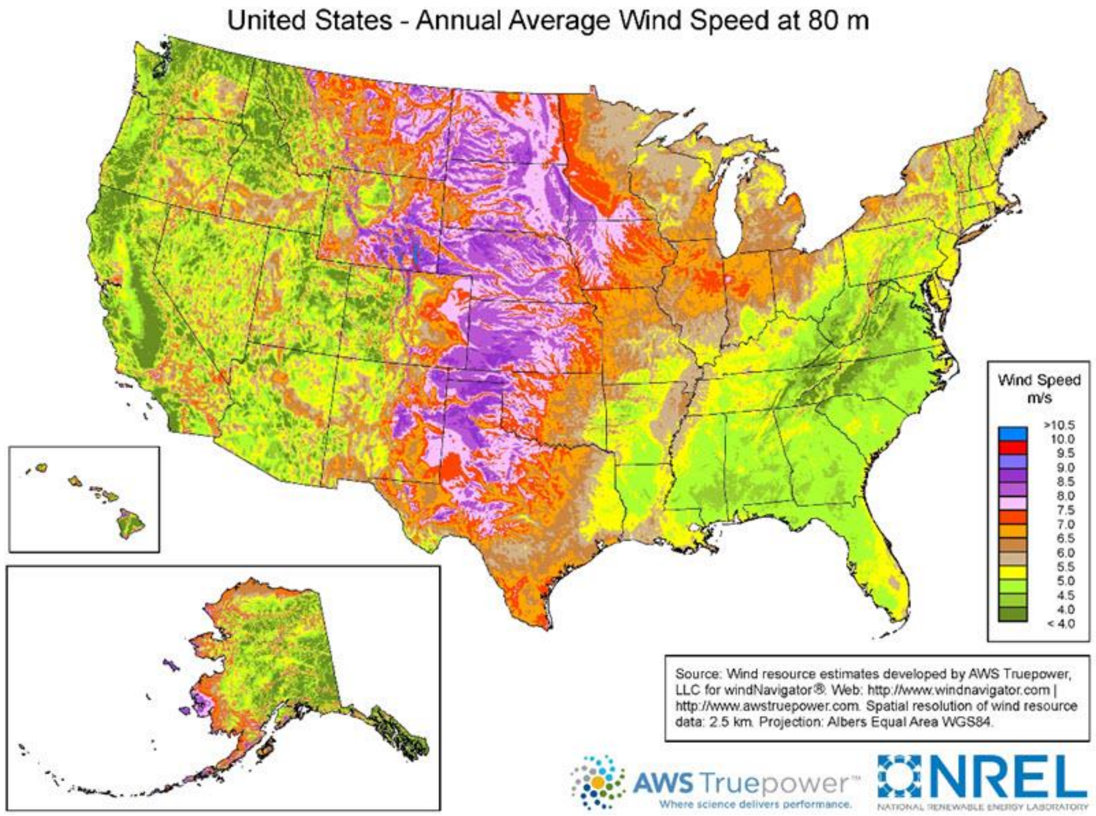

Figure 1. Map of U.S. wind resources
Source: National Renewable Energy Laboratory, U.S. Department of Energy (public domain)

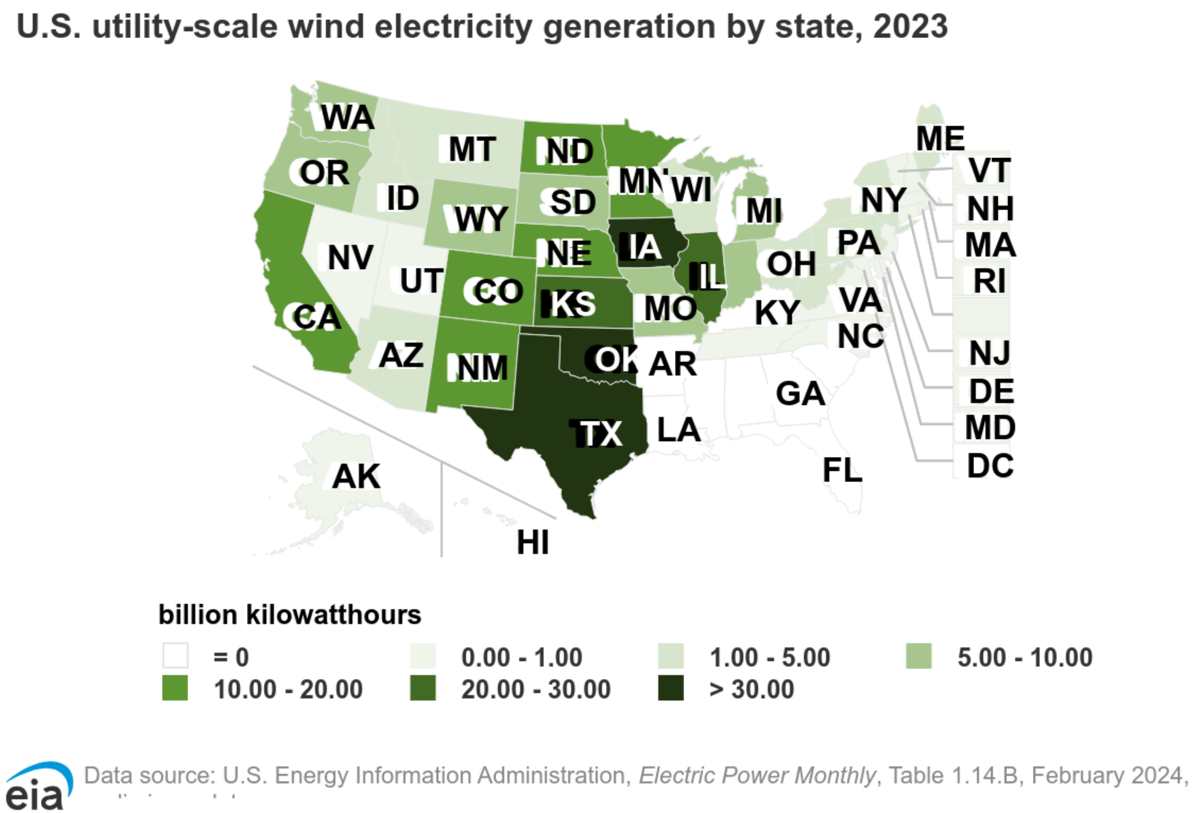

Figure 2. Map of U.S. utility-scale wind electricity generation by state 2023

Overview of offshore wind power plants

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 3.

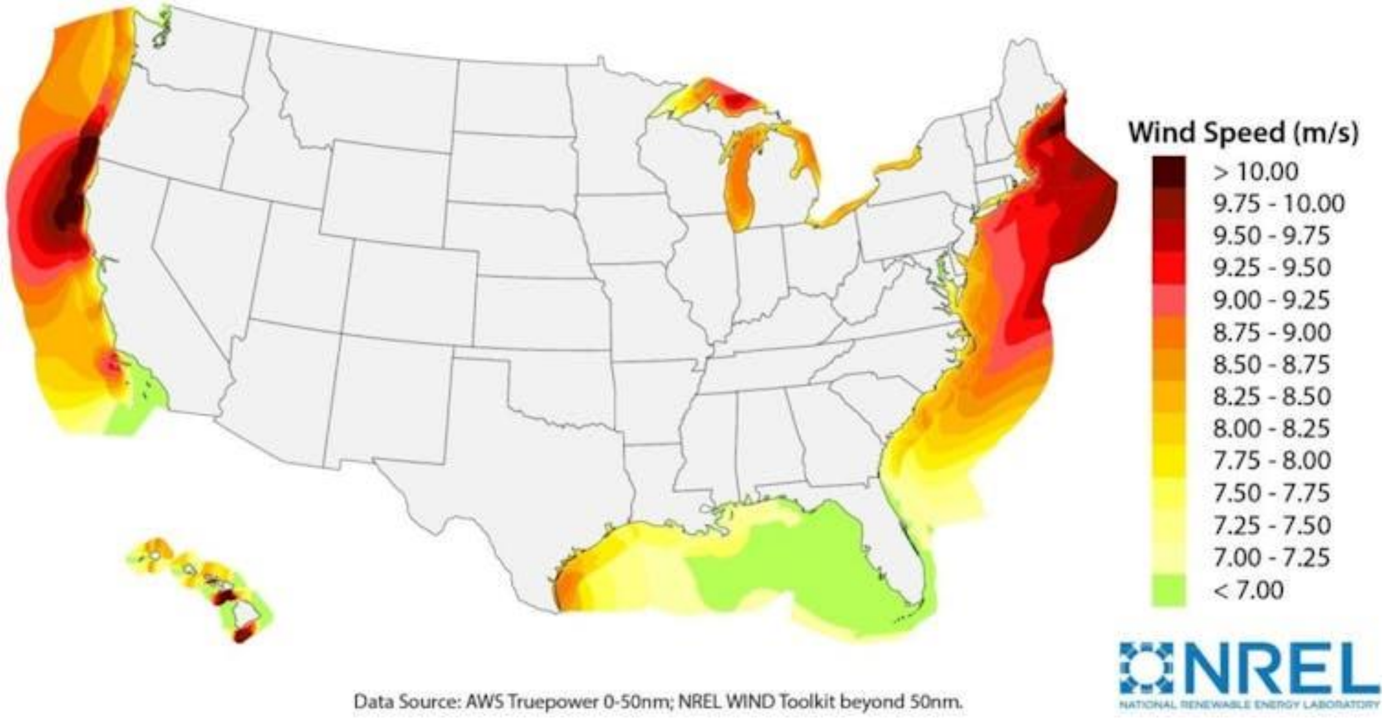

Figure 3. The U.S. Northeast and Northern California have the nation’s strongest offshore winds. (NREL)

Overview of offshore wind power plants

As of July 2024, at least 27 leases of offshore wind projects in federal waters had been issued, representing approximately 27 GW of potential installed capacity (mainly on the east coast), as shown in Figure 4. 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.

