

Review

A Review of Offshore Renewable Energy for Advancing the Clean Energy Transition

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Abstract

Offshore renewable energy resources are abundant and widely available worldwide, offering significant contributions to the clean energy net-zero carbon emission targets. This paper reviews strong and emerging offshore renewable energy sources, including wind (fixed bottom and floating), hydrokinetic wave and tidal energy, floating solar photovoltaics (FPVs) and hybrid energy systems. A literature review of recent sources yields a timely comprehensive comparison of the levelized cost of electricity (LCOE), technology readiness levels (TRLs), capacity factors (CFs) and global generation installed and potential, where offshore wind is recognized as being the strongest contributor to the clean energy transition and thus receives the most attention. Offshore wind grid integration, converter technologies, criticality, resiliency and energy storage integration are presented, in addition to challenges and research directions. While wave, tidal and FPV will never dominate the global grid, they have vital roles to play in the global energy transition; thus, they are reviewed, including technologies, installations, potential, challenges and research directions. Offshore hybrid energy systems, combining different offshore renewable energy sources, are also discussed along with example installations. The paper concludes with a discussion of the potential environmental impacts of offshore renewable energy development, including recommendations.

Keywords: offshore energy; renewables; wind energy; wave energy; tidal energy; floating photovoltaics; hybrid energy systems; energy storage; levelized cost of electricity (LCOE); resiliency; criticality; capacity factor



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1. Introduction

The clean energy transition to meet carbon-free electricity demands will require substantial amounts of renewable energy [1–3]. Several countries have set goals to achieve net-zero carbon by 2050, and it is predicted that, by 2050, two-thirds of the world's energy supply will come from renewable energy sources [1,2]. Offshore energy is a promising pathway for achieving this scale of renewable energy decarbonization technology, as the oceans cover ~70% of the Earth's surface. Several forms of offshore renewable energy are available and are considered as existing and promising contenders in contributing to the global grid, including offshore wind (from both fixed-bottom and floating turbines), marine hydrokinetic wave and tidal energy, as well as floating solar photovoltaics (FPVs). The first significant offshore grid-connected renewable energy installation became operational in

1991—a 5 MW windfarm (Vindeby) off the coast of Denmark consisting of eleven 450 kW turbines [4].

The global cumulative offshore wind installed capacity today has reached ~83.2 GW [4]. While offshore renewable installations are currently associated with higher costs, there are also significant benefits to justify the investment toward cost reductions. Compared to onshore wind, offshore wind resources are stronger, more consistent and yield higher capacity factors (CFs), each to be discussed in more detail [5]. For example, Figure 1 presents the wind resources of the United States (US), produced by the US National Renewable Energy Lab (NREL), giving the annual average wind speed at 100 m above surface level, demonstrating the stronger offshore wind resources [6–10]. From Figure 1, the offshore wind speeds are stronger, varying from 8 to 10 m/s, indicated by the darker blue colors. Power from wind is proportional to the swept area of the blades and the cube of wind speed; thus, small increases in wind speed lead to significant differences in the power produced by the turbine. Another benefit of offshore wind in the US and other countries is that generation is close to the load, where over half the world's population lives within 100 km of a coast, and, in the US, ~80% of the population lives in coastal states.

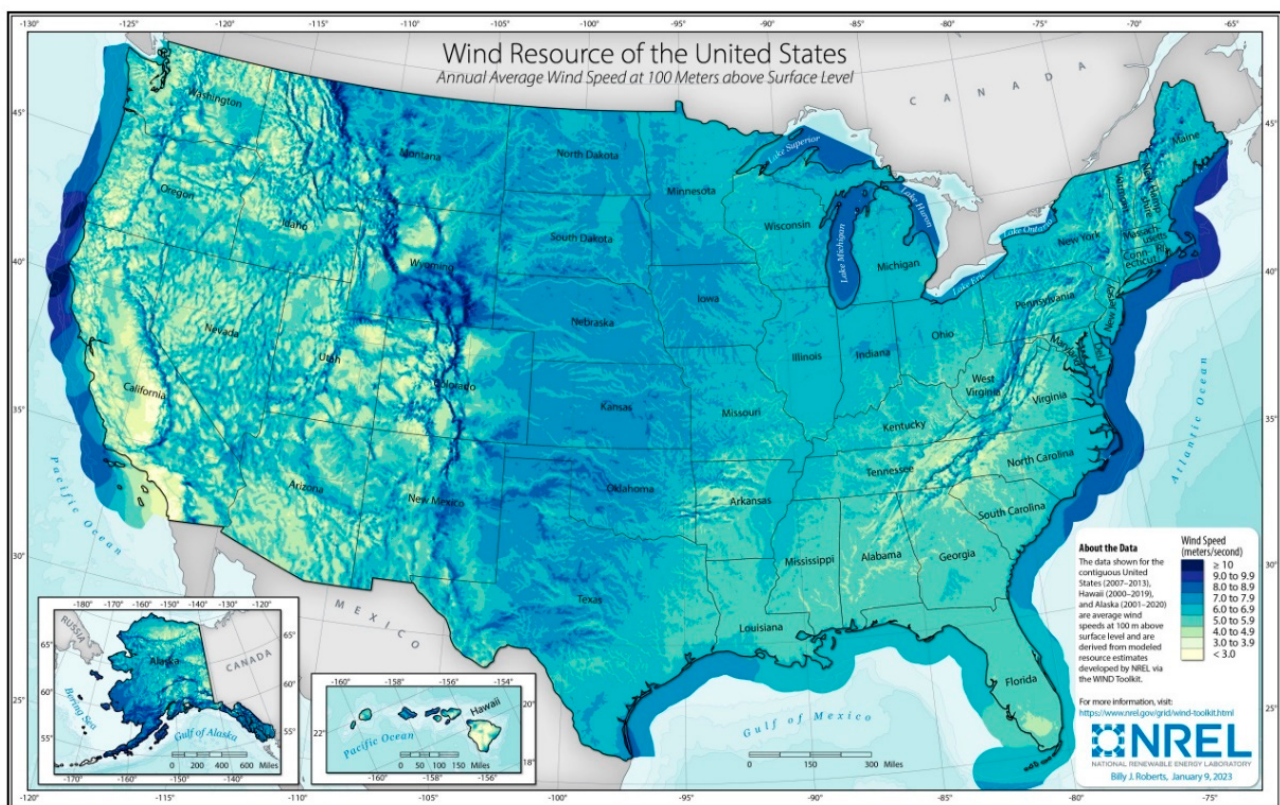


Figure 1. Wind resources of the US, giving the annual average wind speed at 100 m above surface level, demonstrating the stronger offshore wind resources [6–9].

Table 1, constructed from [2,4,11–19], provides a comparison of strong and promising offshore renewable energy generation technologies, including offshore wind (floating and fixed bottom), marine hydrokinetic wave and tidal energy and FVPs, based on their levelized cost of electricity (LCOE), technology readiness level (TRL), capacity factors (CFs) and global power generation installed and potential. From Table 1, it can be concluded that fixed-bottom offshore wind turbines, used in water depths of less than 60–80 m [10] due to economics, have the lowest LCOE, the highest TRL and CFs and the largest installed generation and potential [2,4,16]. Floating offshore wind turbines, typically used in water depths greater than 60–80 m, have the second-highest potential, with a higher estimated

LCOE [2,4,15,16]. The Floating Offshore Wind Shot™, a US government initiative led by the Department of Energy (DOE) to accelerate the development and deployment of floating offshore wind technology, has a goal of a greater than 70% reduction in LCOE by 2035, to 0.045 USD/kWh, which would also help to accelerate the reduction in the LCOE of fixed-bottom wind turbines [16].

Table 1. Comparison of offshore renewable energy technologies, created from results presented in [2,4,11–19].

Offshore Power Generation Technology	LCOE [2] (USD/kWh)	TRL [2] 6—Technology Demo 7—Prototype Demo 8—Qualified System 9—Proven System	Capacity Factor (CF, %)	Global Power Generation (GW)		
				Installed	2030	2050
Wind (fixed)	0.06–0.11	7–9 (high)	45–50 [16]	83 [4]	210 [4,14]	1600 [4]
Wind (floating)	0.07–0.17	7–8 (medium–high)	40–46 [16]	0.278 [4]	2.6 [4,14]	264 [15]
Wave	0.30–0.55	6 (medium)	10–40 [11]	0.028 [17]	0.05 [17]	180 [19]
Tidal stream	0.20–0.46	6 (medium)	20–35 [12]	0.040 [17]	0.18 [17]	120 [19]
Floating PV (FPV)	0.05–0.10	6–8 (medium–high)	15–20 [13]	0.010 [13]	30 [13]	45 [18]

Wave and tidal energy are in the pre-commercial stages of research and development, with higher LCOEs and lower TRLs, as can be seen in Table 1, where it is assumed that wave energy is five years behind tidal [19], and tidal energy is 10 years behind wind [20]. Challenges on the path to scaling up have included technological, research and development costs, environmental concerns and supply chain hurdles [20]. At the same time, the global marine hydrokinetic potentials by 2050 are very strong, predicted to be 180 GW for wave and 120 GW for tidal energy, where the European Union has a total hydrokinetic target of 40 GW by 2050 [19]. The LCOEs of wave and tidal systems are expected to drop in the coming decades, predicting wholesale market price (WMP) parity for both wave and tidal by 2044 [19]. Grid parity occurs when the LCOE of a renewable energy source is equal to or less than the LCOE of conventional sources such as coal-fired power plants and differs by region [21]. In addition to holding future potential, wave and tidal energy also offer advantages over wind energy in that tides and waves are highly predictable and more consistent [22]. In addition, wave and tidal systems can be small-scale, modular or in the form of arrays, enabling a market in remote island communities, where the energy competition is often represented by costly diesel generation [20].

As shown in Table 1, FPV is another promising offshore renewable with relatively high technical readiness and economic and production potential [2,18]. Currently, most implemented FPV projects involve deployments on inland bodies of water, such as lakes, ponds and reservoirs, with the benefits of conserving land space and reducing evaporation [23,24]. In contrast, the oceans offer much more space for large-scale FPV systems, in addition to the benefits of increased solar irradiance in the open ocean and efficiencies due to natural oceanic cooling, increasing PV performance by up to 10% [25–29]. However, research and demonstrations are still underway to ensure that innovative FPV systems can withstand the harsh marine environment of an offshore site [23,30,31]. Offshore FPVs are also compatible for integration with other offshore renewables, such as offshore wind farms and other marine facilities [27], known as hybrid energy systems [32], which will also be discussed in this review paper in Section 6.

In Table 1, the LCOE is calculated as in Equation (1) [21]:

$$LCOE = \frac{CapEx \times FCR + OpEx}{AEP_{net}} \quad (1)$$

where

$LCOE$ = levelized cost of electricity (USD/kWh);

$CapEx$ = capital expenditures (USD/kW), ~USD 5 k/kW Ofs fixed, ~USD 1.5 k/kW onshore;

FCR = fixed charge rate (amortization schedule, %/yr);

$OpEx$ = operational expenditures (USD/kW/yr);

AEP_{net} = net average energy produced (kWh/kW/yr).

