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RESEARCH REVIEW

A systems engineering vision for floating offshore wind cost optimization

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Abstract

The U.S. offshore wind resource potential is vast, and often in close proximity to densely-populated coastal load centers. In many U.S. coastal areas, water depths favor the deployment of floating over fixed-bottom offshore wind technology. Floating offshore wind plants have the potential to be cost-competitive with fixed-bottom installations, but because the technology has not yet been deployed at commercial scale, it is not clear when and with what configurations this potential cost parity can be achieved. This article first reviews the state of floating offshore wind technology and deployments to identify key gaps that must be addressed to bring down the overall cost of energy produced. The article then puts forth a long-term vision for a research program and design methodology that may be able to push floating wind plants toward a lower levelized cost of energy than fixed-bottom offshore wind. The method involves a fully integrated systems-engineering and techno-economic design approach to capture the complex interactions between the physics, manufacturing, installation, and operation of floating wind turbines to achieve transformational cost reductions. The approach also envisions multifidelity and uncertainty management strategies to examine the most robust and viable concepts in the design trade-space. To better focus the computational resources, engineering lessons learned from existing offshore wind systems and concept studies are used to develop a set of criteria that can be applied to prefilter candidate technology building blocks that have the greatest cost reduction potential.

Introduction

Motivation

The U.S. offshore wind technical resource potential is more than 2000 GW,[1] much of which is located near highly populated coastal load centers[2] [1]. This vast potential is distributed over a resource area of which approximately 58% is in water depths of 60 m or more, and that proportion rises to 95% on the Pacific coastline [2]. The fundamental wind turbine technology shift for deployment in deep water is the transition to buoyant support structures from conventional fixed-bottom substructures, which become too costly and more technically challenging in deep water (greater than 50 m based on current industry experience) [3]. Although floating wind turbines present many new technical challenges, they also have many potential benefits compared to fixed-bottom shallow-water systems. Wind speeds can be higher in deep-water regions because they are further from shore, although there are exceptions to this trend. Siting floating projects may be easier near large load centers such as in the North Atlantic, because plants farther from shore may have fewer environmental and human use

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[1] The technical U.S. offshore wind resource potential that is greater than 7 m/s annual average wind speed was calculated to be 2058 GW, considering all ocean and lake areas less than 1000 m depth.

[2] Excludes areas in the Great Lakes deeper than 60 m because technology for floating structures to survive ice conditions is not mature.

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impacts, including viewshed issues.[3] Despite the distance from shore, floating systems may also be easier to install because they have the potential to be fully assembled at regional construction ports, commissioned at quayside, and towed out, reducing expensive labor at sea.

Market overview

As of 2018, seven utility-scale floating offshore turbine projects with ratings of more than 1 MW have been deployed worldwide, proving the technical feasibility of floating concepts [4]. The designs for this first wave of precommercial floating wind turbines adapted substructure concepts directly from the offshore oil and gas industry and relied on mature wind turbine designs intended for land-based or fixed-bottom offshore applications. These first floating turbines successfully demonstrated survivability and energy production, but to achieve economic viability, additional innovations are required [4].

The next phase for floating offshore wind technology is now underway with precommercial pilot plants, improved turbines adapted for floating applications, and more advanced substructures. The mere fact these multi-turbine, precommercial pilot projects are evolving from single-turbine prototypes is a testament to the viability of floating offshore wind turbine technology. The Equinor Hywind plant off the coast of Scotland is the most prominent of these second-generation projects (Figure 1). Globally, there are about 11 pilot-scale floating plant projects under development, in project sizes of 10–50 MW, totaling approximately 229 MW [4]. Collectively, these next generation pilot projects will help benchmark costs for floating offshore wind and demonstrate more streamlined precommercial technology at a lower cost per MW relative to the earlier first wave of prototypes. Although the new designs exhibit significant improvements compared with early prototypes, baseline cost analysis does not indicate economic viability without further optimization, innovation, and up-scaling to commercial plant sizes [5,6].

Preliminary analysis suggests that, in time, floating technology has the potential to achieve a lower cost of energy than its fixed-bottom counterpart [7]. Detailed modeling shows, however, that the needed long-term cost reductions are not likely to come from a single ‘‘break-through’’ invention. Moreover, different water depths and metocean conditions may require different innovations to be cost-competitive. Instead, significant cost reductions will come from a disciplined combination of complementary innovations, or a technology cost reduction pathway. We use the term, ‘‘building blocks’’ to refer to these complementary innovations, which may be technologies (e.g., downwind turbines), design features (e.g., rapid disconnect cables), or installation and operational strategies (e.g., quayside maintenance by towing turbines back to port [8]).

Article overview

This article describes the status of floating offshore wind technology at present, and provides a long-term vision for achieving unsubsidized market competitiveness for floating offshore wind technology across all regions of the United States and other global markets. The pathway to realize this goal requires the use of a new framework customized for floating offshore wind energy systems. The three key features of the framework envisioned in this article are its system-level coverage of the engineering and cost over the lifetime of the plant, its variable levels of fidelity, and its ability to handle uncertain inputs. To incorporate the lessons learned from the oil and gas industry, the fixed-bottom offshore wind industry, and the pilot floating wind projects to date, a set of design criteria known to lower cost can be used as guide or filter within the framework to focus on the most promising concepts. The article then outlines a road map for assembling this design framework and a research plan that exercises the framework to assess new concepts. The background literature associated with these concepts is in the following paragraphs.

FIGURE 1

The Hywind Scotland floating wind farm (Photo: Øyvind Gravas, Woldcam Qc Equinor).

Multidisciplinary analysis and optimization

A multidisciplinary analysis and optimization (MDAO) design approach would be beneficial for any wind turbine system, but may have a higher impact for floating offshore systems due to their lower level of maturity, more complicated physical environment (aero-hydro-elastic loading), compliant nature (motion in all six degrees of freedom), and tight inter-dependencies among their subsystems. For example, the rigid body structural dynamics can impact the power production of the turbine. The characteristics that minimize balance of station (BOS) costs must be integrated at the outset into the designs of the power generation and load paths. The control systems at the turbine and plant level must balance the demands of immediate power generation versus long-term fatigue of the components. An MDAO approach allows the design engineer to rapidly evaluate system-level impacts and cost-benefit trade-offs of component level improvements or new technologies.