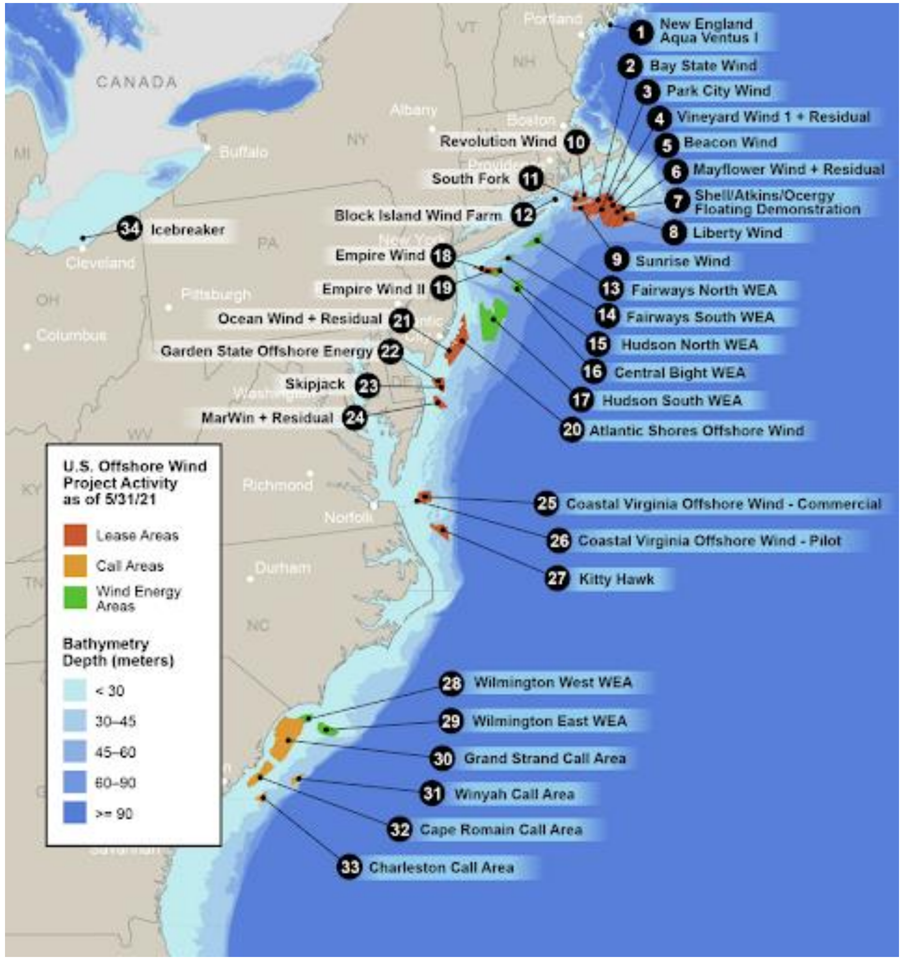

Figure 4. Previously planned offshore wind power plants in the USA east coast. (source: National Renewable Energy Laboratory)

Overview of offshore wind power plants

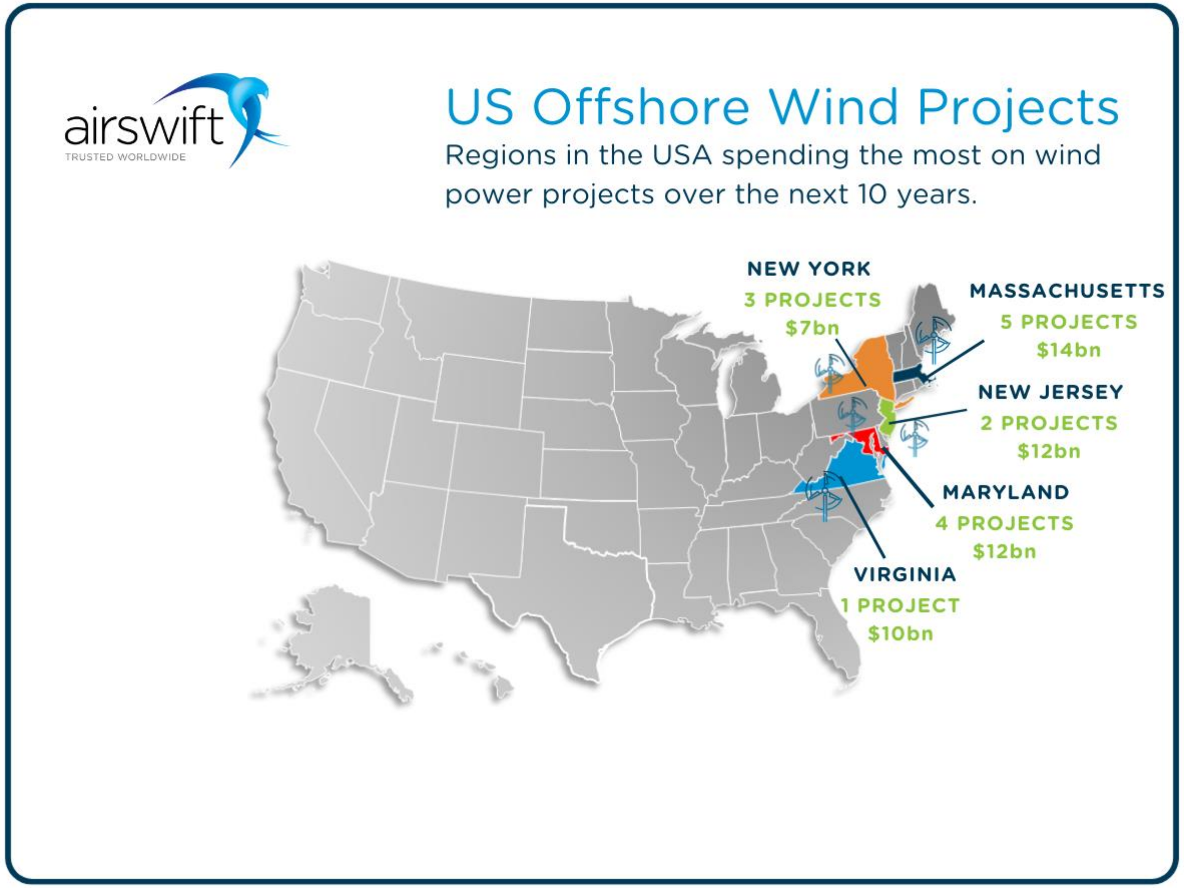

Figure 5: Regions in the USA spending the most on offshore wind projects over the next 10 years.

The wind is now America's top renewable electricity source, and it is expanding.

There are over 20 offshore wind projects slated for the next 5 years with a total value of $61bn.

Massachusetts ($14bn), New Jersey ($12bn), Maryland ($12bn), Virginia ($10bn) and New York (7bn) are the states spending the most on offshore wind power projects over the next 10 years.

Overview of offshore wind power plants

Current situation in USA

But on January 20, 2025, President Trump issued a presidential memorandum to withdraw from disposition for **wind energy leasing all areas in federal waters** (explicitly "…within the Offshore Continental Shelf (OCS) as defined in section 2 of the Outer Continental Shelf Lands Act, 43 U.S.C. 1331"). With respect to existing leases, the memorandum requires that the Secretary of the Interior, "in consultation with the Attorney General as needed, shall conduct a comprehensive review of the ecological, economic, and environmental necessity of terminating or amending any existing wind energy leases, identifying any legal bases for such removal."

Because there is **only one operational wind farm in state waters and only one other wind farm proposed for state waters** (the 11 MW Aqua Ventus I plant in Maine, a demonstration project), President Trump's memorandum effectively pauses all active US wind farm development.

Overview of offshore wind power plants

Current situation in USA

The Trump administration on Monday (May 20) allowed construction to restart on a huge wind farm off the coast of Long Island, a month after federal officials had issued a highly unusual stop-work order that had pushed the $5 billion project to the brink of collapse. In a statement, Gov. Kathy Hochul, Democrat of New York, said she had spent weeks pressing President Trump and Interior Secretary Doug Burgum to lift the government's hold on the wind farm.

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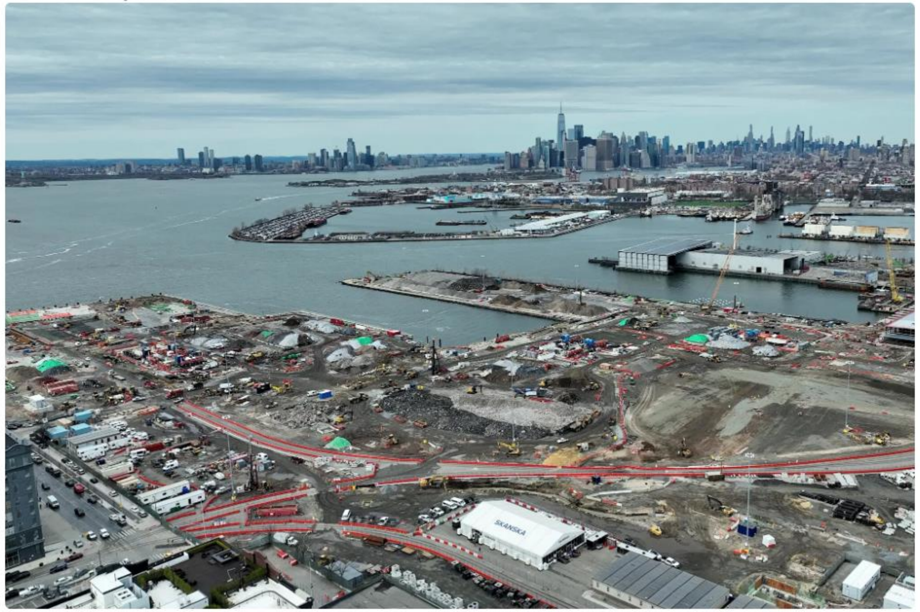
In Reversal, Trump Officials Will Allow Huge Offshore N.Y. Wind Farm to Proceed

Source: By Brad Plumer and Benjamin Oreskes, New York Times • Posted: Tuesday, May 20, 2025

The Trump administration had issued a highly unusual stop-work order on the Empire Wind project last month, leading to intense pushback from officials in New York.