The capacity factor (CF) in Table 1 is a performance indicator defined as the average power output of a device in a given resource environment relative to the actual maximum output power of the device throughout the year, as shown in Equation (2) [33]:

$$CF = \frac{\text{Average Power Output}}{\text{Maximum Power Output}} \times 100\% \quad (2)$$

Contribution and Organization of This Review

This review paper seeks to keep offshore renewable energy stakeholders abreast of currently installed capacities and future generation potentials, as well as the technological, economic and research opportunities and directions. Thus, this paper presents a review of strong and emerging offshore renewable energy sources, including wind (fixed-bottom and floating turbines), marine hydrokinetic (wave and tidal), FPVs and hybrid energy systems, including the comprehensive comparison in Table 1 not found in prior review papers. The rapid developments in offshore renewables over the past few years and future market outlooks are presented, as well as technologies, challenges and opportunities. Recent review papers that have addressed offshore renewables include [34], from 2023, providing a review of energy extraction from wind and oceans, including onshore wind, but it does not include offshore FPV. The 2025 review paper [35] provides a detailed literature review of the state of the art for 2015–2024 for wind, wave and tidal (no FPV), identifying areas with a significant number of research publications (wind and wave) vs. areas that were less frequently discussed (tidal and energy storage) to help identify needs for further development.

The novelty of this paper is the focused review of offshore renewables, beginning with a big-picture overview and comparison of the global generation installed and potential, LCOE, TRLs and CFs. Section 2 presents global offshore wind (both fixed-bottom and floating turbine) installations, market outlooks, permitting processes and technology characteristics. Through the comparison of the LCOE, TRLs, CFs and generation potential, offshore wind is recognized as being the strongest contributor to the clean energy transition. Thus, more attention is given to offshore wind, including grid integration, converter technologies, criticality, resiliency and energy storage integration to buffer the variability and intermittency of wind farm generation and demand. Sections 3–5 present wave, tidal and offshore FPV operational overviews, along with their technologies—for example, installations and challenges. Section 6 presents offshore hybrid energy systems, combining different offshore renewable energy sources, and example installations, and Section 7 presents the potential environmental impacts of offshore renewables. Section 8 details the conclusions reached through this in-depth review, including challenges and research directions. This review paper is needed considering the demand for increased renewables to enable the clean energy transition.

2. Offshore Wind

The global cumulative offshore wind installed capacity as of May 2025 is 83.2 GW, with 48 GW under construction [4]. The International Energy Agency (IEA) expects the total offshore wind capacity to reach 212 GW by 2030 [14], where the Global Wind Energy Council (GWEC) expects that floating wind will account for ~2.6 GW of this total [4]. By 2050, the IEA predicts the offshore wind capacity to reach 1600 GW [5], with floating offshore wind to account for ~264 GW of this total, i.e., over 15% of all offshore wind energy in 2050 [15].

The currently installed 83.2 GW is estimated to power over 73 million homes annually, considering a conservative CF of 0.41 and based on the average UK household electricity consumption of 4.1 MWh/yr [4], as detailed through Equations (3) and (4):

$$83.2 \text{ GW} \times 8760 \text{ h/yr} \times 0.41 \text{ (CF)} = 298.1 \text{ TWh/yr} \quad (3)$$

$$298.1 \text{ TWh/yr} / 4.1 \text{ MWh/yr} = \sim 73 \text{ million homes} \quad (4)$$

Yearly global offshore wind installations from 2006 to 2024 (in MW) are shown in Figure 2 [4]. China is seen as leading, with the most added offshore wind installations for the seventh consecutive year, with drops after 2021 attributed to challenges including insufficient grid connections, complex maritime approvals (discussed in a later subsection) and a slower-than-expected transition from nearshore to deep water. The offshore share of total new wind power installations including onshore was 23% in 2021 and 7% in 2024.

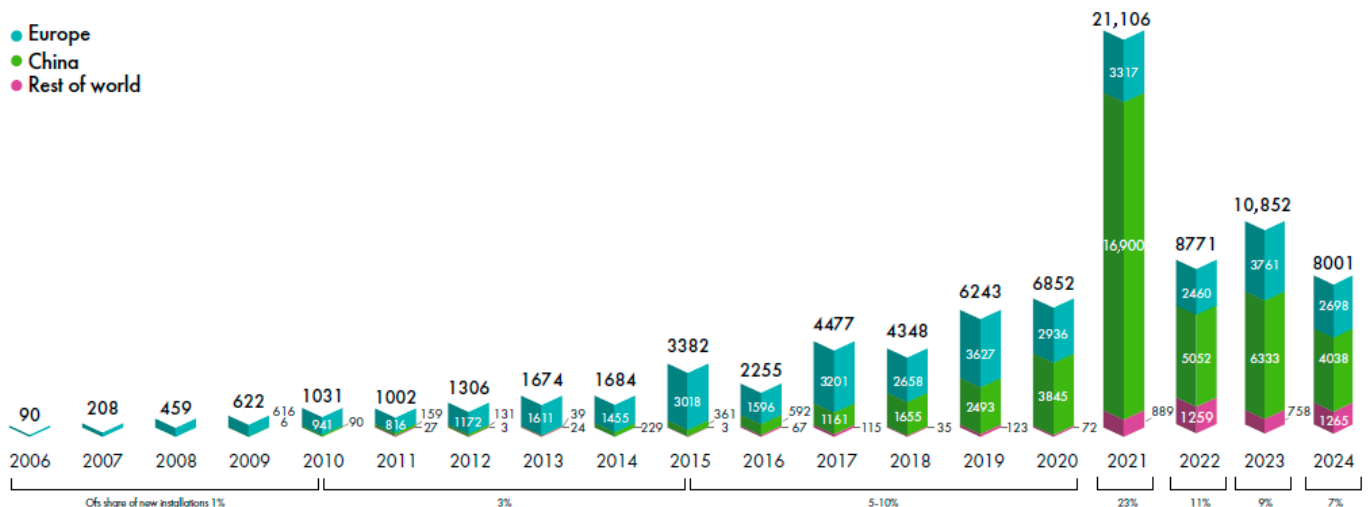


Figure 2. New global offshore wind installations from 2006 to 2024 (in MW) [4].

Figure 3 shows the offshore wind installations by market/country, first as new installations in 2024 as a percentage of the total capacity added in 2024 (8 GW), shown in Figure 3a, and then for each market/country as a percentage of the cumulative global installation (83.2 GW), shown in Figure 3b [4]. China is the absolute offshore wind market leader, with half of the global market, followed by the UK.

Figure 4 shows the global offshore market outlook up to 2034 in MW, for both fixed-bottom and floating wind farms, including the compound annual growth rate (CAGR) [4]. Greater than 350 GW of new capacity is expected to be added over the next decade, bringing the total capacity of installed offshore wind to 441 GW in 2034 [4]. Considering a CF of 0.39 in 2034—a conservative estimate based on advanced technologies likely to increase the CFs—following Equation (3), the 441 GW of installed offshore wind capacity would result in ~1500 TWh. For context, the total global electricity generation in 2024 reached

31,256 TWh [36]. The offshore share of new wind power installations would rise from ~7% in 2024 to ~25% in 2034.

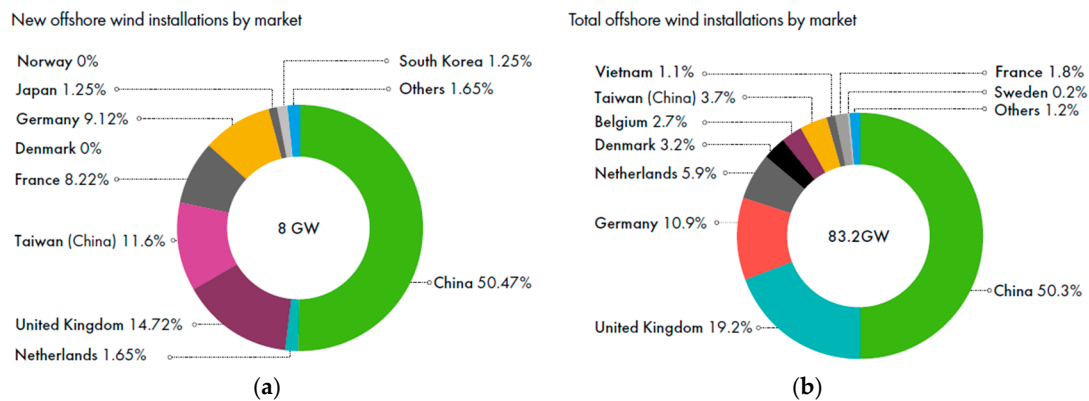


Figure 3. Offshore wind installations by market/country for (a) new installations in 2024 as a percentage of the total capacity added in 2024 (8 GW) and (b) each market/country as a percentage of the cumulative global installations (83.2 GW) [4].

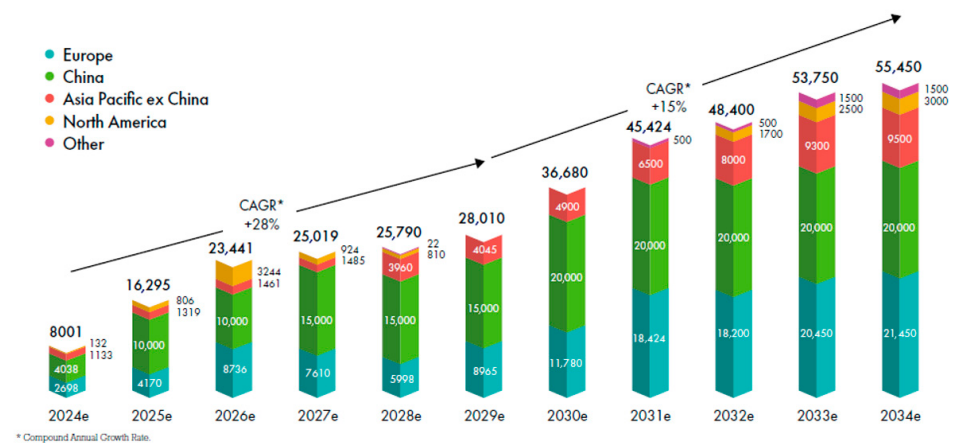


Figure 4. Global offshore market outlook up to 2034 for new offshore wind installations, for both fixed-bottom and floating cases, in MW, including the compound annual growth rate (CAGR) [4].

The trend in the offshore vs. onshore turbine size from 1980 to 2030 is shown in Figure 5. As mentioned in the Introduction, the first offshore wind turbine of 0.45 MW, indicated in 1991, was used in a 5 MW windfarm off the coast Denmark [4]. Compared to onshore wind, offshore wind turbines are larger, where the wind speed increases with height [37], and the power is proportional to the swept area of the blades and the cube of the wind speed. Offshore wind turbines also have more complex support structures to withstand the marine environment.

The calculation of the power extracted from the wind by a turbine is proportional to the swept area of the blades and the cube of the wind speed, as shown in Equation (5):

$$P = \frac{1}{2} \rho A v^3 C_p (W) \quad (5)$$

where

ρ = density of air (1.225 kg/m³);
 A = swept area of the blades (m²);
 v = wind speed (m/s);

C_p = conversion coefficient, to convert KE of wind into mechanical energy (Betz limit is 59.3%).

