International Journal of Energy Research

WILEY

REVIEW ARTICLE OPEN ACCESS

A Structured Techno-Economic and Socio-Regulatory Comparison of Onshore, Fixed-Bottom Offshore, and Floating Offshore Wind Energy Systems

Mohsin Ali Koondhar[1] | Samandar Khan Afridi[1] | Theyab R. Alsenani[2] | Ibrahim Mahariq[3,4,5,6] | Hamed Zeinoddini-Meymand[7] | Farhad Shahnia[8] | Ezzeddine Touti[9]

[1]Department of Electrical Engineering, Quaid-e-Awam University of Engineering, Science and Technology Nawabshah, Nawabshah 67450, Sindh, Pakistan | [2]Department of Electrical Engineering, College of Engineering in Al-Kharj, Prince Sattam Bin Abdulaziz University, Al-Kharj 11942, Saudi Arabia | [3]College of Engineering and Architecture, Gulf University for Science and Technology, Mishref, Kuwait | [4]Department of Electrical and Electronic Engineering, Faculty of Engineering and Architecture, Istanbul Gelisim University, Avcılar- Istanbul, Istanbul 34310, Türkiye | [5]Najjad Zeenni Faculty of Engineering, Al-Quds University, Jerusalem, State of Palestine | [6]University College, Korea University, Seoul 02481, Republic of Korea | [7]Department of Electrical and Computer Engineering, Graduate University of Advanced Technology, Kerman, Iran | [8]School of Engineering and Energy, Murdoch University, Perth, Australia | [9]Center for Scientific Research and Entrepreneurship, Northern Border University, Arar 73213, Saudi Arabia

Correspondence: Mohsin Ali Koondhar (engr.mohsinkoondhar@quest.edu.pk) | Ibrahim Mahariq (ibmahariq@gmail.com) | Hamed Zeinoddini-Meymand (h.zeinaddini@gmail.com)

Received: 15 November 2024 | **Revised:** 31 December 2025 | **Accepted:** 28 February 2026

Academic Editor: Paolo Castaldo

Keywords: comparative analysis | fixed-bottom offshore | offshore wind turbines | onshore wind turbines | renewable energy generation

ABSTRACT

Onshore, fixed-bottom offshore, and floating offshore wind turbines (FOWTs) represent distinct technological pathways for large-scale wind energy deployment, yet comparative assessments often emphasize descriptive characteristics rather than quantified performance trade-offs. This study presents a structured comparison of these three wind energy systems across technology maturity, levelized cost of energy (LCOE), environmental impacts, and socio-regulatory constraints. A harmonized literature synthesis of recent techno-economic data (2018–2024) reveals that onshore wind remains the lowest-cost option (typical LCOE: 30–55 USD/MWh), while fixed-bottom offshore wind exhibits higher but declining costs (60–100 USD/MWh) driven primarily by installation and foundation expenses. Floating offshore wind systems currently show the highest LCOE (90–160 USD/MWh), dominated by platform and mooring costs, yet demonstrate the strongest long-term cost-reduction potential due to access to superior wind resources and deep-water sites. Environmental and social analyses indicate increasing public acceptance challenges for onshore projects, while offshore and floating systems face regulatory complexity and higher capital risk rather than social opposition. The study's contribution lies in a balanced, criterion-based framework that exposes cost drivers, maturity gaps, and deployment constraints across wind technologies, highlighting floating offshore wind as a transitional technology whose competitiveness depends on platform standardization and supply-chain learning effects. The analysis demonstrates that cost parity between floating and fixed-bottom offshore wind is not turbine limited but platform- and financing-driven, with regulatory clarity having a comparable impact to capital expenditure (CAPEX) reductions.

1 | Introduction

The global energy sector is undergoing a fundamental transition driven by the urgent need to mitigate climate change, reduce greenhouse gas emissions, and meet rapidly growing electricity demand [1]. Conventional fossil fuel–based power generation is increasingly constrained by environmental regulations, resource depletion, and sustainability concerns [2]. Within this context, renewable energy technologies have emerged as essential components of future power systems, with wind energy playing a particularly prominent role due to its technological maturity, scalability, and declining cost trends [3, 4]. Over the past two decades, wind energy deployment has expanded significantly across diverse geographical regions, supported by advances in turbine design, power electronics, and grid integration [5]. Initially dominated by onshore installations, wind energy development has progressively extended offshore to exploit stronger and more consistent wind resources [3, 6]. More recently, floating offshore wind technology has been introduced to enable access to deep-water sites that are unsuitable for fixed-bottom foundations [7, 8]. These three platforms onshore, offshore, and floating offshore wind turbines (FOWTs) represent distinct technological pathways, each characterized by different resource conditions, infrastructure requirements, economic profiles, and environmental considerations [9].

Wind energy has been adopted in more than 90 countries worldwide, reflecting its growing role in global electricity generation [10, 11]. By 2020, the cumulative installed wind power capacity reached ~742 GW, of which about 35 GW corresponded to offshore installations as shown in Figure 1. At the end of 2020, 12 countries had surpassed 10 GW of installed wind capacity, while a further 20 countries had exceeded the 5 GW threshold [13]. Regional distribution of installed capacity (IC) reveals a strong concentration in Asia largely driven by China with ~288 GW followed by Europe, where Germany leads with around 62 GW, and North America, dominated by the United States with an IC of about 122 GW is shown in Figure 1. Overall, global wind power capacity expanded at an average annual growth rate of nearly 14.2% over the period from 2006 to 2020 [12].

Existing research has extensively investigated the performance, design, and optimization of individual wind turbine platforms. Numerous studies focus on cost reduction strategies for onshore wind, power conversion and structural challenges for offshore wind, or mooring and stability issues associated with floating offshore systems. However, the majority of this literature remains fragmented, addressing each technology in isolation. As a result, there is limited integrated understanding of how these wind energy platforms compare when evaluated simultaneously across technical performance, economic feasibility, environmental impact, social acceptance, and policy support.

This lack of comprehensive comparative analysis presents a challenge for energy planners and policymakers who must determine optimal deployment strategies under region-specific constraints such as land availability, water depth, grid access, environmental sensitivity, and public perception. Decisions made without a holistic perspective risk suboptimal investment, inefficient resource allocation, and delayed progress toward renewable energy targets.

1.1 | Contribution of This Study

This work does not introduce a new wind energy technology; instead, it contributes a structured and balanced comparison that integrates recent techno-economic data with social and regulatory considerations. By applying identical evaluation criteria across onshore, fixed-bottom offshore, and floating offshore wind systems, the study clarifies trade-offs that are often fragmented across separate reviews. The analysis highlights that the primary barriers to floating offshore wind are not aerodynamic performance but platform-related capital costs and regulatory

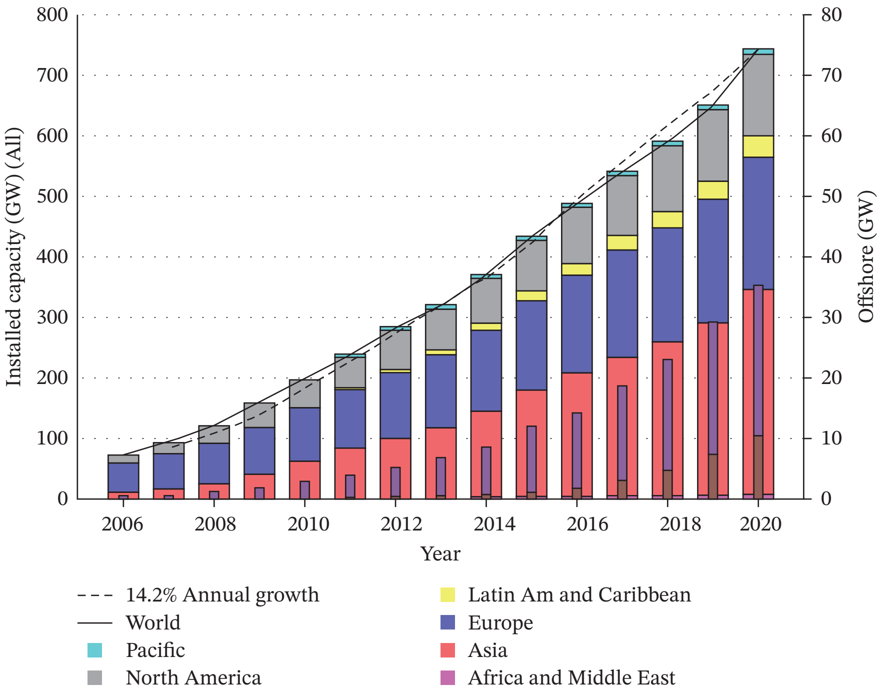

FIGURE 1 | Total installed capacity (IC) of wind energy by region [12].

uncertainty, thereby redirecting attention toward supply-chain learning and standardization as key enablers of future competitiveness. Unlike existing reviews that examine floating offshore wind primarily from a technological or project-specific perspective, this study systematically decomposes levelized cost of energy (LCOE) into platform, installation, O&M, and financing components using harmonized post-2018 data, enabling cross-technology cost attribution.

2 | Comparative Analysis Framework

This section presents a structured comparison of onshore wind, fixed-bottom offshore wind, and floating offshore wind technologies using a unified evaluation framework. Each technology is assessed across five dimensions: (i) technology and design maturity, (ii) techno-economic performance, (iii) environmental impacts, (iv) social and regulatory challenges, and (v) future outlook. Applying identical criteria ensures transparency and enables direct comparison of trade-offs that are often obscured in technology-specific reviews.

2.1 | Technology and Design Characteristics

Wind energy systems are governed by a combination of aerodynamic, structural, electrical, and control-related design characteristics that collectively determine their performance, reliability, and economic viability [14, 15]. The fundamental objective of wind turbine design is to maximize energy extraction from variable wind resources while ensuring structural integrity and operational safety over the system's lifetime [16]. Modern wind turbines primarily operate on the lift-based aerodynamic principle, where rotor blades convert kinetic wind energy into mechanical torque [17]. Blade geometry defined by airfoil shape, chord length, twist angle, and material composition plays a critical role in optimizing the power coefficient (Cp) and minimizing fatigue loads [16]. Advanced composite materials, such as glass- and carbon–fiber–reinforced polymers, are increasingly adopted to achieve high strength-to-weight ratios and enhanced durability [18].

From a structural perspective, turbine design must withstand aerodynamic loads, gravitational forces, and cyclic fatigue [19]. Towers are commonly constructed using tubular steel, concrete, or hybrid configurations to provide adequate hub height and stability [20]. Taller towers enable access to higher wind speeds but increase material usage and installation complexity, requiring careful techno-economic optimization [21]. The drive train configuration is another defining design aspect. Conventional systems employ a gearbox coupled with a doubly fed induction generator (DFIG), while newer designs favor direct-drive permanent magnet generators (PMG) to reduce mechanical complexity and maintenance requirements [22]. Power electronics and grid-interface systems ensure voltage regulation, frequency control, and compliance with grid codes [23]. Control systems integrate sensors, actuators, and algorithms to regulate turbine operation under fluctuating wind conditions [24]. Key mechanisms include yaw control for wind alignment, pitch control for power regulation and load mitigation, and supervisory control systems for fault detection and operational optimization [25]. Collectively, these technological and design characteristics form the foundation for both onshore and offshore wind energy systems, with adaptations based on site-specific constraints [26].

2.1.1 | Onshore Wind Systems

Onshore wind turbines are the most mature and widely deployed form of wind energy technology [27]. Commercial installations typically employ turbines rated between 2 and 6 MW, with hub heights exceeding 100–140 m and rotor diameters above 120 m [28]. Foundations are predominantly gravity-based or piled structures, tailored to site-specific soil conditions [29]. Onshore wind technology has reached technology readiness level (TRL) 9, supported by standardized turbine designs, established supply chains, and extensive operational experience [30]. Onshore wind systems represent the most mature and widely deployed segment of the global wind energy industry, owing to their relatively lower capital costs, technological maturity, and ease of installation compared to offshore alternatives [6]. These systems are typically installed on land-based sites with favorable wind resources, such as plains, ridgelines, and coastal hinterlands [31]. Technologically, onshore wind turbines are predominantly horizontal-axis wind turbines (HAWTs) with rated capacities ranging from a few 100 kilowatts to over 6 MW [32]. Their design emphasizes cost-effectiveness, logistical feasibility, and adaptability to diverse terrain conditions. Standardized components and modular construction facilitate large-scale deployment and reduce manufacturing and maintenance costs [33, 34].

Site selection is a critical factor influencing the performance of onshore wind systems. Wind resource assessment, terrain roughness, land availability, and proximity to transmission infrastructure directly affect energy yield and project economics [35]. However, onshore installations often face constraints related to land-use conflicts, visual impact, noise emissions, and environmental concerns, which may limit turbine size and spacing [36]. From an operational standpoint, onshore wind farms benefit from simpler access for installation, inspection, and maintenance, leading to lower operational expenditures (OPEX) [37]. Grid integration is generally less complex than offshore systems, although variability in wind generation necessitates forecasting tools and grid management strategies to maintain system stability [38, 39]. Despite these advantages, onshore wind systems experience increasing limitations in regions with high land saturation and stricter regulatory frameworks [40]. As a result, technological advancements in turbine efficiency, digital monitoring, and hybrid energy systems are being pursued to enhance energy output without expanding land footprints [41]. Consequently, onshore wind continues to play a vital role in global renewable energy transitions, particularly in developing and land-abundant regions [42].

Figure 2 presents a schematic representation of a conventional onshore HAWT system, highlighting its key structural, mechanical, and control components. The turbine consists of a rotor with aerodynamic blades, which captures the kinetic energy of the wind. The blades are equipped with a pitch control system that adjusts their angle to optimize power generation under varying wind conditions and to protect the turbine during high wind speeds.

The rotor is mounted on a nacelle, which houses critical drive train components such as the gearbox and generator. The

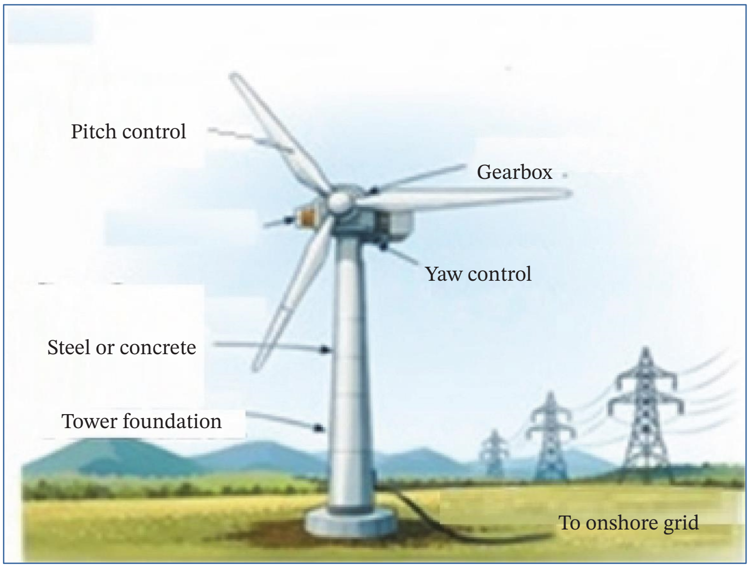

FIGURE 2 | Typical configuration of an onshore wind turbine system.

gearbox increases the rotational speed of the low-speed shaft from the rotor to match the operating requirements of the generator [43]. A yaw control system enables the nacelle to rotate horizontally, ensuring continuous alignment of the rotor with the prevailing wind direction for maximum energy capture. The tower, typically constructed from steel or reinforced concrete, elevates the turbine to higher altitudes where wind speeds are stronger and more consistent. Electrical power generated in the nacelle is transmitted through internal cables down the tower and delivered to the onshore grid, as indicated in the figure. The entire structure is supported by a foundation system, which anchors the turbine securely to the ground and transfers mechanical loads to the underlying soil. Overall, Figure 1 illustrates the integrated operation of aerodynamic, mechanical, and electrical subsystems in an onshore wind turbine, emphasizing how coordinated control and structural design enable efficient and reliable land-based wind energy generation [44].

