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Perspective

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Considerations for the global commercialization of floating offshore wind energy

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Abstract

Floating offshore wind (FOW) has the potential to unlock access to wind resources in deep water where fixed-bottom turbines are not feasible, enabling coastal regions around the world to meet growing energy demands. Although fixed-bottom offshore wind is commercially mature, FOW, which may be needed for water deeper than 60 m, must progress in multiple ways to reach full commercial viability. In this Perspective, we examine the status of the global FOW industry's commercial development across three key areas – technical innovation, industrialization and cross-cutting value. Technical innovation has enabled FOW turbines to perform as well as fixed-bottom turbines, with the promise of future cost reductions. However, the complex architecture of FOW turbines, combining floating structures with more than 8,000 electrical and mechanical parts in wind turbines, requires industrialization efforts such as standardization and supply-chain integration to enable commercial project deployment. FOW can potentially offer unique benefits, including reduced environmental impacts and strengthened economic development in coastal regions, through substantial regional economic activity. Successful coordination across these three areas could help to position FOW as a major contributor to a competitive, reliable and resilient global energy system.

Sections

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Key points

• Floating wind unlocks new opportunities of wind resource utilization worldwide, where ocean depths are too deep for conventional fixed-bottom offshore technology, thus more than doubling the offshore wind energy potential.

• Cost reductions are needed to reach industry maturity, with the potential to be cost-competitive with fixed-bottom offshore wind by the mid-2030s.

• Continued innovation is possible through optimized production processes and risk mitigation, enhanced performance optimization and system reliability.

• Industrialization will likely transition from single-unit production to rapid serial production, by simplifying the design, standardization and modularization of subcomponents, by expanding the supply chain and by developing the infrastructure.

• Reaching gigawatt-scale floating wind projects will likely lower costs, but will involve major investments in ports, vessels, grid connections and industrialization. To incentivize these investments, the industry needs stable technology designs that allow for mass production and longer product lifespans.

• Floating wind can offer cross-cutting societal value, because the wind farms are farther from shore, with fewer community and environmental impacts, as well as higher and more consistent wind resources, better matching of load profiles, increased market values and higher resilience to extreme events.

Introduction

Offshore wind energy is becoming a key part of some national energy portfolios. However, 65–80% of offshore wind resources are located above water depths exceeding 60 m (ref. 1) (Fig. 1a). Although engineering innovations could enable some fixed-bottom offshore wind installations at depths greater than 60 m (ref. 2), floating offshore wind (FOW) technology can unlock areas beyond the reach of fixed-bottom technologies. FOW is at an earlier stage of development compared with fixed-bottom offshore wind, but coastal areas in Europe, the Americas and Asia are launching or operating pilot test projects[2]. To compete with other power sources in terms of cost, value and reliability, FOW necessitates investments on the order of billions of US dollars in infrastructure, technology and supply-chain development[3–5]. International growth in FOW capacity is expected between 2025 and 2029 (Fig. 1b), with a sharp increase in deployment of larger, commercial-scale projects after 2026 (ref. 6). Between 2022 and 2024, FOW has seen a sharp increase in the project pipeline capacity that has advanced to the permitting phase[6].

The competitiveness of FOW in electricity markets depends on technology cost, policy drivers, grid and transmission constraints, and siting constraints as compared with other energy alternatives[7]. Costs are projected to decline substantially over the next decade with the deployment of commercial-scale projects, potentially becoming competitive with fixed-bottom offshore wind by the mid-2030s[8]. Potential benefits from non-price criteria have been modelled and leveraged to support energy policy goals and build public backing[9–11]. These value-adders – including economic growth opportunities and the mitigation of challenges such as extreme weather events, energy price volatility and transmission congestion – require further region-specific analysis, but show strong potential to elevate the strategic value of FOW within global energy systems[12–15].

In this Perspective, we explore three areas – technical innovation, design for industrialization and delivering cross-cutting value – as critical components of FOW's route to industry maturity (Box 1). The technical feasibility of FOW has been demonstrated by the successful deployment of prototypes and pilot-scale projects with capacities of about 50 MW (refs. 16,17) but with high above-market costs[18]. This initial phase has been essential for validating the loads and performance of wind turbines on floating support structures[19], scaling up turbine technology[20] and understanding the challenges of single-turbine deployment logistics[21]. However, the long-term economics of offshore wind energy favour larger projects, and sustained innovation at the over-one-gigawatt scale is necessary to drive meaningful cost reductions[22,23]. Achieving this scale depends on the development of the enabling port, fleet and grid infrastructure[24], and the industrialization of the technology[4,22,25] to decrease cost and shorten development timelines[4,25,26].

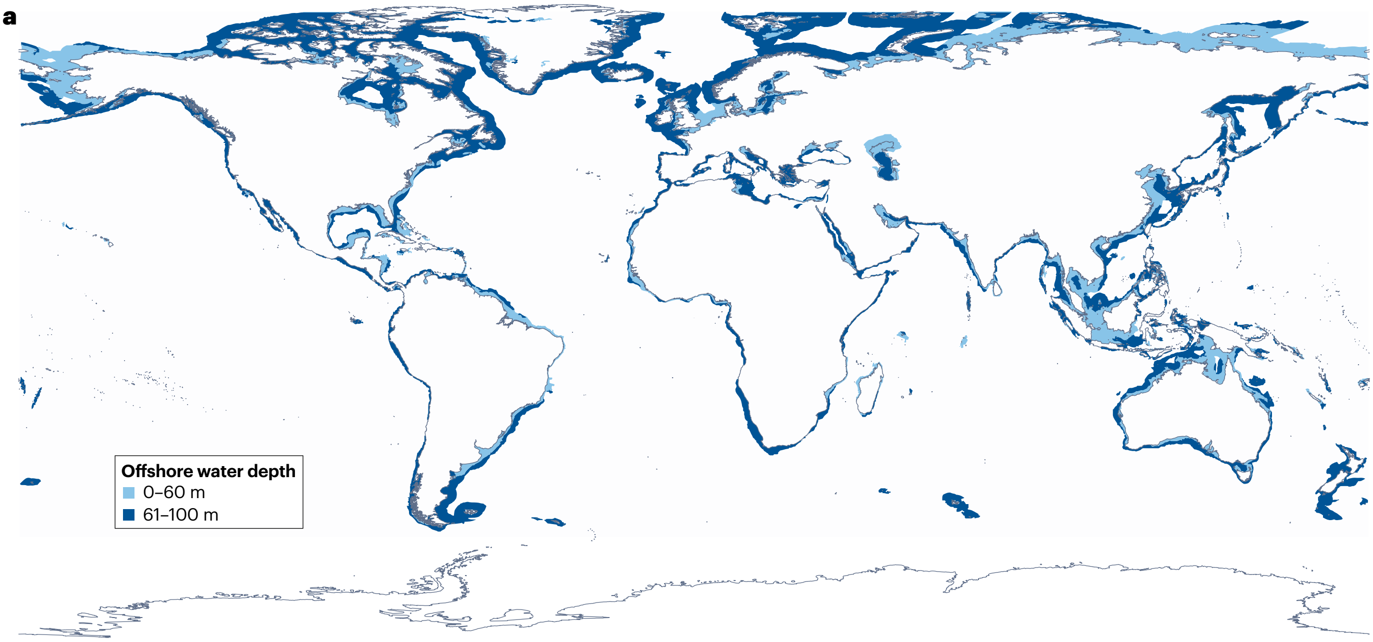
Technical innovation

The FOW industry is not yet mature and sustained technical innovation has the potential to further reduce costs. Until the early 2020s, the focus of innovation was on advancing the necessary design capabilities and demonstrating FOW prototypes to validate both technical feasibility and design accuracy[17,19,27]. As the FOW industry progresses towards commercial-scale projects, the emphasis is likely to shift to optimizing production processes and mitigating risks associated with scaling up turbine technology[20,28]. Once production at scale is achieved, innovation targets could shift towards tackling operational challenges, enhancing performance optimization and system reliability, addressing infrastructure constraints and uncovering additional cost reduction pathways to reach FOW competitiveness.

FOW systems have three conventional archetypes, which are adapted from years of experience in the oil and gas community (Fig. 2). New designs are building on these foundational archetypes to enhance scalability for mass production while driving down the total lifetime costs of each unit[29]. FOW design is inherently complex, shaped by the dynamic interactions between the turbine, the tower, the buoyant floating substructure, the moorings and the control systems. A holistic design approach manages these interactions and overcomes market inertia tied to existing supply chains. For instance, current turbine technologies are primarily developed for fixed-bottom offshore wind applications and are only minimally adapted for floating platforms[30]. Advancing FOW will involve continued development of advanced modelling tools that can capture these system complexities, enabling optimized designs that balance performance and cost.

Integrated designs

Floating wind turbines experience greater dynamic motion and potentially higher loading conditions than fixed-bottom designs[16,31]. As a result, many of the initial floating wind prototypes installed during the 2010s were aimed at validating the performance of wind turbines mounted on floating substructures, as predicted by engineering models. These early prototypes typically featured smaller turbines than those in today's commercial market – ranging from 2 MW to 7 MW (ref. 32). At these smaller scales, wave loads were a primary design a