South Brooklyn Marine Terminal, which is being developed into a staging facility for Equinor's Empire Wind offshore wind project.Equinor, via Reuters

https://governorswindenergycoalition.org/in-reversal-trump-officials-will-allow-huge-offshore-n-y-wind-farm-to-proceed/

Overview of offshore wind power plants

Implication of offshore wind halt on Midwest wind power development

With the current halt and uncertainty on offshore wind power development in the USA, if states on the east coast still purchase to achieve their renewable energy target, one viable option would be the onshore wind power plants in the Midwest + transmission. **Since the total cost of wind in Midwest + transmission is lower than the onshore wind on the east coast. Because the wind resource capacity in Midwest is much higher than that on East coast.**

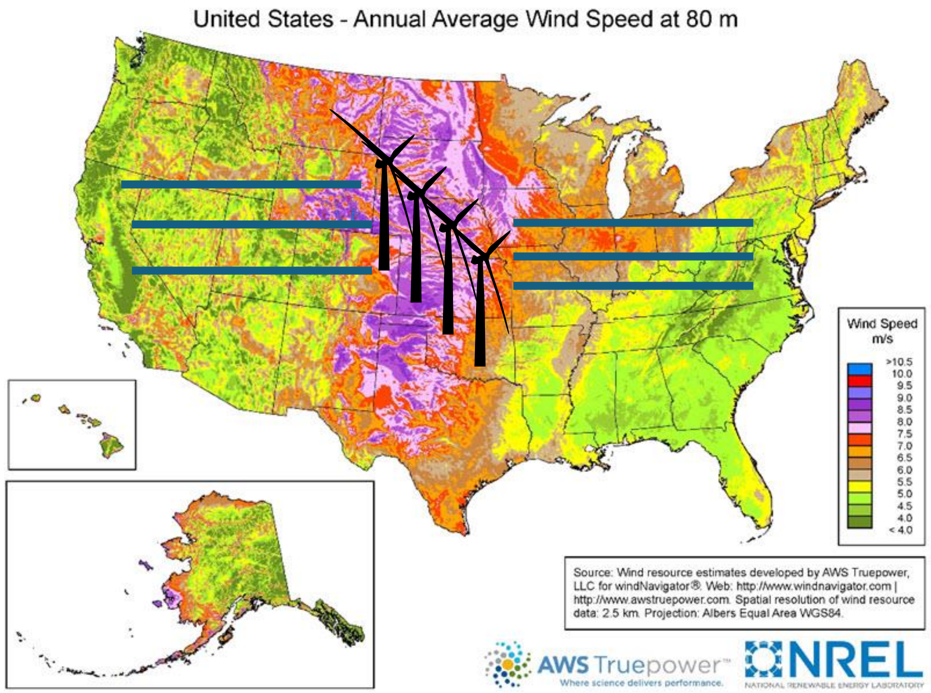


Figure 1. Map of U.S. wind resources

Overview of offshore wind power plants

Offshore wind development in other countries

Figure 6 summarizes the current offshore wind development in different countries. China has led offshore investment with over 41% of the wind farms; the United Kingdom (UK) is a distant second at 15%. However, if all European countries are aggregated, they have over 44% of the wind farms, most of which are in the North Sea.

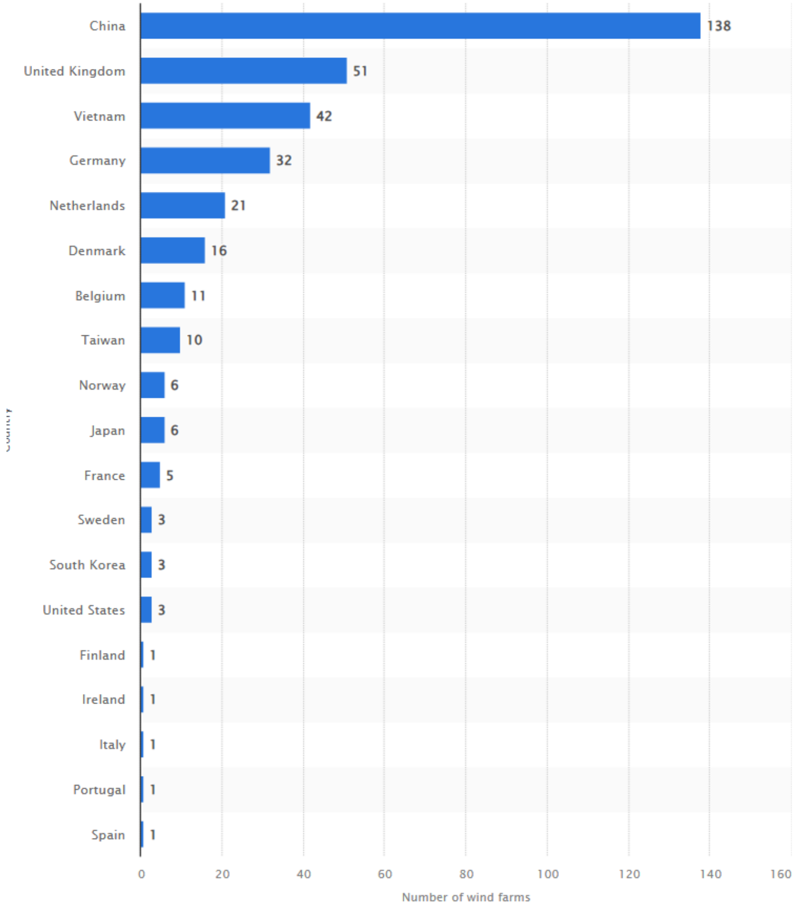


Figure 6: Number of offshore wind farms by country as of April, 2025

Overview of offshore wind power plants

Offshore wind power plant with HVDC

SouthCoast Wind 1

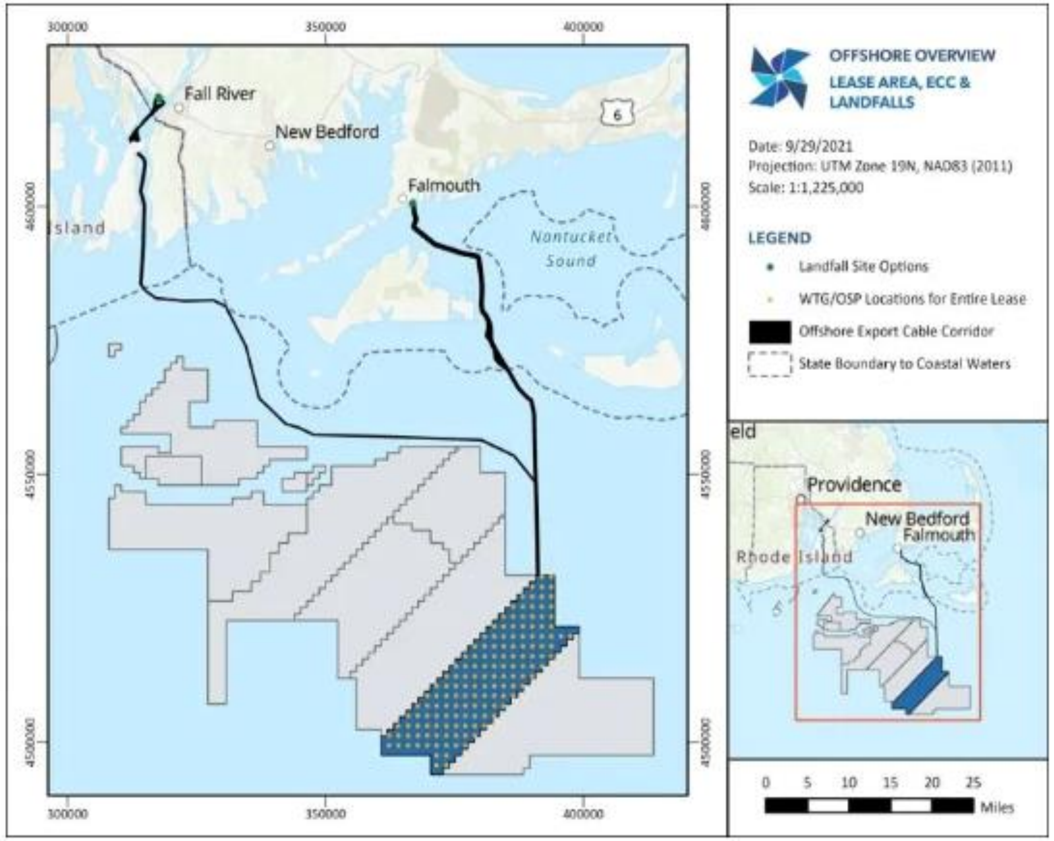


Figure 7. Lease areas of SouthCoast

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

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

Overview of offshore wind power plants

Offshore wind power plants with HVDC

SouthCoast Wind 1

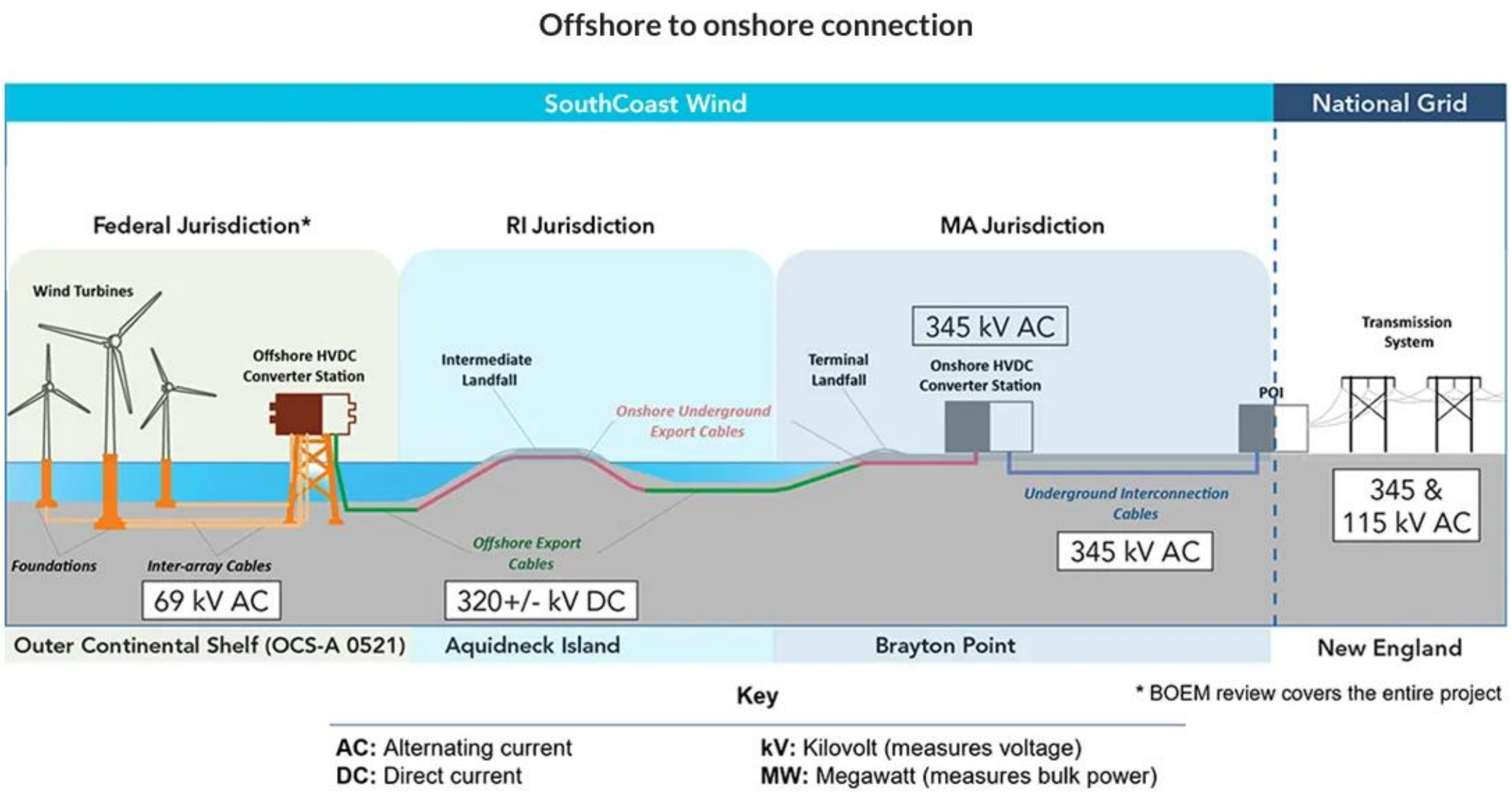


Figure 8. Offshore to onshore connection illustration

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.