MDAO has its roots in the aerospace industry with publications reaching back into the 1960s and 1970s [9,10]. It grew within aerospace and expanded to many more industries with its own dedicated conferences and professional organizations. See Martins and Lambe [11] for a more comprehensive review. With its close ties to the aerospace industry, the wind industry was also a natural application for MDAO practitioners. Kühn et al. [12] performed one of the first cost-based optimizations of an offshore wind plant in 1999. Later, Dykes and Meadows [13] provided a detailed review and position paper on systems engineering and MDAO for wind energy, which triggered the development of the Wind-Plant Integrated System Design & Engineering Model (WISDEM®) tool.

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[3] Musial et al. [2] found that human use conflict diminished from 49% inside 3 nm to less than 8% outside 50 nm.

Using WISDEM, Ning and Dykes [14] identified a cost of energy decrease of 5% for land-based sites and 2% for offshore sites by loosening constraints on rotor tip speed. Fleming et al. [15] showed the ability to increase the power density of a wind farm by approximately 30%. Concurrently, Maki et al. [16] published one of the first system-level optimizations of a wind turbine and found potential for a nearly 30% decrease in the cost of energy. Ashuri et al. [17] used MDAO principles in a system optimization of an offshore turbine and showed a 2.3% improvement in levelized cost of energy (LCOE) compared with an NREL 5 MW reference turbine [18]. This work was focused on the aerostructural interactions of the blades, rotor, and tower and had only loose coupling to wind plant and BOS models. Bottasso et al. [19] started developing a research-focused systems engineering framework, with emphasis on the rotor. This work used multiple inner optimizations instead of one global optimization and culminated in an excellent summary paper by Bortolotti et al. [20]. By most accounts, future interest in MDAO will continue to proliferate within the academic and industrial wind energy communities.

The International Energy Agency (IEA) has also recognized the need for systems engineering tools in wind energy design. A research task has recently been initiated under the IEA, Wind Task 37 – Wind Energy Systems Engineering: Integrated Research, Design, and Development [21]. This task aims to coordinate international research activities toward the analysis of wind power plants as holistic systems by improving the practice and application of systems engineering to wind energy research and development. A couple notable publications from this effort include Perez-Moreno et al. [22], describing a research road map for MDAO in wind energy, and Perez-Moreno et al. [23], which proposed a reference offshore wind plant, designed with MDAO.

Multifidelity optimization

An added feature the multidisciplinary framework for floating offshore wind plant design is the ability to support multifidelity optimization. In this article, levels of fidelity are defined as:

- Low-fidelity models: Simple design or sizing tools that typically deal with steady state or quasi-static conditions;
- Medium/middle-fidelity models: Also referred to as ''engineering-fidelity,'' these models capture the relevant physics, but with some compromises to improve simulation speed so that many simulations can be performed in a design cycle.
- High-fidelity models: Full implementation of the governing equations with minimal simplifications, such as the Navier–Stokes equations with subgrid turbulence models. High-fidelity models are so computationally expensive that only a handful of runs can be made in a few weeks of time. These models are useful for understanding the underlying physics, spot checking the final design, and calibrating and verifying lower-order models.

Typically, design-space optimization is used in the early stages of conceptual design to traverse an extremely broad trade-space and find the optimal regions of benefit per unit cost. To accomplish this task, optimization algorithms need to execute the simulation model many thousands of times, so lower fidelity models that execute rapidly are typically employed in this stage. After promising conceptual designs are found, medium- and high-fidelity models are then employed to fully understand the immediate neighborhood of the trade-space and/or further refine the design to a more detailed level. This is the Traditional Paradigm depicted in Figure 2. Design optimization using high-fidelity tools is an active area of research but heavily dependent on high-performance computing resources and not yet commonplace in industrial applications.

In many applications, the in-step progression of model fidelity alongside the narrowing of design uncertainty works well. However, in other applications, the low-fidelity models can lead the optimization astray to a design space that is later revealed to be infeasible or suboptimal when interrogated by the higher-fidelity models. It could be that the coarser parameterization or representation of the physics failed to capture a phenomenon or constraint that manifests itself in the higher-fidelity models. If the design progresses down a path that is only later determined to be infeasible, the cost of making changes only increases and becomes more disruptive (Figure 2). In these instances, a multifidelity (also referred to as variable

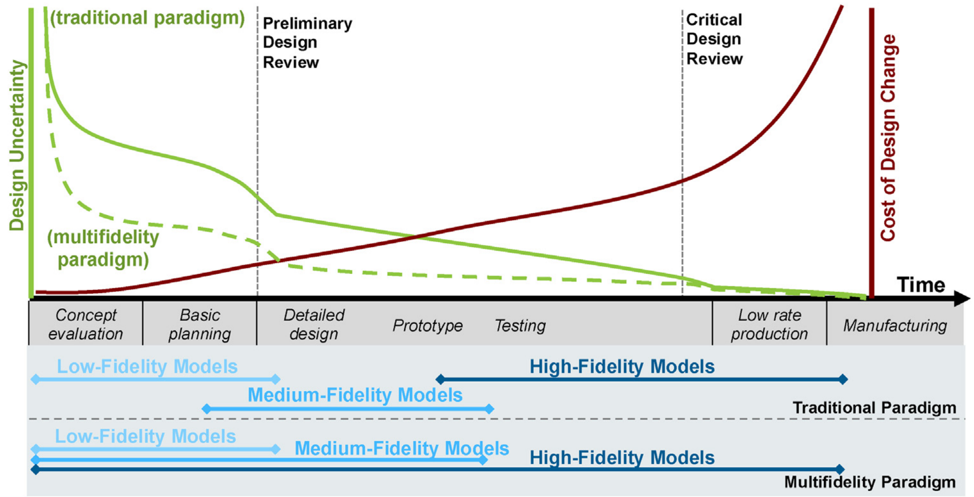

FIGURE 2

Standard engineering design process alongside model fidelity.

TABLE 1

Comparison between land-based and offshore (fixed-bottom or floating) turbine rotor nacelle assemblies [4,29,30].