2.1.2 | Floating Offshore Wind Systems

FOWTs decouple turbine deployment from seabed conditions, enabling installation in water depths exceeding 60 m and extending to several 100 m [45]. Current projects typically use turbine ratings of 8–15 MW, mounted on spar-buoy, semi-submersible, or TLPs. While turbine technology itself is mature, floating support structures and mooring systems remain under development. Consequently, floating offshore wind is assessed at TRL 6–7, reflecting pilot- and early-commercial-stage deployment [46]. Figure 3 presents the three principal floating offshore wind platform configurations that enable wind turbine deployment in deep-water environments where fixed-bottom foundations are not feasible. These platform concepts are designed to provide stability while accommodating dynamic wind, wave, and current loads [47]. The spar-buoy platform achieves stability through a deep, slender cylindrical structure with heavy ballast positioned below the waterline. This configuration lowers the center of gravity and

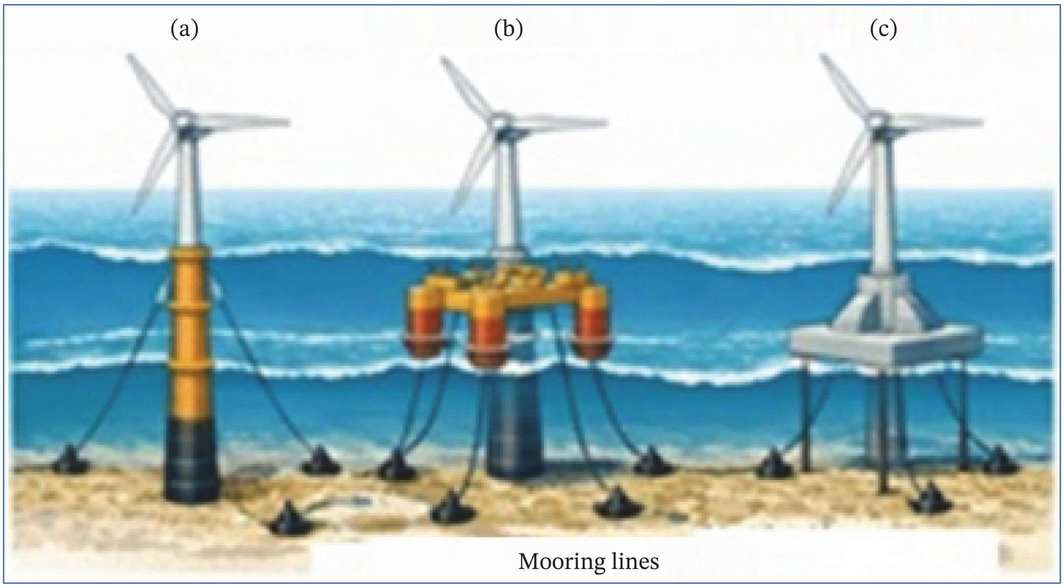

FIGURE 3 | Main floating offshore wind platform concepts. (a) Spar buoy. (b) Semi submersible. (c) Tension leg platform.

minimizes platform motion, making spar systems suitable for very deep waters. However, their large draft requires deep-water ports and specialized installation procedures. The semi-submersible platform consists of multiple buoyant columns connected by horizontal pontoons. Stability is provided by distributed buoyancy rather than deep ballast, allowing for a shallower draft compared sparring designs [48]. Semi-submersible platforms are well suited for assembly in port and towing to site, offering flexibility across a range of water depths and installation conditions. The tension-leg platform (TLP) maintains stability using taut mooring lines anchored to the seabed. These tensioned tendons restrict vertical motion, resulting in minimal heave and pitch responses. TLP systems provide high stability but require precise anchoring and seabed conditions, which can increase installation complexity. All three platform types are secured using mooring and anchoring systems that allow controlled movement while maintaining station-keeping [49]. Figure 3 highlights the structural and operational differences among floating platform concepts, illustrating how each design balances stability, installation requirements, and suitability for deep-water offshore wind applications.

Table 1 provides a side-by-side comparison of onshore and offshore wind turbine systems using critical design and operational indicators [50]. Offshore wind turbines operate in stronger and more uniform wind regimes, with average hub-height wind speeds of ~9 m/s and capacity factors frequently exceeding 50%, which enables individual turbine ratings in the range of 10–15 MW. In contrast, onshore turbines are typically exposed to lower wind velocities, generally between 5 and 8 m/s, resulting in capacity factors of about 30%–40% and comparatively smaller unit capacities of 2–4 MW [51]. The offshore environment allows greater scalability through the deployment of larger rotor diameters and higher hub heights, supported by more consistent wind resources. However, these advantages are accompanied by elevated capital investment requirements and technically demanding installation procedures. Onshore wind systems, by comparison, benefit from lower levelized costs of electricity often around 50 USD/MWh—

TABLE 1 | Assessment of structural design and operational performance characteristics of onshore versus offshore wind turbines [50].

Offshore wind	Onshore wind	Aspect
Peak voltage reaches 123 V under a wind velocity of 9.7 m/s.	Peak voltage reaches 39.5 V at a wind velocity of 8.2 m/s.	Voltage output (simulated)
Turbulence intensity rises by as much as 20% in irregularly optimized layouts, leading to elevated fatigue loads on the structure.	Surface roughness and obstacles introduce variability in wind speeds, while turbulence intensity remains lower than offshore.	Turbulence impact
Employs larger turbines equipped with advanced systems, including floating foundations, featuring hub heights of approximately 150 m.	Uses smaller turbines with simpler designs to enable easier installation and upkeep, generally at hub heights of ~100 m.	Turbine size
Consistently elevated power density results from stronger mean wind speeds across the vertical profile, while the wind shear effect is reduced, yielding hub-height velocities of about 9 m/s.	Lower and more variable, with average hub-height wind speeds of ~5–8 m/s.	Wind speed
Regularly exceeds 50% due to elevated and steady wind regimes.	Usually 30%–40%, with performance strongly dependent on site-specific wind conditions.	Capacity factor
Peak power attains 6 W under a wind velocity of 9.7 m/s.	Peak power attains 1.9 W under a wind velocity of 8.2 m/s.	Power output (simulated)
Turbines with 10–15 MW ratings generate substantially higher energy output.	Turbines rated 2–4 MW produce comparatively lower energy output.	Energy output
Deployment necessitates deep-water foundation structures and high-performance materials to endure hydrodynamic and wave loading.	Surface roughness and obstacles result in variable wind conditions, emphasizing the importance of optimal sitting.	Geographic challenges
Scalability is enhanced by the deployment of larger turbines and access to consistent wind regimes.	Deployment potential is restricted by land-use constraints and community acceptance issues.	Scalability
Characterized by stable wind regimes, resulting in elevated and continuous energy output throughout the year.	Pronounced seasonal fluctuations demand comprehensive wind profiling and system optimization.	Seasonal variation
LCOE is roughly $80 per megawatt-hour.	LCOE is roughly $50 per megawatt-hour.	Levelized cost of energy (LCOE)

and simpler construction and maintenance logistics. Nevertheless, their expansion is increasingly restricted by land-use limitations, social acceptance concerns, and visual and acoustic impacts. Recent offshore developments, including floating foundation technologies, have further expanded deployment potential into deeper waters, albeit at the expense of increased costs associated with complex marine operations and harsh environmental conditions [52]. Overall, the tabulated comparison underscores the inherent trade-offs among performance, scalability, and economic feasibility, thereby supporting informed, site-specific decision-making in wind energy planning.

2.1.3 | Fixed-Bottom Offshore Wind Systems

Fixed-bottom offshore wind turbines extend conventional wind technology into marine environments, enabling access to stronger and more consistent wind resources [53]. Typical turbine capacities range from 6 to 15 MW, with monopile, jacket, and gravity-based foundations used depending on water depth and seabed conditions [54]. Fixed-bottom systems are generally limited to water depths below 50–60 m. The technology is commercially mature, with TRL 8–9, although foundation design and offshore installation remain site-specific and capital-intensive [55]. Fixed-bottom offshore wind systems constitute the most commercially established offshore wind technology and are predominantly deployed in shallow to intermediate water depths, typically up to 50–60 m [7]. These systems utilize seabed-mounted support structures that provide a stable foundation for large-capacity wind turbines operating in marine environments characterized by higher and more consistent wind speeds than onshore locations [56]. The technological configuration of fixed-bottom offshore turbines largely mirrors that of advanced onshore systems, with HAWTs dominating commercial installations [57]. However, offshore turbines are generally larger in scale, with rated capacities exceeding 8 MW, optimized rotor diameters, and increased hub heights to maximize energy capture. Enhanced structural reinforcement and corrosion-resistant materials are essential to withstand harsh marine conditions, including wave loading, saltwater corrosion, and cyclic fatigue [58].

Foundation design is a defining feature of fixed-bottom offshore systems and varies according to seabed conditions, water depth, and environmental loads [59]. Common foundation types include monopiles, widely used in shallow waters due to their simplicity and cost-effectiveness; jacket structures, suitable for deeper waters and complex soil conditions; and gravity-based foundations, which rely on mass and seabed preparation for stability [60]. The selection of an appropriate foundation type is critical for ensuring long-term structural integrity and minimizing installation risks. Installation and logistics represent significant cost components in fixed-bottom offshore wind projects [59]. Specialized vessels, heavy-lift cranes, and precise marine operations are required for foundation installation, turbine erection, and cable lying. Despite higher capital expenditures (CAPEX) compared to onshore systems, fixed-bottom offshore wind benefits from higher capacity factors, reduced visual and acoustic impacts on populated areas, and large-scale project development potential [61]. From an operational perspective, maintenance activities in offshore environments are more complex and weather-dependent, leading to increased OPEX [62]. Consequently, advanced condition monitoring systems, remote diagnostics, and predictive maintenance strategies are increasingly employed to enhance reliability and reduce downtime. Overall, fixed-bottom offshore wind systems represent a critical transitional technology, bridging the gap between mature onshore winds and emerging floating offshore wind solutions in the global expansion of renewable energy infrastructure [63].

Figure 4 illustrates the main foundation solutions adopted for fixed-bottom offshore wind turbines, highlighting their suitability across different water depths and seabed conditions. These foundation types provide rigid structural support by directly transferring turbine loads to the seabed and are commonly applied in shallow to intermediate offshore environments. The monopile foundation, shown on the left, consists of a single large-diameter steel pile driven into the seabed. It is widely used in shallow waters due to its simple design, rapid installation, and cost-effectiveness. Monopiles efficiently withstand lateral loads generated by wind, waves, and turbine operation.

The jacket foundation, depicted in the center, is a lattice-type steel structure supported by multiple piles. This configuration is typically employed in intermediate water depths, where monopiles become less economical or structurally efficient [64]. Jacket foundations distribute loads across several support points, offering enhanced stiffness and improved performance under complex marine loading conditions [65]. The gravity-based foundation, shown on the right, relies on its substantial mass to maintain stability without deep penetration into the seabed. Constructed mainly from reinforced concrete, this foundation type is suitable for shallow waters with firm seabed conditions [66]. Stability is achieved through self-weight and friction between the foundation base and the seabed. Overall, Figure 2 demonstrates how the selection of fixed-bottom offshore wind foundations depends on site-specific parameters such as water depth, seabed characteristics, and environmental loads, ensuring safe and reliable operation of offshore wind turbines.

2.2 | Techno-Economic Performance

The techno-economic performance of wind energy systems is assessed using three widely accepted indicators: CAPEX, OPEX, and LCOE [67]. These metrics collectively capture the upfront investment requirements, long-term operational costs, and overall cost-competitiveness of electricity generation. The values discussed in this section represent harmonized ranges reported in the literature for wind projects commissioned between 2018 and

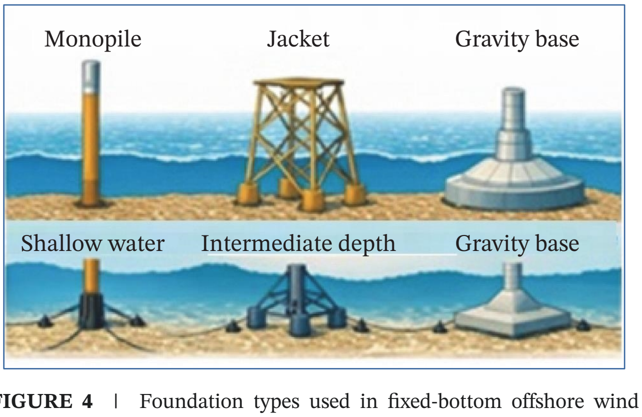

FIGURE 4 | Foundation types used in fixed-bottom offshore wind systems.

2024, ensuring comparability across different technologies and deployment environments [68].

2.2.1 | Capital Cost Structure

Among the three wind energy configurations, onshore wind systems demonstrate the lowest capital intensity, reflecting their technological maturity, standardized turbine designs, and relatively simple installation processes [69]. The majority of onshore CAPEX is associated with turbine supply, which dominates total investment due to the cost of blades, nacelles, and towers. Foundations and civil works constitute a smaller share of total costs, as land-based construction is less complex and does not require specialized equipment or vessels [70]. In contrast, fixed-bottom offshore wind systems require significantly higher capital investment, primarily due to the challenges associated with marine construction. While turbine costs remain substantial, a large portion of total CAPEX is driven by the fabrication and installation of offshore foundations [71]. These structures must withstand combined wind, wave, and current loads, necessitating robust designs and the use of heavy-lift vessels, which increases overall project costs. Floating offshore wind systems currently exhibit the highest capital costs among wind technologies. Unlike fixed-bottom offshore systems, where foundations are anchored directly to the seabed, floating wind relies on complex platform structures and mooring systems to maintain stability in deep waters [72]. As a result, the floating platform and mooring infrastructure represent the dominant cost components, surpassing turbine-related expenses. This cost distribution indicates that the primary economic challenge of floating offshore wind lies in structural and marine engineering requirements rather than in turbine technology itself. Overall, the capital cost structures of onshore, fixed-bottom offshore, and floating offshore wind systems reflect increasing technical complexity and environmental exposure, which directly influence investment requirements and shape their respective techno-economic competitiveness [73].

Table 2 summarizes and compares the capital costs, operational expenses, performance metrics, and overall cost competitiveness of onshore, fixed-bottom offshore, and floating offshore wind technologies. Table 2 highlights how increasing technical complexity and environmental exposure influence both investment requirements and electricity generation costs.

Onshore wind systems exhibit the lowest CAPEX, reflecting their technological maturity, standardized turbine designs, and relatively simple construction and maintenance logistics [71]. Turbine supply constitutes the dominant share of total capital costs, while foundations and installation represent comparatively smaller contributions [74]. OPEX, driven by easy site access and routine maintenance practices were results in the lowest LCOE among the three technologies, despite moderate capacity factors [75]. Fixed-bottom offshore wind systems require significantly higher CAPEX due to the need for robust seabed-mounted foundations, specialized installation vessels, and offshore electrical infrastructure. Although OPEX is also higher because of weather-dependent access and marine maintenance activities, these systems benefit from higher capacity factors enabled by stronger and more consistent offshore wind regimes [76]. As a result, fixed-bottom offshore wind achieves a competitive but higher LCOE compared to onshore systems. Floating offshore wind systems currently demonstrate the highest CAPEX and OPEX, primarily driven by the cost of floating platforms, mooring systems, and dynamic power cables required for deep-water deployment [77]. While their projected capacity factors are comparable to or higher than fixed-bottom offshore systems, the limited commercial experience and complex marine engineering requirements lead to the highest LCOE in the current deployment phase [73].

Overall, Table 2 illustrates the techno-economic trade-offs among wind energy technologies, showing a clear progression from cost-efficient onshore systems to more capital-intensive offshore and floating configurations. The comparison underscores that while offshore and floating wind offer superior energy yields and scalability, their economic competitiveness is strongly influenced by infrastructure maturity, technological learning, and future cost reductions.

2.2.2 | LCOE

This provides a unified metric to evaluate and compare the economic performance of different wind energy technologies by expressing the average cost of electricity generation over a project's

TABLE 2 | Comparative techno-economic performance of onshore, fixed-bottom offshore, and floating offshore wind systems.