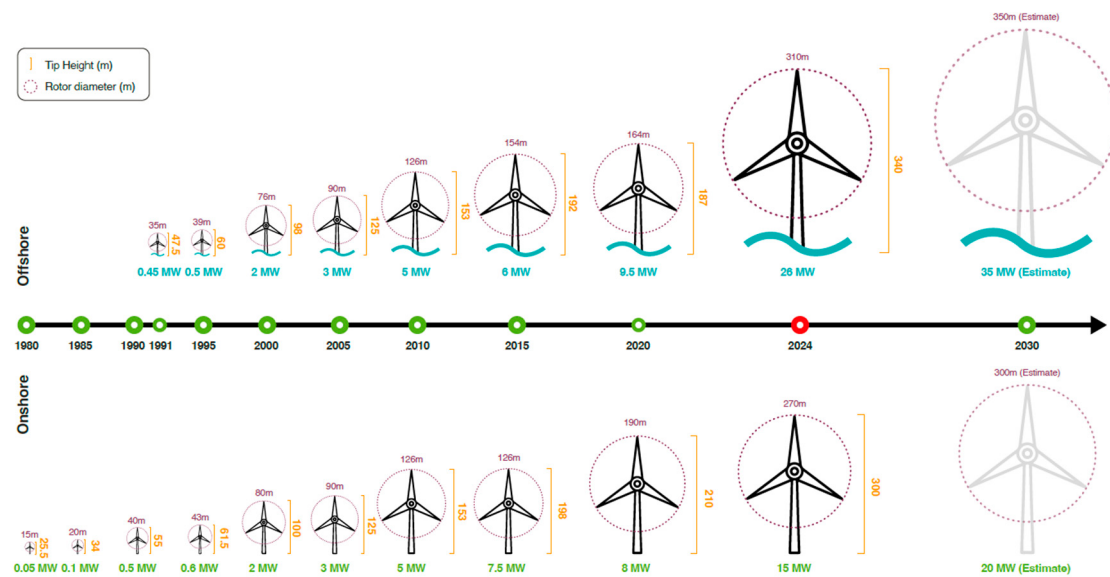


Figure 5. The trend in offshore vs. onshore turbine sizes from 1980 to 2030 [4].

Figure 6 demonstrates the increasing mean wind speed (m/s) vs. hub height above surface level from 100 m to 250 m, for offshore areas of the US, using data from [37]; as the hub height increases, the wind speed increases, because the impact from surface friction forces is reduced.

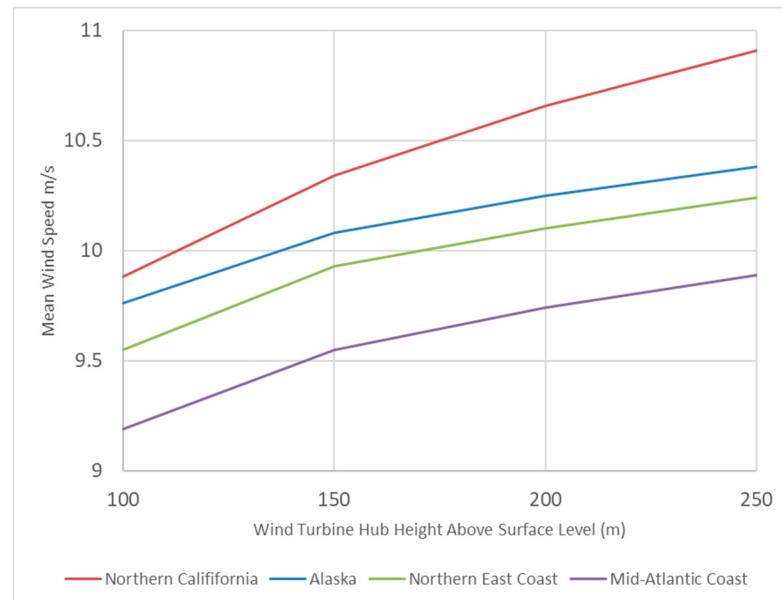


Figure 6. Mean wind speed (m/s) vs. hub height in offshore areas of the US.

In the US, offshore wind energy pipeline projects in the North Atlantic are the most advanced (see Figure 7). Other than in the Gulf of Maine, the US East Coast benefits from a gently sloping continental shelf, facilitating the use of fixed-bottom foundations due to water depths of less than 60–80 m. Thus, the US offshore wind industry first concentrated on the waters off Massachusetts to North Carolina (as we proceed north to south, the wind speeds decrease).

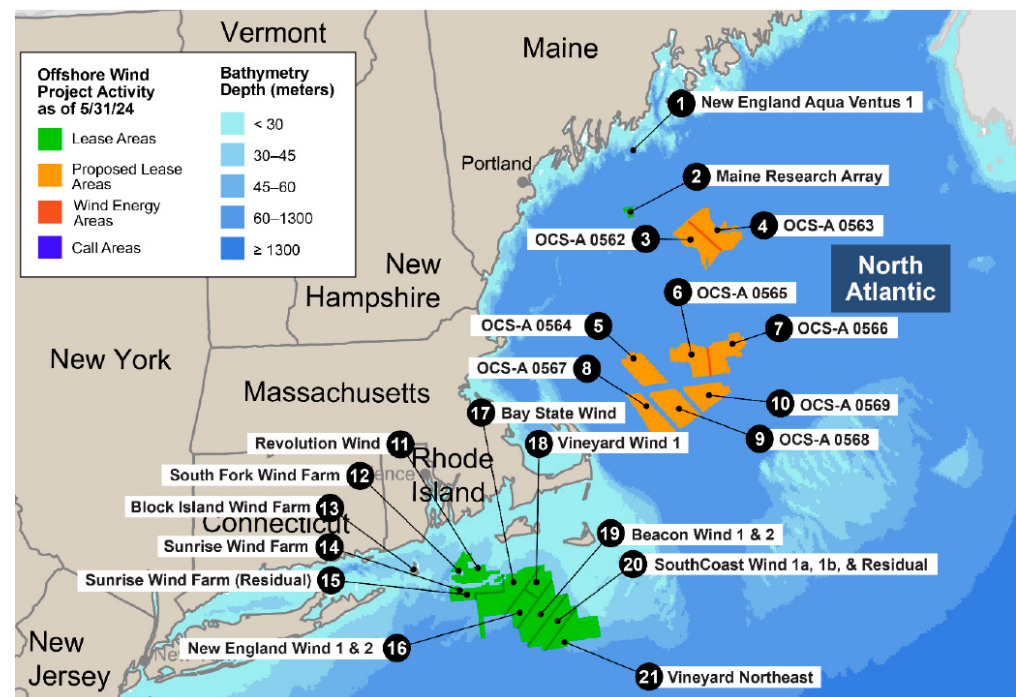


Figure 7. US North Atlantic offshore wind energy pipeline projects [38].

The US offshore wind farm operation and construction activities are summarized below, with the numerical site locations referring to Figure 7 above.

Total of 174 MW in operation:

- 2016 30 MW (5×6 MW), Block Island Wind Farm (13);
- 2020 12 MW, (2×6 MW pilot), Coastal Virginia *;
- 2023 132 MW (12×11 MW), South Fork Wind (12).

Under construction (~6 GW):

- Revolution Wind, 704 MW (11);
- Sunrise Wind, 924 MW (14);
- Vineyard Wind 1, 806 MW (18);
- Empire Wind 1, 810 MW *;
- Coastal Virginia Offshore Wind, 2640 MW *.

* Located in the Mid-Atlantic.

The above projects are not only characterized by the wide variety of installed capacity but also by the wide variety of entities that have invested in offshore wind technology. Table 2 captures the wide array of companies that have projects either ongoing or under development in the US, demonstrating the global impact and potential of this technology.

The US, as with other countries, has experienced project development delays, including due to complex maritime approvals, which will be discussed in the next subsection, as well as due to technical setbacks. In July 2024, the first large-scale wind farm in the US, the Vineyard Wind 1 project, was operating while under construction with 10 turbines (out of the total 62 planned) when a turbine suffered a blade failure due to a manufacturing defect involving insufficient bonding of the blade materials, leaving debris in the water and washing up on Nantucket Island, offshore Massachusetts [39]. Vineyard Wind 1 operations were halted for inspections and then able to resume in January 2025, with plans to complete the 62-turbine wind farm by the end of 2025 [40].

Table 2. US offshore windfarms in service, in construction and under development (adapted from [41]).

Project/In Service	State(s)	Company	Start Construction	First Power	Size (MW)
Block Island	RI	Orsted		2016	29
Coastal Virginia Offshore Wind Pilot	VA	Dominion		2020	12
South Fork	RI, MA	Orsted (50%) and Global Infrastructure Partners (GIP) Skyborn Renewables unit (50%)	February 2022	December 2023	132
Vineyard Wind 1	MA	Iberdrola/Copenhagen Infrastructure Partners	November 2021	January 2024	806
Revolution Wind	RI, MA	Orsted (50%) and Global Infrastructure Partners (GIP) Skyborn Renewables unit (50%)	2023	2026	704
Coastal Virginia Offshore Wind (Commercial)	VA	Dominion (50%)/Stonepeak (50%)	November 2023	2026	2587
Empire Wind 1	NY	Equinor	May 2024	2027	810
Sunrise Wind	RI, MA	Orsted	July 2024	2026	924
New England Wind 1	MA	Iberdrola	2025	2029	791
SouthCoast Wind 1	MA	Ocean Winds (EDP/Engie)	late 2025	2030	1287
Community Offshore Wind 1	NY, NJ	RWE/National Grid	2027	2030	1314
MarWin	MD	US Wind owned by Toto Holding's Renexia			270
Atlantic Shores South 1	NJ	EDF/Shell			1510
Momentum Wind	MD	US Wind owned by Toto Holding's Renexia			809
Excelsior Wind	NY, NJ	Copenhagen Infrastructure Partners' Vineyard Offshore			1314
Leading Light	NY, NJ	Invenergy/energyRE			2400
Vineyard Wind 2	MA	Copenhagen Infrastructure Partners' Vineyard Offshore			1200
Community Offshore Wind 2	NY, NJ	RWE/National Grid			1300
New England Wind 2	MA	Iberdrola			

2.1. Example Offshore Wind Development Process

The regulation of most offshore wind developments is in economic zones that extend 200 nautical miles from shorelines, also called federal waters. In the US, the wind development process is primarily overseen by two bureaus of the US Department of the Interior (USDOI): the Bureau of Ocean Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE). Figure 8 shows the BOEM and BSEE's regulatory

stages and timeline, which is divided into six phases, with the BOEM overseeing the first three and the BSEE the latter three. Note from the timeline that it can take greater than 10 years from planning and analysis to operations. In the US, the Federal Energy Regulatory Commission (FERC) has oversight over the interconnection agreements governing the connection of the offshore wind power lines to the interstate grid. Note that, in the US, the USDOJ issued a July 2025 Memorandum requiring that permitting actions obtain review and approval by the Secretary of the USDOJ [42].

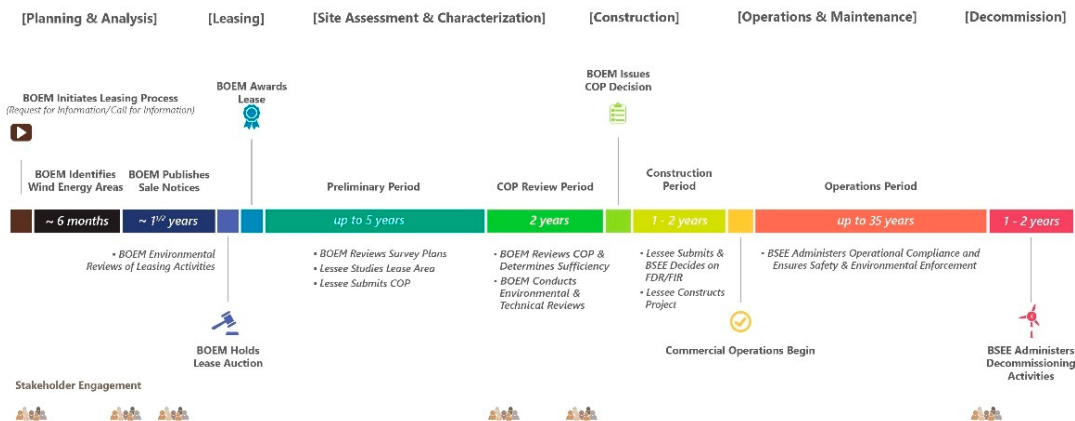


Figure 8. Offshore wind development process in the US: BOEM and BSEE regulatory stages and timeline [43].