	Land-based turbines	Fixed offshore turbines	Floating offshore turbines
Configuration	3-blade downwind	3-blade downwind	3-blade, up/downwind?
Machine rating	1–5 MW	3–15 MW	3–15 MW
Hub height	Max	Min (30 m+blade length)	Min (30 m+blade length)
Rotor diameter	100–130 m	130–170 m	130–170 m
Gearbox	Multiple-stage	Multiple/single-stage or direct-drive	Single-stage or direct-drive

fidelity) optimization strategy that incorporates the higher-fidelity model's insights into the earlier stages of trade-space exploration is advantageous. This strategy might include the use of a reduced-order surrogate of the higher-fidelity model that still captures the key behaviors otherwise missed by an alternative low-fidelity model. Another strategy includes periodic evaluations of the higher-fidelity model amongst the low-fidelity executions to course-correct the optimization algorithm. Significant work has been done to devise strategies that ensure convergence to provably optimal solutions under a variety of problem formulations [24–26].

We advocate that a system-level optimization of a floating offshore wind turbine will require a multifidelity strategy to incorporate middle- and high-fidelity models into the conceptual trade-space exploration. The compliant nature of a floating system means that coupled dynamics must be modeled and accounted for to accurately estimate power production performance and load estimation. These dynamics will also incur additional stability constraints, so they must be evaluated by the system models to uncover their associated trade-space boundaries.

Optimization under uncertainty

Many of the individual input variables within the floating wind optimization problem have some level of uncertainty associated with them. The uncertainty sources can be categorized in many ways, with common labels of aleatory and epistemic, or systematic and random uncertainty [27]. An example of aleatory uncertainty might be the statistical wind and hydrodynamic load profiles as they vary temporally and spatially. An example of epistemic uncertainty is the imperfect representation of the many physical phenomenon within an approximate model or the cost estimates that can be categorized as ''best guesses''. Practically, both the aleatory and epistemic uncertainty can be addressed by assigning probabilistic distributions to the parameters instead of discrete values. These input uncertainties must then be propagated through the simulation to generate uncertain outputs. A Monte Carlo approach is the most rudimentary approach to this step, but the field of uncertainty quantification has developed more rigorous mathematical and computationally efficient methods of propagating uncertainty as well [28]. Nevertheless, traditional optimization algorithms, which try to minimize one or more metrics from a finite set of inputs, are not well equipped to handle uncertainty in the inputs or outputs. When doing design in the presence of uncertainty, the goal is to generate a concept that robustly gives good performance in any unforeseen physical or cost environment to reduce risk. Robust design requires a different set of optimization techniques, but are available in the literature.

Status and gaps for floating wind energy

This section summarizes the current state of floating offshore wind technology and highlights key areas for improvement (through innovation or optimization). The text is divided into turbine-level and plant-level discussions.

Turbine level

Rotor and nacelle

At present, the state of the art for wind turbines on floating substructures is identical to fixed-bottom systems, because purpose-built floating wind turbines have not yet been designed or built. The development of a purpose-built floating wind turbine is not expected until there is sufficient market certainty to justify the development risk to original equipment manufacturers (OEMs) [4].

A broad comparison between land-based, fixed-bottom offshore, and floating offshore turbine rotor nacelle assemblies (RNAs) is shown in Table 1. Two of the most significant trends that differentiate offshore turbines from land-based wind turbines are their larger size and drivetrain architectures [4]. The larger offshore turbine ratings, up to 15 MW, have contributed to major reductions in the BOS costs by reducing the number of turbines required to achieve a desired plant capacity rating. Larger turbines that are fewer in number translate to lower construction costs, lower operation and maintenance (O&M) costs, and higher capacity factors [29]. Land-based turbines are more constrained by transportation and land-use exclusions, so turbine ratings are generally lower [30]. For both land-based and offshore turbines, most are conventional upwind machines. Two exceptions to this trend are Hitachi's 2 MW and 5 MW down-wind turbines, deployed successfully on proof-of-concept floating offshore projects in Japan [31]. Offshore wind turbines have also adopted different drivetrain configurations from land-based designs, with the use of direct-drive generators or geared drivetrains with medium speed generators. These drivetrain configurations have fewer moving parts and promise lower maintenance costs, with the drawback of generally being slightly heavier (in the generator) and costlier up-front than traditional modular gearboxes[4] [32,33]. In floating applications, however, weight may be a stronger cost driver than in fixed-bottom systems, so difficult cost-benefit trade-offs will have to be made. New technologies such as greater use of composites, higher flux magnets, material optimization, and superconducting generators promise weight reductions in direct-drive generators, which could reduce the weight penalties for floating applications and allow further upscaling [34].

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[4] Note that no turbine OEM currently produces a modular geared offshore turbine at the 6+ MW scale [32].

Tower

Floating offshore wind turbines to date use conventional tubular, steel towers to connect the RNA to the substructure. Towers on current offshore wind turbines are generally as short as possible because vertical wind shear in the marine environment is lower and therefore benefits of higher hub heights to access higher wind speeds are not significant enough to offset the added capital cost [30]. Lower center of mass and thrust center also minimizes the stabilization burden on a floating substructure [34].

Nevertheless, offshore hub heights continue to grow because the rotor diameters grow with increasing machine rating and a 25–30 m blade tip clearance with the water surface must be maintained for ship passage [35]. Higher hub heights typically mean wider tower bases, but there are manufacturing and quality-control issues to overcome for large base diameters while keeping modal frequencies away from wave excitation frequencies [36]. For example, rolling and welding thick steel becomes more expensive as sizes and thicknesses increase [37]. To reduce mass and facilitate fabrication, both above and below the waterline, alternative configurations may be sought in the future, including use of guy wires, lattice towers, prestressed concrete towers (e.g., steel and fiber reinforced), and composite towers [34,38,39]. Alternative materials may also help to push tower natural frequencies away from blade passing frequencies and wave frequencies.

Floating substructure

Platform technology is generally based on three classical designs: the spar, semisubmersible, and tension-leg platform (TLP), which are all derived from the oil and gas industry [2,40,41]. Each classical design emphasizes a different method to achieve static stability (although all draw upon elements of the other). The spar uses a low center of gravity through deep-draft ballast, the semisubmersible uses large water-plane area and distributed surface buoyancy, and a TLP uses mooring line tension [2,34]. These three concepts are shown in Figure 3.