Parameter	Fixed-bottom offshore wind	Floating offshore wind	Onshore wind
CAPEX (USD/kW)	2800 – 4500	4500 – 7500	1200 – 1700
Turbine supply share (%)	30 – 40	25 – 35	65 – 70
Foundation/platform share (%)	30 – 40	40 – 50	10 – 15
Electrical infrastructure (%)	15 – 20	15 – 20	5 – 10
Installation & logistics (%)	10 – 15	10 – 15	5 – 10
OPEX (USD/kW/year)	80 – 120	100 – 160	30 – 50
Key OPEX drivers	Vessel hire, offshore access, corrosion protection	Mooring inspection, dynamic cables, marine operations	Routine maintenance, land access
Capacity factor (%)	45 – 55	45 – 60 (projected)	30 – 40
LCOE (USD/MWh)	~70 – 100	~90 – 140	~40 – 60
Technology maturity	Commercially mature	Early commercial/pre-commercial	Fully commercial

entire lifetime [78]. It incorporates capital investment, operation and maintenance (Q&M) costs, grid connection, and decommissioning, normalized by the total discounted energy output [79]. For wind power, LCOE is strongly influenced by technology maturity, installation environment, capacity factor, and financing conditions, leading to noticeable differences among onshore wind, fixed-bottom offshore wind, and floating offshore wind systems. Onshore wind exhibits the lowest LCOE among wind technologies due to its high level of technological maturity and relatively simple installation requirements. Capital and operation costs are comparatively low because turbines are installed on land with straightforward foundations and easy access for maintenance [80]. Although onshore wind generally experiences lower and more variable wind speeds than offshore locations, its modest capacity factors are offset by reduced expenditures, resulting in a typical LCOE range of ~25–55 USD/MWh. Consequently, onshore wind remains the most cost-competitive option for large-scale deployment, particularly in regions with suitable land availability [81]. Fixed-bottom offshore wind shows a higher LCOE than onshore wind but benefits from superior wind resources and increased energy production. Turbines installed on monopile, jacket, or gravity-based foundations in shallow to intermediate waters achieve higher capacity factors due to stronger and more consistent offshore winds. However, these advantages are counterbalanced by elevated capital costs associated with offshore foundations, specialized installation vessels, and subsea grid connections, as well as higher Q&M expenses. As a result, the LCOE of fixed-bottom offshore wind typically falls in the range of 45–85 USD/MWh, reflecting a balance between enhanced energy yield and increased system complexity [82]. Floating offshore wind currently has the highest LCOE among wind technologies, primarily because it is still at an early stage of commercial development. The use of floating platforms, complex mooring systems, and dynamic export cables significantly increases capital and operational costs. Despite these challenges, floating offshore wind can access deep-water sites with exceptional wind resources, leading to very high capacity factors. At present, its LCOE is typically estimated between 70 and 130 USD/MWh; however, substantial cost reductions are expected as the technology matures, supply chains develop, and large-scale deployment is achieved [83]. Table 3 presents a harmonized comparison of LCOE ranges and cost shares across the three wind technologies.

Onshore wind remains the most cost-competitive option, benefiting from mature supply chains and low installation complexity. Fixed-bottom offshore wind shows higher LCOE but has demonstrated a consistent downward trend driven by turbine upscaling and serial installation practices. Floating offshore wind currently exhibits the highest LCOE; however, this is primarily attributable to platform fabrication, installation logistics, and regulatory risk rather than inferior energy conversion efficiency [84].

2.3 | Environmental Impacts

Wind energy technologies are widely regarded as environmentally sustainable due to their very low lifecycle greenhouse gas emissions compared to fossil-fuel-based power generation. However, the nature and magnitude of environmental impacts vary significantly between onshore and offshore wind systems because of differences in installation environments, construction techniques, and ecological interactions. These impacts primarily occur during the manufacturing, construction, and installation phases, while operational impacts are generally limited and site dependent.

2.3.1 | Onshore Wind

The principal environmental impacts of onshore wind energy are associated with land use, visual intrusion, noise emissions, and interactions with wildlife, particularly birds and bats [36]. Wind farms require substantial land areas for turbine spacing and access roads; however, the physical footprint is relatively small, allowing land to remain available for agriculture or grazing [85]. Visual impact is often the most significant public concern, especially in densely populated or scenic regions, and can influence social acceptance of projects. From a climate perspective, onshore wind exhibits very low lifecycle greenhouse gas emissions, typically in the range of 7–12 gCO_2/kWh, with the majority of emissions arising from turbine manufacturing, foundation construction, and transportation [86]. During operation, direct emissions are essentially zero. Noise impacts, including aerodynamic and mechanical noise, are highly site specific and generally decrease rapidly with distance from turbines. These effects can be effectively mitigated through appropriate setback distances, modern turbine design, and operational curtailment strategies. Wildlife impacts primarily involve avian and bat collisions, which depend on site location, migration routes, and turbine layout [87]. Environmental impact assessments, micro-sitting, and seasonal shutdowns during peak migration periods have proven effective in reducing ecological risks. Overall, while onshore wind presents localized environmental challenges, these impacts are well understood and manageable through established regulatory and technical measures [36].

2.3.2 | Fixed-Bottom Offshore Wind

Fixed-bottom offshore wind largely eliminates land-use and visual impacts on coastal communities, making it attractive from a social acceptance standpoint [88]. However, it introduces a distinct set of marine environmental interactions, particularly during the construction and installation phases. The most significant impacts arise from seabed disturbance and underwater noise, especially during pile driving for monopile and jacket foundations. Seabed preparation and foundation installation can temporarily affect

TABLE 3 | Techno-economic comparison of wind energy technologies (2018–2024).

Technology	CAPEX (USD/kW)	Turbine cost share (%)	Foundation/ platform (%)	O&M share (%)	LCOE (USD/MWh)
Onshore wind	1200–1700	65–70	10–15	15–20	30–55
Fixed-bottom offshore	2800–4500	35–45	30-40	20–25	60–100
Floating offshore	4500–7500	25–30	40-50	20–25	90–160

benthic habitats and sediment transport patterns. Although these disturbances are typically localized, they may influence marine organisms such as benthic invertebrates and demersal fish species [89]. Underwater noise generated during pile driving poses potential risks to marine mammals and fish, including behavioral disturbance and temporary hearing impairment. To mitigate these effects, measures such as bubble curtains, noise dampening technologies and seasonal construction windows are increasingly adopted. Lifecycle greenhouse gas emissions for fixed-bottom offshore wind are slightly higher than those of onshore wind, generally ranging between 8 and 14 gCO_2/kWh, due to the energy-intensive nature of offshore foundations, installation vessels, and subsea cabling. Nevertheless, these emissions remain orders of magnitude lower than fossil-fuel-based generation. During operation, offshore wind farms may also create artificial reef effects around foundations, which can enhance local biodiversity under certain conditions. Overall, while fixed-bottom offshore wind presents specific marine environmental challenges, these impacts are largely temporary and can be effectively managed through careful planning, monitoring, and mitigation strategies [59].

2.3.3 | Floating Offshore Wind

Floating offshore wind systems enable wind energy deployment in deep-water environments, thereby avoiding many of the seabed-related impacts associated with fixed-bottom foundations. Because floating platforms are anchored using mooring lines rather than rigid foundations, direct seabed disturbance is significantly reduced, particularly during installation [66]. This characteristic makes floating offshore wind especially attractive in regions with deep coastal waters and sensitive benthic ecosystems. The primary environmental concerns for floating offshore wind relate to mooring systems, dynamic cables, and increased offshore activity. Mooring lines and anchors can interact with benthic habitats, although the spatial footprint is generally smaller and more dispersed than that of fixed-bottom foundations [90]. Dynamic export cables, which accommodate platform motion, introduce additional complexity and may affect marine organisms through electromagnetic fields and localized heating; however, current evidence suggests these impacts are limited and highly site specific. Underwater noise impacts during installation are typically lower than those of fixed-bottom offshore wind, as pile driving is not required for most floating configurations. Instead, noise is mainly generated by anchor installation and vessel operations, resulting in reduced acoustic disturbance to marine mammals and fish. During operation, floating turbines may also contribute to artificial reef effects, potentially enhancing local biodiversity around mooring and anchoring structures [91]. Lifecycle greenhouse gas emissions for floating offshore wind are currently estimated to be slightly higher than those of fixed-bottom offshore systems, typically in the range of 10–16 gCO_2/kWh, due to the additional material requirements for floating platforms, mooring systems, and dynamic cables. Despite this, floating offshore wind remains a low-carbon energy technology with emissions far below those of conventional thermal power generation. As the technology matures and manufacturing processes are optimized, further reductions in lifecycle emissions are expected [92].

Table 4 presents a comparative overview of the key environmental impacts associated with onshore wind, fixed-bottom offshore wind, and floating offshore wind technologies, highlighting how the installation environment influences the type and intensity of environmental interactions.

For onshore wind, the most prominent impacts are related to land use and visual intrusion, particularly in populated or environmentally sensitive areas [36]. Although wind farms require relatively large spatial areas for turbine spacing, the actual land permanently occupied by foundations and access roads is small, allowing continued agricultural or grazing activities. Wildlife interactions, especially with birds and bats, are highly site dependent and represent the main ecological concern during operation. Onshore wind demonstrates the lowest lifecycle greenhouse gas emissions among the three technologies, reflecting its simpler construction requirements and minimal material use [93]. In contrast, fixed-bottom offshore wind largely eliminates terrestrial land-use conflicts and reduces visual impacts for coastal communities. However, environmental impacts are transferred to the marine environment, with seabed disturbance and underwater noise during foundation installation being the dominant concerns. Pile driving can temporarily affect marine mammals and fish, while seabed preparation alters benthic habitats. Despite these challenges, lifecycle greenhouse gas emissions remain very low and only slightly higher than onshore wind due to energy-intensive offshore construction activities [94]. Floating offshore wind further reduces environmental pressures on both land and seabed by enabling deployment in deep-water regions and avoiding rigid seabed foundations. As indicated in Table 4, seabed disturbance is limited to anchor points and mooring lines, and underwater noise levels during installation are generally lower than those associated with fixed-bottom systems. The primary environmental considerations relate to mooring systems and dynamic cables, which may interact with marine habitats but over a relatively dispersed area. Although lifecycle greenhouse gas emissions are currently the highest among wind technologies, they remain low overall and are expected to decline as floating wind technology matures.

Overall, Table 4 demonstrates that while each wind technology exhibits distinct environmental impact profiles, all three options offer substantial environmental advantages compared to conventional fossil-fuel-based power generation. The table underscores the importance of site-specific planning and targeted mitigation strategies to minimize localized environmental effects while maximizing the sustainability benefits of wind energy deployment.

2.4 | Social and Regulatory Challenges

The deployment of wind energy technologies is increasingly shaped not only by technical and economic factors but also by social acceptance and regulatory complexity. These dimensions play a critical role in project timelines, investment risk, and overall feasibility, with distinct challenges observed across onshore, fixed-bottom offshore, and floating offshore wind systems [95]. For onshore wind, social acceptance has emerged as one of the most significant constraints on future expansion. Public concerns are primarily associated with visual intrusion, perceived noise impacts, and competition for land use, particularly in densely populated or agriculturally valuable regions. While technological advancements have reduced actual noise emissions, perception-related concerns continue to influence local opposition. As a result, permitting processes have become more stringent and prolonged in many regions, with increased requirements for public

TABLE 4 | Comparative environmental impacts of onshore, fixed-bottom offshore, and floating offshore wind technologies.

Onshore wind	Fixed-bottom offshore wind	Floating offshore wind	Impact category
Requires terrestrial land; small physical footprint with continued agricultural use	No land use onshore; offshore spatial occupation	No land use onshore; offshore deployment in deep waters	Land use
High in populated or scenic areas	Low to moderate; visible from coast depending on distance	Very low; typically far from coastline	Visual impact
Not applicable	Significant during foundation installation	Low; limited to anchors and mooring lines	Seabed disturbance
Not applicable	High during pile driving; temporary	Moderate during anchoring; lower than fixed-bottom	Underwater noise
Birds and bats; site dependent	Fish and marine mammals during construction	Marine species interaction via moorings and cables	Wildlife interaction
Not applicable	Moderate; foundations may enhance biodiversity	Moderate; moorings and anchors may support habitats	Artificial reef effect
7–12	8–14	10–16	Lifecycle GHG emissions (gCO_2/kWh)
Construction and operation	Construction and installation	Construction and installation	Dominant impact phase
High (siting, curtailment)	High (noise control, timing)	High (optimized mooring design)	Mitigation potential

consultation, setback distances, and legal review. These extended permitting timelines introduce uncertainty for developers and can significantly delay project commissioning, thereby increasing development and financing costs. In comparison, fixed-bottom offshore wind generally encounters fewer issues related to public opposition due to its offshore location and reduced visibility from coastal communities [7]. Nevertheless, the regulatory environment for offshore projects is inherently complex. Developers must navigate marine spatial planning frameworks, comprehensive environmental impact assessments, and multiple permitting authorities governing maritime activities, navigation safety, and ecological protection. Additionally, securing approvals for offshore substations and grid connections often involves coordination between national regulators and transmission system operators. These regulatory requirements can extend development timelines and increase project risk, particularly as projects move into deeper waters and farther from shore [96]. Floating offshore wind faces comparatively limited social opposition because projects are typically located far offshore and have minimal visual or noise impacts on coastal populations. However, the primary challenge lies in regulatory immaturity. Many jurisdictions lack established legal and permitting frameworks for floating platforms, deep-water leasing, and dynamic cabling systems. Uncertainty regarding ownership rights, safety standards, and long-term liability increases perceived investment risk [97]. Consequently, floating offshore wind projects often face higher financing costs, as lenders and insurers account for regulatory uncertainty alongside technological novelty. Addressing these regulatory gaps is critical for accelerating commercial deployment [98].

2.5 | Future Outlook and Research Priorities

The future development trajectories of wind energy technologies differ significantly in terms of cost reduction potential, deployment constraints, and research focus. Understanding these trends is essential for guiding policy design and research investment [99]. For onshore wind, future cost reductions are expected to be incremental rather than transformative. Continued turbine scaling, improved power electronics, and digital optimization techniques such as predictive maintenance and advanced wind forecasting will contribute to modest efficiency gains and operational cost reductions. However, further large-scale expansion is increasingly constrained by land availability, social acceptance, and permitting challenges, suggesting that onshore wind growth may plateau in some mature markets despite its low LCOE [100]. Fixed-bottom offshore wind is likely to experience continued and more substantial LCOE reductions in the near to medium term. Key drivers include the deployment of larger-capacity turbines, improved installation logistics, and the adoption of standardized and modular foundation designs. However, as offshore wind farms are developed farther from shore, grid integration and transmission infrastructure are emerging as critical bottlenecks [38]. Research efforts must therefore focus on offshore grid optimization, high-voltage transmission technologies, and coordinated planning between generation and transmission assets. Floating offshore wind represents the most dynamic and transformative development pathway among wind technologies. Unlike onshore and fixed-bottom offshore wind, future cost reductions are expected to arise primarily from platform standardization, serial manufacturing, and supply-chain learning effects, rather than further aerodynamic improvements. Key research priorities include mooring system optimization, reduction of structural fatigue in floating platforms, advanced control strategies to manage platform motion, and the development of harmonized regulatory frameworks [101]. Progress in these areas is essential to reduce project risk, lower financing costs, and unlock the vast deep-water wind resources required for long-term global decarburization [102].

2.6 | Policy Implications

The comparative assessment of onshore, fixed-bottom offshore, and floating offshore wind technologies highlights the need for technology-specific and adaptive policy frameworks to support cost-effective and sustainable deployment [103]. Given the differing social, environmental, and regulatory challenges associated with each technology, a uniform policy approach is unlikely to yield optimal outcomes [104].

- For onshore wind, policy efforts should prioritize streamlining permitting processes and improving public engagement mechanisms [105]. Clear land-use planning, standardized setback regulations, and early-stage community consultation can reduce opposition and shorten approval timelines. Additionally, policies that support community ownership models or local benefit-sharing schemes may enhance social acceptance and facilitate continued deployment in mature markets [106].
- In the case of fixed-bottom offshore wind, policy attention should focus on coordinated marine spatial planning and grid infrastructure development. Integrated permitting frameworks that align environmental assessments, maritime safety regulations, and grid connection approvals can significantly reduce development risk and project delays. Public investment in offshore transmission infrastructure and shared grid assets may further lower costs and accelerate large-scale deployment [107].
- For floating offshore wind, targeted policy intervention is critical to address regulatory uncertainty and financing barriers [98]. Governments should establish clear legal frameworks for deep-water leasing, floating platform certification, and dynamic cabling systems. Support mechanisms such as pilot project funding, contracts for difference, and risk-sharing instruments can help de-risk early commercial projects and attract private investment. International collaboration and regulatory harmonization are also essential to enable technology standardization and accelerate cost reductions [108].

Overall, the findings suggest that well-designed, technology-specific policies play a decisive role in unlocking the full potential of wind energy. By aligning regulatory frameworks with the maturity level and technical characteristics of each wind technology, policymakers can reduce investment risk, accelerate deployment, and support long-term decarburization goals.

3 | Offshore Wind Turbines

OWTs are a key renewable energy technology, enabling access to strong and consistent offshore winds. Operating in dynamic marine environments, OWTs are designed to withstand wind, wave, and current forces. Structures are primarily made from steel or concrete, ensuring robustness and durability in harsh offshore conditions. Offshore wind offers higher capacity factors (20%–40%) compared to onshore turbines, although deeper waters and greater distances from shore increase development and operational costs.