2.2. Offshore Wind Support Structure Types

Figure 9 shows the offshore wind support structures for both fixed-bottom and floating wind turbines, where, at depths greater than 60–80 m, fixed-bottom foundations become uneconomical and move to floating structures. While ~80% of offshore wind resources lie in waters greater than 60–80 m, most of the world’s installed offshore wind turbines are in depths of less than 60–80 m, using monopile (~80%) and jacket fixed-bottom foundations. For floating wind turbines, a semi-submersible is the dominant platform. The global installed capacity of floating wind is ~278 MW: Norway leads with 101 MW, followed by the UK (78 MW), China (40 MW), France (27 MW), Portugal (25 MW), Japan (5 MW) and Spain (2 MW) [4].

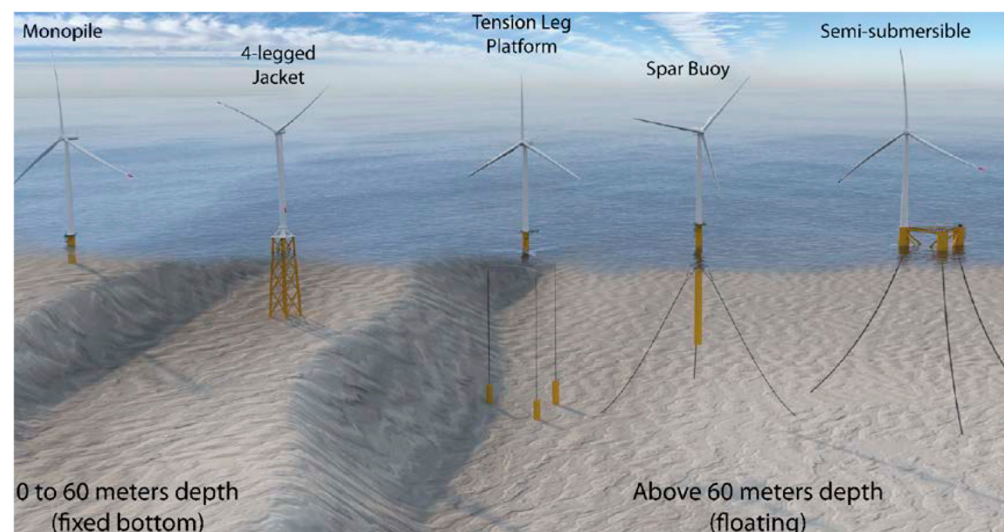


Figure 9. Offshore wind support structures for both fixed bottom and floating wind. Illustration by Joshua Bauer, NREL [10].

Figure 10 shows how the Pacific (West) Coast continental shelf drops off quickly with nearshore depths greater than 60–80 m, thus necessitating floating foundations. The state of California, through the California Energy Commission (CEC), has an offshore wind goal of 25 GW by 2045 [44].

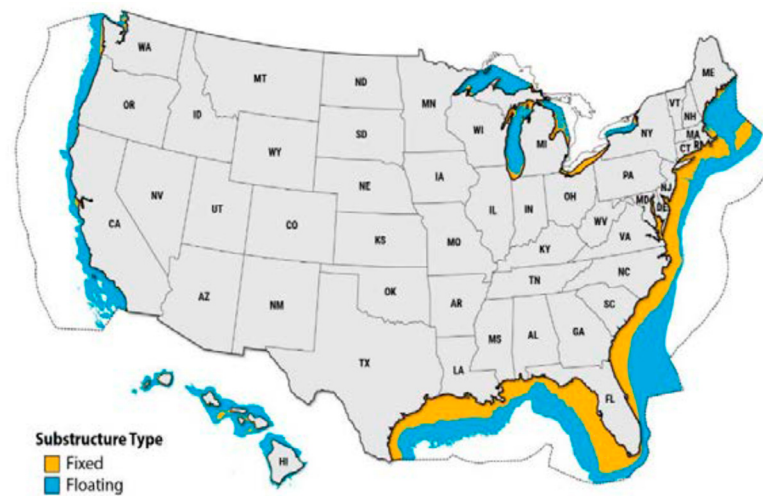


Figure 10. Offshore wind turbine substructure support type given the local bathymetry of the continental shelf, with “fixed-bottom” substructures shown in yellow and floating shown in blue [45].

2.3. Wind Power Plant

The wind turbine power plant is shown in Figure 11, where the rotor (hub and blades) converts the kinetic energy of wind to create torque that spins the generator. The generator converts the mechanical energy into electricity, where the generator can be driven by gearboxes (to increase the low-speed shaft rotational speed to spin the generator) or the generator can be direct drive, as shown in Figure 11.

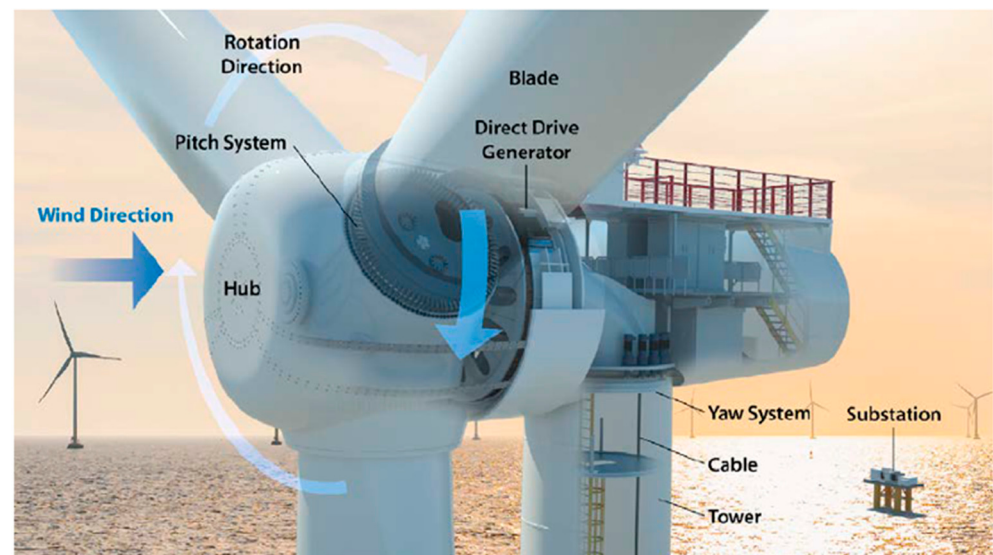


Figure 11. Wind turbine power plant [10].

The two most common wind turbine drivetrains are shown in Figure 12a with a gearbox and Figure 12b without a gearbox, where the power converters will be discussed next [46].

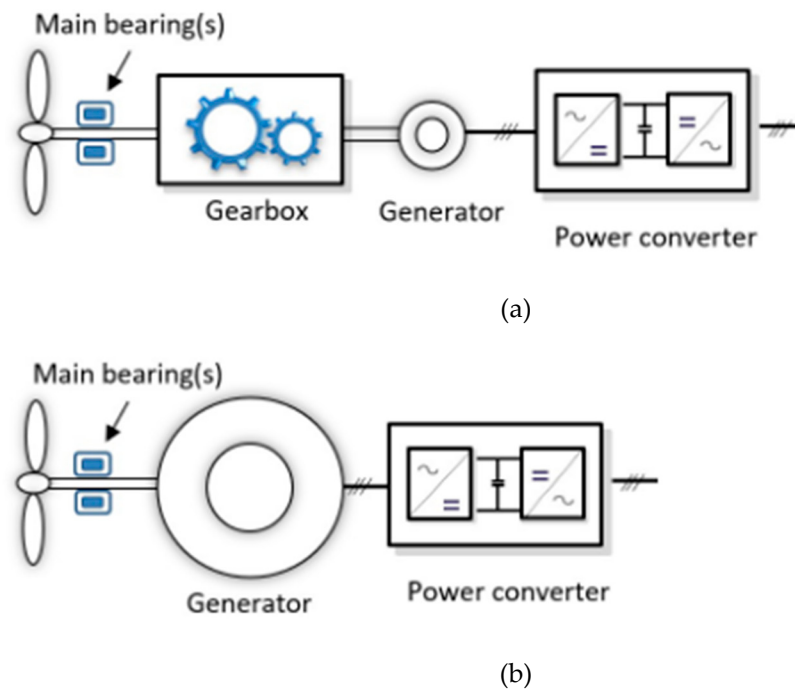


Figure 12. Two most common wind turbine drivetrains. (a) with a gearbox and (b) without a gearbox [46].

2.4. Wind Turbine Power Converters

The wind turbine power converters condition the power produced by the generator. The power converter must fulfill the requirements for both the generator and the power grid [47]. In the past, power converters in small (kW range) wind turbines had the topology shown in Figure 13a due to lower costs and fewer power switches. As seen in Figure 13a, the generator-side converter was a diode rectifier cascaded with a boost converter to stabilize the dc bus, and then a two-level (2L) inverter/voltage source converter (VSC) was employed on the grid side for full control of the grid current injection to minimize the total harmonic distortion (THD) and to optimize the power factor (PF) [46]. For generators in the 1–10 MW range, low-frequency torque pulsations and high THDs caused by the diode rectifier front-end harmonics are harmful to generators; thus, the front-end diode rectifier of Figure 13a was replaced by a 2L six-switch VSC with PF correction, as shown in Figure 13b. Note that a “two-level” (2L) VSC refers to a standard three-leg six-switch converter where the ac line-to-neutral voltage has two levels relative to the positive and negative dc bus. A doubly fed induction generator (DFIG) with a partially loaded back-to-back (BTB) converter is often used for generators of less than 3 MW, while a permanent magnetic synchronous generator (PMSG) with a fully loaded BTB converter is commonly used for generators of greater than 3 MW [46].

For present-day wind turbine power ratings greater than 10 MW, a single 2L BTB converter is not appropriate since the current load on the power devices would be very high [46]. Note that the common grid-side voltage before the transformers in Figure 14 is 690 V. To remedy this, 2L BTB converters are connected in parallel to share the current, as shown in Figure 14a. The power rating can also be upscaled by increasing to a medium voltage (MV) using multilevel inverters, such as a three-level (3L) neutral point clamped (NPC) converter, as shown in Figure 14b.