Overview of offshore wind power plants

West Coast Floating Offshore Wind (California & Oregon)

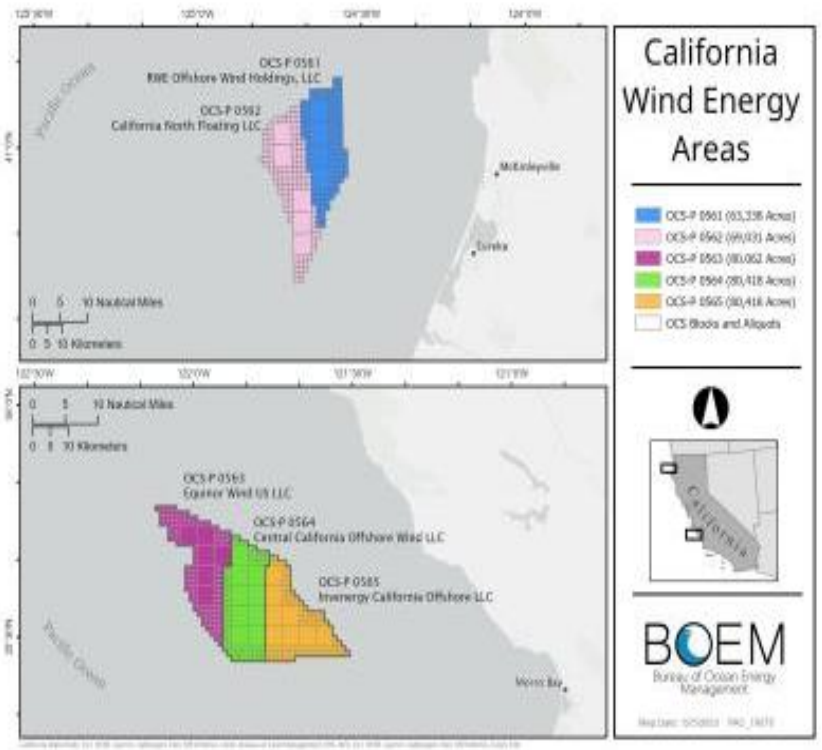


Figure 9. Canopy offshore wind (OCS-P 0561)

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.

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.

Overview of offshore wind power plants

Great Lakes offshore wind

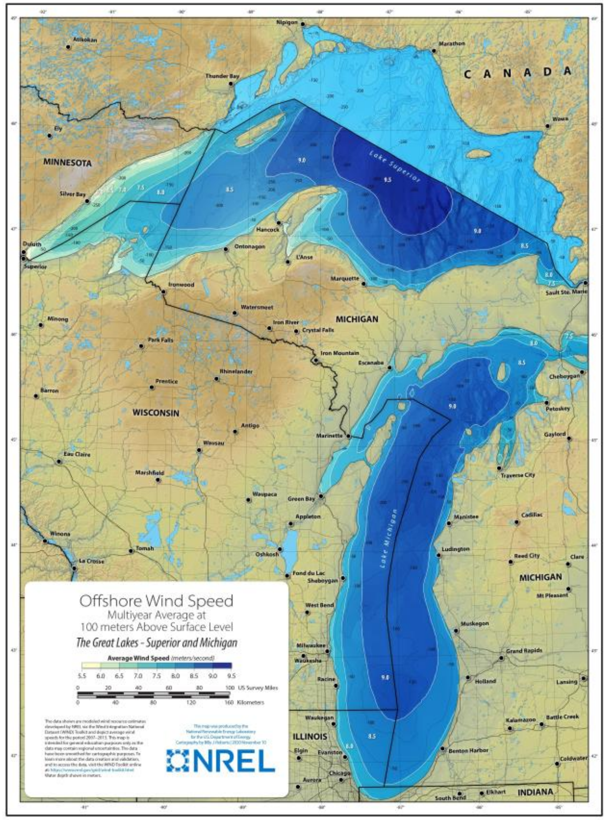


Figure 10. Great Lakes Offshore Wind Speed at 100 Meters | Lake Superior and Lake Michigan

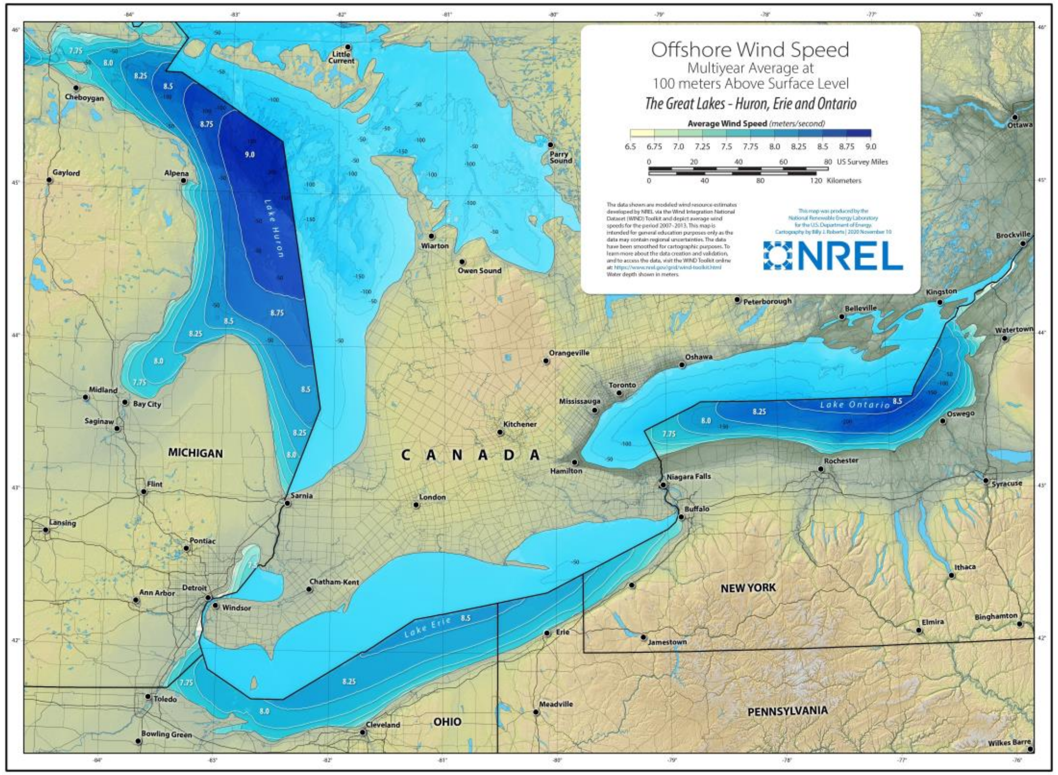


Figure 11. Great Lakes Offshore Wind Speed at 100 Meters | Lakes Huron, Erie, and Ontario

Overview of offshore wind power plants

Great Lakes offshore wind

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
- Environmental Conditions
- Regulatory and Environmental Concerns

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

- Icebreaker Wind Project
- Illinois Rust Belt to Green Belt Pilot Program Act.
- Great Lakes Offshore Wind Energy Consortium.

Topology of wind power plants with HVDC

Overview of HVDC-connected Offshore Wind Power Plant

The offshore wind power collection grid can be AC or DC.