3.1 | Offshore Wind Turbine Technology

Offshore wind energy has emerged as a relatively recent challenge in the global wind industry, with current global installations standing at 8.76 GW shown in Figure 5. Global deployment

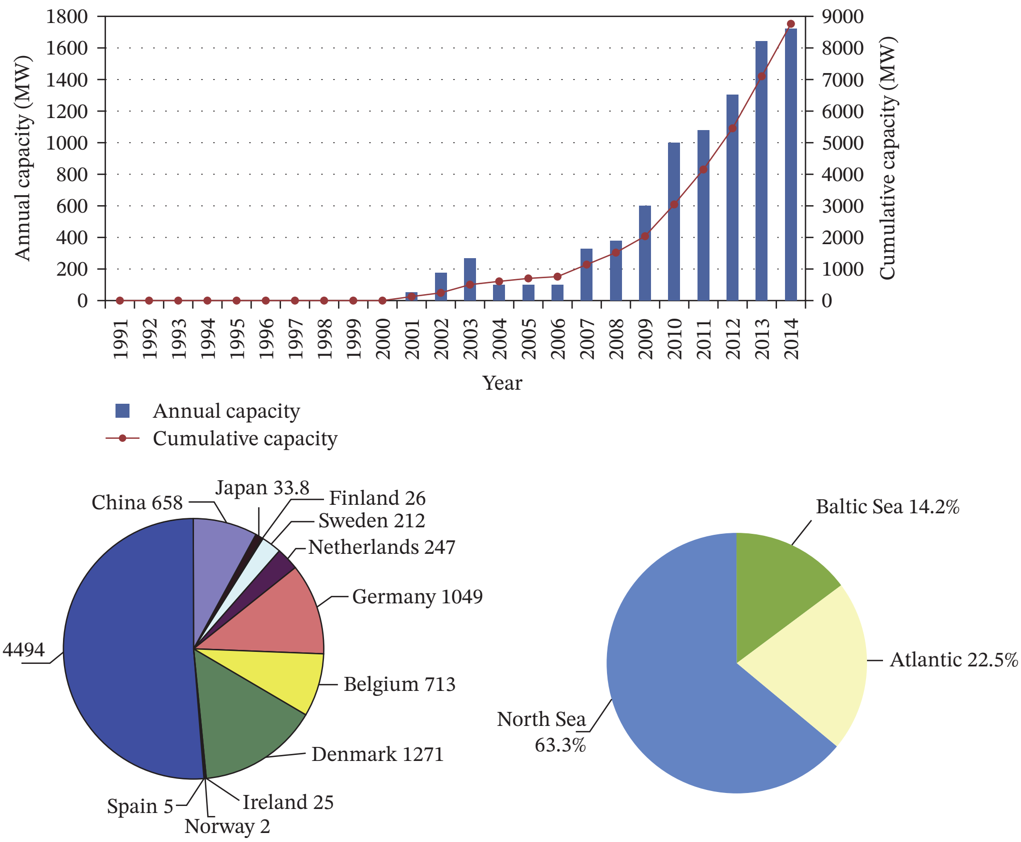

FIGURE 5 | In 2014, the global offshore capacity evolution and cumulative share by nation (in MW), as well as the European cumulative share by sea basin, were examined [109, 110].

of offshore wind power has expanded rapidly in recent years, reaching ~8.76 GW of IC, which corresponds to nearly 2.4% of total global wind installations [111, 112]. Europe accounts for the overwhelming majority of this capacity, hosting about 8.1 GW (around 92.5%) and producing roughly 29.6 TWh of electricity per year. Offshore wind projects are operational in 14 countries worldwide, with the United Kingdom leading at 4.49 GW, followed by Denmark (1.27 GW), Germany (1.05 GW), Belgium (0.71 GW), and China (0.66 GW). Japan, with 50 MW installed, ranks eighth among participating nations [113]. Advancements in offshore wind technology have largely evolved from accumulated experience in onshore wind development as well as engineering practices derived from the oil and gas sector. Modern offshore wind turbines, with rated capacities reaching up to 6 MW, must be specifically designed to withstand harsh marine environments, including strong winds, wave loading, corrosion, and complex installation conditions [114].

Figure 6 shows offshore wind farm ancillary structures and their percentage of European installations [117–119]. Foundation types used on behalf of OWT include mono-piles, jackets, gravity-based structures, and floating platforms, each suited for different water depths and seabed conditions. The installation of OWTs involves a range of specialized approaches, including jack-up vessels, heavy-lift installation ships, and emerging assembly-based concepts designed to streamline offshore construction processes [120]. OWP generally achieves higher capacity factors typically between 20% and 40% primarily because wind speeds over open seas are stronger and more consistent than those near the coast [114]. Despite this advantage, projects located in deeper waters face significantly higher capital and OPEX, which can partially offset the gains in energy production. Overall, the economic performance of offshore wind is becoming increasingly comparable to onshore installations, although it still entails greater upfront investment and maintenance costs [121]. Continuous technological progress aims to enhance performance while reducing lifecycle costs. Current research efforts focus on scaling turbine ratings, strengthening structural reliability, optimizing aerodynamic and electrical design, and developing advanced next-generation support structures suitable for deeper and more challenging marine environments [122].

Representative developments in this field include:

- The adoption of advanced engineering and monitoring strategies aimed at enhancing wind turbine reliability while simultaneously optimizing maintenance procedures to achieve faster interventions and reduced operational costs [114].
- The deployment of next-generation, purpose-designed installation and service vessels that support both construction and maintenance activities, thereby extending the operational 'weather window' and improving the overall efficiency of offshore interventions [123].
- The integration of innovative materials and advanced engineering techniques within a comprehensive turbine design framework to ensure structural resilience under severe marine conditions, alongside the incorporation of real-time condition monitoring and diagnostic systems for improved operational reliability [124].

The upscaling of turbine ratings and the development of new offshore-specific configurations such as mounting wind turbine towers on floating platforms for deep-water applications enable access to stronger and more stable wind resources while reducing visual intrusion from coastal areas [114]. These approaches enhance energy yield, improve economic returns, and expand deployment potential beyond shallow-water sites. Ongoing technological progress in offshore wind turbines continues to prioritize higher power output, enhanced conversion efficiency, improved durability, and cost reductions. Collectively, these innovations strengthen the role of offshore wind as a competitive and sustainable contributor to the global energy transition.

3.2 | Environmental Considerations

OWTs provide renewable electricity, reduce greenhouse gas emissions, and create artificial habitats, but offshore deployment

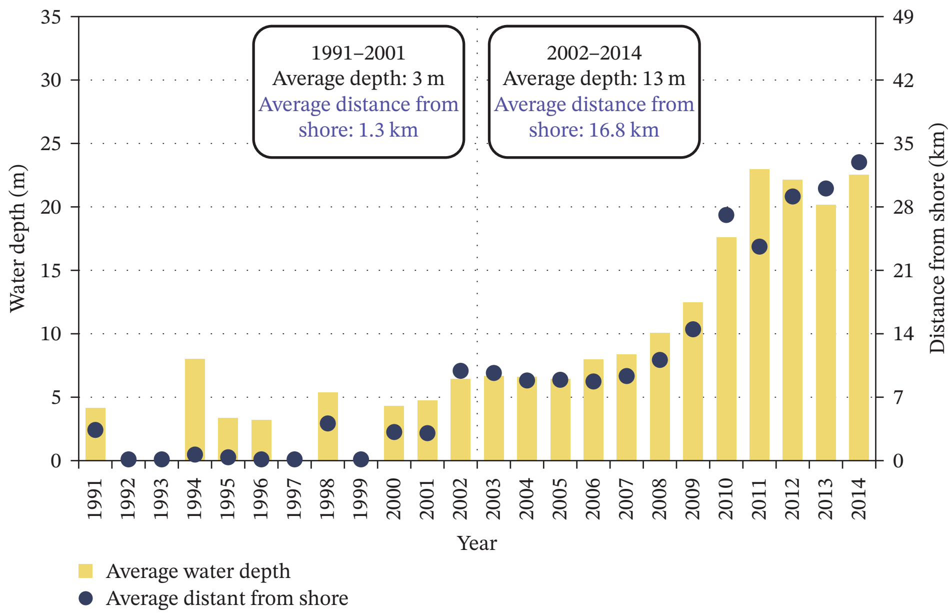

FIGURE 6 | The typical distance from the coast and sea depth of offshore wind projects have changed throughout time [115, 116].

introduces marine-specific environmental impacts. Construction activities can generate underwater noise, seabed disturbance, and electromagnetic fields from submarine cables, affecting marine mammals, fish, and benthic organisms [125]. Operational noise is minimal, and sitting, monitoring, and mitigation measures can minimize ecological disruption. Comprehensive environmental assessments are essential to ensure sustainable offshore wind deployment [126].

3.3 | Policy and Regulatory Frameworks

Government policies and regulatory frameworks are pivotal for offshore wind development [127]. Key measures include:

- Clear licensing and permitting procedures [128].
- Offshore zoning for wind development [129].
- Grid connection facilitation [130].
- Financial incentives (feed-in tariffs, tax credits, RE targets) [131].

Collaboration among government, industry, and local communities ensures sustainable and socially accepted projects [132].

3.4 | Case Studies of Successful Offshore Wind Projects

Case studies provide real-world examples of how offshore wind projects contribute to renewable energy deployment, technology validation, and sustainable development [133]. They allow researchers, policymakers, and industry stakeholders to understand the technical, environmental, and economic implications of different offshore wind solutions [6]. The comparative case study Table 5 highlights key offshore wind projects across different countries, showcasing the diversity in capacity, foundation technology, and contributions to renewable energy generation. The London Array in the UK, with a capacity of 630 MW, demonstrates the feasibility of large-scale offshore wind deployment using monopile foundations in relatively shallow waters [134]. It generates ~2.5 TWh annually, contributing significantly to CO_2 emission reductions and exemplifying efficient project management and grid integration strategies [135].

In contrast, the Block Island Wind Farm in the USA, with a capacity of 30 MW, represents the country's first operational offshore wind project. Utilizing monopile foundations and a direct connection to the mainland grid, this project serves as a regulatory and technological benchmark for U.S. offshore development, supplying clean energy to thousands of households [46]. The Borssele Wind Farm in the Netherlands is a multi-phase project totaling 1.4 GW, employing a combination of monopile and jacket foundations. Its phased development approach enables optimized cost management and energy yield, while also creating job opportunities and supporting regional economic growth [136]. Notably, floating offshore wind technologies are represented by Hywind Scotland and Japan's Fukushima Floating Wind Project [137]. Hywind Scotland, a 30 MW commercial floating farm, uses spar-buoy foundations to access deep-water wind resources, illustrating the potential for energy generation in areas where traditional fixed-bottom solutions are infeasible [138]. The Fukushima Floating project, with a 2 MW semi-submersible foundation, highlights technological innovation and resilience to extreme conditions such as typhoons, providing valuable lessons for floating wind deployment and research [139].

Overall, Table 5 underscores the growing variety of offshore wind technologies and deployment strategies, emphasizing the importance of site-specific foundation selection, energy generation potential, and broader environmental and economic contributions. It also illustrates the trend toward floating platforms, which open opportunities in deeper waters and regions previously unsuitable for offshore wind development.

3.5 | FOWTs

FOWTs extend deployment to deep-water sites, accessing stronger, less turbulent winds and enabling higher energy yields while minimizing visual impact and coastal disruption.

3.5.1 | Platform Types and Technology

Floating offshore wind technology integrates advanced naval architecture with large-scale wind turbines to unlock high-quality wind resources in deep-water regions. Spar-buoy platforms are particularly suited for harsh offshore environments due to their low center of gravity and excellent dynamic performance, although their deep draft limits port compatibility [140].

TABLE 5 | Comparative summary of offshore wind case studies.

Project name	Country	Capacity (MW)	Foundation type	Annual generation (TWh)	Notable contribution
London Array	UK	630	Monopile	2.5	Large-scale deployment, CO_2 reduction
Block Island	USA	30	Monopile	0.1	First U.S. offshore wind farm, regulatory benchmark
Borssele	Netherlands	1400	Monopile & Jacket	5.5	Phased development, economic growth, grid integration
Hywind Scotland	UK	30	Floating (Spar-buoy)	0.1	First commercial floating offshore wind farm, deep water
Fukushima Floating	Japan	2	Semi-submersible	0.007	Typhoon resilience, technological R&D demonstration

Semi-submersible platforms offer greater deployment flexibility and scalability, making them attractive for early commercial projects and pilot farms [141]. Tension leg platforms (TLPs), while offering superior motion control and reduced fatigue loading on turbines, remain technologically complex and capital-intensive. Across all platform types, dynamic mooring systems and flexible subsea power cables are critical components, enabling stable operation under continuous wave, wind, and current loading [142]. Figure 7 illustrates the three principal floating offshore wind platform concepts spar-buoy, semi-submersible, and TLP which enables wind energy deployment in deep waters exceeding 60 m, where fixed-bottom foundations are technically or economically infeasible. The spar-buoy concept relies on a deep, slender cylindrical structure stabilized by ballast, providing excellent hydrodynamic stability and reduced motion response. Semi-submersible platforms achieve stability through multiple interconnected columns and pontoons, offering easier assembly and installation using conventional port infrastructure. TLP systems employ vertical tendons anchored to the seabed, minimizing platform motion but requiring highly precise installation and anchoring systems [143]. Collectively, Figure 7 highlights how different platform designs balance stability, installation complexity, and site adaptability, demonstrating the technological flexibility of floating offshore wind systems.

3.5.2 | Development and Operational Challenges

Despite its strong potential, floating offshore wind faces several development and operational challenges. Platform motion induced by waves and currents increases structural fatigue and complicates turbine control strategies [47]. Mooring systems must withstand long-term cyclic loading while maintaining station-keeping accuracy, and dynamic power cables are subject to higher mechanical stresses compared to fixed-bottom systems [144]. Installation and maintenance operations are also more complex, particularly in remote deep-water locations where weather windows are limited. Additionally, the lack of standardized design practices and limited long-term operational data contribute to higher perceived project risk, influencing financing costs and insurance requirements [145].

FIGURE 7 | Floating offshore wind platform concepts.

3.5.3 | Research and Development

Ongoing research and development efforts are central to improving the competitiveness of floating offshore wind. Key research priorities include reducing platform mass through advanced materials, optimizing mooring configurations to minimize cost and fatigue, and improving aero-hydro-servo-elastic modeling for more accurate performance prediction [146]. Digital twins and condition monitoring systems are increasingly being applied to enhance reliability and reduce Q&M costs. Furthermore, R&D efforts are shifting toward industrial-scale manufacturing, modular platform designs, and standardized certification frameworks, which are essential for accelerating commercialization and investor confidence [147].

3.5.4 | Cost Considerations

Cost considerations play a decisive role in determining the commercial viability of offshore wind technologies, particularly when comparing fixed-bottom and floating offshore wind systems. The total project cost is dominated by CAPEX, followed by O&M costs, and financing conditions, all of which directly influence the LCOE [148].

3.5.5 | CAPEX

For fixed-bottom offshore wind, CAPEX is primarily associated with turbine procurement, foundation fabrication, offshore installation, and grid connection [149]. Due to decades of deployment experience, these costs have declined significantly through standardized monopile and jacket designs, optimized installation vessels, and well-established supply chains [150]. As a result, fixed-bottom projects currently benefit from relatively predictable cost structures and lower investment risk. In contrast, floating offshore wind projects incur higher CAPEX, driven by the complexity of floating platforms, mooring systems, and dynamic export cables. Platform fabrication requires substantial steel or concrete volumes, while mooring lines and anchors must be designed to withstand continuous cyclic loading in deep-water environments. Additionally, the limited availability of specialized installation vessels and ports capable of handling large floating structures further increases upfront costs [151]. These factors collectively explain the higher LCOE values observed for floating offshore wind in Figure 8.

Figure 8 presents a comparative analysis of the LCOE for fixed-bottom and floating offshore wind technologies. Fixed-bottom offshore wind currently exhibits lower LCOE values due to technological maturity, established supply chains, and optimized installation practices [73]. In contrast, floating offshore wind shows higher present-day LCOE, driven primarily by elevated CAPEX related to platform fabrication, mooring systems, and dynamic cabling, as well as higher financing costs stemming from technological uncertainty. However, Figure 8 also illustrates a clear cost convergence trend. As floating offshore wind projects scale up, cost reductions are expected through platform standardization, serial manufacturing, and learning-by-doing effects across the supply chain. Unlike fixed-bottom systems where further cost

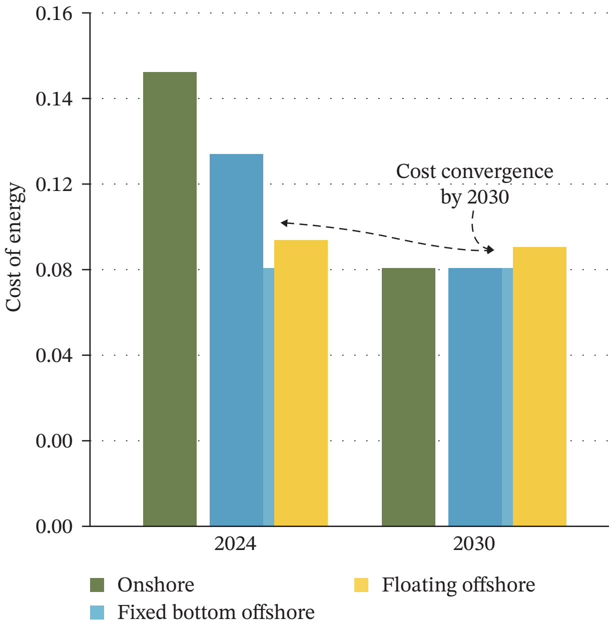

FIGURE 8 | LCOE comparison of onshore, fixed-bottom, and floating offshore wind.

reductions rely mainly on turbine upscaling floating wind cost declines are expected to arise predominantly from structural and logistical optimization. Over the medium to long term, floating offshore wind is projected to achieve LCOE levels comparable to fixed-bottom systems, particularly in regions with deep waters and strong, consistent wind resources [95].