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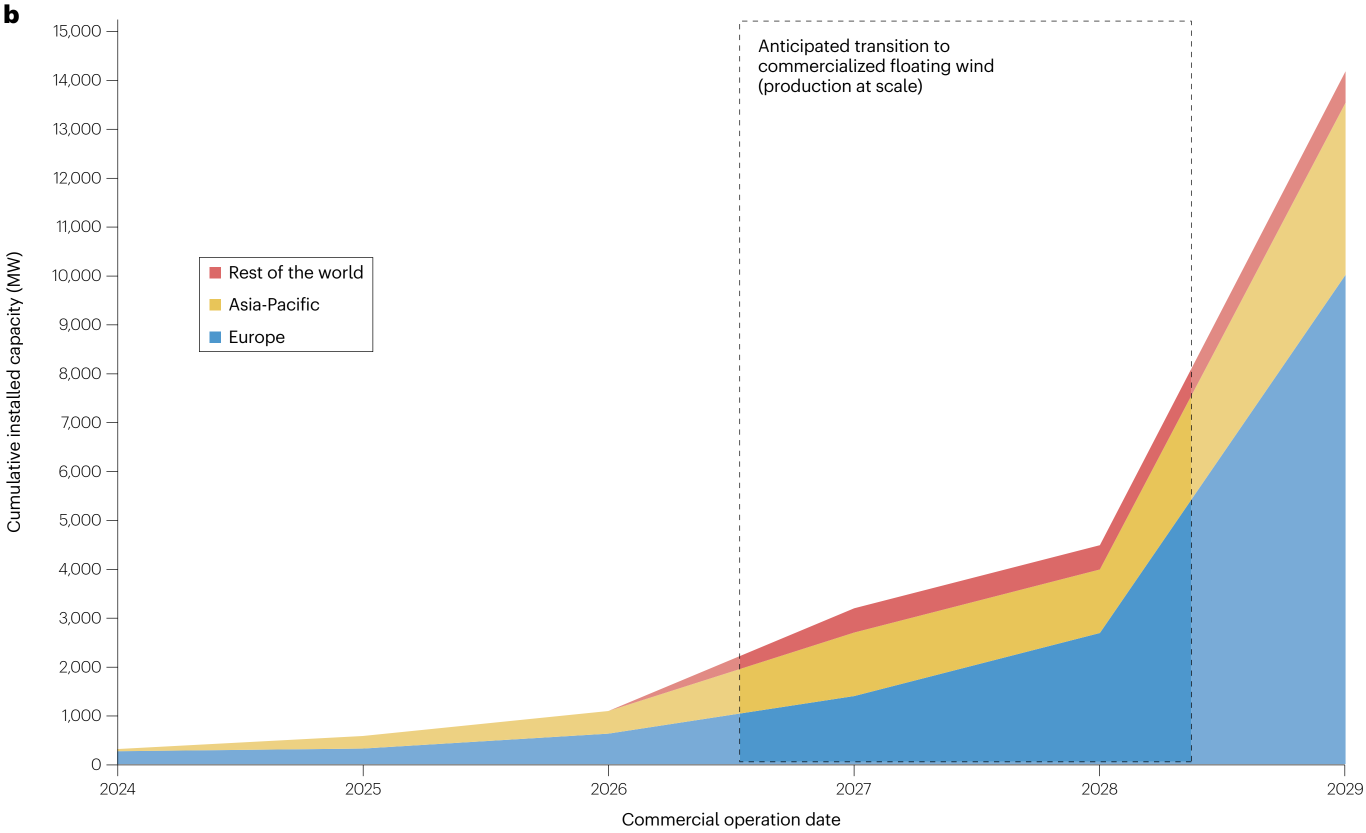
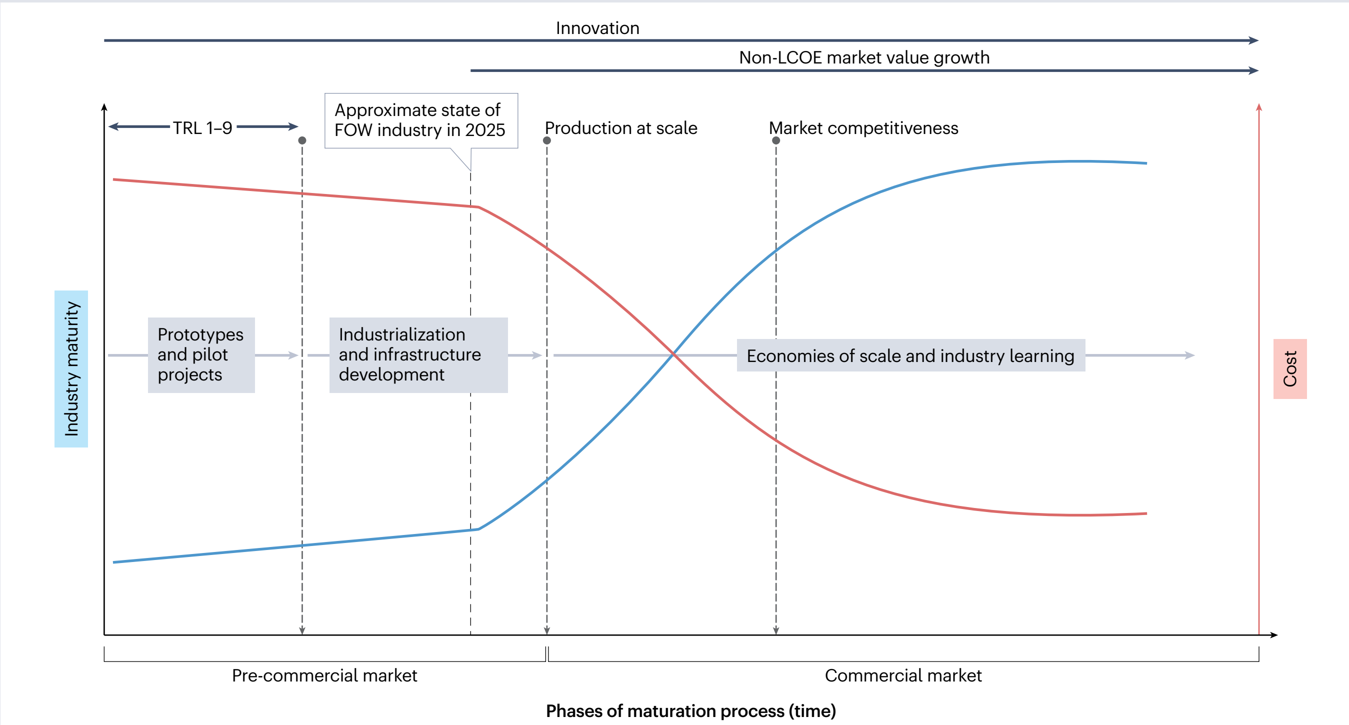


Fig. 1 | Locations of floating offshore wind. a, Distribution of shallow (0–60 m) water depth, where fixed-bottom offshore wind systems can be used, versus deep water (61–1,000 m), where floating wind is expected to be needed. Data are taken from ref. 51. **b**, Estimated cumulative floating offshore wind capacity by location, based on announced commercial operation dates until 2029. MW, megawatts. Data are taken from ref. 6.

Box 1 | Pathway to industry maturity for floating offshore wind

Achieving commercial-scale production for floating offshore wind (FOW) will mark a critical milestone in the industry's path to maturity. For FOW to achieve market competitiveness with other electricity-generating technologies, cost reductions are essential (see the figure) — and these cost reductions hinge on reaching commercial scale. Once achieved, widespread deployment at this scale will drive the industry towards full maturity over time.



LCOE, levelized cost of energy; TRL, technology readiness level.

driver, in contrast to the larger, inertia-dominated systems being developed for commercial-scale deployment[33].

Since about 2023, commercial FOW suppliers have been working with 15-MW turbines, which are planned for operation on fixed-bottom support structures in 2025 (refs. 34,35). Turbine original equipment manufacturers (OEMs) are advancing designs with rotor diameters of at least 260 m, alongside substantially larger nacelle weights and hub heights[36]. Prototypes with a power rating of up to 21.5 MW and a rotor diameter of 276 m are undergoing testing[37], and a turbine with a 310-m rotor and a rated capacity of 25 MW is under active development[38]. Despite this progress, challenges remain in bringing these large turbines into widespread commercial use on floating platforms[37]. Most commercial floating projects are still in the conceptual design phase, with further work needed to optimize designs, de-risk technologies and scale up deployment[39].

Optimized FOW system design involves integration of a wind turbine and a floating substructure; however, in the precommercial phase, the turbine and substructure are often developed independently[40,41]. Integration of these two components usually occurs after designs are established, limiting opportunities for designers to optimize the combined system's response to wind and wave forces. Lack of early collaboration can negatively affect both cost and performance[42]. Conversely, a fully optimized design envisioned during the commercial phase will be collaborative from the start. Collaboration enables management of the complex interactions between turbine and substructure[40]. To accelerate progress towards such an optimized floating wind system, the initial design phase could allow for rapid iterations between the floating substructure designer and the turbine OEMs, ideally fostering a fully integrated design approach from the outset.

In practice, a fully integrated design process requires a degree of commercial success in the industry to incentivize the required collaborations. Early engagement and information exchange between the floating substructure technology teams and turbine OEM teams is key to achieving synergy. Given the substantial resources required to develop new turbines, it is not expected that OEMs will be incentivized to customize turbine designs specifically for floating applications until the market size and market certainty increase[18,43]. In the interim, incremental adaptations of fixed-bottom turbines are helping to unlock performance improvements and cost efficiencies in FOW systems. Given turbine design constraints, most turbine adaptations have been made to the tower and controllers[44,45], and especially to controller features that contribute to the reduction of extreme and fatigue loads[46].

The tower is the structural member that transfers most of the loads between the wind turbine and the floating substructure. In FOW designs (excluding tension-leg substructures), the tower's natural frequency is considerably higher than it is in fixed-bottom wind turbines[47]; it can potentially coalesce with the frequency at which the turbine blades pass the tower (three times per revolution). This can lead to resonance and higher structural loading[41,45].

If the tower's natural frequency is modified by design to be below the blade passing frequency, the FOW turbine is said to operate in a soft–stiff regime. If the tower's natural frequency exceeds the blade passing frequency, it operates in a stiff–stiff regime, which generally requires a heavier, stiffer tower. Smaller turbines that rotate faster typically operate in the soft–stiff regime[48]. As turbines grow larger, their rotational speed and blade passing frequency decrease, making it harder to separate the blade passing excitation from the tower frequency and to maintain the soft–stiff regime. A stiff–stiff design regime could be more advantageous for FOW systems. However, this regime requires early-stage design changes to the tower, which can only be achieved effectively through integrated design processes that consider both the turbine and substructure properties from the outset[40,49].

The turbine control systems, which adjust blade pitch, rotor yaw and generator parameters to optimize performance, have an important role in managing the dynamic response of FOW turbines[50,51]. These control systems must be tuned so that floating substructures can avoid complex issues such as the pitch control feedback amplification caused by apparent wind generated through substructure pitch motion[52]. Floating-specific controls are needed to manage system motion, such as adjusting the rotational speed to avoid resonance with the platform's natural frequency. Although fixed-bottom control systems can be adapted to reduce dynamic loads, these modifications often come at the cost of reduced turbine performance[53,54].

Better integrated control systems that can account for the specific behaviour of a floating platform are envisioned for the commercial phase of FOW. Custom controls come at a relatively low capital cost but can enhance power output and minimize operational loads, for instance, when paired with substructure features like active ballasting[46,55]. Advanced controls can further optimize turbine behaviour during startup and shutdown and under high-stress conditions, reducing fatigue and improving structural efficiency. By making targeted adjustments to control strategies, particularly at low frequencies, fatigue loading can be substantially reduced, thereby increasing overall system reliability[52,56]. Ideally, designing the control system and floating substructure concurrently — a strategy known as control co-design — would maximize load reduction and enable more streamlined, cost-effective floating substructure designs. Realizing the full benefits of control co-design, however, depends on a collaborative and integrated design process between the turbine OEM and the substructure designer[57].

Control strategies at the wind-farm level offer opportunities to improve overall energy production. Because each turbine generates a wake, coordination across turbines can help to maximize total farm output rather than solely focusing on individual turbine performance[58]. A key area of interest is wake steering, in which an upwind turbine is intentionally yawed slightly away from the wind direction to redirect its wake away from downstream turbines, thereby reducing energy losses across the array[59,60]. Farm-level control strategies for floating wind systems will differ because of the platform's compliant motion, potentially increasing the effectiveness of approaches like wake steering. These strategies involve adjusting turbine orientation and leveraging platform movement to further displace wakes and reduce downstream energy losses[61].

Numerical modelling

Offshore wind systems are subject to a complex interplay of forces from wind, waves and currents[62]. Accurately modelling the resulting loads on turbine structures requires the development and application of robust numerical modelling capabilities. For FOW systems, the inherent compliance of the support structure introduces additional degrees of freedom, amplifying the dynamic system coupling and raising concerns about system stability. Gaining a deep physics-based understanding of the interactions between wind, waves and the structural response is critical for making informed design trade-off decisions. However, discrepancies between current engineering design tools and field observations point to the need for improved modelling accuracy. Advanced

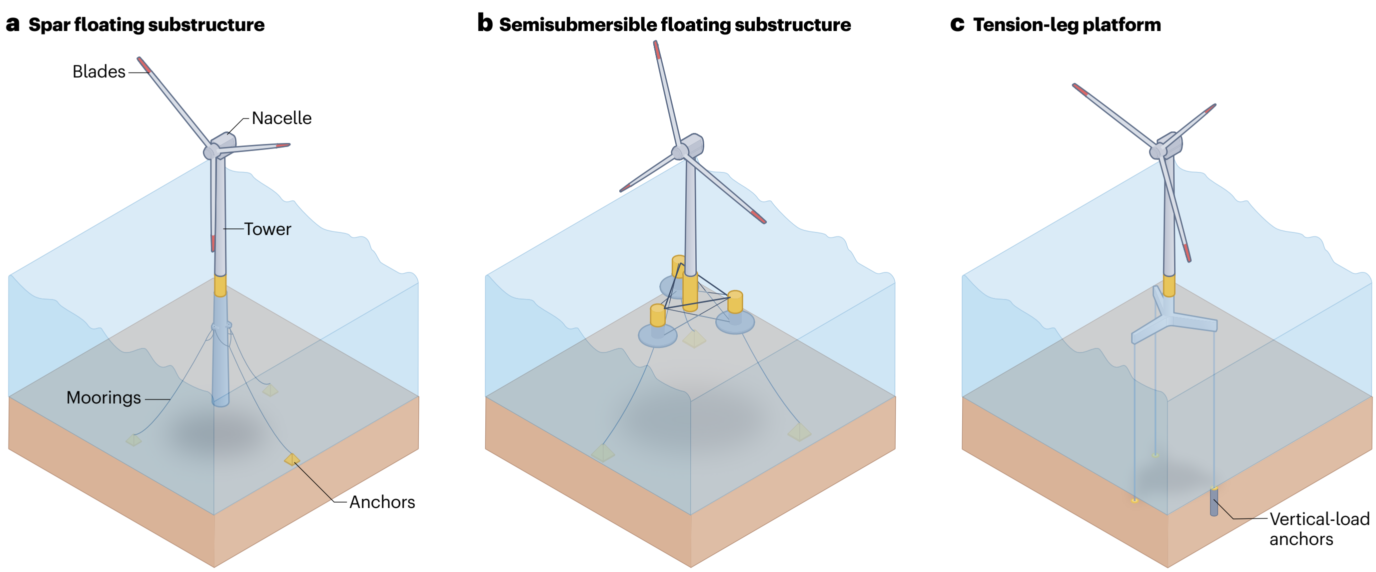


Fig. 2 | Three basic archetypes for floating offshore wind systems derived from the oil and gas industry. a, Spar floating substructure. **b**, Semisubmersible floating substructure. **c**, Tension-leg platform.

simulation tools that can capture intricate, multiscale dynamics are required to bridge the gap and enable design optimization — ultimately reducing costs and improving system reliability across a wide range of operating and extreme conditions[18].