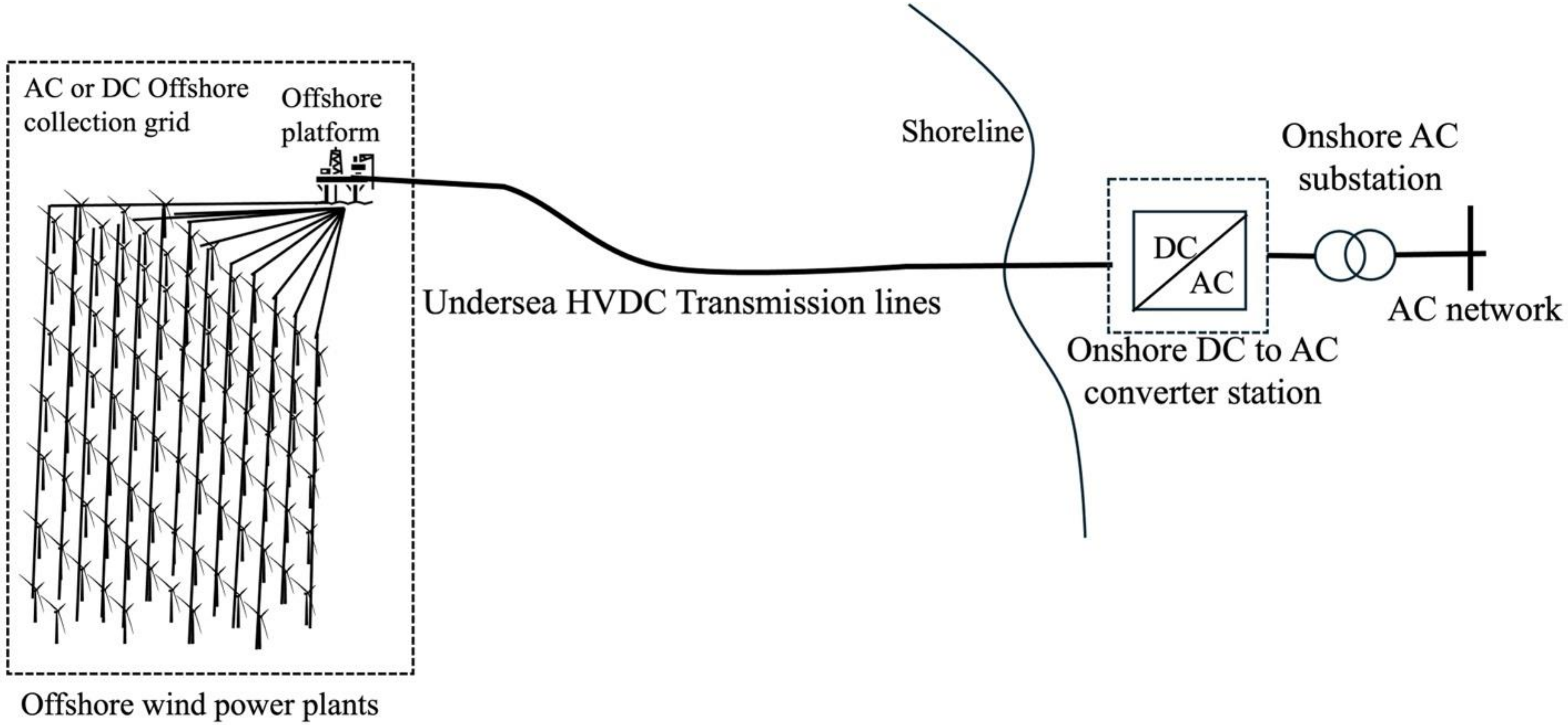


Figure 12: Single-line diagram of offshore wind power plants

Topology of wind power plants with HVDC

HVDC-connected AC Offshore Wind Power Plant

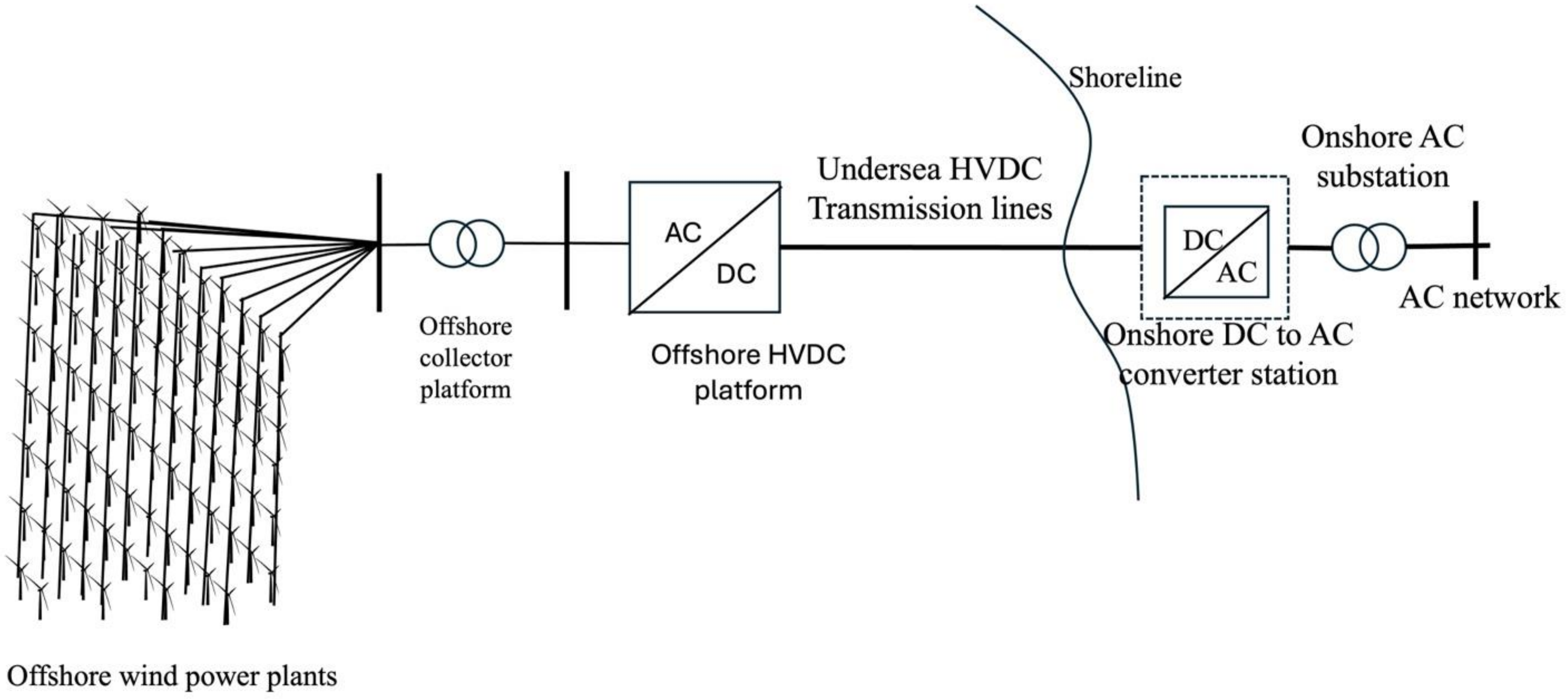


Figure 13. Example of AC connected OWPP with VSC-HVDC lines.

Topology of wind power plants with HVDC

HVDC-connected AC Offshore Wind Power Plant

Figure *14*. Typical scenario for using HVDC technology to connect offshore wind power to the main AC network

Topology of wind power plants with HVDC

HVDC-connected DC Offshore Wind Power Plant

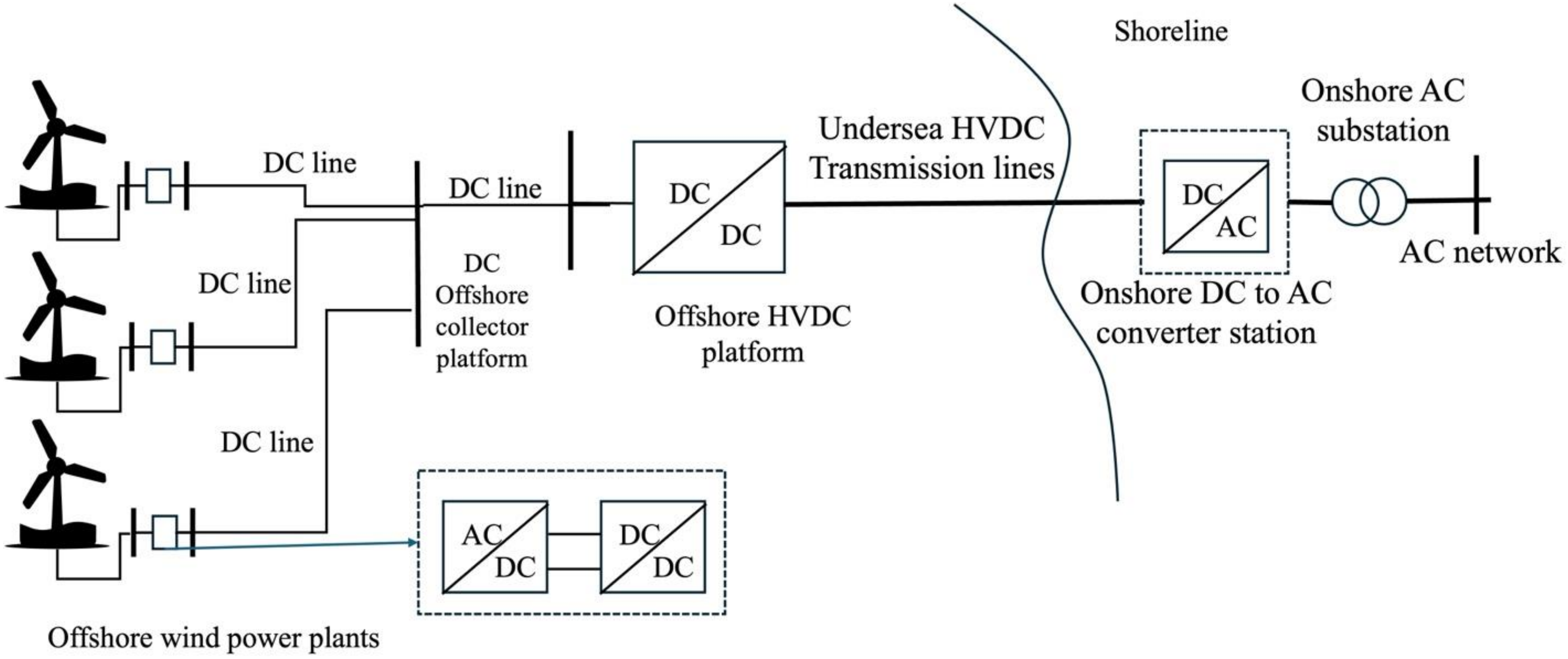


Figure 15. Example of DC connected OWPP with HVDC lines.

Topology of wind power plants with HVDC

HVDC-connected DC Offshore Wind Power Plant

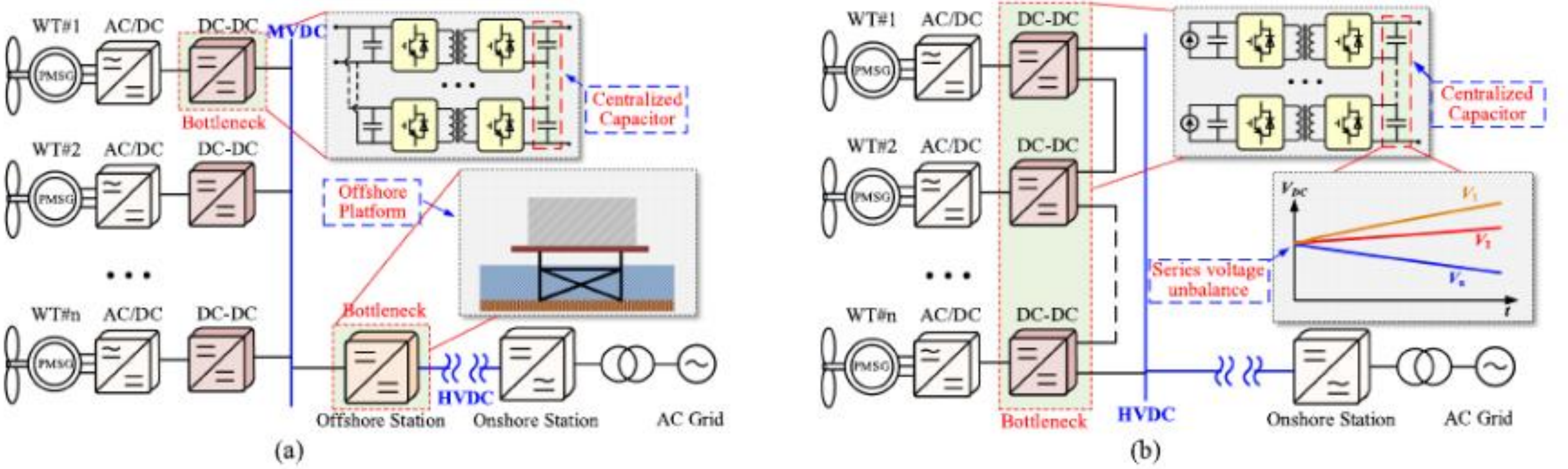


Figure *16*. Traditional all-dc offshore wind power networking scheme. (a) Parallel networking scheme (b) Series networking scheme

Topology of wind power plants with HVDC

Main components of HVDC-connected Offshore Wind Power Plant

There are several main components of a HVDC-connected offshore wind power plants. It includes: **offshore platforms, foundation structure, DC circuit breakers**.