The spars are generally deep draft cylinders, fabricated easily and cheaply, from rolled steel or concrete with ballast added at the lowest point. Their deep draft limits where they can be built and towed, so they cannot easily take advantage of quayside assembly and commissioning [42]. The semisubmersible substructure has been favored by many technology developers in the early stages because buoyancy stabilization at the water plane inherently results in shallower drafts for easier quayside assembly, commissioning, and tow-outs [2,7]. However, the semisubmersible may be disadvantaged with additional joints from the use of truss structures, higher overall mass, and an increased amount of structure near the waterline, leading to increased cost, higher wave loading, and greater fatigue and corrosion risk [40,43]. TLPs have the advantage of lower platform motions under operation and may exhibit the lowest platform mass of the three classical designs. However, they are typically unstable until the mooring lines are connected and tensioned, making installation difficult [2]. They also have higher risk of instability in case of line snap and are more vulnerable to earthquakes and tsunamis due to their reliance on high capacity vertical load anchors [44].

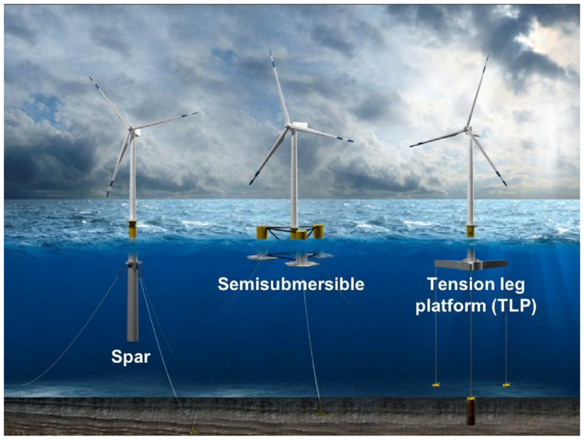


FIGURE 3

Classical floating platform concepts including spar (left), semisubmersible (center) and tension leg platform (right) (Image credit: Josh Bauer, NREL).

Many new platform designs seek cost savings through hybridization of the classical designs to achieve more optimal characteristics. Hybrid concepts may represent a future class of floating wind platforms with transformable configurations adapted to perform under multiple states, including assembly, construction, and load-out, as well as operation on station. For example, spars and TLPs seek the shallower drafts and fully assembled stability of a semisubmersible to allow quayside assembly, commissioning, and tow-out. These next generation hybrid concepts are now emerging with examples such as Stiesdal Offshore Technologies A/S's TetraSpar concept [45] (Figure 4a), GICON's deployable anchor TLP [46], and SBM and IFP Energies Nouvelles' (Figure 4b) deployable tension leg platform [47].

Mooring and anchors

For all floating substructure designs, a mooring and anchoring system is used to keep the substructure on station. The semisubmersible and spar typically use catenary mooring lines attached to drag embedment or suction pile anchors [48]. In these systems, the cost of the mooring lines and chain is driven by the long lengths (more than 4 times the depth) needed to prevent vertical loading on the anchors. A TLP, on the other hand, has shorter, nearly vertical mooring lines that carry loads an order of magnitude higher, increasing the complexity of the anchors and tension legs themselves. Increased anchor complexity also increases capital costs, costs for preconstruction site assessments, and installation [48].

A current technology gap is effective shallow-water mooring systems. For offshore wind deployments in transitional depths, 50–100 m, there is not enough length to create stabilizing weight on conventional catenary mooring lines [49]. Taut mooring lines attaching to TLP platforms are ostensibly a viable option, but have not been sufficiently studied at transitional depths [50]. One solution that may be equally applicable to shallow and deep water, and scales well with turbine size, is angled, semi-taut mooring lines [47,51]. Mooring technology solutions that can address the transitional depths are critical for floating wind market adoption because many existing near-shore lease areas (e.g. Massachusetts) extend into these depths already. Developers in these lease areas will be faced with a decision to either push fixed-bottom substructure technology to even deeper depths or switch to floating substructures with shallow water mooring systems. Having a proven

(a) Image credit and copyright: Stiesdal Offshore Technologies A/S

(b) Image credit and copyright: SBM Off- shore

FIGURE 4

Examples of next-generation concepts.

mooring technology solution at these depths would mitigate the risk to developers of switching to floating turbines.

Controls

Generally, the state of the art for floating wind turbine systems is to design platforms that are inherently resistant to wind and wave excitation, and modify the fixed-bottom OEM control system to further reduce oscillations [52]. However, these adapted fixed-bottom offshore control strategies are most likely suboptimal in floating systems. The compliant nature of the floating wind system allows for large motion excursions, producing low-frequency oscillations in the translational (surge, sway, heave) and rotational (pitch, roll, yaw) degrees of freedom. These large motions lead to increased inertial loading in the system, which must be mitigated to keep the support structure at a reasonable size and to prevent excess fatigue loading on the turbine, which could shorten its life [52–54]. Using a control strategy developed for fixed-bottom turbines in a floating application could induce significant instability [53,54]. Each of the classical designs shown in Figure 3 will exhibit different behaviors in each degree of freedom and as such have different requirements for their controllers [55]. Control strategies that emphasize, *co-design*, where the entire system and controller are designed together, will offer the greatest performance benefit [56]. This may include new active and/or passive actuation technologies that increase damping to wind and wave excitations.

Relevant standards

To ensure survivability, wind turbines are designed following the International Electrical Commission (IEC) 61400 series of standards. IEC 61400-1 prescribes a set of simulations to assess the extreme and fatigue loads the turbine will experience over its lifetime, including operational, idling, start-up and shut-down, and fault conditions [57]. This original standard was then expanded in the IEC 61400-3 standard to address the additional conditions relevant to fixed-bottom offshore wind turbines, which includes wave, current, and tidal conditions in combination with the wind conditions, as well as misalignment between the two [58]. The 61400-3 standard does not specifically address floating wind, but a new guide (IEC 61400-3-2) is soon to be released that discusses the issues that need to be considered for the more compliant, floating system [59]. Since floating offshore wind is still a young technology, this new guide is labeled as a Technical Specification, which does yet have the force of an International Standard.