3.5.6 | O&M Costs

O&M costs represent a significant portion of lifetime project expenditure and differ substantially between fixed-bottom and floating systems. Fixed-bottom offshore wind benefits from mature maintenance strategies, including scheduled inspections, condition monitoring, and the availability of established service infrastructure [152]. However, as projects move farther offshore into deeper waters, accessibility challenges increase, and raising O&M costs. Floating offshore wind presents both challenges and opportunities in this regard. While increased platform motion and harsher offshore environments can accelerate component fatigue and maintenance requirements, floating systems also offer the possibility of tow-to-port maintenance, allowing turbines or entire platforms to be serviced onshore. This approach has the potential to reduce long-term O&M costs, provided that logistical planning and port infrastructure are adequately developed [62].

3.5.7 | Financing and Risk Premiums

Financing conditions are a critical determinant of LCOE, particularly for capital-intensive offshore wind projects. Fixed-bottom offshore wind enjoys lower financing costs due to its technological maturity, extensive operational track record, and well-defined regulatory frameworks [153]. Investors and lenders typically perceive these projects as low-risk infrastructure investments. Floating offshore wind, by contrast, faces higher risk premiums. The limited number of commercial-scale projects, absence of standardized design codes, and uncertainty in long-term performance data contribute to higher weighted average cost of capital (WACC) [154]. As illustrated in Figure 8, these elevated financing costs significantly impact LCOE, even when technical performance is comparable to fixed-bottom systems.

3.5.8 | Cost Reduction Pathways

Cost reduction pathways for offshore wind particularly floating offshore wind are fundamentally different from those of onshore and fixed-bottom systems. While early offshore cost reductions were driven largely by turbine upscaling, floating offshore wind relies more heavily on structural, logistical, and supply-chain optimization. One of the most critical pathways is platform standardization. Current floating projects often employ bespoke platform designs tailored to specific sites, which increases engineering, certification, and fabrication costs [155]. Moving toward standardized, modular platform designs would allow serial production, reduce engineering overhead, and accelerate learning effects across projects. Another major cost reduction mechanism lies in industrialized manufacturing and assembly processes. Floating platforms can be partially or fully assembled at quayside using conventional shipyard infrastructure, minimizing the need for specialized offshore installation vessels. This shift from offshore-intensive to port-based construction reduces weather-related delays, lowers vessel day rates, and improves overall schedule certainty. As port infrastructure adapts to floating wind requirements, economies of scale are expected to significantly lower fabrication and installation costs [156].

Mooring system optimization represents an additional pathway for cost reduction. Moorings and anchors account for a substantial share of floating wind CAPEX, particularly in deep-water environments. Advances in synthetic mooring materials, shared mooring systems between turbines, and optimized anchor layouts can reduce both material usage and installation complexity [157]. Similarly, improvements in dynamic subsea cable design, including enhanced fatigue resistance and simplified routing strategies, are expected to lower lifetime costs and improve system reliability. Finally, learning-by-doing and digitalization play a crucial role. As more floating wind projects are deployed, operational data will inform improved design standards, maintenance strategies, and risk assessment models. Digital twins, advanced condition monitoring, and predictive maintenance tools enable early fault detection, reduce unplanned downtime, and lower O&M expenditures [158].

3.5.9 | Long-Term Economic Perspective

From a long-term economic perspective, the competitiveness of offshore wind technologies cannot be evaluated solely on present-day LCOE. Instead, broader system-level and strategic factors must be considered [159]. Floating offshore wind enables access to vast deep-water wind resources that are unavailable to fixed-bottom systems [7]. These regions often exhibit stronger and more consistent wind regimes, resulting in higher capacity factors and reduced intermittency, which enhance the economic value of generated electricity. As shallow-water sites become saturated and permitting constraints intensify, the marginal cost of fixed-bottom offshore wind is expected to rise. In contrast, floating offshore wind offers a scalable pathway for continued offshore expansion without competing for limited near shore space. Over time, this spatial flexibility is likely to translate into lower development risk, improved social acceptance, and more predictable long-term deployment pipelines [160]. From an energy system perspective, floating offshore wind also contributes to grid stability and decarburization goals. Higher capacity factors and smoother power output profiles reduce the need for backup generation and storage, lowering system-wide costs that are not fully captured by project-level LCOE metrics. In regions with high electricity demand near coastal urban centers, floating wind can reduce transmission congestion and associated infrastructure costs by enabling offshore generation closer to load centers. In the long term, floating offshore wind may also benefit from cross-sector integration, such as coupling with offshore hydrogen production, carbon-neutral fuels, and energy storage systems [161]. These integrated energy hubs can enhance revenue streams, improve asset utilization, and increase overall project bankability. When these additional value streams are considered, floating offshore wind may achieve economic parity or even superiority over fixed-bottom systems in certain markets [162].

4 | Discussion of Technical and Operational Challenges Associated With Onshore, Fixed-Bottom, and Floating Offshore Wind

4.1 | Onshore Wind Energy

Although onshore wind energy is the most technologically mature and cost-effective wind technology, it faces persistent technical and operational challenges that increasingly influence project feasibility [163]. One major technical issue is wind turbulence and shear caused by complex terrain, forests, and built environments. These effects increase cyclic loading on blades, towers, and drive train components, accelerating fatigue damage and raising maintenance requirements over the turbine lifetime. Cold climate operation introduces additional challenges such as icing, which reduces aerodynamic efficiency and increases structural loads. From an operational standpoint, grid integration has become a critical concern in regions with high onshore wind penetration [38]. Transmission bottlenecks, curtailment, and insufficient grid flexibility can significantly reduce effective energy output. Furthermore, land acquisition and access logistics particularly in mountainous or remote areas—raise construction complexity and cost. Social acceptance remains one of the most influential non-technical barriers, as visual impact, perceived noise, and land-use conflicts often prolong permitting processes and create regulatory uncertainty [164].

4.2 | Fixed-Bottom Offshore Wind Energy

Fixed-bottom offshore wind technology benefits from stronger and more stable wind resources but operates under significantly harsher environmental conditions [59]. Technically, the combined loading from wind, waves, and currents imposes complex structural demands on turbines and foundations. Fatigue resistance becomes a dominant design consideration, especially for monopiles and jacket structures exposed to long-term cyclic wave loading. Seabed variability further complicates foundation design, requiring extensive geotechnical surveys and site-specific engineering solutions [165]. Operational challenges are closely linked to offshore accessibility and weather dependency. Installation and maintenance activities are restricted by limited weather windows, leading to higher vessel standby times and increased OPEX. Specialized installation vessels and heavy-lift equipment are required, which are subject to supply constraints and high charter costs [166]. Electrical infrastructure poses additional challenges, as export cable installation, protection, and long-distance transmission increase both technical risk and system losses. Although fixed-bottom offshore wind is a mature technology, its deployment is inherently limited by water depth, restricting scalability in regions with steep continental shelves [55].

4.3 | Floating Offshore Wind Energy

Floating offshore wind represents the most technically complex and operationally challenging wind technology due to its interaction with highly dynamic marine environments. Unlike fixed-bottom systems, floating turbines experience six-degree-of-freedom platform motion, which directly influences aerodynamic performance, structural loading, and control system stability [47]. Managing these coupled aero-hydro-servo-elastic interactions requires advanced numerical models, real-time control algorithms, and extensive experimental validation. Mooring systems and anchoring solutions are subject to continuous cyclic loading, increasing fatigue, and inspection requirements. Dynamic power cables face additional stresses due to platform motion, making cable design, and reliability a critical challenge [142]. Installation and commissioning are logistically demanding, particularly in deep-water locations far from shore, where port infrastructure and specialized vessels may be limited. Maintenance operations are further complicated by accessibility constraints and harsh environmental conditions, although the tow-to-port maintenance strategy offers potential long-term advantages. In addition to technical issues, floating offshore wind faces institutional and regulatory challenges, including the absence of standardized design codes and limited long-term operational data. These uncertainties increase perceived project risk, leading to higher financing costs and insurance premiums. As commercial-scale projects remain limited, accelerating knowledge transfer and standardization is essential for widespread deployment [167].

4.4 | Comparative and System-Level Perspective

From a comparative standpoint, onshore wind is primarily constrained by social acceptance and grid integration challenges, while fixed-bottom offshore wind is limited by environmental conditions, installation complexity, and water depth constraints [168]. Floating offshore wind, despite its current technical and economic challenges, offers a transformative pathway to overcome spatial limitations and access high-quality wind resources in deep waters. At the system level, the successful integration of all three technologies requires coordinated planning, advanced grid infrastructure, and targeted policy support. Continued innovation in materials, control systems, digital monitoring, and installation strategies will be critical to addressing these challenges. As operational experience grows and standardization improves, floating offshore wind is expected to transition from a demonstration technology to a central pillar of future offshore renewable energy systems [95]. Table 6 provides a quantitative comparison of onshore, fixed-bottom offshore, and floating

TABLE 6 | Comparative technical and operational challenges of onshore, fixed-bottom offshore, and floating offshore wind.

Aspect	Onshore wind	Fixed-bottom offshore wind	Floating offshore wind
Typical water depth	On land (0 m)	~5–60 m (up to ~70 m in advanced projects)	~60–1000 m (commercial focus: 80–300 m)
Wind resource quality	Moderate wind speeds; high turbulence	High wind speeds; low turbulence	Very high and consistent wind speeds
Structural loading	Turbulence-driven fatigue loads	Combined wind–wave–current cyclic loads	Six-degree-of-freedom motion; coupled aero-hydro-servo-elastic loads
Foundation/platform type	Shallow concrete or piled foundations	Monopile, jacket, gravity-based	Spar, semi-submersible, TLP
CAPEX range	~1.2–1.8 MUSD/MW	~2.5–4.5 MUSD/MW	~4.0–7.5 MUSD/MW
O&M cost share (of LCOE)	~10%–20%	~20%–30%	~25%–35%
Installation complexity	Low; road transport and land cranes	High; offshore vessels and weather windows	Very high; port assembly, towing, deep-water mooring
Operation & maintenance access	Easy, year-round	Weather-limited offshore access	Difficult offshore access; potential tow-to-port advantage
Grid connection	Short-distance transmission; curtailment risk	Long export cables (30–150 km)	Long-distance dynamic subsea cables
Environmental constraints	Visual impact, noise, land-use conflict	Seabed disturbance, underwater noise	Reduced seabed impact; mooring and EMF concerns
Regulatory & permitting risk	High at local level (NIMBY)	Moderate; marine spatial planning	High; regulatory immaturity
Financing risk (WACC)	Low (~4%–6%)	Medium (~6%–8%)	High (~8%–12%)
Technology maturity	Fully mature	Mature and commercial	Early commercial/pre-commercial
Scalability potential	Limited by land availability	Limited by shallow-water sites	Very high in deep-water regions

offshore wind technologies across key technical, operational, and economic dimensions. The table highlights how increasing deployment depth is accompanied by rising technical complexity, capital investment, and operational cost share, while also offering access to higher-quality wind resources.

Onshore wind systems operate entirely on land and therefore avoid marine-related engineering challenges. Their relatively low CAPEX, typically ranging from 1.2 to 1.8 MUSD/MW, reflects simple foundation requirements, conventional installation methods, and well-established supply chains. Q&M costs account for only 10%–20% of the overall LCOE due to easy site accessibility and mature maintenance practices [169]. However, onshore wind is constrained by moderate wind resources, higher turbulence intensity, grid congestion in high-penetration regions, and increasing social acceptance challenges, which limit large-scale expansion despite its economic advantage [170]. Fixed-bottom offshore wind occupies an intermediate position in Table 6, both technically and economically. These systems are typically deployed in water depths between 5 and 60 m and benefit from stronger and more consistent wind resources than onshore installations [171]. Capital costs increase significantly to ~2.5–4.5 MUSD/MW, primarily due to marine foundation fabrication, offshore installation vessels, and export cable infrastructure. Q&M costs account for around 20%–30% of LCOE, reflecting weather-dependent access and higher logistical complexity. Although fixed-bottom offshore wind is commercially mature, its scalability is limited by seabed conditions and water depth, restricting deployment in regions with steep continental shelves [172]. Floating offshore wind represents the most technically advanced and cost-intensive technology in Table 6. These systems operate in deep waters, typically beyond 60 m and extending to depths of several 100 m, enabling access to vast and high-quality wind resources. As shown in the table, floating wind currently exhibits the highest CAPEX, ranging from 4.0 to 7.5 MUSD/MW, driven by floating platform fabrication, mooring systems, dynamic subsea cables, and higher financing risk. Q&M costs also represent a larger share of LCOE (25%–35%), reflecting complex offshore conditions and limited operational experience. Despite these challenges, floating offshore wind offers exceptional scalability potential and reduced land-use and visual impacts, positioning it as a critical technology for long-term offshore wind expansion [173].

The discussion interprets the comparative findings presented in Section 3 by examining the underlying drivers of techno-economic performance, environmental trade-offs, and socio-regulatory constraints across onshore, fixed-bottom offshore, and floating offshore wind technologies. Rather than reiterating descriptive characteristics, the focus is placed on why observed differences arise, how they influence deployment decisions, and what they imply for future wind energy strategies.

4.5 | Interpreting Technology Maturity and Design Trade-Offs

The clear stratification in technology readiness among the three wind systems reflects the cumulative effects of deployment scale, supply-chain standardization, and operational experience. Onshore wind has reached full commercial maturity (TRL 9) due to decades of iterative optimization, enabling incremental efficiency gains rather than disruptive cost reductions [30]. As a result, further improvements are expected to be evolutionary, driven primarily by digitalization, predictive maintenance, and selective repowering rather than radical design changes. Fixed-bottom offshore wind occupies an intermediate position where turbine technology is mature, but foundation and installation practices remain partially site-specific [174]. Although the turbines themselves share many design principles with onshore systems, the offshore environment introduces structural, logistical, and operational complexities that prevent full cost convergence. The increasing use of larger monopiles and jacket foundations illustrates a shift toward standardization; however, this trend is constrained by vessel availability and water-depth limitations. Floating offshore wind represents a fundamentally different development trajectory. While the turbine subsystem has reached commercial maturity, the overall system remains limited by the readiness of floating platforms and mooring solutions. This decoupling explains why floating wind exhibits lower system-level maturity despite using turbines comparable in size to fixed-bottom offshore installations [101].

The discussion thus reinforces that technology maturity in wind energy should be assessed at the system level rather than at the component level, particularly for emerging offshore configurations.

4.6 | Economic Drivers of LCOE Differences

The observed divergence in LCOE across wind technologies is primarily driven by capital cost composition rather than energy conversion efficiency. Onshore wind benefits from high turbine cost shares and comparatively low balance-of-plant expenditures, enabling LCOE values in the range of 30–55 USD/MWh under favorable wind conditions [175]. In contrast, fixed-bottom offshore wind exhibits higher LCOE due to the disproportionate influence of foundation fabrication, offshore installation, and grid connection costs. Even as turbine ratings increase and capacity factors improve, these non-turbine costs limit the pace of cost reduction. The results indicate that further LCOE reductions in fixed-bottom offshore wind are increasingly dependent on logistical optimization and serial installation methods rather than turbine scaling alone [176]. Floating offshore wind displays the highest LCOE values, typically exceeding 90 USD/MWh, despite access to superior wind resources. This apparent paradox is resolved by examining CAPEX structure: platform and mooring systems dominate total costs, while turbine costs represent a smaller share compared to other technologies. Consequently, improvements in aerodynamic efficiency or rotor size have limited impact on overall economics. Instead, platform standardization, modular fabrication, and learning-by-doing across multiple projects emerge as the dominant cost-reduction mechanisms. This finding redirects attention away from turbine-centric optimization and toward offshore civil and marine engineering innovation [177].