These platforms can be categorized into two main types: **collector platforms** and **HVDC platforms**

Figure 17. Alstom’s GIS collection substations

Figure 18. Siemens Energy HVDC offshore wind converter station

Topology of wind power plants with HVDC

Main components of HVDC-connected Offshore Wind Power Plant

Foundation structure are shown in the figure below.

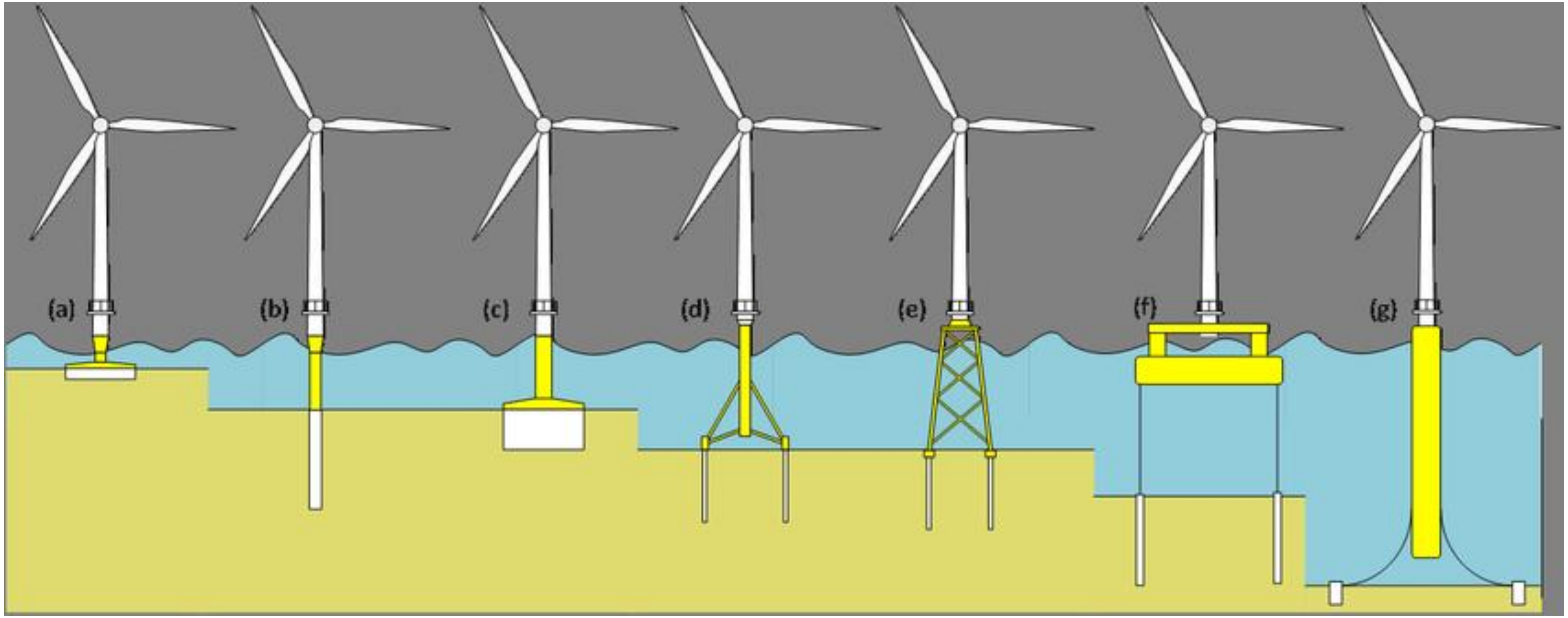


Figure 19. Support structures for offshore wind turbines. (a) Gravity based foundation, (b) monopile, (c) suction caisson, (d) tripod, (e) jacket, (f) tension leg platform and (g) ballast stabilised spar buoy.

Topology of wind power plants with HVDC

Main components of HVDC-connected Offshore Wind Power Plant

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.

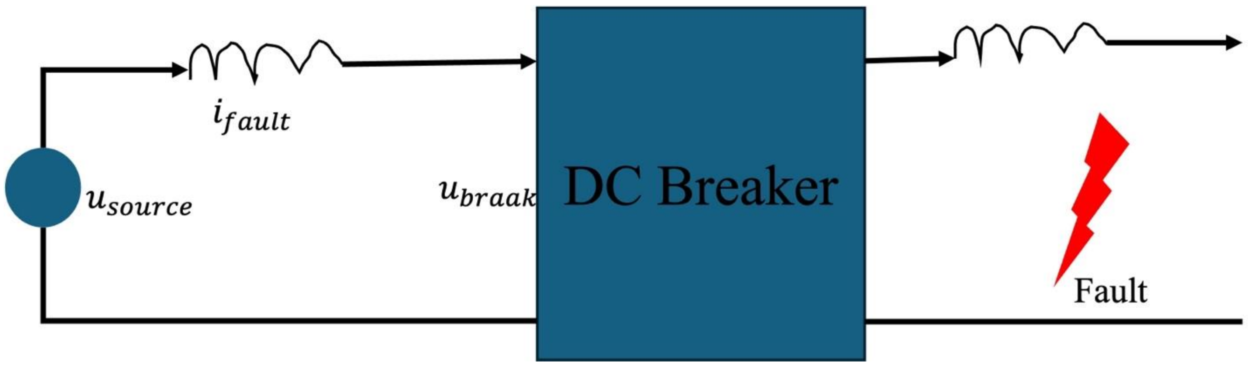


Figure 20. DC breaker in HVDC grid

Figure 21. PCS-8300 HV DC Circuit Breaker

Topology of wind power plants with HVDC

AC collected Offshore Wind Power Plant Topologies

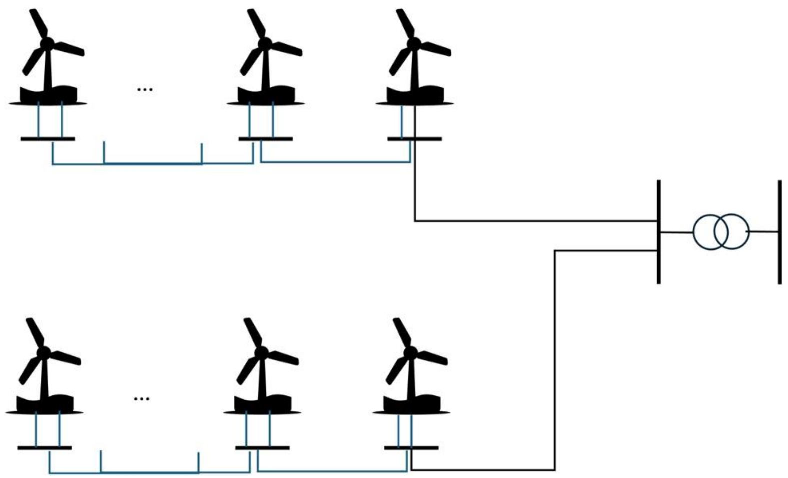


Figure 22. Radial collection configuration.

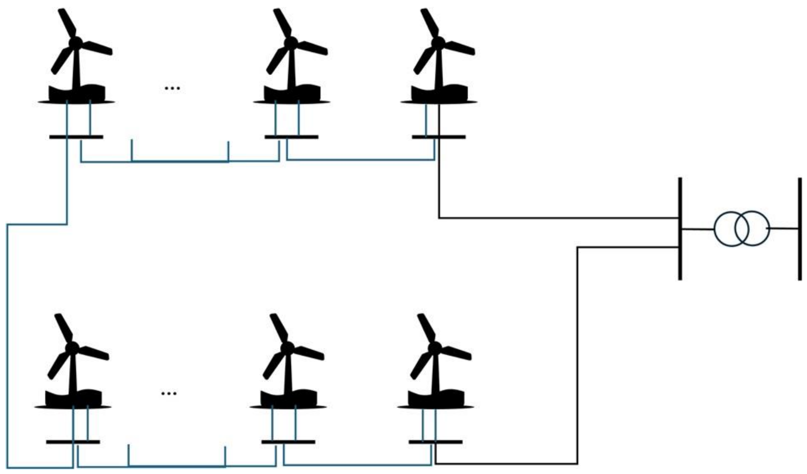


Figure 23. Ring collection configuration.