As will be discussed in the following Section, the goal of the standards is to ensure survivability, meaning that the wind turbine can produce power for 20 years with a prescribed minimal probability of failure. A wide range of designs can meet this minimal threshold with most of these designs being nowhere close to an optimized solution. Further constraints and guidelines are needed to develop a design that is cost-effective. The work in this paper seeks to help identify the components that are needed to push design innovation toward these more cost-optimized design solutions.

Plant level

Wake and array effects

To develop a successful commercial wind project, one needs to not only consider the design of the individual turbine systems, but the design of the entire wind plant. Plant design focuses on the array placement (or layout) of the turbines and the control strategies that will maximize power [60,61] and minimize loads across the plant. Land-based and fixed-bottom turbines have yaw motors to align with the dominant wind direction, and yaw-based steering of wakes away from downstream turbines is an active area of research [15,62]. However, recent preliminary analysis has shown that wake-steering via tilting or pitching an upstream rotor has even greater potential for maximizing power production [63]. Most of these studies to date have focused on land-based or fixed-bottom applications, and will need to be revisited for the floating application with compliant motion. The degree of platform motion will likely require new aerodynamic tools [64,65] before attacking plant-level flow control and array optimization. Future floating wake steering research will also have to consider the different degree of yaw or tilt control authority on a floating platform [66].

Manufacturing, installation, operations, and maintenance

At the present time, the floating offshore wind industry remains too small to have established its own methods for manufacturing, installation, operation, and maintenance. Consequently, manufacturing and installation methods tend to be based on practices from the fixed-bottom and offshore oil and gas industry. However, the oil and gas industry may not provide the necessary insights for floating offshore wind because platform cost is much less of an issue and serial manufacturing is largely absent [47]. Floating wind-specific approaches are needed, but the investment in the development of maintenance strategies and new vessels is unlikely to occur until a more established industry emerges. Fixed-bottom offshore wind practices are transferrable for some manufacturing and installation tasks, but are inadequate for others, such as main component replacement. For this task, some substructure concepts allow for disconnecting the platform from its moorings and towing the turbine and substructure to a service port [44,67]. For the substructure designs where this is not a possibility, the complexities of marine operations for component replacement are considerable and vessel arrangements that minimize relative movements of turbine, vessel, and crane must be devised [35]. This is an example of the need to incorporate O&M strategies into the engineering design of the turbine.

Another complexity for floating installations beyond fixed-bottom plants is the need for specialized, catenary interarray electrical cabling [44]. Fixed-bottom installations can bury all electrical cabling, but in a floating plant only the export cable that connects to the onshore grid is projected to be buried underneath the sea floor. The interarray cables that link one turbine to another typically terminate at an electrical substation for the plant, which also must be supported by its own floating substructure [68]. Furthermore, as the turbine rating continues to grow, so too must the ratings of the cables and substation grow to handle the increased power and loading from platform motion. Finally, development of robust, dynamic cables will also be required as the motion of the floating turbine platforms and array substation places dynamic loads on the cabling [69].

Grid integration

Grid integration research is fundamental to understanding the overall value and benefits of offshore wind to the power system. Although grid connections from offshore wind plants to the land-based grid have been completed many times over for fixed-bottom installations, there are still challenges and room for new innovations and thinking. The switch to a floating setting does not add or subtract from these challenges or potential solutions. High voltage direct current (HVDC) export cables will likely be used due to the larger distances from shore of floating offshore wind projects [70,71]. Nevertheless, with the lack of an existing offshore electrical cabling grid in the U.S., there is an opportunity to develop newer, more innovative approaches. These innovations may be found in inter-array cabling, power electronics technology (converters, transformers, etc.), transmission voltages, or in common substations serving multiple plants [70,71]. Furthermore, the growing importance of secondary services to the utility grid beyond the traditional value of a kilowatt-hour (e.g. frequency inertia and stability, voltage support, economic dispatch, reserves, resilience, etc.), should also be kept in mind [72].

Environmental impact

As the number of offshore wind installation has grown, so too has the awareness and number of studies about the impact of these installations on marine life. Although the hazard of spinning blades to birds has been more publicized, the greatest environmental issue identified for offshore wind is the impact of acoustic noise generated from pile driving during the installation of fixed-bottom supports on marine mammals [73,74]. From this perspective, floating wind plants would be less intrusive to the marine ecosystem. On the other hand, some are concerned that the network of electrical cables and mooring lines may interfere with migrating marine life, such as whales [75], although there is no evidence yet to support these fears. Some of the impacts of offshore wind can also be beneficial, such as habitat gain for benthic organisms with cascading benefits through the food chain [73].

On the human-impact side, there are fears that extensive offshore wind plant development could significantly encroach upon fishing territory [76,77]. One proposed resolution is the allowance of transit lanes through the offshore wind farm [78]. The ability of floating wind turbines to be located further from shore, in deeper water depths, might reduce the imposition upon the fishing industry. Lessons from the efforts to mitigate the environmental and land-use impact of land-based turbines may be relevant.

Vision for advancement of floating offshore wind

This paper describes a path to achieving low cost floating offshore wind energy that the authors believe can be accelerated by adopting a design paradigm that draws from collective experience and lessons learned implemented in a fully integrated, systems engineering design approach. The intent is for this new design capability to be able to close the gaps identified in the previous section.

Current approach: Iterative

Before presenting this vision for a new design approach, it is helpful to review the current state of the art and examine why floating offshore wind energy necessitates a new paradigm [79,80]. A graphical depiction of the current design paradigm, labeled the *Iterative* paradigm, is shown in Figure 5 and reflects the current market reality where multiple companies and stakeholders have to come together to develop an offshore wind plant (fixed-bottom or floating). Each company brings to the table its own area of expertise and profit motive. A large OEM designs the turbine and tower, another company designs the substructure, and the two must iterate a few times to develop a controller that minimizes the loads and maximizes the power as much as possible. The combined turbine-substructure product is handed to a developer, who tackles