4.7 | Environmental Trade-Offs Across Deployment Contexts

Environmental performance across wind technologies is characterized by a shift in impact type rather than magnitude. All three systems demonstrate low lifecycle greenhouse gas emissions, with differences largely attributable to material intensity and installation processes [178]. Onshore wind exhibits the lowest lifecycle emissions but faces increasing land-use and visual constraints in densely populated regions [179]. Fixed-bottom offshore wind transfers environmental interaction from terrestrial to marine ecosystems. While seabed disturbance and construction noise pose localized ecological risks, these impacts are largely confined to installation phases and can be mitigated through regulatory controls and technological measures [125]. Importantly, the operational phase of offshore wind introduces minimal ongoing emissions or pollution. Floating offshore wind alters the environmental balance further by minimizing continuous seabed disturbance. However, the introduction of dynamic mooring systems and longer subsea cables introduces new environmental uncertainties that are not yet fully captured in lifecycle assessments. This suggests that environmental evaluation frameworks developed for fixed-bottom offshore wind may not be directly transferable to floating systems, highlighting the need for technology-specific impact metrics as deployment scales [180].

4.8 | Social Acceptance and Regulatory Constraints as Economic Factors

The analysis confirms that social and regulatory factors increasingly function as implicit economic constraints rather than external considerations [181]. Onshore wind faces growing public resistance in several regions, translating into longer permitting timelines, increased litigation risk, and higher development costs. These social constraints partially offset onshore wind's inherent cost advantage and limit its expansion potential in mature markets. Fixed-bottom offshore wind experiences fewer social acceptance issues but is subject to complex regulatory environments involving marine spatial planning, environmental impact assessments, and cross-jurisdictional grid connections [182]. Regulatory delays in offshore projects directly affect financing costs, as extended development periods increase exposure to market and policy uncertainty. Floating offshore wind currently benefits from reduced public opposition due to its distance from shore; however, this advantage is counterbalanced by regulatory immaturity. In many jurisdictions, permitting frameworks for floating platforms, deep-water leasing, and dynamic cabling remain underdeveloped [183]. The resulting uncertainty elevates investment risk premiums and contributes to higher LCOE. These findings indicate that regulatory clarity may be as influential as technological progress in determining the commercial viability of floating offshore wind.

4.9 | Implications for Deployment Strategy and Policy

The comparative findings suggest that no single wind technology represents a universally optimal solution. Instead, deployment strategies should be context-specific and aligned with regional constraints [184]. Onshore wind remains the most cost-effective option where land availability and social acceptance permit. Fixed-bottom offshore wind is best suited to regions with shallow continental shelves and strong grid infrastructure. Floating offshore wind is strategically relevant for deep-water regions with limited onshore or shallow offshore potential. From a policy perspective, the results underscore the importance of aligning support mechanisms with dominant cost drivers. Continued subsidies for turbine innovation alone are unlikely to accelerate floating offshore wind competitiveness [185]. Instead, targeted support for platform industrialization, port infrastructure, and standardized permitting processes is likely to yield greater system-level cost reductions. Policymakers should therefore view floating offshore wind not as an extension of offshore wind policy, but as a distinct infrastructure-intensive energy system requiring tailored regulatory frameworks [186].

4.10 | Limitations and Outlook

While this study provides a harmonized comparison of wind technologies using recent data, it remains constrained by variability in regional cost structures and evolving market conditions [187]. LCOE values are sensitive to financing assumptions, capacity factors, and regulatory environments, which may differ across regions. Nonetheless, the consistent application of identical evaluation criteria enables robust relative comparison and supports generalizable insights. Looking forward, the findings suggest that floating offshore wind should be evaluated through a long-term transition lens [188]. Its current economic disadvantage does not reflect fundamental performance limitations but rather early-stage system integration challenges. As platform standardization and regulatory clarity improve, floating offshore wind is likely to transition from a niche solution to a central component of offshore wind expansion in deep-water regions [189].

5 | Conclusion

This study presents a structured and balanced comparison of onshore, fixed-bottom offshore, and floating offshore wind energy systems using harmonized technical, economic, environmental, and socio-regulatory criteria. Rather than introducing new wind technologies, the contribution lies in clarifying trade-offs that are often fragmented across technology-specific studies. The analysis confirms that onshore wind remains the most cost-competitive option, with mature supply chains and low capital intensity yielding LCOE values typically below 55 USD/MWh. Fixed-bottom offshore winds enables access to superior wind resources and higher capacity factors but incurs higher costs driven primarily by foundations, installation, and grid connection requirements. Floating offshore wind extends wind deployment into deep-water regions and minimizes seabed disturbance; however, it currently exhibits the highest LCOE, largely due to platform fabrication, mooring systems, and regulatory uncertainty rather than limitations in turbine performance. Environmental impacts differ in nature rather than magnitude across technologies. All systems demonstrate low lifecycle greenhouse gas emissions, while site-specific land-use or marine ecological considerations dominate local impacts. Social acceptance and regulatory frameworks increasingly act as binding constraints, influencing permitting timelines, financing costs, and ultimately deployment feasibility. Overall, the findings indicate that future wind energy expansion will rely on a portfolio approach rather than a single dominant technology. Incremental improvements are expected for onshore and fixed-bottom offshore wind, whereas floating offshore wind competitiveness will depend on platform standardization, supply-chain learning, and regulatory harmonization. These insights support more informed technology selection and policy design tailored to regional geographic, social, and institutional conditions.

Author Contributions

Conceptualization, investigation, methodology, software, supervision, validation, writing – original draft preparation: Mohsin Ali Koondhar. Conceptualization, methodology, software, validation, writing – original draft preparation: Samandar Khan Afridi and Theyab R. Alsenani. Investigation, methodology, validation, writing – review & editing: Ibrahim Mahariq and Ezzeddine Touti. Methodology, software, project administration, validation, writing – review & editing: Hamed Zeinoddini-Meymand and Farhad Shahnia.

Acknowledgments

The authors extend their appreciation to the Northern Border University, Saudi Arabia for supporting this work through project number "NBU-CRP-2026–2448."

Funding

No funding was received for this research.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. S. Wang, C. Zheng, T. Ma, et al., "Tooth Backlash Inspired Comb-Shaped Single-Electrode Triboelectric Nanogenerator for Self-Powered Condition Monitoring of Gear Transmission," *Nano Energy* 123 (2024): 109429.

2. K. R. Abbasi, M. Shahbaz, J. Zhang, M. Irfan, and R. Alvarado, "Analyze the Environmental Sustainability Factors of China: The Role of Fossil Fuel Energy and Renewable Energy," *Renewable Energy* 187 (2022): 390–402.

3. C. Zhang, M. Liu, Z. Liu, et al., "A Multiple Model Type-3 Fuzzy Control for Offshore Wind Turbines Using the Active Rotary Inertia Driver (ARID)," *Ocean Engineering* 313 (2024): 119337.

4. L. Liu, Z. Li, H. Kang, et al., "Review of Surrogate Model Assisted Multi-Objective Design Optimization of Electrical Machines: New Opportunities and Challenges," *Renewable and Sustainable Energy Reviews* 215 (2025): 115609.

5. A. S. Darwish and R. Al-Dabbagh, "Wind Energy State of the Art: Present and Future Technology Advancements," *Renewable Energy and Environmental Sustainability* 5 (2020): 7.

6. N. Bento and M. Fontes, "Emergence of Floating Offshore Wind Energy: Technology and Industry," *Renewable and Sustainable Energy Reviews* 99 (2019): 66–82.

7. D. Rowell, B. Jenkins, J. Carroll, and D. McMillan, "How Does the Accessibility of Floating Wind Farm Sites Compare to Existing Fixed Bottom Sites?" *Energies* 15, no. 23 (2022): 8946.

8. Z. Zeng and S. M. Goetz, "A General Modeling and Analysis of Impacts of Unbalanced Inductance on PWM Schemes for Two-Parallel Interleaved Power Converters," *IEEE Transactions on Power Electronics* 39, no. 10 (2024): 12235–12248.

9. S. K. Afridi, M. A. Koondhar, M. I. Jamali, et al., "Winds of Progress: An In-Depth Exploration of Offshore, Floating, and Onshore Wind Turbines as Cornerstones for Sustainable Energy Generation and Environmental Stewardship," *IEEE Access* 12 (2024): 66147–66166.

10. M. Arshad and B. O'Kelly, "Global Status of Wind Power Generation: Theory, Practice, and Challenges," *International Journal of Green Energy* 16, no. 14 (2019): 1073–1090.

11. Y. Liu, H. Yao, P. Di, et al., "Region of Attraction Estimation for Power Systems With Multiple Integrated DFIG-Based Wind Turbines," *IEEE Transactions on Sustainable Energy* 16, no. 4 (2025): 3095–3109.

12. R. J. Barthelmie and S. C. Pryor, "Climate Change Mitigation Potential of Wind Energy," *Climate* 9, no. 9 (2021): 136.

13. C. Li, J. M. Mogollón, A. Tukker, and B. Steubing, "Environmental Impacts of Global Offshore Wind Energy Development Until 2040," *Environmental Science & Technology* 56, no. 16 (2022): 11567–11577.

14. J. Meyers, et al., "Wind Farm Flow Control: Prospects and Challenges," *Wind Energy Science Discussions* 2022 (2022): 1–56.

15. Q. Meng, Y. He, S. Hussain, J. Lu, and J. M. Guerrero, "Day-Ahead Economic Dispatch of Wind-Integrated Microgrids Using Coordinated Energy Storage and Hybrid Demand Response Strategies," *Scientific Reports* 15, no. 1 (2025): 26579.

16. A. A. Firoozi, F. Hejazi, and A. A. Firoozi, "Advancing Wind Energy Efficiency: A Systematic Review of Aerodynamic Optimization in Wind Turbine Blade Design," *Energies* 17, no. 12 (2024): 2919.

17. U. K. Patel, N. Alom, and U. K. Saha, "Lift-Based Offshore Vertical-Axis Wind Turbines for Power Generation: Current Status of Technology and Future Direction of Numerical Research," *Wind Engineering* 49, no. 3 (2025): 782–809.

18. D. K. Rajak, P. H. Wagh, and E. Linul, "Manufacturing Technologies of Carbon/Glass Fiber-Reinforced Polymer Composites and Their Properties: A Review," *Polymers* 13, no. 21 (2021): 3721.

19. Q. Meng, Y. He, S. Hussain, J. Lu, and J. M. Guerrero, "Low Carbon Optimization for Wind Integrated Power Systems With Carbon Capture and Energy Storage Under Carbon Pricing," *Scientific Reports* 15, no. 1 (2025): 32714.

20. G. Malliotakis, P. Alevras, and C. Baniotopoulos, "Recent Advances in Vibration Control Methods for Wind Turbine Towers," *Energies* 14, no. 22 (2021): 7536.

21. H. Zhang, H. Wang, X. Zhou, J. Hu, and B. Zhou, "Numerical Investigation of a Three-Dimensional Integrated System Combining an Inertial Built-in Wave Energy Converter Array and a Floating Breakwater," *Energy* 326 (2025): 136102.

22. A. Bensalah, G. Barakat, and Y. Amara, "Electrical Generators for Large Wind Turbine: Trends and Challenges," *Energies* 15, no. 18 (2022): 6700.

23. S. Yan, L. Meegahapola, Y. Yang, and F. Blaabjerg, "Grid-Supporting Renewable Energy Systems With Power Electronics Interfaces," *IEEE Open Journal of Power Electronics* 6 (2025): 1609–1640.

24. W. Gao, K. Xiahou, Y. Liu, et al., "Transient Frequency-Voltage Support Strategy for VSC-MTDC Integrated Offshore Wind Farms Based on Perturbation Observer and Funnel Control," *IEEE Transactions on Sustainable Energy* 16, no. 3 (2025): 1931–1943.

25. J. Yang, L. Fang, D. Song, et al., "Review of Control Strategy of Large Horizontal-Axis Wind Turbines Yaw System," *Wind Energy* 24, no. 2 (2021): 97–115.

26. S. Spyridonidou and D. G. Vagiona, "Systematic Review of Site-Selection Processes in Onshore and Offshore Wind Energy Research," *Energies* 13, no. 22 (2020): 5906.

27. Y. Jing, J. Zhang, L. Su, et al., "A Novel Modular DC Chopper Based on Combination of Fully and Semi-Controlled Devices for Offshore Wind VSC-HVDC Transmission System," *IEEE Transactions on Power Electronics* 41 (2025): 1282–1296.

28. F. Papi and A. Bianchini, "Technical Challenges in Floating Offshore Wind Turbine Upscaling: A Critical Analysis Based on the NREL 5 MW and IEA 15 MW Reference Turbines," *Renewable and Sustainable Energy Reviews* 162 (2022): 112489.

29. S. Wang, Z. Zhang, C. Sun, et al., "Multifunctional Tribovoltaic Coating for Self-Powered in Situ Sensing With Exceptional Tribological Robustness and Charge Transport," *Advanced Functional Materials* 36, no. 8 (2025): e14190.

30. S. Bhattacharya, D. Lombardi, S. Amani, et al., "Physical Modelling of Offshore Wind Turbine Foundations for TRL (Technology Readiness Level) Studies," *Journal of Marine Science and Engineering* 9, no. 6 (2021): 589.

31. A. Wan, C. Du, K. AL-Bukhaiti, and P. Chen, "Optimizing Combined-Cycle Power Plant Operations Using an LSTM-Attention Hybrid Model for Load Forecasting," *Journal of Mechanical Science and Technology* 39, no. 10 (2025): 6371–6380.

32. A. Elkodama, A. Ismaiel, A. Abdellatif, S. Shaaban, S. Yoshida, and M. A. Rushdi, "Control Methods for Horizontal Axis Wind Turbines (HAWT): State-of-the-Art Review," *Energies* 16, no. 17 (2023): 6394.

33. L. Liu, H.-W. Tai, T. Wang, L. Qiao, and K.-T. Cheng, "Analyzing Cost Impacts Across the Entire Process of Prefabricated Building Components From Design to Application," *Scientific Reports* 15, no. 1 (2025): 9300.

34. A. Wan, H. Zhang, T. Chen, K. AL-Bukhaiti, and W. Wang, "A Hybrid Deep Learning Model for Robust Aeroengine Remaining Useful Life Prediction," *Signal, Image and Video Processing* 19, no. 7 (2025): 550.

35. M. N. Zakir, A. R. Abasin, A. S. Irshad, S. Elias, A. Yona, and T. Senjyu, "Practical Wind Turbine Selection: A Multicriterion Decision Analysis for Sustainable Energy Infrastructure," *Practice Periodical on Structural Design and Construction* 29, no. 3 (2024): 04024028.

36. L. Sander, C. Jung, and D. Schindler, "Global Review on Environmental Impacts of Onshore Wind Energy in the Field of Tension Between Human Societies and Natural Systems," *Energies* 17, no. 13 (2024): 3098.

37. R. Wiser, M. Bolinger, and E. Lantz, "Assessing Wind Power Operating Costs in the United States: Results From a Survey of Wind Industry Experts," *Renewable Energy Focus* 30 (2019): 46–57.

38. S. W. Ali, M. Sadiq, Y. Terriche, et al., "Offshore Wind Farm-Grid Integration: A Review on Infrastructure, Challenges, and Grid Solutions," *IEEE Access* 9 (2021): 102811–102827.

39. A. Wan, S. Peng, K. AL-Bukhaiti, Y. Ji, and S. Ma, "The Early Warning Method for Offshore Wind Turbine Gearbox Oil Temperature Based on FSTAE-ATT," *Sustainable Computing: Informatics and Systems* 47 (2025): 101180.

40. Z. Miao, X. Meng, X. Li, and B. Liang, "Influence Weights of Key Parameters and Optimization Strategies for Non-Contact Thermoelectric Generator Performance Enhancement," *Energy* 339 (2025): 139120.

41. Y. Xia, K. Wang, Y. Huang, T. Lin, L. Shi, and F. Wu, "Bounded Rational Decision-Making Modeling and Analysis in Local Energy Markets: A State-of-the-Art Review," *Renewable and Sustainable Energy Reviews* 226 (2026): 116310.

42. H. van Meijl, H. Bartelings, S. van Berkum, H. D. Cui, Z. S. Kristkova, and W. J. van Zeist, "The Russia-Ukraine War Decreases Food Affordability but Could Reduce Global Greenhouse Gas Emissions," *Communications Earth & Environment* 5, no. 1 (2024): 59.

43. Y. Zhou, Z. Han, Q. Zhai, L. Wu, X. Cao, and X. Guan, “A Data-and-Model-Driven Acceleration Approach for Large-Scale Network-Constrained Unit Commitment Problem With Uncertainty,” *IEEE Transactions on Sustainable Energy* 16, no. 4 (2025): 2299–2311.

44. R. Li, P. Cheng, and H. Lan, “Full Analytical Model of AC Copper Losses in Hollow Conductors of High-Speed Electric Motors,” *IEEE Transactions on Transportation Electrification* 11, no. 1 (2025): 1091–1105.