Reducing the cost of FOW calls for modelling and optimization frameworks that balance simulation accuracy with computational efficiency. Multi-fidelity modelling offers one such approach by integrating high- and low-fidelity simulations in one capability for design optimization[63]. High-fidelity models capture the detailed physics and serve as benchmarks, whereas lower-fidelity models enable rapid exploration of design alternatives. Artificial intelligence (AI) and machine learning techniques are valuable tools in this context, offering the ability to develop fast, data-driven surrogate models trained on high-fidelity simulations or field data. These surrogate models can accelerate the iterative design process while retaining the ability to resolve critical system behaviours. A layered, multi-fidelity modelling approach — integrated within a broader optimization framework — allows engineers to refine designs intelligently and systematically, improving reliability and cost-effectiveness while managing the computational burden[63,64].

In practice, turbines operate as part of larger wind farms, collectively generating amounts of power similar to that generated by thermal power plants[65]. In these farm-scale systems, the cost of electricity is based not only on the capital expenditures, but the long-term operations and maintenance (O&M) expenses[66,67]. Numerical modelling plays a key part in both phases: design and O&M. The use of a 'digital twin' — a real-time, virtual model of the wind farm that mirrors the actual physical system — can allow operators to better understand farm behaviour, optimize energy capture and manage load distribution effectively. These models also facilitate condition-based monitoring, reducing the need for costly on-site inspections and supporting predictive maintenance strategies that can prevent costly system failures. Digital twins, especially when coupled with AI modelling, can enhance operational efficiency and lower maintenance costs, contributing to the overall cost reduction and commercial viability of floating wind technology[68].

To ensure the accuracy of these advanced modelling approaches, rigorous validation against empirical data is essential. Initial validation is often conducted through scaled experiments in wind tunnels and wave tanks, but these facilities struggle to accurately replicate the combined effects of wind and waves[52]. The scaling laws that govern wind and wave dynamic behaviour diverge when the scale of the test article is changed, preventing accurate physical subscale representations[69]. Consequently, full-scale validation using data from commercial FOW systems is often necessary to achieve the accurate modelling capabilities that are needed to accelerate industry maturity. This level of validation hinges on industry cooperation — sharing data from field-testing of actual turbines — which can be challenging in a competitive industry. A coordinated validation effort among technology-agnostic government agencies, universities and industrial partners would help the FOW industry to move more rapidly towards the necessary cost reductions and industry maturity[70].

Innovation areas

One of the primary cost drivers for FOW is the weight of the floating substructure[21]. Reducing substructure weight has a compounding effect on overall costs — lower material and manufacturing expenses, reduced loads on the station-keeping systems and less demanding infrastructure requirements for fabrication and installation[71]. Weight reduction is particularly effective for some substructure designs, such as those developing composite- or hybrid-structure platforms to reduce material usage and promoting modular production to shorten the construction period. These design optimization steps may also result in further reductions in the life-cycle carbon footprint for FOW[72,73].

Increasing reliability and minimizing the maintenance needs of floating wind substructures are important for enhancing the overall lifetime value of FOW systems and reducing O&M costs[56]. Future substructure designs could prioritize ease of maintenance and minimize the need for corrective interventions. Innovations in materials, such as those focused on corrosion management, and low-maintenance hull designs will be key areas for advancement. Automated inspection and maintenance solutions using embedded sensors, drones and autonomous underwater vehicles are expected to reduce operational risks, enhance safety and further drive down O&M costs[74]. Increased digitalization would enable the transition to more remote and automated O&M. In addition, developing designs and strategies that allow for efficient in situ component exchange can help to minimize downtime and improve system availability[75].

Station-keeping systems represent another priority area for innovation, particularly in the design and installation of components that are both reliable and easy to maintain. As with floating substructures, mooring components must be designed to be industrialized for mass production. These systems would be versatile and capable of installation in a wide range of water depths, from shallow to ultradeep waters. Furthermore, novel anchor designs would address challenging seabed conditions, such as hard or cemented soils, while minimizing vessel and installation footprints[76].

Effective station-keeping systems for FOW could be designed to protect the subsea power export system, given that the development of reliable offshore high-voltage electric infrastructure is a major factor in achieving utility-scale deployment[77]. Array power cables connect the FOW turbines to a substation, and the export cables relay energy to an onshore substation. This electricity-delivery infrastructure is a mature technology in fixed-bottom offshore wind plants where the cables are static along their entire length, but FOW farms at utility scale might require floating substations[78], which produces the challenge of accommodating the dynamic movements inherent to floating systems while ensuring reliable power flow[22,79]. The FOW solution is expected to entail a co-optimization trade-off to achieve a cost-effective balance between reasonable measures to constrain substation motion and increased cable durability[80,81].

As FOW projects are likely to be sited farther from shore, high-voltage direct current (HVDC) cables and meshed network configurations could be necessary to efficiently transmit energy to reduce losses[80,82]. Wind farms with sector-coupled storage options in the form of electrolyser capacity have been shown by modelling to benefit particularly from the use of HVDC[83]. Developing HVDC backbones that link multiple floating wind farms could further drive down costs, making them pivotal to overcoming barriers to utility-scale deployment of floating wind technology[21].

De-risking new designs ensures bankability and lowers the financial costs of development. The adoption readiness level framework is an example of a tool focused on establishing a path to commercializing technological innovation[84]. As of 2024, the industry has built 287 MW of floating wind capacity[6] with prototypes and precommercial pilot projects, comprising archetypal designs such as semisubmersibles[19] and spars[17], as well as more novel hybrid spar designs like the Tetraspar and the Wheel floating substructures. Beyond technological innovation, the rapid and safe adoption of promising technologies requires a supportive framework that ensures that the most cost-effective solutions can be considered for commercialization without compromising the industry's high standards for reliability and safety[85]. Demonstrating these innovations and their effectiveness through field experience will help FOW become as competitive as possible for global energy needs.

Design for industrialization

Once the global FOW industry achieves commercial scale, deployment at this larger scale is expected to enable cost reductions through industry learning and economies of scale that exploit that growth. With field experience, increases in reliability and lower costs can be achieved through greater design efficiencies and volume production (Box 1). Accelerating production rates for commercial-scale deployment are likely to involve supply chains and supporting infrastructure to transition from single-unit production to rapid serial production. This industrialization involves the integration, simplification and regionalization of custom prototype designs and automation of their manufacturing, assembly and installation for the major components[25,26,28].

Standardization has an important role in the industrialization process by establishing uniformity and modularization across components and subcomponents, simplifying the design and expanding the supply chain's potential vendor base. However, it would be beneficial to balance standardization to avoid stifling technological innovation, as FOW technology is still at a nascent stage[2,25,26]. Although all components of FOW will benefit from industrialization, this Perspective article focuses on the two largest components: the turbines and the floating substructures.

Major component manufacturing and assembly

Turbine technology has achieved a more mature level of industrialization than floating substructures because the same turbine models are shared by both fixed-bottom and floating wind applications. The fixed-bottom wind sector has widely deployed 15-MW turbines, and these have achieved lower costs in competitive auctions[36,86]; 15-MW turbines require fewer units per project to meet energy targets than their lower-rated predecessors, but rapid upscaling over the past few years could have temporarily slowed some aspects of industry learning while the larger manufacturing facilities were being built and retooled[20,87]. By comparison, USA-land-based wind reached substantial cost reductions through a decade of steady production of 2-MW turbines starting around 2008, achieving a 63% cost reduction over 13 years[28,88]. OEMs have acknowledged the challenging trade-offs between turbine upscaling and technology maturity, with some advocating for a temporary halt on upscaling to allow the technology to mature and stabilize[89].

Manufacturing processes for floating substructures are at an early stage in 2025, as production has been limited to small demonstration projects[6]. Consequently, there is considerable potential to improve efficiency through the development of more streamlined, scalable production methods. The complexity of industrializing floating substructure manufacturing has increased because of the large number of substructure designs competing for the available floating wind infrastructure[90]. The current precommercial one-off manufacturing methods must be adapted to serial manufacturing methods to establish serial production lines for the most promising designs. This will require large supply-chain investments and design modifications to facilitate industrialization.

Modularization of floating substructure subcomponents can facilitate the on-site assembly of the floating substructures and turbines. Modular designs allow construction operations to take place closer to project sites and enable greater diversity and competition in the supply chain. To address the anticipated shortage of skilled welders, some substructure designs could favour bolted or pinned fastener systems, while others could explore welding robots at the assembly location[26,91]. Industrialization must also extend to the final offshore assembly, including anchors, mooring lines, electrical cables and connections to the floating substructure, creating a comprehensive framework for efficient, large-scale production and deployment of FOW farms.

Floating substructure material drivers

Both concrete and steel are being considered as the base materials for floating substructures, the heaviest and most costly part of the FOW turbine system. The choice of substructure materials could have broad implications for the pace of industrialization and commercialization, driving full-system design, the life-cycle cost of energy, infrastructure requirements and regional economic development[24,26].

Concrete substructures can be up to five times heavier than steel structures for the same turbine size, and because concrete needs several weeks to cure before assembly and load-out, more inshore storage space is needed to hold multiple units[26]. Consequently, the port area capacity requirements at the fabrication sites for concrete substructures are much greater than for steel substructures. Fabrication facilities do not need to be co-located at staging and installation ports (S&I ports), which means that steel hulls additionally benefit from the pre-existing worldwide supply chain of modular steel units[92].

Although concrete structures are heavier and require more material than steel structures, the unit price of concrete is much less than the unit price of the imported plate steel needed for steel substructures[93]. One solution under investigation to reduce infrastructure cost and speed up production includes fabricating concrete substructures in the water on submersible platforms to eliminate the need for dry-land transport and storage[25]. Other possible advances aim to accelerate concrete-curing times, which could streamline production and reduce the inshore storage footprint[93,94]. Another innovation is the use of lightweight aggregates that can reduce concrete density by as much as 50% without any loss of strength but at some additional cost and higher porosity[94,95]. However, more analysis is needed to determine the scalability of the supply chain for these raw materials for offshore grade concrete near prospective floating offshore wind sites.

A large fraction of the weight in a concrete substructure is the reinforcement steel, or rebar, that is needed to carry the tensile loads. Rebar-reinforced concrete is often used by the construction industry and can usually be sourced locally which might make it attractive from the perspective of increased job creation, energy security and decreased supply-chain risk[94]. In general, more analysis and demonstration is needed to determine cost and value chain trade-offs between concrete and steel, as rapidly evolving design innovations (outlined above) could disrupt conventional industrialization strategies.

Standardization

With roughly 8,000 mechanical and electrical parts per turbine, wind energy systems are inherently complex[96]. Standardization of certain components and subcomponents can simplify designs, create consistency, increase mass production and broaden the vendor base, as is already the case in onshore wind. This in turn can lower costs and increase the reliability. One example is in the solar photovoltaic industry, in which a learning rate of 20% in the production of silicon-based solar panels resulted in an 80% reduction in utility-scale life-cycle cost between 2010 and 2024 (refs. 97,98). Although the lower solar project life-cycle cost is largely attributable to lower-cost panels, the exponential growth of the solar industry since 2010 has also driven lower operating expenses and increased project design life[97,98]. Wind turbines are more complex than solar panels, but benefit from the accumulated experience standardizing onshore and offshore fixed-bottom windfarms. Precommercial FOW systems must transition in a similar manner to the solar industry to reap similar benefits[25].

Not all components can be standardized, especially if it requires disclosure of proprietary design information, but some subcomponents common to multiple designs, such as bearings, wire, constituent materials and fasteners, might be appropriate for standardization. For example, agreeing on standard sizes, weights or voltage limits would enable greater uniformity in manufacturing multiple upstream parts[96,99]. However, standardization might not be appropriate for fully assembled substructures and turbines, as dictating specific designs or architectures could hinder innovation at an early stage of maturation[29,100,101].