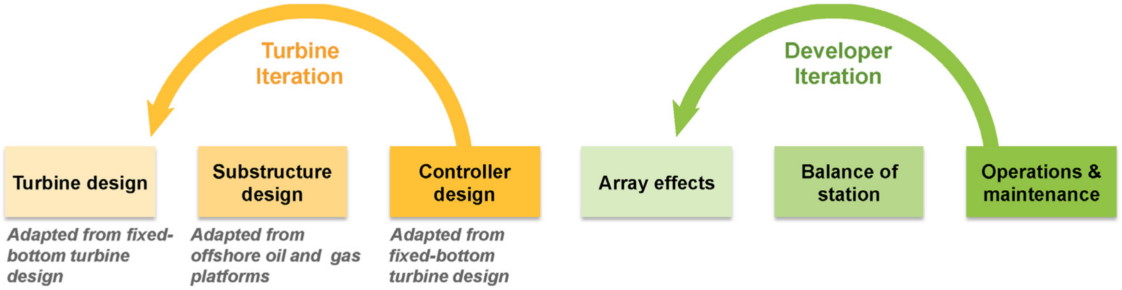
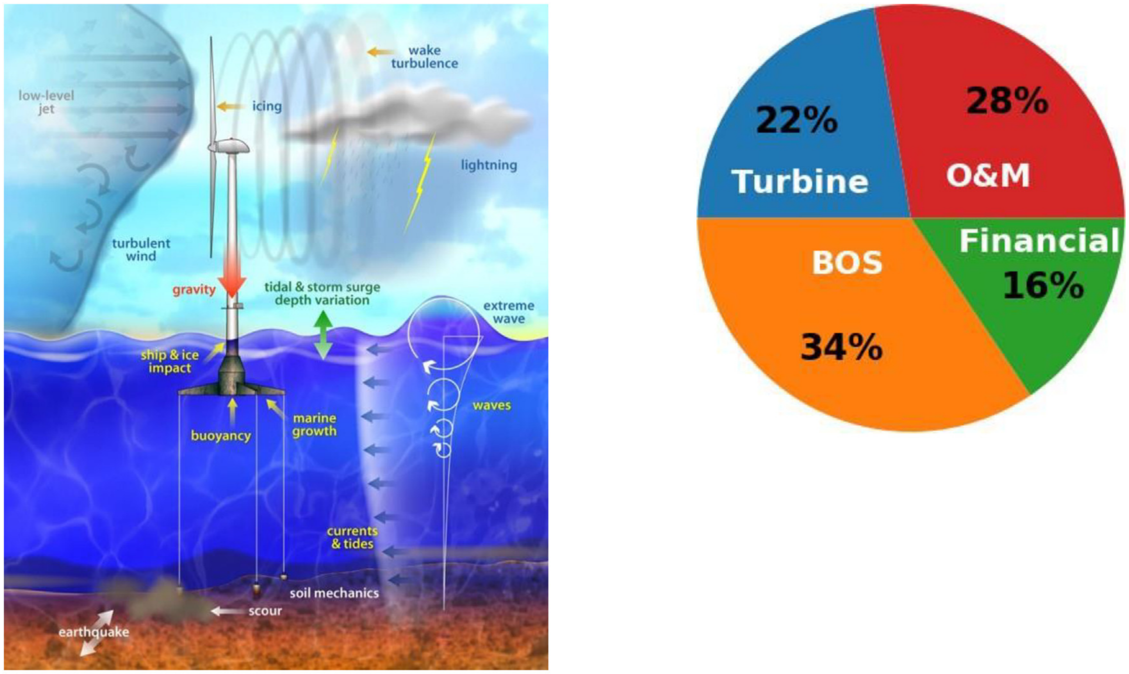


FIGURE 5

``Iterative'' floating offshore wind plant design.



(a) Illustration by Al Hicks, NREL

(b) Source: Mone et al. [81]

FIGURE 6

Complexity of the physical environment and cost breakdown for floating offshore wind energy systems.

array layouts and the logistics of assembly, installation, and operational maintenance.

There is a strong argument to be made that the *Iterative* paradigm has proven to be extremely successful in growing the offshore wind industry and market size. There has been tremendous growth in offshore wind installations over the past decade, especially in Europe. Although the *Iterative* paradigm is a reflection of market realities, if used to tackle the design of a floating offshore wind plant, it would likely arrive at a sub-optimal solution. The *Iterative* approach is inadequate for floating offshore wind energy systems because of the tremendous increase in complexity of the physical environment, the engineering solutions, and the logistics. Figure 6a shows a diagram of the physical environment that a floating offshore wind turbine exists in. The list of physical phenomena that must be well characterized is long and spans many disciplines. Engineers do their best to understand this environment and design a good product despite the daunting complexity. However, the turbine capital costs represent just 22% of the LCOE of the system [81]. All the other capital costs are buried in the logistics, BOS, financing, and O&M details, which can be as complex as the turbine engineering (Figure 6b). Because these other costs are also tightly integrated with the chosen turbine-substructure design, a more holistic and integrated design approach can be beneficial.

Proposed approach: Integrated

Ultimately, a fully integrated, systems-engineering design approach is needed to produce major, transformational cost reductions in floating wind energy. A graphical comparison of this *Integrated* design paradigm is shown in Figure 7. Essentially, an analysis framework for wind plants must capture the entire power path, from the aerodynamics to the generator and grid; the entire load path, from the blades to the nacelle through the tower and foundation; the controller that balances power production versus loads; and the entire balance sheet, from concept through decommissioning. Executing this proposed approach in a closed-loop optimization framework is critical to achieve superior cost and performance gains. However, a multidisciplinary exploration of the trade-space, the set of all possible designs, is a computationally intensive task. Focusing the attention of the engineer on design

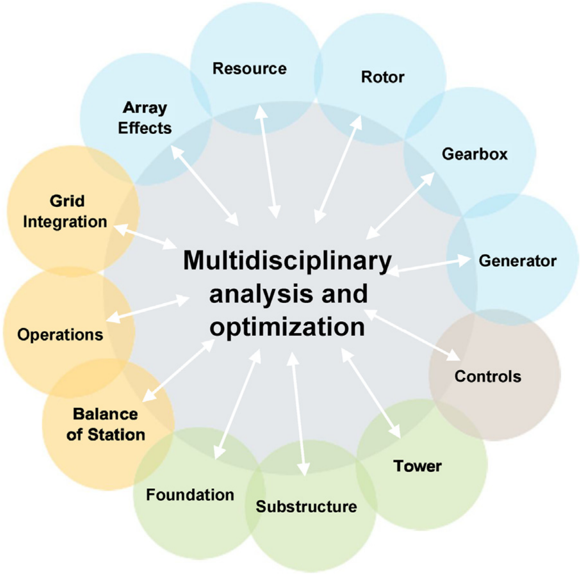


FIGURE 7

``Integrated" floating offshore energy design paradigm featuring multidisciplinary design analysis and optimization.

criteria that are known from experience and techno-economic modeling (via cost-benefit trade-off and sensitivity studies) to have the greatest impact on cost would effectively narrow the trade-space and accelerate the optimization. Therefore, this approach also puts forth a set of cost-cognizant design criteria or constraints, by which the vast number of design options can be culled to those with long-term cost-competitive potential.