45. R. C. Ramachandran, C. James Desmond, F. Judge, et al., “Floating Offshore Wind Turbines: Installation, Operation, Maintenance and Decommissioning Challenges and Opportunities,” *Wind Energy Science Discussions* 2021 (2021): 1–32.

46. C. Constant, C. Clark, M. Koleva, et al., “Energy Clusters Offshore: A Technology Feasibility Review,” (National Renewable Energy Laboratory (NREL) (2024).

47. S. Bashetty and S. Ozcelik, “Review on Dynamics of Offshore Floating Wind Turbine Platforms,” *Energies* 14, no. 19 (2021): 6026.

48. J. Liang, S. Wu, and T. Lu, “Portfolio Selection and Optimal Planning for Hydrogen Energy Storage Systems Composed of Heterogeneous Electrolyzer and Fuel Cell Technologies in Industrial Park Multi-Energy Systems,” *Applied Energy* 403 (2026): 127001.

49. Y. Yang, G. Yan, G. Mu, and Z. Chen, “Hierarchical Bidding Strategy for Heterogeneous P2H Loads and Wind Power: State-Driven Aggregation and Switching Time Scheduling,” *Energy* 334 (2025): 137766.

50. M. S. Tanvir and A. Etminan, “Comparative Analysis of Offshore and Onshore Wind Turbines: Efficiency, Design, and Environmental Impact,” *Wind Engineering* (2025): 0309524X251386646.

51. A. Bonou, A. Laurent, and S. I. Olsen, “Life Cycle Assessment of Onshore and Offshore Wind Energy-From Theory to Application,” *Applied Energy* 180 (2016): 327–337.

52. S. Fan, Z. Ma, T. Liu, C. Zheng, and H. Wang, “Innovations and Development Trends in Offshore Floating Photovoltaic Systems: A Comprehensive Review,” *Energy Reports* 13 (2025): 1950–1958.

53. S. El-Gharbawy, “Navigating Offshore Wind Technology: From Fixed-Bottom to Floating Systems,” in *Offshore Technology Conference*, (OTC, 2025).

54. F. Manzano-Agugliaro, M. Sánchez-Calero, A. Alcayde, et al., “Wind Turbines Offshore Foundations and Connections to Grid,” *Inventions* 5, no. 1 (2020): 8.

55. L. Huang, “Offshore Wind Turbines,” in *Ocean Renewable Energy Systems: Harnessing Wind, Wave, Tidal, and Solar Power at Sea*, (Springer, 2025): 9–42.

56. M. A. M. Almherigh, “Evaluation of Finite Element Analysis Techiques Applied to a Floating Offshore Wind Turbine,” (University of Salford (2005).

57. T. Shahzad, S. Nawaz, and M. Tabassum, “Renewable Energy Deployment and Guidelines for Responsible AI Adoption,” in *Explainable Artificial Intelligence and Solar Energy Integration*, (IGI Global, 2025): 363–392.

58. F. Du, R. Mo, Z. Guo, J. Wang, Y. Yang, and S. Zhang, “Overview of Wear-Resistant Coatings in Marine Environments,” *Journal of Marine Science and Engineering* 13, no. 11 (2025): 2121.

59. D. Gao, X. Pan, B. Liang, B. Yang, G. Wu, and Z. Wang, “A Review and Design Principle of Fixed-Bottom Foundation Scour Protection Schemes for Offshore Wind Energy,” *Journal of Marine Science and Engineering* 12, no. 4 (2024): 660.

60. M. James and S. Haldar, “Design Strategies of Offshore Wind Turbines in Shallow and Deep Water-Indian Perspective,” *Indian Geotechnical Journal* 54, no. 5 (2024): 1999–2014.

61. S. Bhattacharya and G. Nikitas, “Wind Energy: Status and Outlook With Focus on Offshore Wind,” *Energy and Climate Change* (2025): 197–224.

62. F. X. Correia da Fonseca, L. Amaral, and P. Chainho, “A Decision Support Tool for Long-Term Planning of Marine Operations in Ocean Energy Projects,” *Journal of Marine Science and Engineering* 9, no. 8 (2021): 810.

63. B.-Q. Chen, K. Liu, T. Yu, and R. Li, “Enhancing Reliability in Floating Offshore Wind Turbines Through Digital Twin Technology: A Comprehensive Review,” *Energies* 17, no. 8 (2024): 1964.

64. A. Henderson, M. Collu, and M. Masciola, “Overview of Floating Offshore Wind Technologies,” in *Floating Offshore Wind Energy: The Next Generation of Wind Energy*, (Springer, 2016): 87–132.

65. S. Jalbi, G. Nikitas, S. Bhattacharya, and N. Alexander, “Dynamic Design Considerations for Offshore Wind Turbine Jackets Supported on Multiple Foundations,” *Marine Structures* 67 (2019): 102631.

66. S. Rui, H. Zhang, H. Xu, X. Zha, M. Xu, and K. Shen, “Seabed Structures and Foundations Related to Deep-Sea Resource Development: A Review Based on Design and Research,” *Deep Underground Science and Engineering* 3, no. 2 (2024): 131–148.

67. C. Guo, W. Sheng, D. G. De Silva, and G. Aggidis, “A Review of the Levelized Cost of Wave Energy Based on a Techno-Economic Model,” *Energies* 16, no. 5 (2023): 2144.

68. A. McCoy, et al., “Offshore Wind Market Report,” (2024).

69. B. Salvador-Gutierrez, L. Sanchez-Cortez, M. Hinojosa-Manrique, et al., “Vertical-Axis Wind Turbines in Emerging Energy Applications (1979-2025): Global Trends and Technological Gaps Revealed by a Bibliometric Analysis and Review,” *Energies* 18, no. 14 (2025): 3810.

70. I. Kurt, E. Boulougouris, and D. Pachakis, “Comparative Technical-Economic Evaluation of Offshore Container Port Systems,” *Ships and Offshore Structures* 18, no. 10 (2023): 1367–1379.

71. M. Shields, P. Beiter, J. Nunemaker, A. Cooperman, and P. Duffy, “Impacts of Turbine and Plant Upsizing on the Levelized Cost of Energy for Offshore Wind,” *Applied Energy* 298 (2021): 117189.

72. C. V. Amaechi, A. Reda, H. O. Butler, I. A. Ja’e, and C. An, “Review on Fixed and Floating Offshore Structures. Part I: Types of Platforms With Some Applications,” *Journal of Marine Science and Engineering* 10, no. 8 (2022): 1074.

73. S. Santhakumar, C. Heuberger-Austin, H. Meerman, and A. Faaij, “Technological Learning Potential of Offshore Wind Technology and Underlying Cost Drivers,” *Sustainable Energy Technologies and Assessments* 60 (2023): 103545.

74. J. Bosch, I. Staffell, and A. D. Hawkes, “Global Levelised Cost of Electricity From Offshore Wind,” *Energy* 189 (2019): 116357.

75. A. Ioannou, A. Angus, and F. Brennan, “Parametric CAPEX, OPEX, and LCOE Expressions for Offshore Wind Farms Based on Global Deployment Parameters,” *Energy Sources, Part B: Economics, Planning, and Policy* 13, no. 5 (2018): 281–290.

76. P. Papadopoulos, D. W. Coit, and A. A. Ezzat, “Seizing Opportunity: Maintenance Optimization in Offshore Wind Farms Considering Accessibility, Production, and Crew Dispatch,” *IEEE Transactions on Sustainable Energy* 13, no. 1 (2022): 111–121.

77. F. D. McAuliffe, F. M. Judge, and J. Murphy, “Modelling the Installation of Next Generation Floating Offshore Wind Farms,” *Applied Energy* 374 (2024): 124001.

78. R. K. Samal and M. Tripathy, “A Novel Distance Metric for Evaluating Impact of Wind Integration on Power Systems,” *Renewable Energy* 140 (2019): 722–736.

79. B. Li, P. Wang, P. Sun, R. Meng, J. Zeng, and G. Liu, “A Model for Determining the Optimal Decommissioning Interval of Energy

Equipment Based on the Whole Life Cycle Cost," *Sustainability* 15, no. 6 (2023): 5569.

80. J. McMorland, M. Collu, D. McMillan, and J. Carroll, "Operation and Maintenance for Floating Wind Turbines: A Review," *Renewable and Sustainable Energy Reviews* 163 (2022): 112499.

81. T. Kiunke, N. Gemignani, P. Malheiro, and T. Brudermann, "Key Factors Influencing Onshore Wind Energy Development: A Case Study From the German North Sea Region," *Energy Policy* 165 (2022): 112962.

82. S. H. Qazi, M. D. Kalhoro, D. Bozalakov, and L. Vandevelde, "Transforming Grid Systems for Sustainable Energy Futures: The Role of Energy Storage in Offshore Wind and Floating Solar," *Batteries* 11, no. 6 (2025): 233.

83. C. Thai and J. Brouwer, "Comparative Levelized Cost Analysis of Transmitting Renewable Solar Energy," *Energies* 16, no. 4 (2023): 1880.

84. A. Martinez and G. Iglesias, "Multi-Parameter Analysis and Mapping of the Levelised Cost of Energy From Floating Offshore Wind in the Mediterranean Sea," *Energy Conversion and Management* 243 (2021): 114416.

85. F. Albanito, S. Roberts, A. Shepherd, and A. Hastings, "Quantifying the Land-Based Opportunity Carbon Costs of Onshore Wind Farms," *Journal of Cleaner Production* 363 (2022): 132480.

86. R. Bhandari, B. Kumar, and F. Mayer, "Life Cycle Greenhouse Gas Emission From Wind Farms in Reference to Turbine Sizes and Capacity Factors," *Journal of Cleaner Production* 277 (2020): 123385.

87. T. E. Katzner, D. M. Nelson, A. T. Marques, et al., "Impacts of Onshore Wind Energy Production on Biodiversity," *Nature Reviews Biodiversity* 1, no. 9 (2025): 567–580.

88. L. Huang, *Ocean Renewable Energy Systems: Harnessing Wind, Wave, Tidal, and Solar Power at Sea* (Springer Nature).

89. N. E. Ray, S. Bonaglia, E. L. Cavan, et al., "Biogeochemical Consequences of Marine Fisheries and Aquaculture," *Nature Reviews Earth & Environment* 6, no. 3 (2025): 163–177.

90. L. Huang, "Wave Energy Converters," in *Ocean Renewable Energy Systems: Harnessing Wind, Wave, Tidal, and Solar Power at Sea*, (Springer, 2025): 43–68.

91. M. Glarou, M. Zrust, and J. C. Svendsen, "Using Artificial-Reef Knowledge to Enhance the Ecological Function of Offshore Wind Turbine Foundations: Implications for Fish Abundance and Diversity," *Journal of Marine Science and Engineering* 8, no. 5 (2020): 332.

92. M. Jin, R. Tang, Y. Ji, F. Liu, L. Gao, and D. Huisingh, "Impact of Advanced Manufacturing on Sustainability: An Overview of the Special Volume on Advanced Manufacturing for Sustainability and Low Fossil Carbon Emissions," *Journal of Cleaner Production* 161 (2017): 69–74.

93. K. Xu, J. Chang, W. Zhou, et al., "A Comprehensive Estimate of Life Cycle Greenhouse Gas Emissions From Onshore Wind Energy in China," *Journal of Cleaner Production* 338 (2022): 130683.

94. A. Benitez, C. Wulf, B. Steubing, and J. Geldermann, "Scenario-Based LCA for Assessing the Future Environmental Impacts of Wind Offshore Energy: An Exemplary Analysis for a 9.5-MW Wind Turbine in Germany," *Energy, Sustainability and Society* 14, no. 1 (2024): 49.

95. A. Robertson, W. Musial, M. Shields, A. Aubault, M. Ikari, and L. Kitzing, "Considerations for the Global Commercialization of Floating Offshore Wind Energy," *Nature Reviews Clean Technology* 1, no. 10 (2025): 734–749.

96. M. Kubacka, M. Matczak, M. Kałas, L. Gajewski, and M. Burchacz, "Weather Risk Management in Marine Survey Campaigns for the Offshore Investment Projects in the Polish Exclusive Economic Zone," *Weather, Climate, and Society* 13, no. 4 (2021): 899–911.

97. F. Mao, Y. Yuan, and F. Zhang, "Firm-Level Perception of Uncertainty, Risk Aversion, and Corporate Real Estate Investment: Evidence From China's Listed Firms," *Economic Analysis and Policy* 85 (2025): 1428–1441.

98. T. A. Hansen, E. J. Wilson, J. P. Fitts, et al., "Five Grand Challenges of Offshore Wind Financing in the United States," *Energy Research & Social Science* 107 (2024): 103329.

99. G. Zakhidov, "Economic Indicators: Tools for Analyzing Market Trends and Predicting Future Performance," *International Multidisciplinary Journal of Universal Scientific Prospectives* 2, no. 3 (2024): 23–29.

100. H. Wojtaszek, P. F. Borowski, M. Handschke, et al., "Wind Energy in Transition: Development, SocioEconomic Impacts, and Policy Challenges in Europe," *Energies* 18, no. 11 (2025): 2811.

101. E. Kostecka, T. Miller, I. Durlik, and A. Nerć, "Artificial Intelligence in Floating Offshore Wind Turbines: A Critical Review of Applications in Design, Monitoring, Control, and Digital Twins," *Energies* 18, no. 22 (2025): 5937.

102. Y. Ning, L. Wang, X. Yu, and J. Li, "Recent Development in the Decarbonization of Marine and Offshore Engineering Systems," *Ocean Engineering* 280 (2023): 114883.

103. Y. Wen, J. Wu, P. Lin, and Y. M. Low, "The Role of Offshore Wind and Solar PV Resources in Global Low-Carbon Transition," *Science Advances* 11, no. 43 (2025): eadx5580.

104. N. Gunningham and D. Sinclair, "Regulatory Pluralism: Designing Policy Mixes for Environmental Protection," in *Environmental Law*<, (Routledge, 2019): 463–490.

105. X. Gao, S. Zhou, and T. Luo, "Navigating Wind Energy Siting in the US: The Role of Permitting and Siting Regulations and Public Engagement," *Energy Policy* 205 (2025): 114692.

106. A. S. Santarlacci, H. Angelo, Á. NdeSouza, et al., "Benefit Sharing Governance Framework: Pathways for Financial Benefit Sharing in Traditional Communities," *Sustainability* 16, no. 7 (2024): 2650.

107. X. Guo, X. Chen, X. Chen, P. Sherman, J. Wen, and M. McElroy, "Grid Integration Feasibility and Investment Planning of Offshore Wind Power Under Carbon-Neutral Transition in China," *Nature Communications* 14, no. 1 (2023): 2447.

108. E. Viardot, I. P. Mccarthy, and J. Chen, "Standardization in a Digital and Global World: State-of-the-Art and Future Perspectives," *IEEE Transactions On Engineering Management* 68, no. 1 (2021): 11–17.

109. "Evwind, Wind Energy," (Revee (2022).

110. P. Bórawski, A. Bełdycka-Bórawska, K. J. Jankowski, B. Dubis, and J. W. Dunn, "Development of Wind Energy Market in the European Union," *Renewable Energy* 161 (2020): 691–700.

111. I. Sood, E. Simon, A. Vitsas, B. Blockmans, G. C. Larsen, and J. Meyers, "Comparison of Large Eddy Simulations Against Measurements From the Lillgrund Offshore Wind Farm," *Wind Energy Science* 7, no. 6 (2022): 2469–2489.

112. M. A. Koondhar, L. Albsha, S. A. Mahmoud, L. G. Amin, and I. Mahariq, "Comparative Analysis of Onshore, Offshore, and Floating Wind Turbines for Renewable Energy Systems: A Review," *Ocean Engineering* 343 (2026): 123243.

113. "Fixed Offshore Wind," (Tethys (2022).

114. J. Kaldellis and M. Kapsali, "Shifting Towards Offshore Wind Energy—Recent Activity and Future Development," *Energy Policy* 53 (2013): 136–148.

115. S. Cavazzi and A. Dutton, "An Offshore Wind Energy Geographic Information System (OWE-GIS) for Assessment of the UK's Offshore Wind Energy Potential," *Renewable Energy* 87 (2016): 212–228.

116. H. Díaz and C. Guedes Soares, "Review of the Current Status, Technology and Future Trends of Offshore Wind Farms," *Ocean Engineering* 209 (2020): 107381.

117. M. Durstewitz and B. Lange, "Ja, wie laufen sie denn nun?" in *Meer – Wind – Strom: Forschung am ersten deutschen Offshore-Windpark alpha ventus*, (Springer Fachmedien Wiesbaden, 2016): 165–174.