Market forces during the initial commercialization of the FOW industry will filter out many floating substructure designs, because only a fraction will have all the commercial attributes necessary to incentivize their adoption. An example from the fixed-bottom offshore wind market is the monopile configuration, which gained substantial cost advantages relative to the gravity base or jacket configurations because the monopole supply chain reached industrial scale before its competitors[90,102,103]. The improvements in floating substructure designs are being driven by the need to enable large-scale commercial projects. In this context, allowing market forces to determine which designs advance to commercial maturity will foster competition and innovation.

Industrial standardization should not be confused with the development of standard design practices. The development of international standards and certification practices, such as those established by the International Electrotechnical Commission (IEC) will help FOW to reach technological maturity. The IEC 61400-3-2 Technical Standard provides a foundation for safe and reliable design practices across the industry[104]. However, international FOW design standards take 5 years or more to develop, and as a result they lag real-time industry experience and advances[104–106]. To bridge this gap and help FOW technology to mature faster, the industry can leverage best practice from related fields like offshore oil and gas[107], share insights from pilot projects through technical journals, support International Energy Agency research initiatives[108], hold networking conferences and contribute to peer-reviewed industry guidelines[78,109]. These efforts should expedite the adoption of proved methodologies and strengthen the foundation for the FOW sector's growth and maturation.

Enabling infrastructure for serial production

Commercializing FOW is likely to involve extensive enabling infrastructure for full-scale project development during the preconstruction, construction and operation phases (Fig. 3). Two of the main barriers to industrialization and commercialization of FOW are the billions of dollars needed in up-front capital investments in ports, vessels and transmission infrastructure and the years required to build them[3,5,24]. The larger the turbines, the greater these costs and time commitments become[20].

Ports. The construction of S&I ports – facilities where the major components are assembled and commissioned – tends to be the pacing item for FOW projects[24]. New S&I ports require high-capacity cranes capable of lifting more than 100 tonnes to a height of 150 m or more, with quayside drafts 8–10 m deep, channels over 100 m wide and no overhead restrictions. In addition, they should ideally be within 100 km of ocean deployment sites[110–114]. The port network development strategy would benefit by being in line with the technology drivers and system design. One of the key pieces of equipment that differentiates the bespoke FOW S&I port from the many conventional fixed-bottom offshore wind ports is the heavy, high-lift ringer crane that must be installed and located at the quayside (Fig. 4). These specialized cranes assemble the turbines onto the floating substructures prior to commissioning and tow-out and take over the primary heavy-lift function provided by the wind turbine installation vessels used in fixed-bottom wind[110,111,115].

Secondary manufacturing ports are also part of the ports network. They have fewer height restrictions than the S&I ports and therefore can be easier to locate and less expensive to build. Existing industrial facilities, such as shipyards, can be well suited to manufacturing some tier 1 subcomponents (such as fully assembled wind-turbine nacelles, and major components like blades, towers, floating substructures and cables) without using high-value space at the primary S&I port[24]. Whereas serial production of the major tier 1 components favours coastal regions, smaller tier 2 components and tier 3 raw-material manufacturing can rely more on existing local or regional supply chains. They are not as constrained by waterfront-access requirements, do not have the same geographic sensitivities and their components can more easily be obtained from the broader domestic or global supply chains.

An example global tier 2 and 3 supply chain could have flat panel components being manufactured in East Asia, where shipbuilding is traditionally strong[116], and cylindrical components fabricated in Europe, where most monopiles are produced[117]. In the USA, heavy industrial capabilities exist that can be adapted for tier 2 and tier 3 components but it is desirable also to build up tier 1 capabilities to increase domestic manufacturing and lower the cost[6]. Although domestic and/or local content is always desirable, experience from fixed-bottom wind projects suggests that commercial scale can generally be achieved without factory commitments in the region of project development.

FOW energy demonstration projects have been too small to justify the necessary investment for the critical port infrastructure needed for serial production at commercial scale[6]. Instead, small projects have relied on existing port infrastructure, which typically does not have the capacity or production scale to serve the current turbine technology platform from a single staging area. For pilot-scale projects, multiple, geographically dispersed ports are typically used, with suboptimal production rates and a high levelized cost of energy: over US$200 per MWh (ref. 6). Industrialization is likely to involve a coordinated and purpose-built network of ports located near project sites, each equipped for final assembly, integration and commissioning. Regional ports must also support manufacturing and O&M activities, with sufficient vessels and logistics infrastructure to ensure seamless connectivity between them[24,26].

Vessels. The size of the global fleet of vessels for building and maintaining FOW is insufficient to meet the growing demand of the commercial FOW project pipeline[24]. FOW requires smaller, less expensive vessels than fixed-bottom wind installations, because most of the heavy-lift wind turbine installation and assembly occurs at the quayside[36]. Early demonstration projects required large and expensive floating cranes[118], but

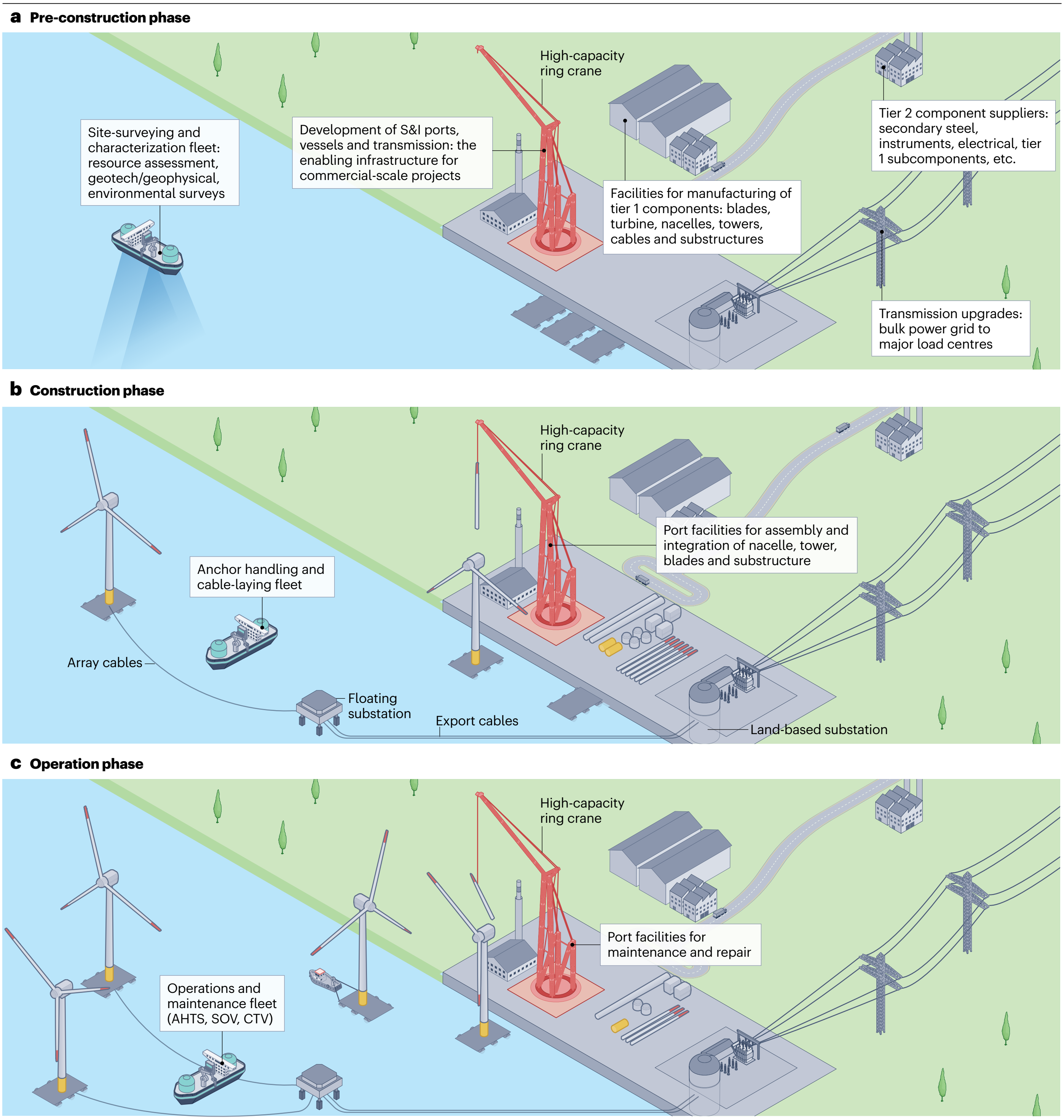


Fig. 3 | Enabling infrastructure to commercialize floating wind energy. a, Preconstruction phase. **b**, Construction phase. **c**, Operations phase. AHTS, anchor handling tug supply; CTV, crew transfer vessel; S&I, staging and installation; SOV, service operation vessel.

through industry learning, semisubmersible and hybrid configurations have been designed to avoid the need for large ships[118]. Nevertheless, deep-sea operations for FOW will still rely on specialized ships that have not yet been fully adapted. The immature industry lacks large-scale O&M plans, posing higher risks and incurring higher O&M costs during initial phases[119]. Industry learning is expected to accelerate cost reductions with

Fig. 4 | High-capacity ringer cranes are integrated into the S&I ports that are needed for quayside assembly of floating offshore wind turbines. The photo in Mandal, Norway, shows an 8.6-MW turbine being lifted onto a 107-m spar buoy as part of the 88-MW Hywind Tampen project in Norway. The Hywind Tampen project was installed in 2023 and was the largest floating offshore wind (FOW) project at the time of its installation[156]. MW, megawatt; S&I, staging and installation. Image courtesy of Mammoet.

larger deployments, and many O&M training programmes have already been established to build the needed skills[85,120].

One of the main challenges for FOW O&M is conducting large component repairs and replacements at sea. The prevailing approach involves disconnecting mooring lines and cables and towing the turbine assembly to an inshore O&M port, which is likely not to be the most efficient solution in the long run[24]. To enable at-sea repair, the FOW industry might ultimately require a new class of heavy-lift vessels with a higher degree of dynamic motion compensation[21]. In the specific case of the USA, vessel logistics are subject to policy, which restricts access to the global fleet, increasing the need for an expanded USA-flagged fleet to support all offshore wind deployments[121]. Building up vessel capacity might be discouraged by uncertainty surrounding turbine scaling-up trends. However, the reduced vessel requirements for FOW might help to mitigate this problem. Nevertheless, it is crucial for the industry to converge on a stable technology platform to increase the product life cycles, which would allow investors in FOW infrastructure to recover their costs[122].

Transmission. Attractive areas for offshore wind projects, such as some areas off the Pacific coast of the USA, are located hundreds of kilometres from access to the bulk power grid[123]. The construction of adequate land-based grid interconnection capacity could be addressed early in the preconstruction phase of an FOW project, because transmission planning and construction can take longer than FOW project development[124]. The key transmission issue unique to FOW projects, which tend to be farther from shore, is the need to develop and demonstrate reliable offshore electrical infrastructure hardware such as subsea and floating offshore substations, dynamic array and export cables, and HVDC systems[124,125].

Without enabling infrastructure such as ports, vessels and transmission, FOW farms are likely to be constrained to a smaller scale and higher cost[126]. Therefore, the offshore wind industry must demonstrate sufficient market scale and near-term market certainty to attract infrastructure investment. A key indicator of market scale is the global project pipeline, which is between 100 GW (ref. 6) and 244 GW (ref. 97), based on active projects moving through the regulatory process. Most FOW projects in these pipelines are in the early planning phase with longer timelines and higher uncertainty, which can dampen confidence for near-term investment.

However, market demand signals are bolstered globally by national and subnational policies that create market certainty. The worldwide aggregation of all national ambitions (fixed and floating), both implicit and explicit, is over 800 GW, twice the size of the global project pipeline, which may potentially boost investor confidence[127]. Because FOW shares more than two-thirds of its supply chain with the fixed-bottom wind industry, the advancement of offshore wind in general could help to achieve industrialization and commercialization goals for FOW[128]. Some of this crossover might already be happening: 9 GW of FOW projects advanced to the permitting stage by the end of 2023, a 40-fold increase since the end of 2022 (ref. 6).