Pathway to cost-effective designs

One common misconception with multidisciplinary design analysis and optimization (MDAO) is that the design framework and optimization algorithms replace the engineer and dilute the value of intuition and experience. For the application of floating offshore wind energy systems, the engineer and experience will always be essential for generating useful analysis results. The evolution of floating offshore wind technology toward more cost-optimized designs can be viewed as steps to narrow the trade-space based on the hierarchy shown in Figure 8. At the broadest level, the entire trade-space includes all possible designs, whether feasible and cost-effective, or not. Next, consensus-based standards through the International Electrotechnical Commission and American Petroleum Institute must be met. Note that for offshore floating wind turbines, as described above, there are only technical specifications that act as guidelines that have not yet been codified into official standards yet. Furthermore, standards are intended to ensure that the turbines operate in a safe and predictable manner. They do not ensure that the turbines will be cost-effective or profitable for their operators. These standards are encapsulated in design frameworks, such as the one proposed here, through constraints. This is the first step in narrowing the trade-space depicted in Figure 8. However, even a fully mature certification process would serve mainly to reduce deployment risk, not drive innovation or push the technology toward lower-cost designs. This is the motivation for the second step in Figure 8, which arrives at a smaller region of the trade-space that encompasses the designs with the potential to be cost-competitive. Concepts in this space satisfy a rubric of criteria focused on lowering cost, which are detailed below. Essentially, the real-world lessons learned from floating turbine prototypes and tank tests are also integrated into the design framework. They manifest themselves in the underlying architecture of the design framework, the geometry parameterization, the constraints, design variables, and other options available to the user. Without this experience, the optimized designs that come out of the framework would likely fail to gain credibility among the offshore wind community. Using these criteria to further narrow the design space allows the engineers and their optimization tools to focus on the region of the trade-space that has the greatest cost-reduction potential. The final step in Figure 8 identifies the floating wind designs with the highest potential for cost reduction and commercial competitiveness through a system-level, multifidelity, multidisciplinary optimization of the remaining trade-space. Only the designs that demonstrated the highest merit in the lower fidelity screenings would be afforded the resources to engage in this optimization.

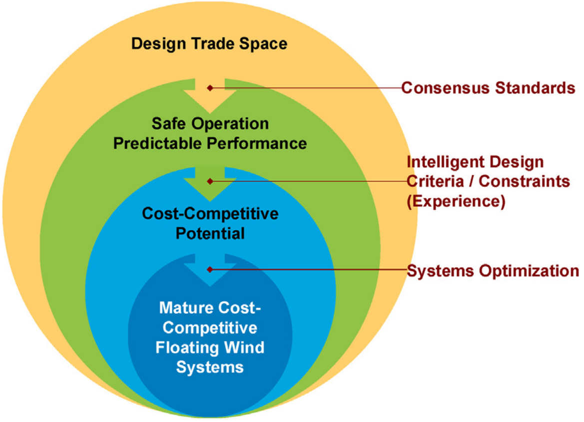


FIGURE 8

Narrowing the trade-space to accelerate floating system optimization.

Design constraints for cost-competitive potential

An initial list of the design constraints that could quickly hone in on designs that have the potential to be cost-competitive are listed below. The first two criteria are obvious prerequisites, but are included for completeness. In general, these criteria represent the major cost drivers, as proposed by the authors and observed from industry experience, but may not be an exhaustive list as further information is received from the broader industry and academic communities.

Maximize energy production: Designs should maximize net energy production potential at a given site to be beneficial to the end users and profitable to developers.

Regulatory and standards compliance: Within the optimization process, it must be ensured that final designs comply with all local and national regulations and permitting requirements.

Design standardization: A mass-produced floating turbine design should be easily adaptable to many sites, independent of water depth or sea state. This applies to all major components of the design, not just the floating platform.

Manufacturability: The platform should be economically manufacturable and transportable from facilities with relatively easy access to assembly locations.

Deployability: The assembled system should have a hydrodynamically stable configuration for assembly and tow-out to enable use of common ports near deployment sites. The assembled system should be adaptable to the conditions at regional facilities during assembly and tow-out without expensive conversions (e.g., tilting spars, transforming flexible hulls, shallow draft systems).

Maintainability: The system design should use reliable proven turbine systems and implement O&M strategies that minimize human labor at sea and heavy lift vessel use through in situ maintenance. The platform design should maximize accessibility or allow for easy tow-back to quayside maintenance facilities.

Scalability: Designs should be able to demonstrate neutral or advantageous cost scaling to turbine sizes of about 15 MW, with corresponding rotor sizes of approximately 240 m and tower heights of 150 m [82]. Scale-up potential shall be estimated using increased infrastructure requirements and system mass as proxies for cost.

Minimize operational loading and platform motion: The platform response to aerodynamic and hydrodynamic loading should demonstrate a neutral or small increase in turbine structural loading relative to a fixed-bottom system.

Weight minimization: The system design should avoid features that add additional weight above the waterline or raise the center of gravity. Features that reduce weight above the waterline may enable corresponding weight and material reductions in the substructure.

Corrosion control: The system design should seek to minimize the long-term effects of corrosion and environmental degradation by reducing exposure and through active mitigation, especially with regard to avoidance of and/or protection of corrosive materials near the waterline. This is especially important to minimize long term O&M costs.

Decommissioning: The removal or repowering of the system should be described as part of the design and efforts to minimize these costs should be demonstrated. Ease of removal should be part of the original design basis.

Design framework implementation

Overview

To reach the lowest-cost end point for floating designs, a system-level optimization methodology for the floating wind plant must be implemented. Our approach is to build on laboratory- and industry-based experience to create a robust design capability and approach that can lead to cost-effective floating turbine systems deployed by 2030.[5] This capability will require engineering tools to design systems comprising innovative technical and operational building blocks that span disciplines. To comply with structural and operational constraints early in the design phase, this framework will require multifidelity capabilities. To account for unknown performance and costs of new technology, the framework will also require uncertainty management strategies. To be a valuable tool to the broader community, it will be open-source and widely available.