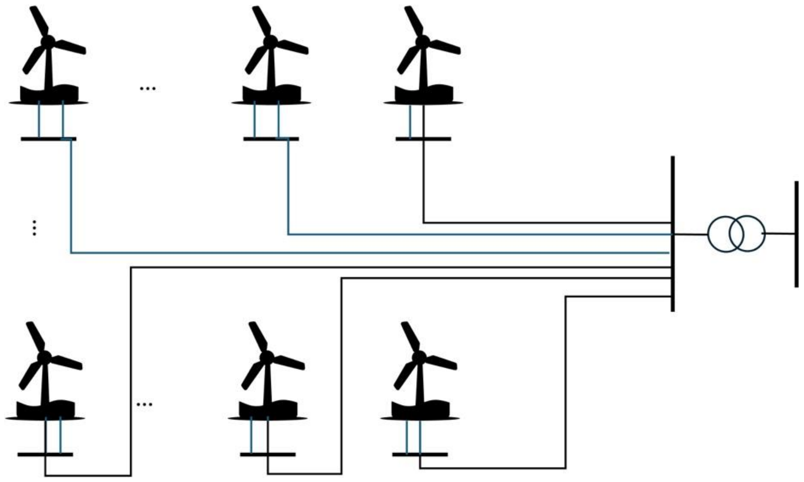


Figure 24. Star collection configuration

Topology of wind power plants with HVDC

DC collected Offshore Wind Power Plant Topologies

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

Parallel Topology

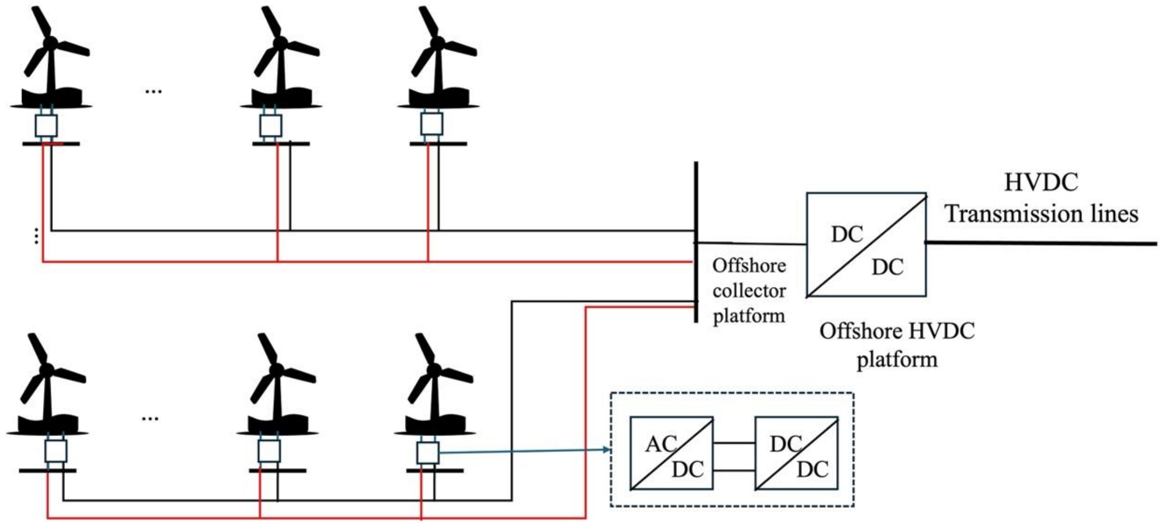


Figure 25. Configuration (a) of DC OWPP

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.

Topology of wind power plants with HVDC

DC collected Offshore Wind Power Plant Topologies

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

Parallel Topology

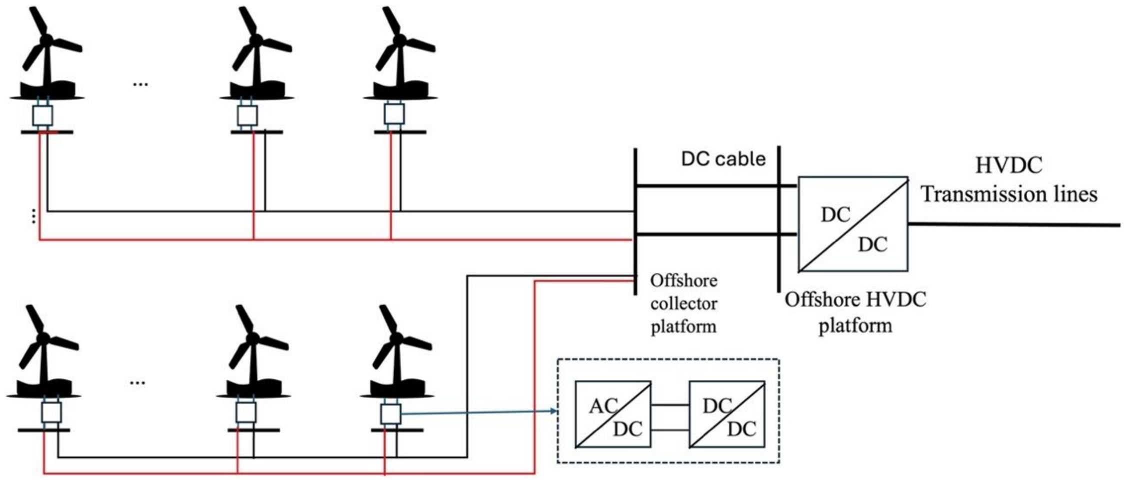


Figure 26. Configuration (b) of DC OWPP

Configuration (b): Similar to the previous design, this configuration (shown in Figure *26*) 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.

Topology of wind power plants with HVDC

DC collected Offshore Wind Power Plant Topologies

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

Parallel Topology

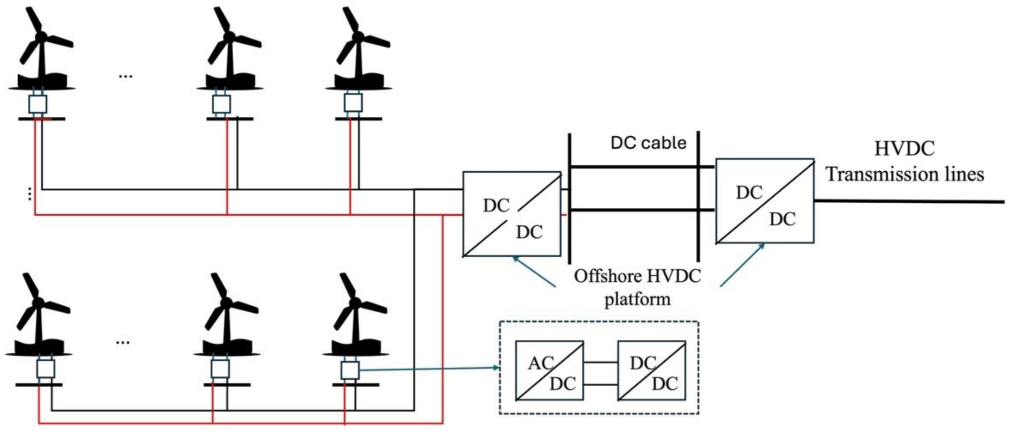


Figure 27. Configuration (c) of DC OWPP

Configuration (c): To minimize export cable losses, this design proposes installing a DC/DC power converter on an intermediate offshore platform (Figure *27*). As a result, the output voltage is stepped up twice—once at the wind turbine level and again at the collector platform.

Topology of wind power plants with HVDC

DC collected Offshore Wind Power Plant Topologies

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

Parallel Topology

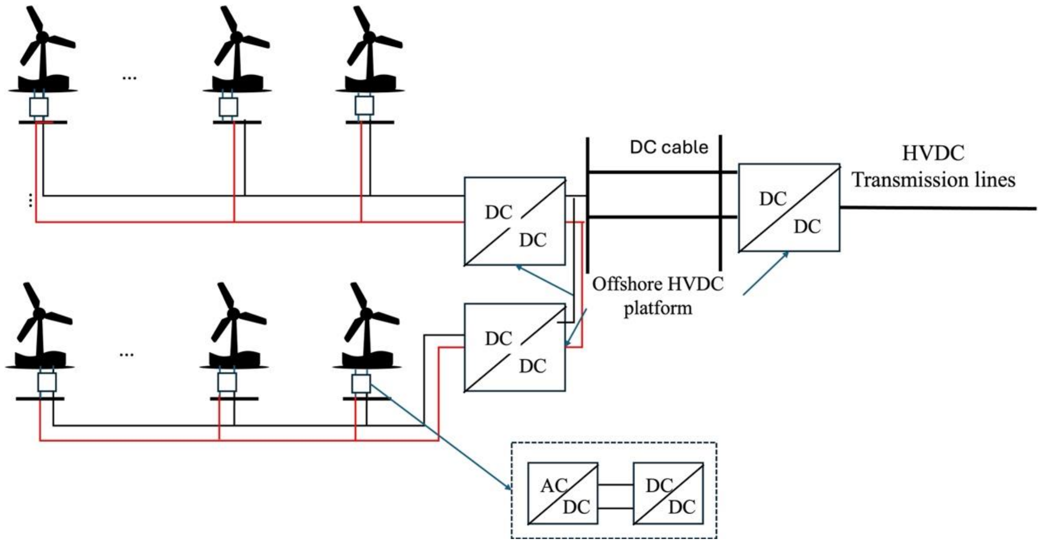


Figure 28. Configuration (d) of DC OWPP

Configuration (d): This arrangement (Figure *28*) 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.