Delivering cross-cutting value

Commercial-scale adoption is expected to achieve some of the necessary cost reductions on the path to market competitiveness (Box 1) in global electricity markets. However, life-cycle costs are only one element of the cross-cutting value that an energy-generation technology can offer. We define this value as the net impact on stakeholders, the environment, the market and the economy, based on the cost of energy and the additional benefits (or consequences) attributed to widespread deployment. Importantly, the value proposition is not unique to floating wind; it is relevant for any energy technology and may be particularly impactful in nations with strong incentive-based systems. The place of FOW in future energy markets will be strongly influenced by how well its cross-cutting value aligns with local electricity market design and energy needs. If the benefits of FOW correspond to the priorities established by citizens, grid operators, regulators and policymakers — which include a combination of affordability, grid reliability, low emissions, low environmental impacts, resource availability and local economic impact[129] — then FOW is likely to be able to compete effectively in the market.

Achieving a market-competitive state might require the evolution of both FOW technology and market design. As an example, potential FOW markets in Europe, North America and Asia have started to encourage non-cost benefits through means including multifactor selection criteria in competitive procurement auctions, promised investments to local economies or stakeholder groups and regulatory frameworks designed to help meet policy targets[129–131]. Enabling FOW to deliver its highest potential cross-cutting value is likely to require stable, reliable market demand with predictable offtake mechanisms to support a project portfolio large enough to achieve economies of scale and to attract the necessary supply-chain and infrastructure investment[132,133].

With stable and predictable industry development, FOW can contribute to grid stability, resource adequacy and resiliency; enable commercial-scale projects to be built far offshore, away from regions with conflicting land-use or shallow-water spatial constraints; minimize environmental impacts; and create local supply chains with associated jobs and economic benefits[14]. The costs of FOW are expected to decrease substantially as the industry matures and expands to commercial-scale deployment[8]. The timeline to achieve these cost reductions could be shortened through coordinated action among FOW developers, OEMs, energy-system planners and policymakers. Their collaboration should integrate these non-cost value-adders into regional energy planning systems, enabling FOW to be evaluated on the basis of overall value.

Cost of energy, grid reliability and spatial impacts

Reducing the costs of FOW will likely be a key element of market competitiveness. In some projections, FOW achieves cost parity with fixed-bottom offshore wind in select scenarios by the mid-2030s, potentially reaching a levelized cost of energy (LCOE) below US$100 per MWh (refs. 6,8). Building at least 7 GW of FOW in Europe has the potential to reduce the LCOE to €53–76 per MWh (ref. 131).

A survey of 140 global wind experts estimated that the LCOE of a floating wind project could be 50% lower in 2050 than in 2025 (ref. 134). The expected 2050 LCOE was around 45% lower than anticipated by a similar survey conducted 5 years earlier, suggesting that optimism between 2015 and 2020 about the future cost projections of FOW has increased[135]. Economic headwinds in the early 2020s caused short-term cost increases for fixed-bottom offshore wind, but cost projections for the industry indicate the potential for long-term reductions[136].

Cost reductions are influenced by economies of unit scale, economies of plant scale, resource economies of scale, grid-system value economies and production efficiencies[137]. The complex system-level interactions of a FOW plant make it challenging to isolate the cost reduction potential from a single innovation[18]. Advances in the physical design, manufacturing, transmission, installation, operation and financing of FOW projects will have to proceed concurrently to incrementally reduce costs[134]. However, even assuming these cost reductions are realized, power sector capacity expansion models that optimize for lowest system costs tend to estimate markedly lower FOW deployment than policy targets[7,83]. This mismatch indicates that competing purely based on least cost likely undercounts some of the potential value-adders of FOW. As such, the value energy planners are placing on non-project cost factors is important for FOW commercialization.

Other factors may influence the selection of FOW in competitive tenders or auctions, even at higher costs, depending on how its economic and environmental benefits are valued[129]. Additional bidding criteria in offshore wind tenders that weight factors such as local content, system integration, ecological mitigation or environmental impact in the awards of competitive lease sales have become more common since 2018 (ref. 129). System planners develop generation portfolios so that the grid can always meet load requirements as well as be responsive to high-stress periods and outages. FOW has the potential to offer value to the existing electric grid (Fig. 5). FOW has a strong correlation between generation and load profiles[138,139], it can enable higher responsiveness to shifts in load by reducing grid congestion[11], and in some scenarios is better suited to extreme events such as providing reliable winter energy supply in areas where other energy supplies may be limited.

Large FOW projects can be deployed near coastal load centres, but farther offshore than fixed-bottom offshore wind, where there

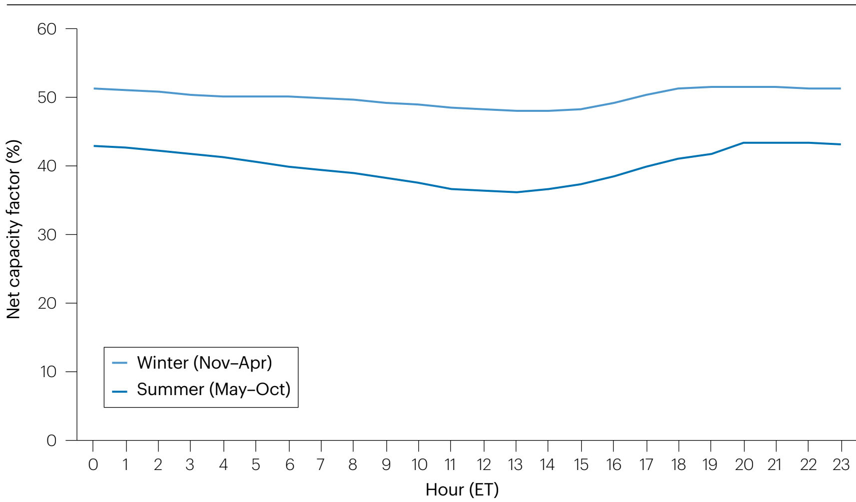


Fig. 5 | Net capacity factor in the summer and winter for a representative offshore wind site in northeastern USA[157]. ET, eastern time.

are higher and more consistent wind resources[138], which results in smoother production profiles and potentially less volatile prices. Lower price volatility, high-capacity credits and avoided grid losses and/or costs are inherently tied to the wind resource and proximity to load. As the commercialization of FOW advances, identifying and quantifying these value streams by region will be important for incorporating them in energy-system planning.

A one-gigawatt utility-scale wind-energy plant requires an area of approximately 250 km^2 whether it is offshore or on land, although the footprint can vary substantially based on project-specific technology, terrain and site conditions[140,141]. Part of the value of FOW comes from the opportunity to avoid major land-use conflicts compared with onshore wind farms, and to remove site conflict with other ocean users, whose needs may overlap more often with fixed-bottom offshore wind closer to shore[142]. Locating projects farther offshore in deeper waters requires a thorough understanding of the trade-offs between potentially higher wind resource, increased electrical export system costs and potentially different environmental impacts[143]. Balancing these factors can help to maximize the value contribution from floating wind projects.

Environmental impact

FOW presents an opportunity to improve both substructure and turbine designs with greater consideration for environmental impacts – particularly related to material use and effects on the marine ecosystem, including mammals, fish, birds and aquatic plants. However, the scientific understanding of FOW's environmental effects remains at an early stage[144,145]. One environmental benefit of FOW that has been acknowledged is that floating support structures do not require pile-driving into the seabed, thus avoiding the percussive noise that can disturb marine wildlife[143]. The range of design options for floating substructures also offers the opportunity for nature-inclusive approaches, such as incorporating surfaces that support marine life and the creation of habitats for mussels, corals and fish breeding.

The structural flexibility of floating systems allows for innovative designs that reduce material consumption, enhance recyclability and minimize environmental disruption during decommissioning[146]. Conversely, there is a risk that FOW development could result in negative impacts on the environment[147]. Although the percussive noise during anchor installation is less than that of fixed-bottom wind, it could still disturb domestic and migratory marine species[148]. As the FOW industry moves towards semi-taut mooring lines, which require anchor piles instead of drag-embedment anchors, installation noise might be increased, although the spatial extent of the contact with the seafloor would be reduced[149]. Similarly, laying or burying cable or mooring lines on the seabed could increase turbidity and negatively affect local fauna. Even far-from-shore wind plants could still be visible from the coast and have viewshed impacts on local communities.

FOW projects have implications for the fishing industry, which has expressed some concern about the impact on navigation safety, ability to use mobile gear, ecological influences on the fish resource, potential compensation mechanisms, and levels of engagement during the development process[150]. Station-keeping systems and the lateral motion of floating turbines (the watch circle) could be of particular interest to the fishing community, as the moving turbines and spread of mooring lines and array cables within the water column could affect fishing practices and navigation[28]. Novel designs that reduce the footprint of the mooring system could reduce the impacts on fisheries while also decreasing project costs, and conceptual designs have demonstrated modest increases in acceptance from the fishing community[151].

By embracing co-design processes that integrate nature-inclusive principles, FOW systems have the potential not only to mitigate negative environmental impacts but also to add ecological value, benefiting both system planners and key environmental stakeholders[146].

Local impact

Cost, grid value and environmental impact are key motivators for the FOW industry, but perhaps the most cited factor is the opportunity to create local jobs and spur economic growth[11,15,100,152]. An economic impact assessment conducted for a hypothetical one-gigawatt commercial-scale project off the coast of California estimates that over 13,000 full-time-equivalent direct, indirect and induced jobs would be needed during the construction phase, along with an additional nearly 700 jobs during the operational phase. These estimates correspond to a gross domestic product in the USA of over US$1.6 billion[153]. Of these estimated construction jobs, 75% would be in the supply chain, which has been a particular focus for decision-makers[153].

Offshore wind supply chains are already concentrated on the coast to be near project development sites, and because the major components such as blades, towers and floating substructures are too large to transport over land[3,154]. This component-size constraint directly links the economic opportunity associated with offshore wind to port communities where the major manufacturing will take place. This requirement for coastal manufacturing sites will be particularly prevalent for FOW, where the integration of the wind turbine with the floating substructure will take place at a regional port that would ideally comprise at least a 100-acre site for an efficient production line[24,155]. A conceptual network of ports along the west coast of the USA has been evaluated[24] that could provide services throughout the life cycle of FOW projects, including subcomponent manufacturing, assembly, S&I and O&M. The study indicates that a deployment of 55 GW by 2045 could require over 50 port sites to be built throughout the region (which includes the manufacturing sites needed to fabricate most of the major components).

Tier 2 and tier 3 suppliers of subcomponents and subassemblies could potentially require five times as many manufacturing jobs than tier 1 manufacturers[3]. As a result, not all of a FOW supply chain would need the coastal space and equipment required for tier 1 components, offering a substantial role for inland manufacturing facilities as well as smaller ports or shipyards. Distributed supply-chain assets represent a potential for broader geographic participation where individual states or countries can realize economic benefits. As the FOW industry evolves through the phases of commercialization and maturity, the supply chain must evolve concurrently to optimize substructure designs and supporting infrastructure[26,87,111]. This would require coordination between technology providers and local governments to understand workforce and infrastructure requirements, coupled with an attractive business environment to foster investment.

Revitalizing marine infrastructure and coastal communities through the build-out of FOW projects is attractive to some policymakers[152]. A major industrialized port can serve as an economic hub for a community, bringing stability, jobs and a sense of identity; however, many port communities in potential FOW regions face a range of health, environmental, educational, economic and workforce-related burdens. Introducing a new industry into these ports has the potential to create substantial benefits for these communities in terms of new jobs, economic growth and local infrastructure investment. However port development may benefit from avoiding exacerbating previous issues related to pollution, traffic congestion, creating jobs that are

Glossary

Blade pitch
The angle of a wind turbine blade relative to the oncoming wind, which can be adjusted to control the rotor speed, power output and structural loads.

Control systems
The hardware and software used to monitor, manage and optimize the performance of wind turbines and the overall wind farm to ensure safe operation, maximize power output and coordinate turbine responses to environmental conditions.

Draft
The vertical distance between the waterline and the bottom of a floating wind platform or vessel.

Fixed-bottom offshore wind
Offshore wind turbines that are installed on foundations fixed directly to the seabed, typically in water depths up to 60 m; common types include monopiles, jackets and gravity-based systems.

Monopile
A single, large-diameter cylindrical steel foundation driven into the seabed to support offshore wind turbines.

Operations and maintenance
(O&M). O&M activities are those required to keep wind turbines and associated infrastructure running efficiently and safely, including inspections, repairs, part replacements and performance monitoring (and controls updating).

Original equipment manufacturers
(OEMs). Companies that design and produce the tier 1 components of wind turbines, such as blades, nacelles and towers.

Rotor yaw
The rotation of the entire wind turbine nacelle and rotor around the vertical axis to align the rotor with the wind direction for optimal energy capture.