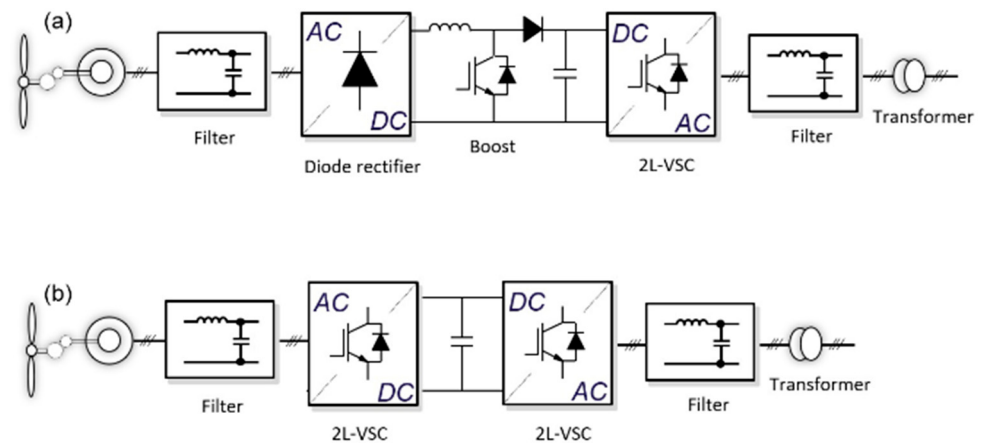


Figure 13. Generator-side converter: (a) for small (kW) turbines, a diode rectifier cascaded with a boost converter was used, with a two-level inverter on the grid side; (b) for 1–10 MW turbines, two back-to-back (BTB) VSCs were used [46].

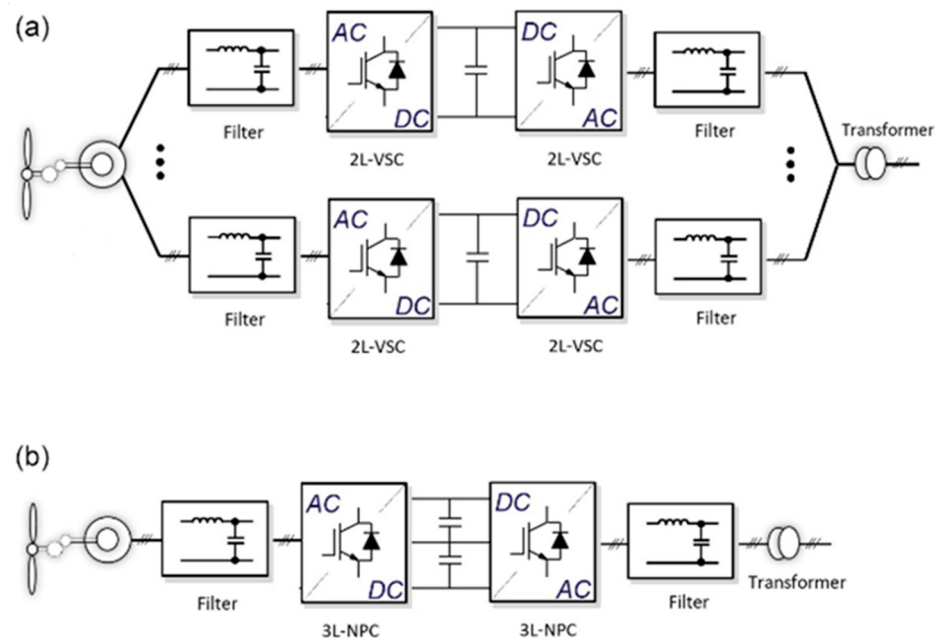


Figure 14. For wind turbine power ratings greater than 10 MW, (a) 2L BTB converters are connected in parallel to share the current or (b) MV using multilevel inverters is applied, such as a three-level (3L) neutral point clamped (NPC) converter [46].

A matrix converter is another strong candidate for wind applications, being a direct variable-frequency AC-AC converter, where a matrix of switches is used to directly interface two three-phase AC systems [48]. Matrix converters can offer significant size reductions in the range of 30% [49], enabling applications where the matrix converter can be embedded into the electric machine itself [50–54]. These high power densities, in addition to low THD and high efficiencies, are motivating researchers to explore matrix converter applications in wind applications [55].

2.5. Offshore Wind Turbine Criticality

Given the criticality of offshore wind turbine drivetrain components, dedicated condition-monitoring systems are becoming mainstream, including for the gearbox, main bearings and generator. The outputs of condition monitoring are used to support anomaly detection, fault diagnostics and prognostics models. There exists room for improvement

regarding the performance of predictive prognostics modeling, which is an opportunity for further research [46]. These models can be data-driven, e.g., for supervisory control and data acquisition (SCADA)-based condition monitoring, machine learning (ML) and artificial intelligence (AI) technologies are being pursued. A key objective of fault prognostics is predictions of components' remaining useful life (RUL). Among drivetrain components, bearing faults have been prevalent and are being investigated by industry and researchers [46].

2.6. Offshore Wind Converter Resiliency

As wind penetration increases, conventional grid inertia available on the system is decreasing, weakening the grid's ability to withstand and recover from disturbances (resiliency). Thus, wind turbine converter resilience is the ability of the converter to withstand and recover from disturbances. The grid-following mode control of grid-side converters has been the mainstream, which regulates the active and reactive power output and ties into the grid to match the voltage and frequency [56–59].

Grid-forming mode control applied to the grid-side converter enables wind power converters to regulate the grid current and actively support the grid voltage, frequency and system inertia, so that the inertia in the wind turbines can be used to support the grid [46].

2.7. Offshore Wind Farms Incorporating Battery Energy Storage at Onshore Substations

The offshore wind farm variability between generation and demand can be buffered by installing battery energy storage at onshore substations. When the wind farm generation exceeds the demand, the battery can store the excess energy to be discharged later, when the demand exceeds the supply, to help balance the grid. This integration of energy storage with wind farms can greatly enhance grid flexibility, where the surplus energy that would otherwise cause negative prices (where generators pay to sell power) could be diverted to storage during low-demand periods correlated with high wind/solar energy production (oversupply). Energy storage can reduce price volatility by making more power available during peak periods, when energy is more expensive. Examples of energy storage integrated with offshore wind farms include the following:

- Hornsea 3 Offshore Wind Farm (2.9 GW), off England, Tesla batteries (600 MWh, 300 MW, fully operational in 2026);
- Revolution Wind Farm (704 MW), off Martha's Vineyard, Tesla batteries (40 MWh);
- RWE (German) developing 41 MWh, 35 MW Li-ion battery storage to support offshore wind farms (Netherlands).

With the mention of negative pricing, note that improved forecasting models (e.g., AI-driven) for renewable energy generation are needed to better predict supply and allow for the more efficient scheduling of power plants.

2.8. Offshore Wind Farm Substations

Offshore substations collect the ac power from turbines across a wind farm (Figure 15 [60]) at ~66 kV or greater using inter-array cables and then high-voltage transformers in an offshore substation step up the voltage, e.g., to 220 kV, and export the power to shore through buried subsea export cables (see photo of an offshore substation from the Vineyard Wind 1 windfarm in Figure 16 [61]). Note that high-voltage dc (HVDC) wind farm transmission systems offer a reduced number of cables and losses with increased efficiency, although they require additional offshore ac/dc converter stations and onshore ac/dc converters at the onshore substation; thus, they are a good option for wind farms that are 35 miles or more from the coast [60]. Examples of offshore wind farm HVDC transmission include the world's largest wind farm (the UK's Dogger Bank Wind Farm, at

3.6 GW, which plans to be fully operational by 2027), as well as several other North Sea wind farm projects. In the US, the Sunrise Wind Farm is expected to become the first US offshore wind farm to use an HVDC transmission system.

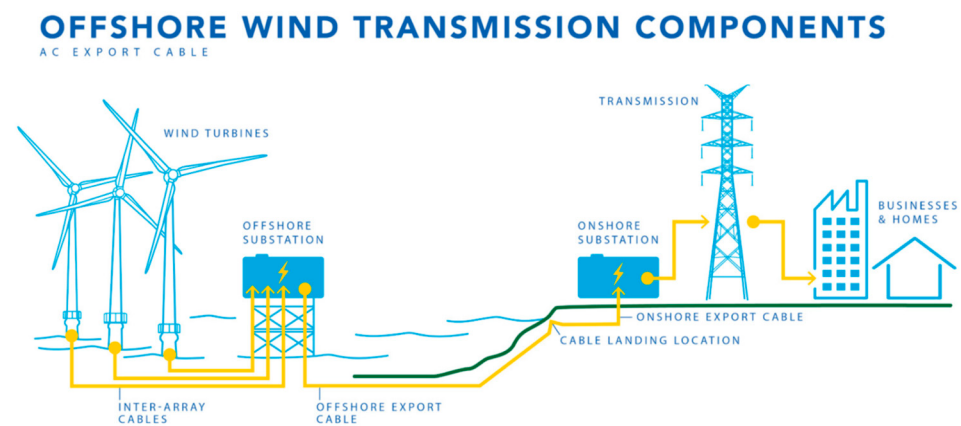


Figure 15. Offshore wind farm transmission system major components [60].

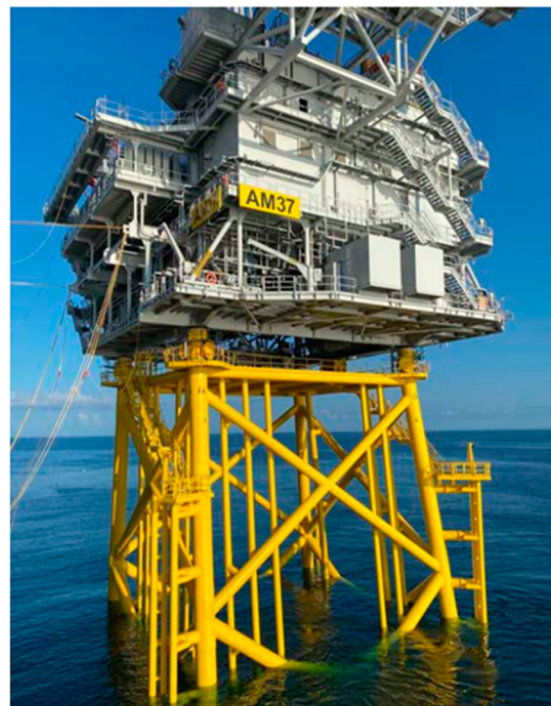


Figure 16. Photograph of offshore wind farm substation [10].

2.9. Offshore Wind Farm Wake Effects

Wind farm wake effects arise when the wind slows and becomes more turbulent after passing through a wind turbine, disrupting the airflow to downwind turbines, as shown in Figure 17. A wake effect study of a proposed wind farm off the US East Coast showed a reduction in total power generation of 34–38% due to wake effects, where the primary reduction results from wakes formed between turbines of a single wind farm [62]. Offshore wind farms have lower surface roughness and less turbulence than onshore wind farms, which reduces load fatigue and extends turbine life. However, the lower surface roughness also slows the wake recovery process, producing wakes that persist for longer periods and distances (up to 55 km/34 mi downwind) [62].



Figure 17. Wake effects from Vattenfall turbine array in the North Sea. Photo via NOAA [63].

3. Wave Energy

Wave energy converters (WECs) can be designed to harness both the kinetic energy (KE) and potential energy (PE) of the water within a wave and convert this energy into usable electricity. Potential applications include grid installations employing (MW-scale) devices, similar to wind farms, as well as niche, autonomous and off-grid applications (kW-scale) such as vessel charging, robotic systems, operating equipment and data gathering [22]. The Earth is essentially a large heat exchange machine driven by the Sun, where the uneven heating of the Earth's surface creates winds and the winds drive the waves. Thus, wave energy is a concentrated form of solar energy, resulting in higher energy density potentials (water is 832 times denser than air; thus, more power can be extracted from a smaller volume), and it can be more predictable and forecastable [22]. While wave energy generators enable improved predictability, the typical capacity factors are lower than for both fixed and floating offshore wind generation, ranging from 10 to 40% [11].