118. L. Wang, A. Kolios, X. Liu, D. Venetsanos, and R. Cai, "Reliability of Offshore Wind Turbine Support Structures: A State-of-the-Art Review," *Renewable and Sustainable Energy Reviews* 161 (2022): 112250.

119. European Wind Energy Association, "Pure Power-Wind Energy Targets for 2020 and-Ewea," (2011).

120. M. A. Koondhar, L. Albasha, I. Mahariq, B. B. Graba, and E. Touti, "Reviewing Floating Photovoltaic (FPV) Technology for Solar Energy Generation," *Energy Strategy Reviews* 54 (2024): 101449.

121. M. Majidi Nezhad, R. U. Shaik, A. Heydari, A. Razmjoo, N. Arslan, and D. Astiaso Garcia, "A SWOT Analysis for Offshore Wind Energy Assessment Using Remote-Sensing Potential," *Applied Sciences* 10, no. 18 (2020): 6398.

122. X. Sun, D. Huang, and G. Wu, "The Current State of Offshore Wind Energy Technology Development," *Energy* 41, no. 1 (2012): 298–312.

123. Z. Jiang, "Installation of Offshore Wind Turbines: A Technical Review," *Renewable and Sustainable Energy Reviews* 139 (2021): 110576.

124. B. Yang and D. Sun, "Testing, Inspecting and Monitoring Technologies for Wind Turbine Blades: A Survey," *Renewable and Sustainable Energy Reviews* 22 (2013): 515–526.

125. B. Taormina, J. Bald, A. Want, et al., "A Review of Potential Impacts of Submarine Power Cables on the Marine Environment: Knowledge Gaps, Recommendations and Future Directions," *Renewable and Sustainable Energy Reviews* 96 (2018): 380–391.

126. R. Hall, E. Topham, and E. João, "Environmental Impact Assessment for the Decommissioning of Offshore Wind Farms," *Renewable and Sustainable Energy Reviews* 165 (2022): 112580.

127. S. Salvador, L. Gimeno, and F. J. S. Larruga, "The Influence of Regulatory Framework on Environmental Impact Assessment in the Development of Offshore Wind Farms in Spain: Issues, Challenges and Solutions," *Ocean & Coastal Management* 161 (2018): 165–176.

128. Z. Barr, J. Roberts, W. Peplinski, A. West, S. Kramer, and C. Jones, "The Permitting, Licensing and Environmental Compliance Process: Lessons and Experiences Within U.S. Marine Renewable Energy," *Energies* 14, no. 16 (2021): 5048.

129. H. Obane, Y. Nagai, and K. Asano, "Assessing the Potential Areas for Developing Offshore Wind Energy in Japanese Territorial Waters Considering National Zoning and Possible Social Conflicts," *Marine Policy* 129 (2021): 104514.

130. H. Yu, S. Niu, Y. Shang, Z. Shao, Y. Jia, and L. Jian, "Electric Vehicles Integration and Vehicle-to-Grid Operation in Active Distribution Grids: A Comprehensive Review on Power Architectures, Grid Connection Standards and Typical Applications," *Renewable and Sustainable Energy Reviews* 168 (2022): 112812.

131. T. Kurbatova, I. Sotnyk, O. Prokopenko, I. Bashynska, and U. Pysmenna, "Improving the Feed-in Tariff Policy for Renewable Energy Promotion in Ukraine's Households," *Energies* 16, no. 19 (2023): 6773.

132. T. Pauna, J. Lehtinen, J. Kujala, and K. Aaltonen, "The Role of Governmental Stakeholder Engagement in the Sustainability of Industrial Engineering Projects," *International Journal of Managing Projects in Business* 16, no. 8 (2023): 77–99.

133. M. Tsakalerou, D. Efthymiadis, and A. Abilez, "An Intelligent Methodology for the Use of Multi-Criteria Decision Analysis in Impact Assessment: The Case of Real-World Offshore Construction," *Scientific Reports* 12, no. 1 (2022): 15137.

134. K. Sunday and F. Brennan, "A Review of Offshore Wind Monopiles Structural Design Achievements and Challenges," *Ocean Engineering* 235 (2021): 109409.

135. A. W. Adegboyega, E. C. Ani, S. O. Oladunni, and A. S. Pramanik, "Project Management Tools in Renewable Energy Integration: A Review of US Perspectives," *Engineering Science & Technology Journal* 5, no. 7 (2024): 2364–2378.

136. X. Peng, X. Guan, Y. Zeng, and J. Zhang, "Artificial Intelligence-Driven Multi-Energy Optimization: Promoting Green Transition of Rural Energy Planning and Sustainable Energy Economy," *Sustainability* 16, no. 10 (2024): 4111.

137. R. Wada, A. R. Nejad, K. Iijima, et al., "Floating Offshore Wind in Japan: Addressing the Challenges, Efforts, and Research Gaps," *Wind Energy Science Discussions* 2025 (2025): 1–58.

138. D. Stockhouse, M. Phadnis, A. Henry, et al., "A Tutorial on the Control of Floating Offshore Wind Turbines: Stability Challenges and Opportunities for Power Capture," *IEEE Control Systems* 44, no. 5 (2024): 28–57.

139. E. Marino, M. Gkantou, A. Malekjafarian, et al., "Offshore Renewable Energies: Exploring Floating Modular Energy Islands—Materials, Construction Technologies, and Life Cycle Assessment," *Journal of Ocean Engineering and Marine Energy* 11, no. 4 (2025): 1157–1182.

140. Y. Liu, S. Han, and J. Yan, *Offshore Wind Farm Technology* (Springer, 2025).

141. A. I. Manolache and G. Andrei, "A Comprehensive Review of Multi-Use Platforms for Renewable Energy and Aquaculture Integration," *Energies* 17, no. 19 (2024): 4816.

142. B. C. Cerik and L. Huang, "Recent Advances in Mechanical Analysis and Design of Dynamic Power Cables for Floating Offshore Wind Turbines," *Ocean Engineering* 311 (2024): 118810.

143. S. I. Badulin, V. V. Vershinin, D. G. Levchenko, et al., "A Project of Concrete Stabilized Spar Buoy as a Coastal Environmental Observation and Maritime Safety Platform," *Journal of Ocean Engineering and Marine Energy* 7, no. 1 (2021): 115–127.

144. B. Sebastian, D. Karmakar, and M. Rao, "Parametric Study on the Effect of Mooring Configurations on the Dynamic Responses of the Septon Semi-Submersible 5 MW Floating Wind Turbine," *Journal of Ocean Engineering and Marine Energy* (2025): 1–34.

145. S. Gatti, *Project Finance in Theory and Practice: Designing, Structuring, and Financing Private and Public Projects* (Elsevier, 2023).

146. O. Imafidon, T. F. Ediagbonya, and J. P. Nsekanabo, "Hydroelastic Response and Fatigue Life Prediction of Floating Offshore Wind Turbine Platforms Under Complex Sea States," *Ocean Engineering* 341 (2025): 122635.

147. T. Zou, "Technological Innovation Promotes Industrial Upgrading: An Analytical Framework," *Structural Change and Economic Dynamics* 70 (2024): 150–167.

148. L. Sens, U. Neuling, and M. Kaltschmitt, "Capital Expenditure and Levelized Cost of Electricity of Photovoltaic Plants and Wind Turbines–Development by 2050," *Renewable Energy* 185 (2022): 525–537.

149. G. Rubio-Domingo and P. Linares, "The Future Investment Costs of Offshore Wind: An Estimation Based on Auction Results," *Renewable and Sustainable Energy Reviews* 148 (2021): 111324.

150. J. Vetters, G. Thomassen, and S. Van Passel, "Getting Stakeholders Aboard for Offshore Wind Decommissioning: A Qualitative Study on End-of-Life Challenges in Belgium," *Energy Research & Social Science* 120 (2025): 103873.

151. A. Crowle and P. Thies, "Floating Offshore Wind Turbines Port Requirements for Construction," *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment* 236, no. 4 (2022): 1047–1056.

152. A. Turnbull and J. Carroll, "Cost Benefit of Implementing Advanced Monitoring and Predictive Maintenance Strategies for Offshore Wind Farms," *Energies* 14, no. 16 (2021): 4922.

153. M. Revest, "Enabling Renewable Hydrogen Development in Light of the Clean Energy Transition'How Do the Existing EU Legal Framework and State Aid Rules Treat the Investment Dynamics for Renewable Hydrogen Development?" (UiT Norges arktiske universitet (2024).

154. G. M. Meheretu, A. K. Worku, M. T. Yihunie, R. K. Koech, and G. A. Wubetu, "Techno-Economic Analysis of Local Manufacturing of Perovskite Photovoltaic Modules for Electricity Generation in Ethiopia," *Energy Conversion and Management: X* 28 (2025): 101274.

155. C. V. Amaechi, A. Reda, H. O. Butler, I. A. Ja'e, and C. An, "Review on Fixed and Floating Offshore Structures. Part II: Sustainable Design Approaches and Project Management," *Journal of Marine Science and Engineering* 10, no. 7 (2022): 973.

156. H. Díaz and C. Guedes Soares, "Approach for Installation and Logistics of a Floating Offshore Wind Farm," *Journal of Marine Science and Engineering* 11, no. 1 (2023): 53.

157. R. Striani, H. Jiang, M. V. Biroli, Y. Shao, and S. Wang, "Review of Floating Offshore Wind Turbines With Shared Mooring Systems," *Journal of Marine Science and Engineering* 13, no. 12 (2025): 2341.

158. L. Rojas, Á. Peña, and J. Garcia, "AI-Driven Predictive Maintenance in Mining: A Systematic Literature Review on Fault Detection, Digital Twins, and Intelligent Asset Management," *Applied Sciences* 15, no. 6 (2025): 3337.

159. N. Mangat, "Optimal Offshore Wind Turbine Size and Standardisation Study," Tech. Rep (2022).

160. M. V. Chester and B. Allenby, "Toward Adaptive Infrastructure: Flexibility and Agility in a Non-Stationarity Age," *Sustainable and Resilient Infrastructure* 4, no. 4 (2019): 173–191.

161. M. Manolache, A. I. Manolache, and G. Andrei, "Floating Solar Energy Systems: A Review of Economic Feasibility and Cross-Sector Integration With Marine Renewable Energy, Aquaculture and Hydrogen," *Journal of Marine Science and Engineering* 13, no. 8 (2025): 1404.

162. H. C. Havinga, H. A. van der Loos, and M. Steen, "Collaboration or Competition? Interactions Between Floating and Fixed-Bottom Offshore Wind in Norway," *Environmental Innovation and Societal Transitions* 52 (2024): 100872.

163. M. Elkelawy, Z. A. Atta, and H. Seleem, "Technological Advances, Efficiency Optimization, and Challenges in Wind Power Plants: A Comprehensive Review," *Pharos Engineering Science Journal* 1, no. 1 (2024): 57–65.

164. D. Nel and A. Taeihagh, "Tackling the Soft Non-Technical Challenges of the Adoption of Complexity Science in Policymaking," *Policy Sciences* 58, no. 4 (2025): 643–678.

165. L. Luo, Z. Li, Z. Zhou, W. Wang, and W. Wang, "Assessing Suction Bucket Jacket Foundation Installations in the South China Sea: Insights From Field Installation Experiences," *Marine Structures* 96 (2024): 103630.

166. D. J. House, *Cargo Work: for Maritime Operations* (Routledge, 2024).

167. D. C. Makepa and C. H. Chihobo, "Barriers to Commercial Deployment of Biorefineries: A Multi-Faceted Review of Obstacles Across the Innovation Chain," *Heliyon* 10, no. 12 (2024): e32649.

168. L. Pokorny, "The Social Construction of Wind Energy Risk: A Mixed-Methods Analysis of Community Opposition Formation and Information Dynamics in US Offshore Wind Development," (2025).

169. E. Muñoz-Cerón, J. C. Lomas, J. Aguilera, and J. de la Casa, "Influence of Operation and Maintenance Expenditures in the Feasibility of Photovoltaic Projects: The Case of a Tracking Pv Plant in Spain," *Energy Policy* 121 (2018): 506–518.

170. C. Medina, C. R. M. Ana, and G. González, "Transmission Grids to Foster High Penetration of Large-Scale Variable Renewable Energy Sources–A Review of Challenges, Problems, and Solutions," *International Journal of Renewable Energy Research (IJRER)* 12, no. 1 (2022): 146–169.

171. Y. Zhang, D. Zhang, and H. Jiang, "A Review of Offshore Wind and Wave Installations in Some Areas With an Eye Towards Generating Economic Benefits and Offering Commercial Inspiration," *Sustainability* 15, no. 10 (2023): 8429.

172. K. L. Roach, M. A. Lackner, and J. F. Manwell, "A New Methodology for Upscaling Semi-Submersible Platforms for Floating Offshore Wind Turbines," *Wind Energy Science* 8, no. 12 (2023): 1873–1891.

173. A. Alsharif and M. O. Ajaj, "Harnessing Offshore Wind Energy: Challenges and Technological Advancements," *The Open European Journal of Engineering and Scientific Research (OEJESR)* 1 (2025): 12–22.

174. A. Al Mowafy, S. Lotfian, and F. Brennan, "Decommissioning Offshore Wind Fixed Steel Pile Foundations: A Critical Review," *Energies* 17, no. 21 (2024): 5460.

175. G. E. Arnaoutakis, G. Kefala, E. Dakanali, and D. A. Katsaprakakis, "Combined Operation of Wind-Pumped Hydro Storage Plant with a Concentrating Solar Power Plant for Insular Systems: A Case Study for the Island of Rhodes," *Energies* 15, no. 18 (2022): 6822.

176. D. G. Caglayan, D. S. Ryberg, H. Heinrichs, J. Linßen, D. Stolten, and M. Robinius, "The Techno-Economic Potential of Offshore Wind Energy With Optimized Future Turbine Designs in Europe," *Applied Energy* 255 (2019): 113794.

177. J. Mei, G. Zheng, and L. Zhu, "Organizational Learning for Implementing Product Platforms: A Case Study of an Automotive Manufacturer," *Creativity and Innovation Management* 31, no. 4 (2022): 680–695.

178. Y. Feng and L. Zhang, "The GHG Intensities of Wind Power Plants in China From a Life-Cycle Perspective: The Impacts of Geographical Location, Turbine Technology and Management Level," *Sustainability* 15, no. 5 (2023): 4449.

179. K. Xu, H. Zhu, S. Zhang, et al., "Land use Impacts the Environmental Benefits of Wind Energy Farms in China," *Communications Earth & Environment* 6, no. 1 (2025): 905.

180. P. Beiter, et al., *The Cost of Floating Offshore Wind Energy in California Between 2019 and 2032* (National Renewable Energy Lab, 2020).

181. J. Child and T. Tsai, "The Dynamic Between Firms' Environmental Strategies and Institutional Constraints in Emerging Economies: Evidence From China and Taiwan," *Journal of Management Studies* 42, no. 1 (2005): 95–125.

182. M. D. Khan, S. D. Hasil, and N. A. Zahid, "Life-Cycle Reliability of Offshore Wind Turbine Support Structures: Challenges and Opportunities in Repurposed Oil Platforms," *International Journal of Ocean Systems Management* 2, no. 2 (2025): 153–208.

183. C. A. Garrido-Mendoza, "Industrialization Challenges in Floating Wind," in *Large Floating Solutions: Design, Construction, Legality of Offshore Structures and Buoyant Urbanism*, (Springer, 2025): 171–193.

184. P. Lehmann and P. Söderholm, "Can Technology-Specific Deployment Policies Be Cost-Effective? The Case of Renewable Energy Support Schemes," *Environmental and Resource Economics* 71, no. 2 (2018): 475–505.

185. H. Zhu, Z. Du, J. Wu, and Z. Sun, "Innovation Environment and Opportunities of Offshore Wind Turbine Foundations: Insights From a New Patent Analysis Approach," *World Patent Information* 68 (2022): 102092.

186. K. Xu, *Decision-Support Frameworks for MCDA Method Selection and Emission Abatement Technology Assessment in the Maritime Sector* (University of Southampton, 2025).

187. S. Zupok, E. Chomać-Pierzecka, A. Dmowski, S. Dyrka, and A. Hordyj, "A Review of Key Factors Shaping the Development of the US Wind Energy Market in the Context of Contemporary Challenges," *Energies* 18, no. 16 (2025): 4224.

188. R. Fofack-Garcia, C. Mazé, G. Safi, et al., "Socio-Political Acceptability of Floating Offshore Wind Farms in France: Challenges and Perspectives for Marine Governance Towards Sustainability," *Ocean & Coastal Management* 236 (2023): 106513.

189. L. Serri, D. Airoldi, F. Lanni, et al., "Technical and Economic Challenges for Floating Offshore Wind Deployment in Italy and in the Mediterranean Sea," *WIREs Energy and Environment* 13, no. 4 (2024): e533.