Spar
A floating wind turbine substructure characterized by a tall, cylindrical design that achieves stability through deep draft and heavy ballast located at the bottom of the structure.

Staging and integration port
(S&I port). Receives, stages and stores offshore wind components and integrates the wind turbine with the floating substructure; additional manufacturing activities, such as floating substructure assembly, can take place at this port.

Tier 1 components
Finished components provided by a manufacturer to an offshore wind project developer, such as blades, nacelles, towers and floating substructures.

Tier 2 components
Subassemblies that have specific functions within a tier 1 component, such as a pitch system for blades.

Tier 3 components
Commonly available subcomponents that are integrated into tier 2 subassemblies, such as motors, bolts and gears.

Transmission congestion
A bottleneck in an electrical grid that occurs when transmission lines do not have sufficient available capacity to transmit enough electricity to meet demand.

Wake
The region of slower, more turbulent airflow that forms behind a wind turbine as it extracts energy from the wind.

not accessible to the local workforce, affecting local sites of historical or cultural importance, or disregarding the priorities of the local communities[24]. Commercializing and maturing the floating wind industry will require ports, project developers and manufacturers to be able to effectively engage with local communities, consider the trade-offs and develop ways to maximize the benefits while minimizing harms.

Summary and future perspectives

In this Perspective, we reviewed the commercial status of FOW technology development and three critical concurrent areas for reaching industry maturity: technological innovation, industrialization and articulation of its cross-cutting value to the energy system. We discussed examples of how technical innovations such as integrated design approaches between turbines and floating substructures, advanced turbine control systems, digital twins and automation in operation and maintenance could contribute to a potential 50% reduction in life-cycle costs by 2050.

Scaling FOW from pilot projects to commercial utility-scale deployment is likely to require infrastructure investments of tens of billions of dollars in the USA alone[5,24]. These investments will likely facilitate near-term cost reductions and lay the groundwork for serial production, standardization and industry learning that will lead to the goal of long-term industry maturity (Box 1). Additionally, the FOW industry needs to understand, quantify, articulate and demonstrate the value streams it can provide to build and sustain public confidence in large-scale deployment of this new technology. Quantifying the local and regional benefits with respect to grid reliability, reduced carbon emissions and strengthening coastal economies could help to assure stakeholders that FOW can be implemented cost-effectively without sacrificing comfort or security.

Industry research has already identified and documented opportunities for FOW industry growth[25] but forward momentum can be disrupted by exogenous global economic variables that cast doubt on the market's viability and by endogenous variables that limit commercialization and growth. The FOW industry needs to demonstrate long-term market stability and technology consistency at both a regional and global level to attract the supply-chain and infrastructure investments needed to commercialize at utility scale. FOW energy resources are large in coastal areas that have a need for reliable energy (Fig. 1a), but markets in these areas have not been established and key stakeholders responsible for the electric grid need better assurance of cost and reliability. Even with numerous national policies that support offshore wind development, investors need better long-term market certainty. Market certainty could be increased by industry commercializing the 15-MW turbine technology platform (or some agreed upon limit) and stabilizing turbine growth in alignment with infrastructure capacity limits[28].

Technology consistency, reliability and confidence can likely be achieved by the development of mature design tools, standards and practices and through accumulated operating experience. Concurrently, designs can be optimized with consideration for life-cycle costs and existing infrastructure constraints. Ideally, regulatory frameworks could be streamlined, and approval/consent timelines shortened to facilitate deployment. Building community trust through stakeholder engagement and fostering coexistence with other marine activities, such as fishing and aquaculture[146], are also beneficial key components of a successful development strategy. The establishment of globally optimized supply chains and the development of bespoke S&I port facilities near FOW sites are likely to be critical enablers for efficient deployment and service. Incentivizing investments in critical FOW infrastructure might be necessary to allow FOW to compete based on resource adequacy and cost (while delivering broader benefits, such as grid stability). By addressing the three areas detailed in this paper – technological innovation, industrialization and cross-cutting value – FOW has the potential to become economically competitive in new energy markets, contributing[26] to a reliable and resilient energy system.

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References

1. Musial, W. & Ram, B. Large-scale offshore wind power in the United States: assessment of opportunities and barriers. *National Renewable Energy Laboratory* http://www.nrel.gov/docs/fy10osti/40745.pdf (2010).
2. Guide to a floating offshore wind farm. *BVG Associates* https://guidetofloatingoffshorewind.com/ (2023).
3. Shields, M., Stefek, J., Oteri, F., & Kreider, M. A supply chain road map for offshore wind energy in the United States. *National Renewable Energy Laboratory* https://www.nrel.gov/docs/fy23osti/84710.pdf (2023).
4. Torr, R. Strategic infrastructure and supply chain development: summary report. *Catapult: Offshore Renewable Energy* https://fowcoe.co.uk/wp-content/uploads/2023/09/FOW-PR19-Strategic-Infrastructure-Dev-Summary-May-22-AW3.pdf (2022).
5. Sabina, B. Building a national network of offshore wind ports. *Oceantic Network* https://oceantic.org/building-a-national-network-of-offshore-wind-ports/ (2023).
6. McCoy, A. et al. Offshore wind market report. *National Renewable Energy Laboratory* https://www.nrel.gov/docs/fy24osti/90525.pdf (2024).
7. Beiter, P., Mai, T., Mowers, M. & Bistline, J. Expanded modelling scenarios to understand the role of offshore wind in decarbonizing the United States. *Nat. Energy* **8**, 1240–1249 (2023).
8. Annual technology baseline. *National Renewable Energy Laboratory* https://atb.nrel.gov/ (2024).
9. Offshore wind policy and market assessment: a global outlook. *European Union/FOWInd* https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2022/12/2022121976.pdf (2014).
10. AB 525 Offshore Wind Energy Strategic Plan: Draft Commission Report Volume 1 Overview of AB 525 Strategic Plan. *California Energy Commission* https://www.energy.ca.gov/publications/2023/ab-525-offshore-wind-strategic-plan (2024).
11. New Jersey's offshore wind workforce assessment through 2035. *NJEDA* https://www.njeda.gov/wp-content/uploads/2022/09/2022-NewJersey-OSW-Workforce-Assessment-Report.pdf (2022).
12. Offshore wind reliability analysis. *Union of Concerned Scientists* https://ucs-documents.s3.amazonaws.com/clean-energy/Offshore-Wind-Reliability-Analysis-Muller-UCS.pdf (2024).
13. Novachek, J. & Schwarz, M. Evaluating the grid impact of Oregon offshore wind. *National Renewable Energy Laboratory* https://www.nrel.gov/docs/fy22osti/81244.pdf (2021).
14. Floating offshore wind — a global opportunity. *Global Wind Energy Council* https://www.gov.br/mme/pt-br/assuntos/secretarias/sntep/geracao-energia-eletrica-offshore/estudos-e-documentos-base/gwec-report-floating-offshore-wind-a-global-opportunity.pdf (2022).
15. Maine offshore wind roadmap: executive summary. *Maine Governor's Office* https://www.maine.gov/energy/sites/maine.gov.energy/files/inline-files/Maine_Offshore_Wind_Roadmap_February_2023_ExSum.pdf (2023).
16. Butterfield, S., Musial, W., Jonkman, J. & Sclavounos, P. Engineering challenges for floating offshore wind turbines. In *Proc. Copenhagen Offshore Wind Conf.* (National Renewable Energy Laboratory, 2005).
17. Nielsen, F. Perspectives and challenges related to offshore wind turbines in deep water. *Energies* **15**, 2844 (2022).
18. Barter, G. E., Robertson, A. & Musial, W. A systems engineering vision for floating offshore wind cost optimization. *Renew. Energy Focus* **34**, 1–16 (2020).
19. Cermelli, C., Roddier, D. & Weinstein, A. Implementation of a 2MW floating wind turbine prototype offshore Portugal. In *Proc. Offshore Technology Conf.* OTC-23492-MS (Offshore Technology Conference, 2012).
20. Janocha, M. J. et al. Exploring the technical boundaries in upscaling floating offshore wind turbines. In *Proc. ASME 43rd Int. Conf. Ocean, Offshore and Arctic Engineering* V007T09A047 (ASME, 2024).
21. Hong, S., McMorland, J., Zhang, H., Collu, M. & Halse, K. H. Floating offshore wind farm installation, challenges and opportunities: a comprehensive survey. *Ocean. Eng.* **304**, 117793 (2024).
22. Musial, W. Scaling the offshore wind industry and optimizing turbine size. *National Renewable Energy Laboratory* https://www.nrel.gov/docs/fy25osti/92118.pdf (2024).
23. Shields, M., Beiter, P. & Nunemaker, J. A systematic framework for projecting the future cost of offshore wind energy. *National Renewable Energy Laboratory* https://www.nrel.gov/docs/fy23osti/81819.pdf (2022).
24. Shields, M., Cooperman, A., Kreider, M., Oteri, F. & Gill, Z. The impacts of developing a port network for floating offshore wind energy on the west coast of the United States. *National Renewable Energy Laboratory* https://www.nrel.gov/docs/fy23osti/86864.pdf (2023).
25. FLoating Offshore Wind ReadINess (FLOWIN) Prize. *AmericanMade* https://americanmadechallenges.org/challenges/flowin/docs/FLOWIN_Official_Prize_Rules.pdf (2022).
26. PR36: advanced manufacturing of substructure components. *BVG Associates/Catapult* https://fowcoe.co.uk/wp-content/uploads/2024/10/PN000536-RPT-009-Advanced-Manufacturing-of-Sub-Structure-Components.pdf (2024).
27. Wiley, W. et al. Definition of the Stiesdal Offshore TetraSpar Floating Wind System for OC6 Phase IV. NREL/TP--5700-86442 *National Renewable Energy Laboratory* https://www.osti.gov/servlets/purl/2203218/, https://doi.org/10.2172/2203218 (2023).
28. Musial, W. et al. Challenges and opportunities for floating offshore wind energy in ultradeep waters of the central Atlantic. *National Renewable Energy Laboratory* https://www.nrel.gov/docs/fy24osti/90608.pdf (2024).
29. Adoption Readiness Levels (ARL) framework. *US DOE* https://www.energy.gov/technologytransitions/adoption-readiness-levels-arl-framework (2024).
30. Hegazy, A., Naaijen, P. & Van Wingerden, J.-W. Control design for floating wind turbines. Preprint at *Wind Energ. Sci. Discuss.* https://doi.org/10.5194/wes-2025-68 (2025).
31. Robertson, A. N. & Jonkman, J. M. Loads analysis of several offshore floating wind turbine concepts. In *21st Int. Ocean and Polar Engineering Conf.* 443 (ISOPE, 2011).
32. Floating offshore wind turbine development assessment: final report and technical summary. *ABSG Consulting Inc.* https://www.boem.gov/sites/default/files/documents/renewable-energy/studies/Study-Number-Deliverable-4-Final-Report-Technical-Summary.pdf (2021).
33. Xing, Y., Wang, S., Karuvathil, A., Balakrishna, R. & Gaidai, O. Characterisation of extreme load responses of a 10-MW floating semi-submersible type wind turbine. *Heliyon* **9**, e13728 (2023).
34. Empire Wind. *Wikipedia* https://en.wikipedia.org/wiki/Empire_Wind (2025).
35. Milestone for Germany's largest offshore wind farm under construction: first "EnBW He Dreiht" wind turbine is now in place. *EnBW* https://www.enbw.com/press/enbw-he-dreiht-offshore-wind-farm.html (2025).
36. Musial, W. Considerations for floating wind energy development in the Gulf of Maine. *National Renewable Energy Laboratory* https://www.nrel.gov/docs/fy23osti/86550.pdf (2023).
37. Radowitz, B. Siemens Energy CEO: 21MW offshore wind giant is only 'test turbine'. *Recharge* https://www.rechargenews.com/wind/siemens-energy-ceo-21mw-offshore-wind-giant-is-only-test-turbine/2-1-1778452 (12 February 2025).
38. Memija, A. World's first 26 MW offshore wind turbine rolls off production line. *Offshore Wind* https://www.offshorewind.biz/2024/10/14/worlds-first-26-mw-offshore-wind-turbine-rolls-off-production-line/ (14 October 2024).
39. Henrique, A. I. D. et al. Global Offshore Wind Report. *Global Wind Energy Council* https://www.gwec.net/reports/globaloffshorewindreport (2025).
40. Gupta, A., Desai, A., McDonald, G. & Sarada, S. Comparison between coupled and uncoupled dynamic analysis of offshore wind turbine generators (WTG) support structures. In *Offshore Technology Conf. (OTC)* OTC-32326-MS (Offshore Technology Conference, 2023).
41. Aubault, A., Cermelli, C. & Roddier, D. WindFloat: a floating foundation for offshore wind turbines — part III: structural analysis. In *Proc. ASME 28th Int. Conf. Ocean, Offshore and Arctic Engineering* OMAE2009-79232 213–220 (ASME, 2009).
42. Havinga, H. C., van der Loos, H. Z. A., & Steen, M. Collaboration or competition? Interactions between floating and fixed-bottom offshore wind in Norway. *Environ. Innov. Soc. Trans.* **52**, 100872 (2024).
43. Lico, E. Wind turbine technology evolution is diverging quickly between China and the rest of the world. *Wood Mackenzie* https://www.woodmac.com/news/opinion/wind-turbine-technology-evolution-is-diverging-quickly-between-china-and-the-rest-of-the-world/ (2024).
44. López-Queija, J., Robles, E., Jugo, J. & Alonso-Quesada, S. Review of control technologies for floating offshore wind turbines. *Renew. Sustain. Energy Rev.* **167**, 112787 (2022).
45. Papi, F., Bianchini, A., Ferri, G., Bruschi, N. & Marino, E. Influence of tower design on floating offshore wind turbine dynamics. In *Proc. Int. Conf. Offshore Mechanics and Arctic Engineering* V008T09A053 (ASME, 2023).
46. Wang, L. Experimental investigation of advanced turbine control strategies and load-mitigation measures with a model-scale floating offshore wind turbine system. *Appl. Energy* **355**, 122343 (2024).
47. Harger, A. et al. Modal analysis of 15 MW semi-submersible floating wind turbine: investigation on the main influences in natural vibration. *Wind* **3**, 548–566 (2023).
48. Engebretsen, E., Stampoultzoglou, A., Borgen, E. & Schafhirt, S. Design challenges and novel solutions for tower designs of next generation floating wind turbines. *SINTEF* https://www.sintef.no/globalassets/project/eera-deepwind-2023/presentasjoner/substructures_borgen.pdf (2023).
49. Jonkman, J. et al. Functional requirements for the WEIS toolset to enable controls co-design of floating offshore wind turbines. In *Proc. 3rd Int. Offshore Wind Technical Conf.* V001T01A007 (ASME/NREL, 2021).