Figure 18 presents the global annual mean distribution of wave power estimation for a 10-year period in kW/m of crest length (perpendicular to the direction in which the wave is moving toward shore) [64]. With the global winds traveling from west to east, the strongest wave energy potentials tend to be on the western coasts of land masses, as can be seen in Figure 18. Stronger sites start at midlatitudes, between 30° and 60° north and south of the equator, where the density of wave power ranges within tens of kW per meter of crest length [44].

WECs generally fall into six main categories based on their principles of operation, with examples including configurations, optimal conditions and device names shown in Figure 19 [44]. As can be seen from Figure 19, WECs function at different depths and conditions, and they may be floating, submerged or attached to a fixed structure.

The power from a wave is given in Equation (6),

$$P = \frac{\rho g^2 T H^2}{32\pi} \text{ W/m of crest length} \quad (6)$$

where

ρ = density of seawater (1025 kg/m³);

g = accel. due to gravity (9.8 m/s²);

T = period of wave (s) (average 6–8 s);

H = wave height (m) (average 1.5–3.5 m).

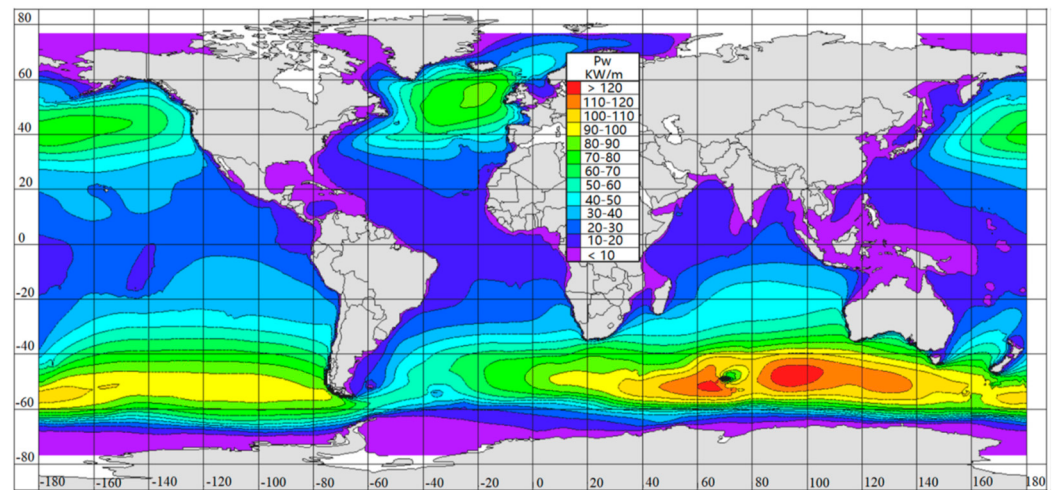


Figure 18. Global distribution of annual mean wave power estimation in kW/m, spanning a 10-year period [64].

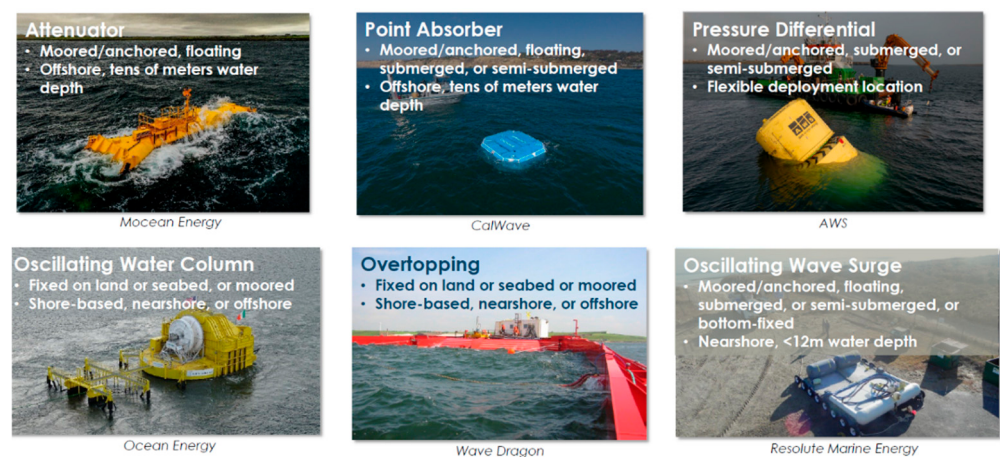


Figure 19. Examples of the six main WEC types, including the configurations, optimal conditions and device names or developers of each device shown [44].

Many wave energy demonstration and testing projects have been installed globally over the past two decades resulting in a cumulative installed wave energy capacity of 28 MW [17], as shown in Table 1. With wave energy being in the pre-commercialization stage, these installed demonstrations are decommissioned after testing. However, the future potential is strong, with the IEA predicting 180 GW by 2050 [19]. An example of a grid-connected wave energy converter is Eco Wave Power's 100 kW array floaters at the Jaffa Port in Israel [65]. The world's first commercial MW-scale (up to 20 MW) wave energy project is also planned by Eco Wave Power for Portugal, in the city of Porto, using their wave energy array floaters in 1 MW modules, expected to be operational in 2026 [66]. Eco Wave Power's uniquely shaped floaters are a type of a point absorber device [67,68] that can be attached to existing man-made structures (such as piers, breakwaters and jetties), thus simplifying the installation process while enabling maintenance and accessibility, and it operates as shown in [69].

The point absorber WEC configuration depicted in the upper middle of Figure 19 has also received much research and development attention, where Figure 20a shows the relative surge and heave motions. The WEC shown in Figure 20b is a point absorber based on a direct drive rotary (DDR) system developed by C-Power [22]. The WEC direct drive concept enables the direct coupling of the buoy's velocity and force to the generator without using intermediate stages of conversion, such as hydraulic (fluid compression)

or pneumatic (air compression). Thus, the system shown in Figure 20 converts the surge and heave motion into high-torque rotary motion, using DDR generators to provide highly efficient energy conversion.

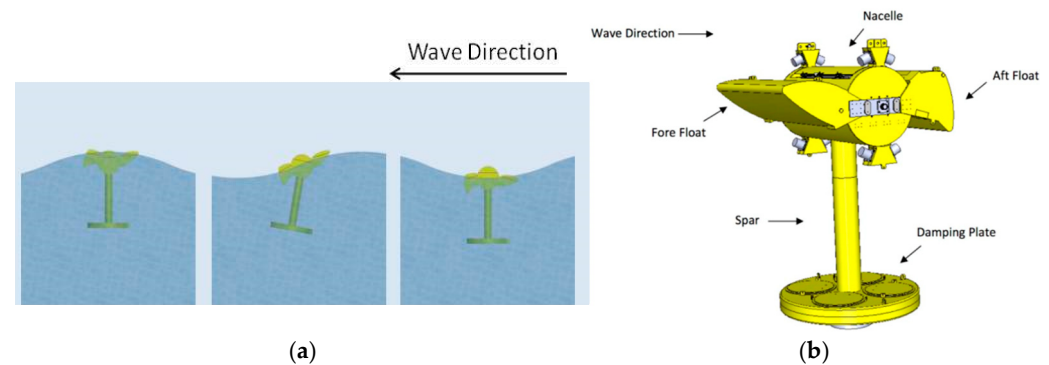


Figure 20. Point absorber WEC: (a) surge and heave motion; (b) SeaRAY direct drive rotary system (adapted from [22]).

4. Tidal Energy

Offshore hydrokinetic energy can be harnessed from the tides, both from “tidal currents” and from non-tidal “ocean currents”. A tidal current is the periodic ebb and flow of coastal tidal waters associated with the rise and fall of the tides [70]. Ocean currents involve the primarily continuous currents in the circulatory system of the oceans [71]. Tidal and ocean current technologies can be grouped into three main categories: tidal barrage, tidal current turbines and ocean current turbines. Tidal barrage is considered an established technology, similar in operation to a hydropower dam, capturing the PE created by the difference in sea level between high and low tides. Implementation has been limited to only a few locations around the world due to site availability, environmental effects and high capital costs [71,72]. Two of the world’s largest tidal barrages are the Sihwa Lake (South Korea) and the La Rance (France) cases, generating 254 MW and 240 MW, respectively [22,34,70]. The remainder of this section will be dedicated to emerging tidal current turbines and ocean current turbines.

Tidal current turbines and ocean current turbines are technologies undergoing research, including advanced numerical simulation methods [73,74], and are at the pre-commercial stage of development [71]. There are many common aspects between design technologies to harness tidal currents and ocean currents, often grouped together as “tidal stream” technologies, where the KE in water that is moving can be converted to electrical energy in a similar fashion as in a wind turbine [22]. Typical current speeds of 0.5–3 m/s are generally targeted for consideration of tidal stream energy conversion, where the highest speeds are closest to the surface. Figure 21 illustrates the global patterns of tidal energy, where the white lines are lines of constant tidal phase, called cotidal lines, differing by 1 h. The colors indicate where the tides—and thus tidal currents—are strongest, as high tidal ranges are commonly considered to be required for fast tidal currents. The red-colored areas display larger and stronger tidal ranges, and blue indicates areas that have lower and thus weaker tidal ranges.

Tides can be predicted accurately years in advance, and tidal currents are predictable at minute time scales, but they are variable and occur in relatively narrow channels augmented by headlands. Tidal current speeds vary and reverse direction, although they are not influenced by the weather; therefore, their variability is deterministic and not stochastic like wind energy and wave energy [22]. Like wave energy, the higher density of water, being 832 times greater than that of air, results in tidal turbines having the opportunity to extract more power per turbine rotor swept area than wind turbines; therefore, tidal

turbines can be smaller than wind turbines for equivalent power capacities [22]. Even with the improved predictability, tidal generation is not considered dispatchable, with Table 1 providing the typical capacity factors of 20–35%, lower than for both fixed and floating offshore wind generation [12].

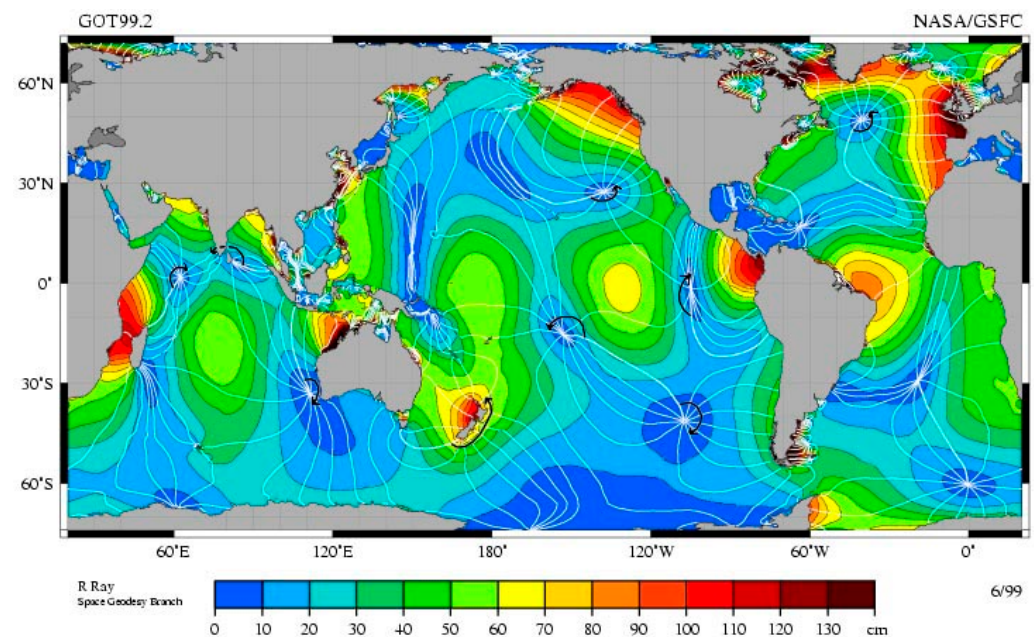


Figure 21. Global distribution of semi-diurnal tidal amplitude [75].