Topology of wind power plants with HVDC

DC collected Offshore Wind Power Plant Topologies

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

Series Topology

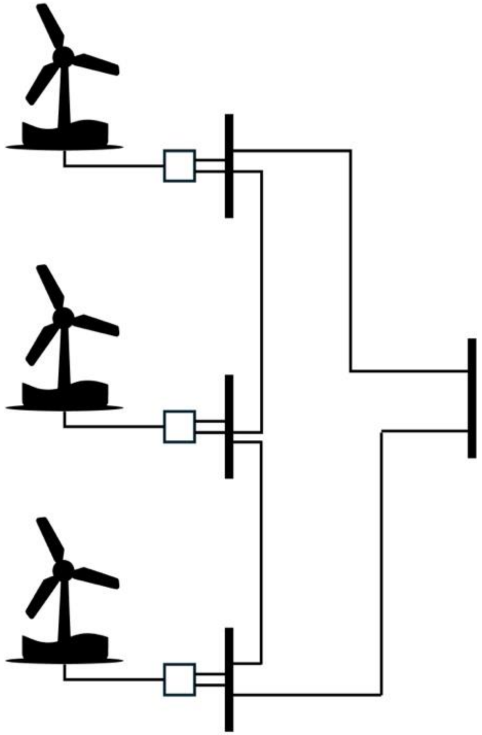


Figure 29. Series collection for DC OWPP

Topology of wind power plants with HVDC

DC collected Offshore Wind Power Plant Topologies

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

Hybrid Topology

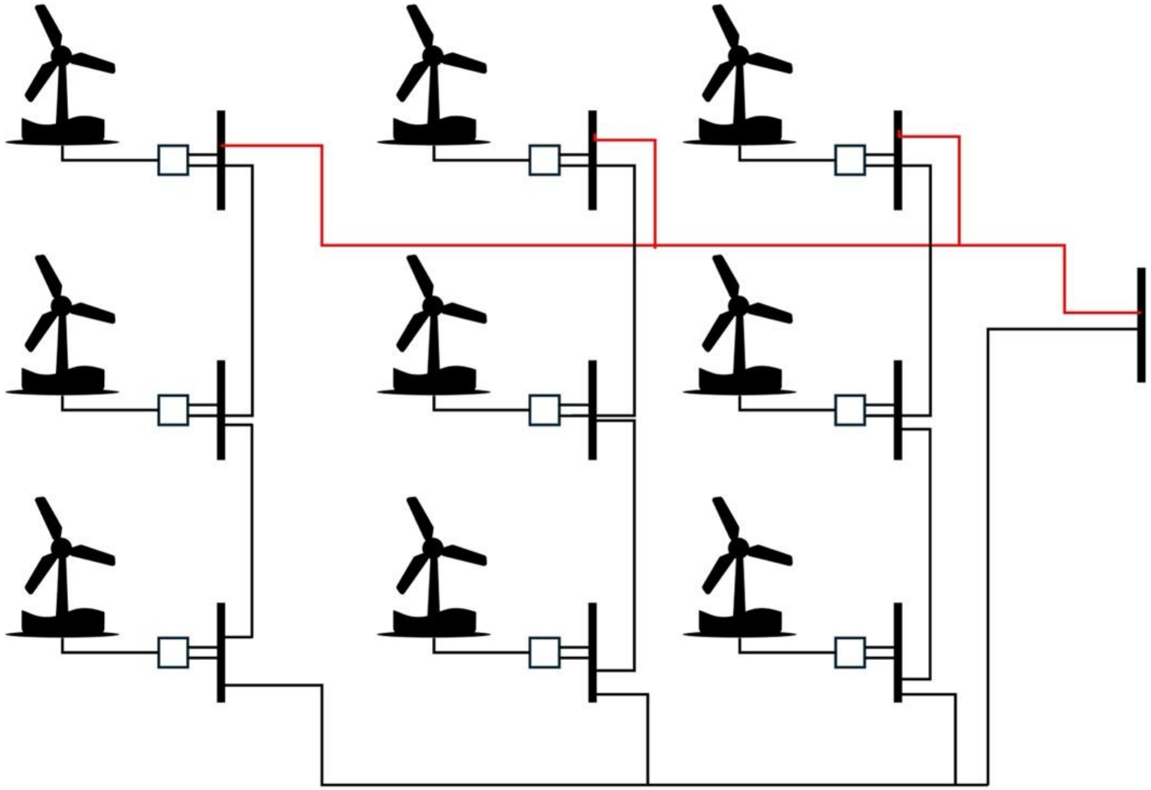


Figure 30. Hybrid collection of DC OWPP

HVDC equipment limits

Power Ratings for HVDC Technology

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

HVDC equipment limits

Current Ratings for HVDC Technology

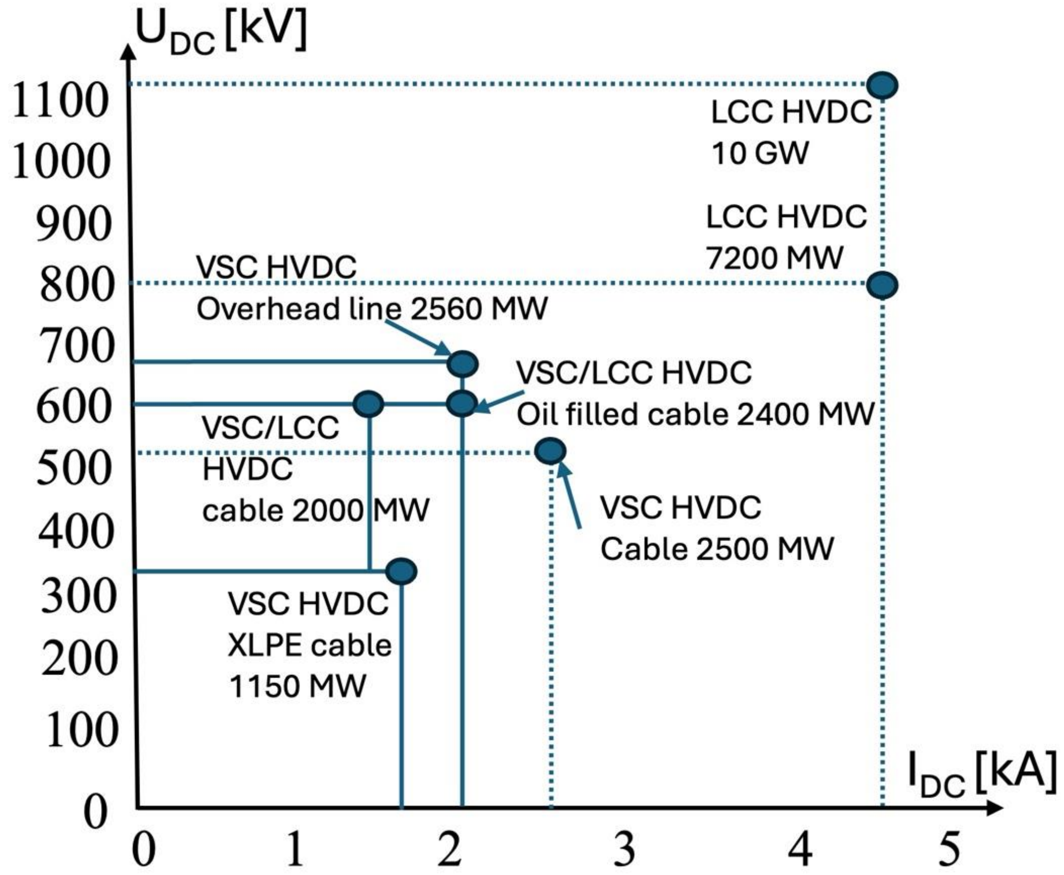


Figure 31. Current rating for HVDC systems (U_{DC} refers to the pole voltage, in a bipolar or symmetrical monopole setup, P=$2 \cdot UDC \cdot IDC$)

AC/DC transmission economic comparison

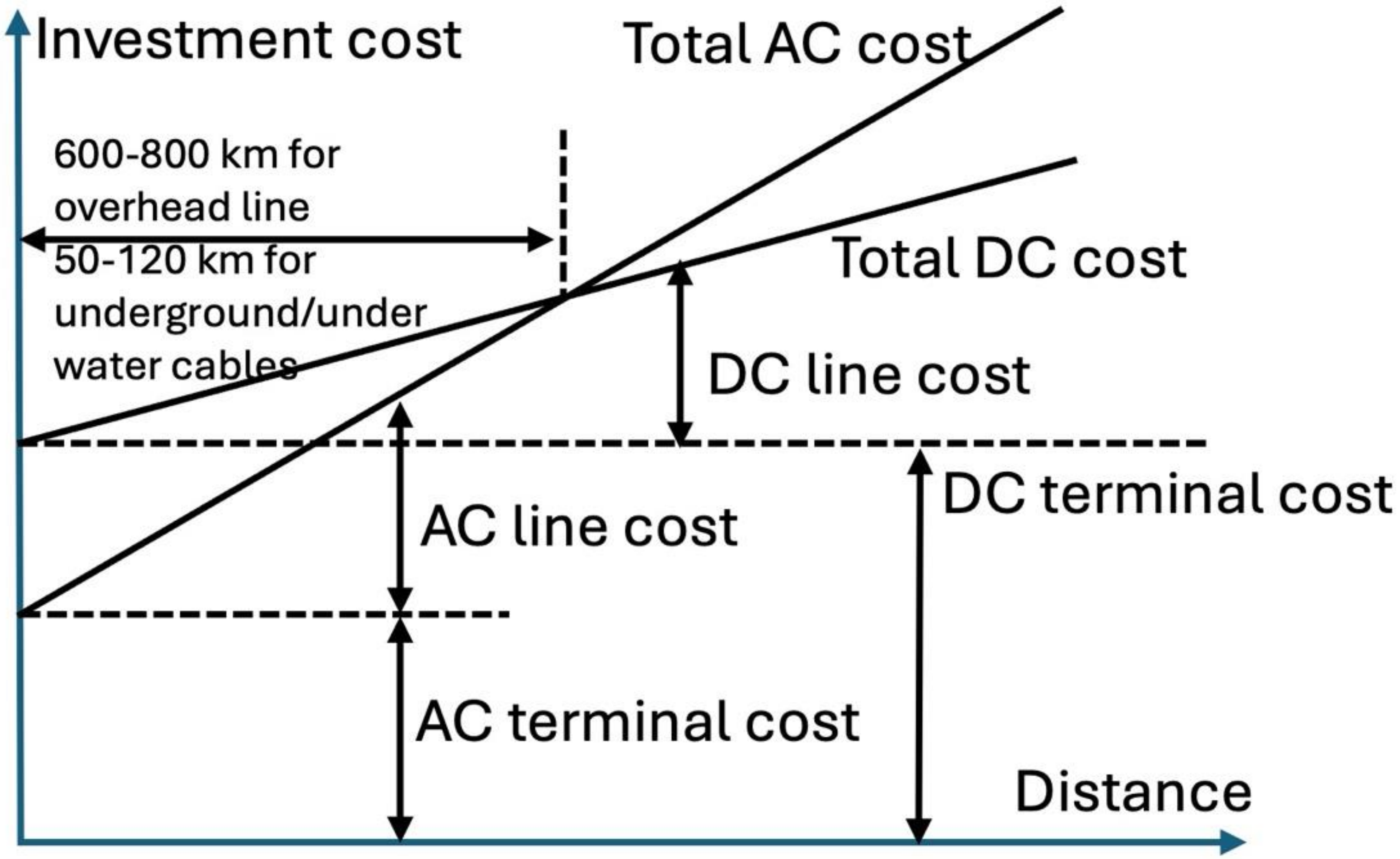


Figure 32. HVDC vs. HVAC cost.

AC/DC transmission economic comparison

DC Transmission Losses

Table 2. Typical breakdown of LCC HVDC Converter Station Losses

Item	Total Losses in %
Converter transformers	~35%
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

Total converter station losses are typically **around 0.7% to 1%** of transmitted power, with transformer and valve losses being the dominant components.

AC/DC transmission economic comparison

VSC-HVDC Losses

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

Item	Total Losses in %
Converter transformers	~13
Thyristor valves	~70
Phase reactors	~8
Auxiliary losses	~9

The **total loss of a VSC-HVDC converter station** is typically in the range of: **1.5% to 2.5% of the transmitted power (per terminal)**
This is **higher than LCC-HVDC**, which generally has losses around **0.7% to 1.0%** per terminal.

Key takeaways

- 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 and DC (Direct Current) collection grids.
- There are Offshore Platforms in OWPP: Collector Platforms, HVDC Platforms, foundation structure, DC circuit breaker.
- 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 to 120 km offshore) due to lower losses and fewer required conductors.