50. Salic, T. Control strategies for floating offshore wind turbines: challenges and trends. *Electronics* **8**, 1185 (2019).
51. Pao, L., Sinner, M. & Pusch, M. Control of floating offshore wind energy systems: an introduction to the special issue. *IEEE Control. Syst.* **44**, 24–27 (2024).
52. Skaare, B., Hanson, T. D. & Nielsen, F. G. Importance of control strategies on fatigue life of floating wind turbines. In *Proc. Conf. Offshore Mechanics and Arctic Engineering* OMAE2007-29277 (ASME, 2007).
53. Larsen, T. J. & Hanson, T. D. A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine. *J. Phys. Conf. Ser.* **75**, 012073 (2007).
54. Jonkman, J. M. Influence of control on the pitch damping of a floating wind turbine. In *Proc. Wind Energy ASME Symp.* NREL/CP-500-42589 (American Institute of Aeronautics and Astronautics, 2008).
55. Yu, W., Zhou, S. T., Lemmer, F. & Cheng, P. W. Control co-design optimization of floating offshore wind turbines with tuned liquid multi-column dampers. *Wind Energy Sci.* **9**, 1053–1068 (2024).
56. Stockhouse, D. A tutorial on the control of floating offshore wind turbines: stability challenges and opportunities for power capture. *IEEE Control. Syst.* **44**, 28–57 (2024).
57. Zalkind, D. & Bortolotti, P. Control co-design studies for a 22 MW semisubmersible floating wind turbine platform. *J. Phys. Conf. Ser.* **2767**, 082020 (2024).
58. Meyers, J. Wind farm flow control: prospects and challenges. *Wind Energy Sci.* **7**, 2271–2306 (2022).
59. Fleming, P. A. Evaluating techniques for redirecting turbine wakes using SOWFA. *Renew. Energy* **70**, 211–218 (2014).
60. Simley, E., Millstein, D., Jeong, S. & Fleming, P. The value of wake steering wind farm flow control in US energy markets. *Wind. Energy Sci.* **9**, 219–234 (2024).
61. Mahfouz, M. Y. & Cheng, P. W. Effect of mooring system stiffness on floating offshore wind turbine loads in a passively self-adjusting floating wind farm. *Renew. Energy* **238**, 121823 (2025).
62. Veers, P. Grand challenges in the science of wind energy. *Science* **366**, eaau2027 (2019).
63. Jasa, J., Bortolotti, P., Zalkind, D. & Barter, G. Effectively using multifidelity optimization for wind turbine design. *Wind Energy Sci.* **7**, 991–1006 (2022).
64. Jonkman, J. et al. Functional requirements for the WEIS toolset to enable controls co-design of floating offshore wind turbines. In *Proc. 3rd Int. Offshore Wind Technical Conf.* V001T01A007 (ASME, 2021).
65. Pryor, S. C., Barthelmie, R. J. & Shepherd, T. J. Wind power production from very large offshore wind farms. *Joule* **5**, 2663–2686 (2021).
66. Castella, X. T. & Xavier, F. *Operations and maintenance costs for offshore wind farm. Analysis and strategies to reduce O&M costs*. MSc thesis, Univ. Politècnica de Catalunya and National Taiwan University of Science and Technology (2020).
67. McMorland, J., Collu, M., McMillan, D. & Carroll, J. Operation and maintenance for floating wind turbines: a review. *Renew. Sustain. Energy Rev.* **163**, 112499 (2022).
68. Branlard, E., Jonkman, J., Brown, C. & Zhang, J. A digital twin solution for floating offshore wind turbines validated using a full-scale prototype. *Wind Energy Sci.* **9**, 1–24 (2024).
69. Otter, A. A review of modelling techniques for floating offshore wind turbines. *Wind Energy* **25**, 5 (2021).
70. Maniaci, D. C. et al. Offshore wind energy validation experiment hierarchy. *J. Phys. Conf. Ser.* **2767**, 062039 (2024).
71. Ghigo, A., Cottura, L., Caradonna, R., Bracco, G. & Mattiazzo, G. Platform optimization and cost analysis in a floating offshore wind farm. *J. Mar. Sci. Eng.* **8**, 835 (2020).
72. Brussa, G., Grosso, M. & Rigamonti, L. Life cycle assessment of a floating offshore wind farm in Italy. *Sustain. Prod. Consum.* **39**, 134–144 (2023).
73. Saeed, N. A novel design of multifunctional offshore floating platform structure based on topology optimization. *Eng. Struct.* **306**, 117782 (2024).
74. Khalid, O., Hao, G., MacDonald, H., Cooperman, A. & Desmond, C. Cost–benefit assessment framework for robotics-driven inspection of floating offshore wind farms. *Wind Energy* **27**, 152–164 (2024).
75. Bayati, I. et al. Onsite major component replacement technologies for floating offshore wind: the status of the industry. *World Forum Offshore Wind* https://wfo-global.org/wp-content/uploads/2023/02/WFO-FOWC-OM-White-Paper-2-Final.pdf (2023).
76. Cerfontaine, B. et al. Anchor geotechnics for floating offshore wind: current technologies and future innovations. *Ocean Eng.* **279**, 114327 (2023).
77. Santhakumar, S., Heuberger-Austin, C., Meerman, H. & Faaij, A. Technological learning potential of offshore wind technology and underlying cost drivers. *Sustain. Energy Technol. Assess.* **60**, 103545 (2023).
78. Floating substations: the next challenge on the path to commercial scale floating windfarms. *DNV* https://www.dnv.com/article/floating-substations-the-next-challenge-on-the-path-to-commercial-scale-floating-windfarms-199213/ (2021).
79. Cooperman, A. Investigation of the challenges of offshore wind in ultradeep water. *National Renewable Energy Laboratory* https://www.nrel.gov/docs/fy25osti/90849.pdf (2024).
80. Sarveswaran, E. *Dynamic Cable Connection and Topology Comparison. Public Summary Report* (Floating Offshore Wind Centre of Excellence, 2024).
81. Cerik, B. C. & Huang, L. Recent advances in mechanical analysis and design of dynamic power cables for floating offshore wind turbines. *Ocean Eng.* **311**, 118810 (2024).
82. Ryndzionek, R. & Sienkiewicz, J. Evolution of the HVDC link connecting offshore wind farms to onshore power systems. *Energies* **13**, 1914 (2020).
83. Glaum, P., Neumann, F. & Brown, T. Offshore wind integration in the North Sea: the benefits of an offshore grid and floating wind. in *2023 19th International Conference on the European Energy Market* 1–7 (IEEE, 2023).
84. Roberts, D. The Department of Energy has gotten serious about technology commercialization. *Volts* https://www.volts.wtf/p/the-department-of-energy-has-gotten (16 October 2024).
85. Learning from incidents. *Global Offshore Wind Health and Safety Organisation* https://www.gplusoffshorewind.com/work-programme/workstreams/learning-from-incidents (2025).
86. Jansen, M. Policy choices and outcomes for offshore wind auctions globally. *Energy Policy* **167**, 113000 (2022).
87. Mangat, N., Zinderen, G. J., Hansen, L. F. & Sevilla, F. Optimal offshore wind turbine size and standardisation study. *DNV Services* https://topsectorenergie.nl/documents/334/20220519_RAP_DNV_Optimal_Offshore_Wind_Turbine_Size_and_Standardisation_F.pdf (2022).
88. Wiser, R. et al. Land-based wind market report. *Energy Markets and Policy Berkeley Lab* https://www.energy.gov/sites/default/files/2023-08/land-based-wind-market-report-2023-edition.pdf (2023).
89. Dehoorne, D. & Henseler, F. It's time to slow down on turbines if we really want to scale up the offshore wind industry. *Vestas Blog* https://www.vestas.com/en/media/blog/technology/-it-s-time-to-slow-down-on-turbines-if-we-really-want-to-scale-u (2024).
90. Peterson, R. Floating wind's industrialization depends on narrowing the platform design pool. *Aegir Insights* https://www.aegirinsights.com/opinion-floating-winds-industrialization-depends-on-narrowing-the-platform-design-pool (15 September 2023).
91. Wahidi, S. I., Oterkus, S. & Oterkus, E. Robotic welding techniques in marine structures and production processes: a systematic literature review. *Mar. Struct.* **95**, 103608 (2024).
92. Nekouvaght Tak, A., Taghaddos, H., Mousaei, A. & Hermann, U. Evaluating industrial modularization strategies: local vs. overseas fabrication. *Autom. Constr.* **114**, 103175 (2020).
93. Dagher, J. H., Goupee, A. J. & Viselli, A. M. Optimized floating offshore wind turbine substructure design trends for 10–30 MW turbines in low-, medium-, and high-severity wave environments. *Designs* **8**, 72 (2024).
94. Mathern, A., Haar, C. & Marx, S. Concrete support structures for offshore wind turbines: current status, challenges, and future trends. *Energies* **14**, 1995 (2021).
95. Agrawal, J., Gupta, T., Sharma, R. & Panwar, N. L. A comprehensive review on the performance of structural lightweight aggregate concrete for sustainable construction. *Construct. Mater.* **1**, 39–62 (2021).
96. Wind energy: supply chain deep dive assessment. *US DOE* https://www.energy.gov/sites/default/files/2022-02/Wind%20Supply%20Chain%20Report%20-%20Final%202.25.22.pdf (2022).
97. Renewable power generation costs in 2023. *International Renewable Energy Agency* http://large.stanford.edu/courses/2024/ph240/lutz1/docs/irena-2024.pdf (2024).
98. Utility-scale solar: empirical trends in deployment, technology, cost, performance, PPA pricing, and value in the United States. *Lawrence Berkeley National Laboratory* https://emp.lbl.gov/sites/default/files/2024-10/Utility%20Scale%20Solar%202024%20Edition%20Slides.pdf (2024).
99. Perera, C., Nagarur, N. & Tabucanon, M. Component part standardization: a way to reduce the life-cycle costs of products. *Int. J. Prod. Econ.* **60–61**, 109–116 (1999).
100. Advancing offshore wind energy in the United States: U.S. Department of Energy strategic contributions toward 30 gigawatts and beyond. *US DOE* https://www.energy.gov/sites/default/files/2023-03/advancing-offshore-wind-energy-full-report.pdf (2023).
101. Ho, J.-Y. & O'Sullivan, E. Dimensions of standards for technological innovation – literature review to develop a framework for anticipating standardisation needs. *IFM* https://www.ifm.eng.cam.ac.uk/uploads/Ho_2015_Dimensions_of_Standards_for_Technological_Innovation_rev.pdf (2015).
102. Zheng, S., Li, C. & Xiao, Y. Efficient optimization design method of jacket structures for offshore wind turbines. *Mar. Struct.* **89**, 103372 (2023).
103. Fried, S., Ozkan, D. & Halldén, K. Low-carbon, nature-inclusive concrete gravity-based foundations for offshore wind turbines. OSPRE-2022-02. *Tufts University* https://doi.org/10.60965/aryd-h033 (2022).
104. Wind turbines — part 3: design requirements for offshore wind turbines. IEC 61400-3-1:2019 *International Electrotechnical Commission* https://webstore.iec.ch/en/publication/29360 (2019).
105. Conformity assessment in the wind energy industry. *ARESCA* https://share.ansi.org/Shared%20Documents/Standards%20Activities/International%20Standardization/IEC/Communications%20Committee/Conformity%20Assessment%20in%20the%20Wind%20Energy%20Industry.pdf (2019).
106. U.S. offshore wind standards. *Oceantic Network* https://oceantic.org/u-s-offshore-wind-standards/ (2024).
107. Floating wind turbines. *American Bureau of Shipping* https://www.bsee.gov/sites/bsee.gov/files/tap-technical-assessment-program//669ab.pdf (2012).
108. Hall, M. et al. *The IEA Wind Task 49 Reference floating wind array design basis* (IEA Wind, 2024).
109. Wood, M. Ten steps to keep up with fast-paced technology and develop better standards! *IEC Blog* https://www.iec.ch/blog/ten-steps-keep-fast-paced-technology-and-develop-better-standards (23 June 2023).
110. Trowbridge, M., Lim, J. & Phillips, S. California floating offshore wind regional ports assessment. *Bureau of Ocean Energy Management* https://www.boem.gov/sites/default/files/documents/renewable-energy/studies/BOEM-2023-010.pdf (2023).
111. Crowle, A. P. & Thies, P. R. Floating offshore wind turbines port requirements for construction. *J. Eng. Marit. Env.* **236**, 1047–1056 (2022).
112. Maine Department of Transportation. Searsport offshore windport project. *MaineDOT* https://www.maine.gov/mdot/projects/searsport/windport/ (2024).