Tidal stream energy converters (TECs) also generally fall into six main categories based on their principles of operation, and examples including configurations, optimal conditions and device names are shown on Figure 22 [44]. TECs vary by size, shape and energy capture methods, and their characteristics depend on the available resource, deployment area and mounting methods.

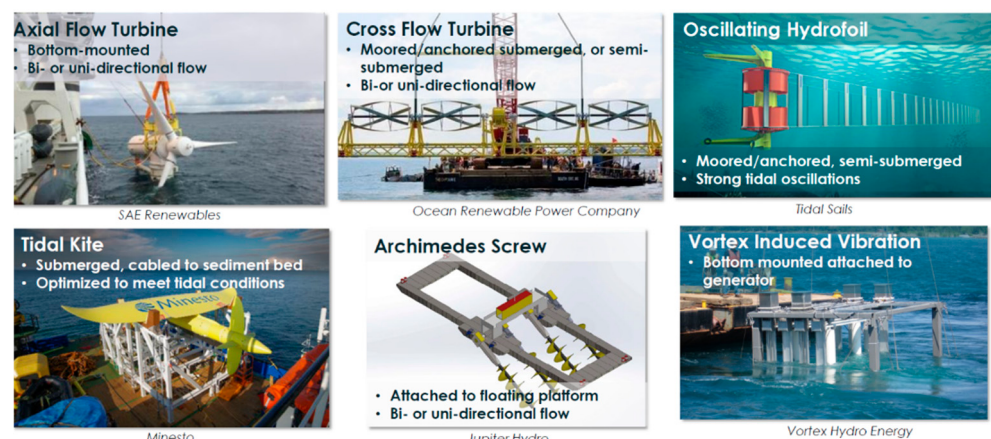


Figure 22. Examples of the six main TEC archetypes, including the configurations, optimal conditions and the device names or developers of each device shown [44].

The power from tidal current and ocean current turbines is given in Equation (7),

$$P = \frac{1}{2} \rho A v^3 C_p \text{ in W} \quad (7)$$

where

ρ = density of water (1025 kg/m³);

A = swept area of the turbine (m^2);

v = velocity of the water flow (m/s);

C_p = power coefficient representing turbine's efficiency (~35–45%, Betz limit is 59.3%).

As with wave energy, many TEC demonstration and testing projects have been installed globally over the past two decades, resulting in a cumulative installed capacity of 40 MW [17], as shown in Table 1. Likewise, since TECs are in the pre-commercialization stage, these installed demonstrations are decommissioned after testing. However, the future potential is strong, with the IEA predicting 120 GW by 2050 [19]. An example of an operating tidal stream installation is SAE's "MeyGen" array of four 18 m diameter rotors, where each turbine has a rated capacity of 1.5 MW at a speed of 3 m/s, for an installed capacity of 6 MW [76]. The MeyGen array, operational since 2018, consists of horizontal-axis, three-blade axial flow turbines, as shown in the upper left of Figure 22. The MeyGen project has been approved to become the world's first commercial scale tidal array at 59 MW, with the buildout planned from 2027 to 2029. The MeyGen offshore lease and site resource allow for scaling up to 269 turbines, producing up to 398 MW [20].

5. Floating Solar Photovoltaics (FPVs)

FPV systems are emerging technologies where solar PV installations are placed on top of bodies of water, rather than on land or on the rooftops of buildings [2]. Currently, the deployment of FPV systems on inland waterways is more common, with the benefits of conserving land space and reducing evaporation, whereas the application of offshore FPV systems is an emerging opportunity [23]. While only ~10 MW of FPV has been installed, the future outlook is strong, with China alone planning 15–20 GW installed capacity by 2030 [77]. In the region of the North Sea, the Dutch government has set a target of installing 45 GW by 2050 [78]. Compared to land-based PV systems, FPV systems operate at lower temperatures, and minimizing the clearance from the water to maximize the PV cell cooling effect can boost the generation efficiency by ~10% [25–29]. Since FPV systems are located in open ocean environments, they can also benefit from the reduced effects of shading, resulting in more consistent and stronger solar irradiance [79], yielding further increased overall system efficiencies, resulting in a ~13–14% increase in power production compared to their freshwater counterparts [27,80].

FPVs can be categorized into four different groups based on the wave heights that they can withstand, i.e., 1 m, 2 m and 10 m wave heights [2,13]. The primary components of FPV systems include the floats, the PV modules and the necessary electrical equipment, in addition to the mooring and anchoring systems [27], as shown in Figure 23 [81]. Offshore FPV float compositions can be either rigid float structures or flexible float structures. Flexible floating FPV structures are emerging as being more appropriate for marine environments considering the challenging sea conditions, although they still commonly support rigid crystalline silicon PV panels [27]. Thin-film PV modules are beneficial because of their cost-effectiveness and lightweight nature and their high efficiencies. Thus, the potential FPV applications employing flexible floating structures along with thin-film PV modules show promise [27].

A primary challenge with FPV is working to ensure that they can withstand the complex and extreme conditions of sea environments, the corrosiveness of seawater and the severe sea conditions impacted by wind, waves and currents [23,27,75]. Offshore FPV systems experience prolonged exposure to the salt in seawater, serving to accelerate the processes of corrosion, which can lead to a significant reduction in the lifespans of PV modules [27,82]. In offshore FPV systems, the support floats are also vulnerable to damage in severe sea conditions [27]. Fortunately, progress is being made regarding FPV salt-resistant marine materials to reduce corrosion and marine fouling, more robust mooring

systems to withstand typhoon-/hurricane-level wind speeds (83–92 mph or 133–148 km/h) and planning maintenance access [83].

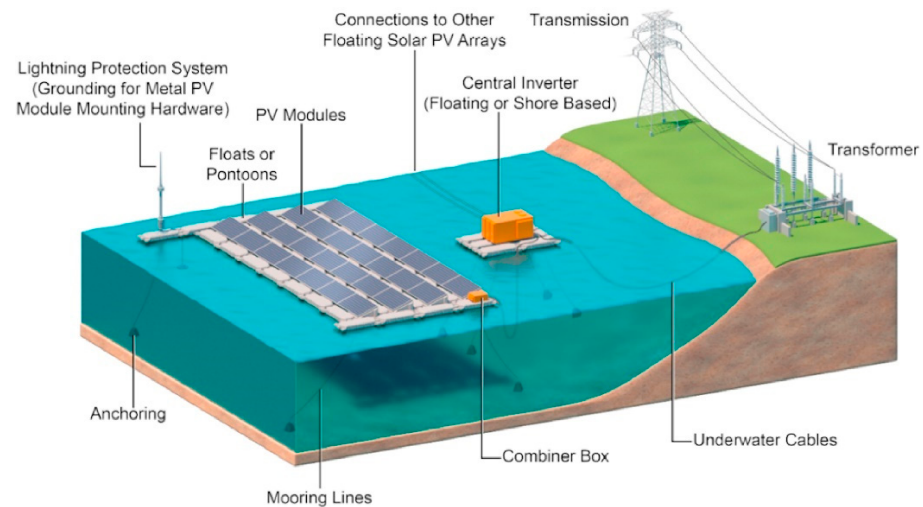


Figure 23. Schematic of a floating PV system [81].

To further encourage FPV developments and technologies, advancements are also being made to improve the numerical models in order to perform accurate preliminary installation site assessments. In [81], advanced numerical models of FPV systems are presented, considering the different types of floating platforms, including the implementation of mooring systems specific to the installation sites, taking into account the weather and sea conditions resulting in specific wind and wave motion.

The deployment of offshore FPV systems has accelerated in recent years, with the first commercial offshore FPV project in a full-seawater environment deployed by Sinopec (China Petroleum and Chemical Corporation) in July 2025. The 7.5 MW offshore FPV plant spans 60,000 square meters and is integrated with a nearby pile-based FPV plant that is already operational [83]. Sinopec plans to expand the floating offshore platform to 23 MW, enabled through three key innovations: corrosion-resistant components, a storm-resilient anchoring system and improved maintenance access [83]. This project is much smaller compared to one of the largest offshore FPV projects in the world, located 8 km off the eastern coastline of Dongying City in Shandong Province, China [84]. The first batch of units from this project was recently connected to the grid. The project covers 1223 hectares of ocean surface and is rated at full capacity at 1 GW and projected to generate 1.78 billion kWh of electricity annually upon completion. The project is being developed by Guohua Energy Investment Co., Ltd., a subsidiary of China's state-owned CHN Energy. The project development model combines integrated fish farming with PV power generation to increase the utilization of the marine infrastructure [85]. Besides aquaculture, note that offshore FPVs are also uniquely positioned to be integrated with offshore wind farms and other marine facilities [27], which will be discussed in the next section on hybrid energy systems.

6. Hybrid Energy Systems

Hybrid energy systems can be designed to maximize the use of energy infrastructure [86] and increase availability and grid flexibility while buffering fluctuations, as shown in Figure 24. Combining various clean offshore technologies into hybrid energy systems, e.g., offshore wind–FPV or offshore wind–wave systems, the integration of energy storage, etc., is another emerging opportunity, providing complementary energy sources for increased power generation and lowered LCOEs. For example, offshore wind and FPV co-located power generation can effectively utilize electrical equipment such as inverters

and cables, thereby reducing system operation and maintenance costs [27]. NREL has developed a “Hybrid Optimization and Performance Platform” (HOPP), a software tool that enables the detailed analysis and optimization of hybrid power plants to the component level [2].

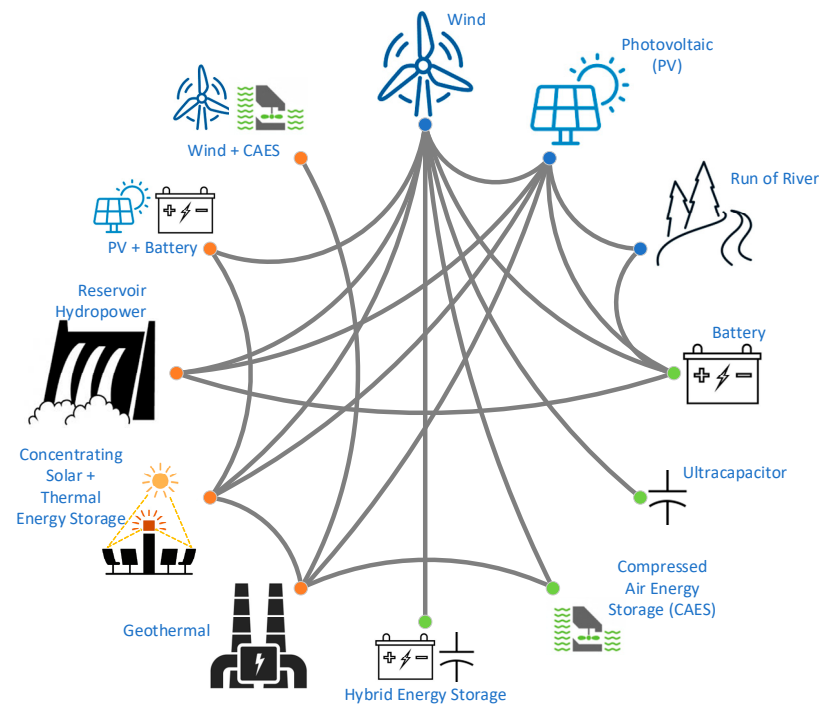


Figure 24. Hybrid energy system arcs indicating proposed technology pairs, where the blue nodes depict variable renewable energy, the orange nodes are less variable renewable energy and the green nodes are energy storage (adapted from [87]).

Figure 25 gives an example of the generation outputs over a 24 h period from wind, PV and hybrid systems including energy storage. Note the negative correlation between the wind and the solar production, where hybrid energy systems result in a more stable energy supply and increased infrastructure and cable utilization [23]. Certainly, the complementary energy system depends on the location, and hybrid energy systems consisting of offshore renewables offer a strong solution.

Example offshore hybrid energy storage systems include Floating Power Plant’s SEAWORTHY, which includes floating wind (4.3 MW), wave (0.8 MW) and hydrogen using a 1 MW electrolyzer, which can produce ~300 kg/day/MW, along with a 48 MWh battery, located off the coast of Spain [32].

CrossWind, a joint venture of Shell and the Dutch energy provider Eneco, is employing hydrogen production at their Baseload Power Hub within the Hollandse Kust Noord wind farm (759 MW), utilizing a 2.5 MW electrolyzer and a 5 MWh battery [89]. The platform is 19 m × 41 m, weighs 2200 tons and is similar in concept to the schematic shown in Figure 26 [90]. In addition, for the same wind farm, a contract has been awarded to offshore specialist Oceans of Energy for 0.5 MW of FPV using 1500 solar panels to be installed between the turbines, expected to be fully commissioned in 2025 [91].

The OceanSun Haiyang hybrid plant shown in Figure 27 consists of a fixed-bottom wind farm (20 MW planned) and FPV (0.5 MW) off Yantai, China. The project combines wind and FPV using OceanSun flexible floating structures. Note that this project represents the first offshore FPV effort to operate within the “double 30” sea environment, which is defined by having an offshore distance of 30 km, with a water depth of 30 m and extreme wave heights of 10 m [27].

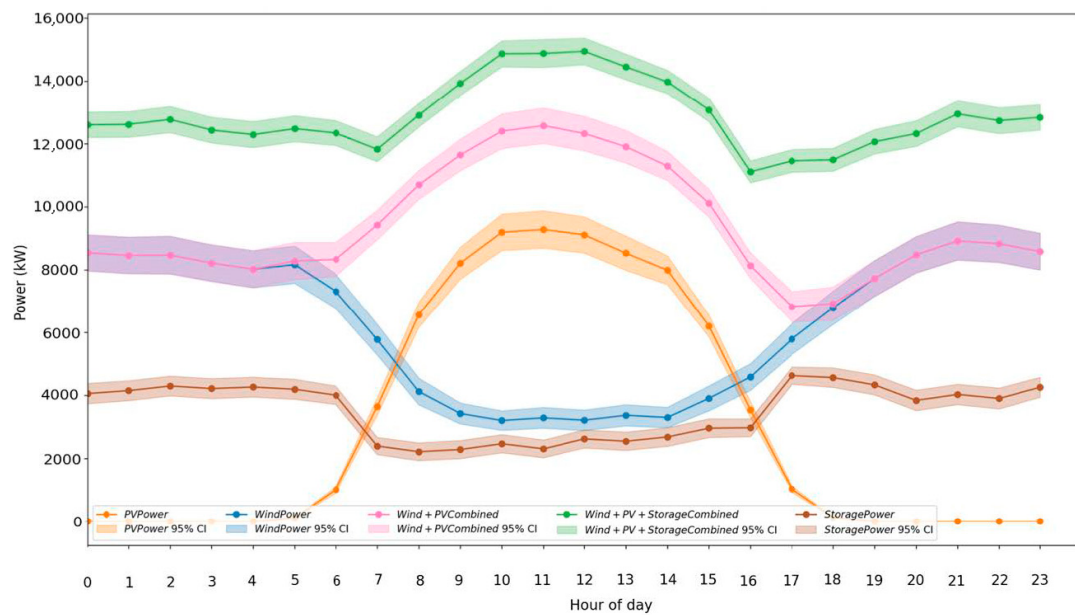


Figure 25. Demonstration of complementary energy systems including wind, PV and energy storage [88].

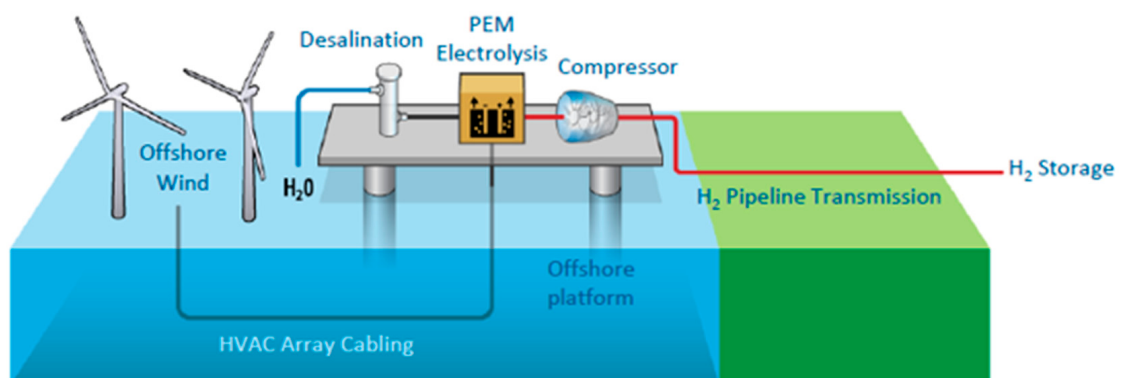


Figure 26. Centralized offshore H₂ production transmitted to shore via a pipeline [90].



Figure 27. The OceanSun Haiyang hybrid plant consists of a fixed-bottom wind farm (20 MW planned) and FPV (0.5 MW) off Yantai, China [27].

7. Potential Environmental Impacts of Offshore Renewable Energy

Environmental impacts [20] to the marine environment (e.g., sea life and birds) include those from vessels, construction, transmission infrastructure, operations, noise and lighting. In addition, transmission infrastructure disturbances of the seafloor environment (benthic) during and after construction include effects such as the following:

- Habitat disturbances, which affect species abundance and displacement;
- Creation of new habitats, which may increase species and biodiversity;
- Changes in migratory paths and animal/mammal behaviors;
- Sea life and bird collisions, e.g., with fast-moving turbines;
- Upwelling changes, where deep, cold and nutrient-rich water rises to the surface could be reduced, reducing nutrient cycling and oxygen flows;
- Sediment transport affecting the shoreline, e.g., potential unintended erosion, as well as accumulation.

Note that electromagnetic fields (EMFs) from subsea cables have not been determined to negatively affect species [92]. Overall, the proposed offshore renewable energy projects can benefit by seeking to understand the potential environmental impacts, where appropriately scaled pilot demonstrations can be built into the regulatory process that consider the environmental factors specific to their regions [20].

8. Conclusions

This paper reviewed offshore renewable energy sources including wind, wave, tidal, floating solar PV (FPV) and hybrid energy systems as contributors to the clean energy transition. Comparisons of the levelized cost of electricity (LCOE), technology readiness levels (TRLs), capacity factors (CFs) and power generation potential were presented. Fixed-bottom offshore wind turbines, typically located in water depths of less than 60–80 m, were recognized to have the highest TRL and largest global generation potential, i.e., 1600 GW by 2050, while the current LCOE remains one of the lowest, i.e., USD 0.06–0.11/kWh. Floating offshore wind turbines, typically used in water depths greater than 60–80 m, were found to have the second-highest potential of 264 GW by 2050, with a higher LCOE of ~USD 0.07/kWh to ~USD 0.17/kWh.

With offshore wind having the greatest global generation potential, a significant portion of the paper was concentrated on offshore wind installation statistics, market expectations, regulatory processes, technologies, opportunities and challenges. The current installed global offshore wind capacity is 83.2 GW, with China being the leader. Challenges to offshore wind development were discussed, including insufficient grid connections, complex maritime approvals and slower-than-expected transitions from nearshore to deep water. The criticality of offshore wind was discussed, including the need to mainstream the dedicated condition monitoring of systems, including the gearbox, main bearings and generator. It was noted that future research directions and opportunities exist, both regarding the performance of prognostics modeling, including predictions of components' remaining useful life (RUL), and the encountered prevalent bearing faults. Converter resiliency was also presented, including the need for research on the grid-forming mode control of the grid-side converters so that wind turbine converters can actively support the grid voltage, frequency and system inertia, enabling the inertia of wind turbines to support the grid. In addition, matrix converters were noted as an opportunity for future research. Wind farm wake effects were also presented, where, due to the lower surface roughness of offshore wind farms, their wakes persist for longer periods and distances than in onshore wind farms and can extend up to 55 km.

Wave and tidal energy systems were found to have lower TRL numbers of 6 (medium) and higher LCOEs, while their predicted LCOE reduction trends predict wholesale market

price (WMP) parity by 2044. Wave and tidal resource assessments and power calculations were also presented, as well as converter operations. Both wave energy converters (WECs) and tidal energy converters (TECs) were found to fall into six main categories based on their principles of operation. Examples of WECs and TECs were presented, including configurations, optimal conditions and device names. Future research directions include addressing the scalability challenges, including technological and environmental concerns, costs and supply chain hurdles.

Offshore FPV was also presented as an emerging resource with strong potential and challenges including surviving the harsh ocean environment. Progress and future research directions were noted in terms of corrosion-resistant marine materials, more robust mooring systems, maintenance planning to enable successful deployment and improvements in numerical modeling. Offshore FPV was also noted as being uniquely positioned for integration with offshore wind farms and other marine facilities in hybrid energy systems, which were presented as opportunities to maximize the use of energy infrastructure while providing more consistent power. The paper concludes with a discussion of the potential environmental impacts of offshore renewable energy developments, including a recommendation for appropriately scaled pilot demonstrations built into the regulatory process that consider the environmental factors specific to the region.

Considering the significant energy potential and opportunities for offshore renewable energy presented in this paper, and the increased need for decarbonization for the clean energy transition, an elevated drive to decrease LCOEs is anticipated, in addition to further addressing negative pricing scenarios. Regarding LCOEs, considering that ~80% of offshore wind resources lie in waters greater than 60–80 m, floating offshore wind has significant potential, motivating the Floating Offshore Wind Shot™ initiative to accelerate the development and deployment of floating offshore wind technology, with the goal of a greater than 70% reduction in the LCOE by 2035, to 0.045 USD/kWh. Technology advancements presented to avoid negative pricing included increasing grid flexibility with enhanced energy storage, as well as improved forecasting models (e.g., AI-driven) for renewable energy generation to better predict the supply and allow for the more efficient scheduling of power plants.

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