113. Pier Wind Project concept phase. *Moffatt & Nichol* https://www.moffattnichol.com/project/pier-wind-concept-phase#:~:Text=With%20deep%2C%20calm%20waters%2C%20wide,the%20growing%20offshore%20wind%20industry (2023).
114. California ports gear up to build offshore wind ports. *AJOT Insights* https://www.ajot.com/insights/full/ai-california-ports-gear-up-to-build-offshore-wind-ports (2024).
115. Farrell, J. Assembling the world's largest floating offshore wind farm. *Cranes and Lifting* https://www.cranesandlifting.com.au/assembling-the-worlds-largest-floating-offshore-wind-farm/ (2023).
116. Hakimian, R. Could basalt reinforcement replace steel in infrastructure construction? *New Civil Engineer* https://www.newcivilengineer.com/innovative-thinking/could-basalt-reinforcement-replace-steel-in-infrastructure-construction-09-05-2023/ (9 May 2023).
117. Mission critical: building the global wind energy supply chain for a 1.5°C world. *Global Wind Energy Council (GWEC)/Boston Consulting Group (BCG)* https://marketintelligence.gwec.net/wp-content/uploads/2023/12/MISSION-CRITICAL-BUILDING-THE-GLOBAL-WIND-ENERGY-SUPPLY-CHAIN-FOR-A-1.5%C2%B0C-WORLD.pdf (2024).
118. Ramachandran, C. R. Floating wind turbines: marine operations challenges and opportunities. *Wind. Energy Sci.* **7**, 903–924 (2022).
119. Paquette, J. et al. An operations and maintenance roadmap for U.S. offshore wind. NREL/TP--5000-87371 *National Renewable Energy Laboratory* https://www.osti.gov/servlets/purl/2361054/ (2024).
120. Interactive offshore wind training course overview. *DNV* https://www.dnv.com/energy/training/interactive-offshore-wind-training-course-overview/ (2025).
121. Jones Act/Merchant Marine Act of 1920 46 U.S.C. §§ 861–889. *United States Congress* https://tile.loc.gov/storage-services/service/ll/uscode/uscode1958-00904/uscode1958-009046024/uscode1958-009046024.pdf (1920).
122. Ambrizaite, O., Torbabi, C., Van Damme, N., Velez, D., & Wallemacq, M. Standardization of turbine design and installation vessels to accelerate the offshore wind industry in the United States. *J. Sci. Policy Gov.* **25**, jspg250101 (2024).
123. Jacobson, A. Transmission alternatives for California north coast offshore wind. Vol. 1: Executive Summary. *Schatz Energy Research Center* https://schatzcenter.org/pubs/2022-OSW-R1.pdf (2022).
124. Brinkman, G., Bannister, M., Bredenkamp, S. & Carveth, L. Atlantic offshore wind transmission study. *National Renewable Energy Laboratory* https://www.nrel.gov/docs/fy24osti/88003.pdf (2024).
125. Berg, K., Mattson, F. & Kochmann, M. Floating substations joint industry project. In *Offshore Technology Conf*. TC-35478-MS (Offshore Technology Conference, 2024).
126. Musial, W. Scaling the offshore wind industry and optimizing turbine size. *National Renewable Energy Laboratory* https://docs.nrel.gov/docs/fy25osti/92118.pdf (2024).
127. Wind market intelligence. *TGS* https://www.tgs.com/wind/market-intelligence (2024).
128. Musial, W. et al. Oregon offshore wind site feasibility and cost study. *National Renewable Energy Laboratory* https://www.nrel.gov/docs/fy20osti/74597.pdf (2019).
129. Lassen, L. & Seiple, B. Sea change: navigating the trillion-dollar offshore wind opportunity. *Wood Mackenzie* https://www.woodmac.com/horizons/sea-change-navigating-the-trillion-dollar-offshore-wind-opportunity/#:~:Text=The%20trillion%2Ddollar%20offshore%20wind%20opportunity,-Offshore%20wind%20is&Text=confidence%20in%20it.-,Costs%20fell%2050%25%20between%202015%20and%202020%20and%20are%20expected,cost%3B%20it's%20also%20about%20location (2022).
130. Beiter, P., Kitxing, L., Spitsen, P. & Noonan, M. Toward global comparability in offshore wind procurement. *Joule* **5**, 1305–1327 (2021).
131. State agreement approach process guidance document. *New Jersey Board of Public Utilities* https://www.nj.gov/bpu/pdf/ofrp/SAA%20Process%20Overview.pdf (2021).
132. Beiter, P., Heeter, J., Spitsen, P. & Riley, D. Offshore wind report. *National Renewable Energy Laboratory* https://www.nrel.gov/docs/fy20osti/76079.pdf (2020).
133. Scaling up floating offshore wind towards competitiveness. *Wind Europe* https://windeurope.org/wp-content/uploads/files/policy/position-papers/20211202-WindEurope-Scaling-up-Floating-Offshore-Wind-towards-competitivenes.pdf (2021).
134. Wiser, R., Rand, J. & Seel, J. Expert elicitation survey predicts 37% to 49% declines in wind energy costs by 2050. *Nat. Energy* **6**, 555–565 (2021).
135. Wiser, R. et al. Expert elicitation survey on future wind energy costs. *Nat. Energy* **1**, 16135 (2016).
136. Fuchs, R. The cost of offshore wind energy in the United States from 2025 to 2050. *National Renewable Energy Laboratory* https://docs.nrel.gov/docs/fy24osti/88988.pdf (2023).
137. Beiter, P. Expert perspectives on the wind plant of the future. *Wind Energy* **25**, 8 (2022).
138. Bodini, N. Global offshore wind dataset. *Earth Syst. Sci. Data* **16**, 1965–1982 (2023).
139. Jorgensen, F. Floating wind energy cost trends and outlook. *Wind Energy* **24**, 976–989 (2021).
140. Harrison-Atlas, D., Lopez, A. & Lantz, E. Dynamic land use implications of rapidly expanding and evolving wind power deployment. *Environ. Res. Lett.* **17**, 044064 (2022).
141. Mulas Hernando, D., Musial, W., Duffy, P. & Shields, M. Capacity density considerations for offshore wind plants in the United States. *National Renewable Energy Laboratory* https://www.nrel.gov/docs/fy24osti/86933.pdf (2023).
142. Zuckerman, G. R., Lopez, A., Williams, T., Green, R. & Buster, G. Impacts of siting considerations on offshore wind technical potential in the United States. *National Renewable Energy Laboratory* https://www.nrel.gov/docs/fy23osti/85088.pdf (2023).
143. Maxwell, S. M. Potential impacts of floating wind turbine technology for marine species and habitats. *J. Environ. Manag.* **307**, 114577 (2022).
144. Danovaro, R. Making eco-sustainable floating offshore wind farms: siting, mitigations, and compensations. *Renew. Sustain. Energy Rev.* **197**, 114386 (2024).
145. Farr, H., Ruttenberg, B., Walter, R. K., Wang, Y.-H. & White, C. Potential environmental effects of deepwater floating offshore wind energy facilities. *Ocean. Coast. Manag.* **207**, 105611 (2021).
146. Khan Afridi, S. 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**, 66147–66166 (2024).
147. Martorana, P. et al. Evaluation of the environmental impacts due to floating offshore wind farms. In *Proc. OCEANS 2024* https://doi.org/10.1109/OCEANS55160.2024.10753957 (2024).
148. Amaral, J. et al. The underwater sound from offshore wind farms. *Acoust. Today* **16**, 13–21 (2020).
149. Cooperman, A. et al. Assessment of offshore wind energy leasing areas for Humboldt and Morro Bay wind energy areas, California. *National Renewable Energy Laboratory* https://doi.org/10.2172/1865877 (2022).
150. Haggett, C. et al. Offshore wind projects and fisheries: conflict and engagement in the United Kingdom and the United States. *Oceanography* **33**, 38–47 (2020).
151. Green, R., MacDonald, S., Fuchs, R. & Hall, M. Social acceptance of a reduced-footprint synthetic mooring system for floating offshore wind turbines in the Gulf of Maine. *National Renewable Energy Laboratory* https://www.nrel.gov/docs/fy23osti/85503.pdf (2023).
152. *Assembly Bill 525 Offshore Wind Strategic Plan. Vol. I Overview Report*. CEC Report 17-MISC-01 (California Energy Commission, 2024).
153. Ramazani, C. & Rastad, M. The economic and employment impact of floating offshore wind projects in California's central coast. *California Polytechnic State Univ.* https://content-calpoly-edu.s3.amazonaws.com/cei/1/documents/Full-Report-Ramezani-Rastad-Final-5-22-23_2.pdf (2023).
154. Offshore wind supply chain directory. *Massachusetts Clean Energy Center (MassCEC)* https://www.masscec.com/our-focus/offshore-wind/offshore-wind-supply-chain-directory (2023).
155. Massachusetts offshore wind ports and infrastructure assessment: north shore. *Massachusetts Clean Energy Center (MassCEC)* https://files-cdn.masscec.com/research/wind/MA%20OSW%20Ports%20%26%20Infrastructure%20Assessment%202022%20-%20North%20Shore_0.pdf (2022).
156. Hywind tampen: the world's first renewable power for offshore oil and gas. *Equinor* https://www.equinor.com/energy/hywind-tampen (2025).
157. Urya, J., Anders, B., Beiter, P., Brown-Sacacino, J. & Gilman, P. Pathways to commercial liftoff: offshore wind. *US DOE* https://luciatian.com/publications/April-2024-LIFTOFF_DOE_Offshore-Wind-Liftoff-2.pdf (2024).

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Competing interests

A.A. is the CTO of Ocergy Inc., a technology company that provides engineering services and floating technology to a wide variety of floating windfarm developers globally, from the early phases of engineering. All other authors declare no competing interests.

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