Existing tools

For floating wind turbine engineering models, that focus primarily on turbine physics, it is imperative to capture the coupling between the environmental excitations and response of the full system under both normal (for fatigue) and extreme (for ultimate) loading conditions through the use of ‘‘aero-hydro-servo-elastic’’ tools. An extensive review of these tools was recently conducted by both Cordle and Jonkman [83] and the INNWIND project [84] with many of them still under validation against measured physical data to ensure their accuracy across a broad range of floating systems and conditions [85,86]. As designs evolve and are optimized against tighter margins to lower cost, the capabilities and fidelities of these tools may not be sufficient to represent the configurations of new concepts. Additional tool development will likely be required as a result.

For wind systems engineering design tools, there are a number of packages that combine disciplines modularly, but are focused purely on the turbine system and do not consider BOS or operational aspects of wind energy.

Neither the engineering focused tools or the current set of systems engineering tools are sufficiently equipped to fulfill all of the requirements of the desired framework. The engineering focused tools lack the cost awareness and systems deisgn perspective needed. Conversely, the systems engineering tools lack sufficient fidelity of the physics to capture all of the critical design drivers. Instead, these two classes of tools must come together so that their strengths complement the weaknesses of the other. We have recently embarked on long effort to develop design tools that can fulfill this vision, which is described in further detail in the following subsection, and others may be striving toward a similar goal.

Tool development

The U.S. Department of Energy Advanced Research Projects Agency-Energy (ARPA-E) recently initiated a new program, Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servo-control (ATLANTIS), to revolutionize floating offshore wind turbine design and design tools through controls co-design (simultaneous optimization of control scheme and configuration). Under this program, NREL and its collaborators from the University of Illinois Urbana-Champaign and Colorado State University will develop the Wind Energy with Integrated Servo-control (WEIS) toolset. WEIS aims to satisfy all of the requirements identified here and enable multifidelity, controls co-design (CCD) optimization of both conventional and innovative, cost-effective, floating offshore wind turbines in an open-source, user-friendly, and flexible solution.

WEIS will capture all of the critical nonlinear dynamics, system interactions, and life-cycle cost elements for a large range of floating offshore wind turbine archetypes and control actuators and sensors. The WEIS tool will generate system-optimal physical designs that enable innovative control strategies to stabilize highly flexible dynamics, reduce loads, and yield cost-competitive solutions. WEIS will be developed based on a concurrent design and optimization approach using proven CCD methods [88]. As shown in Figure 9, key features of WEIS include a system optimizer, both a rapid conceptual

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[5] We loosely define cost-effective either by cost parity with local competitors or willingness to sell floating offshore wind electricity at wholesale prices.

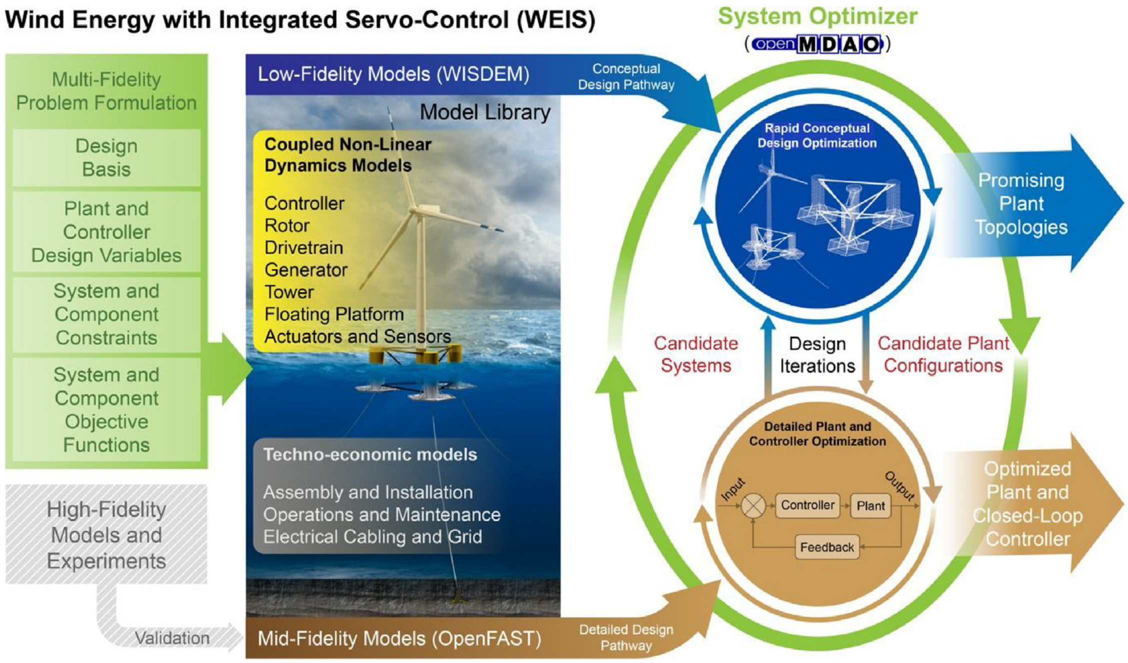

FIGURE 9

Wind Energy with Integrated Servo-control (WEIS) overview.

design optimization loop (driven by low-fidelity models based on WISDEM) and a detailed plant and controller optimization loop (driven by mid-fidelity OpenFAST-based models). Figure 9 shows, from left to right, a set of multifidelity problem definitions that supply the process with load cases, plant and controller design variables, system and component constraints, and objective functions. Load cases will include the full IEC 61400 set, including normal operation, storm, transportation, installation, and maintenance modes as well as user-defined load cases.

At the heart of WEIS is a multi-fidelity hierarchy of models that matches the natural, iterative design process that evolves from abstract concepts to detailed manufacturing plan. Figure 10 illustrates three tiers of multifidelity co-design iteration. The top-level WEIS optimization strategy will be guided by trust region multi-fidelity management, which has been well researched in the literature [26,89–91]. This is an effective coordination strategy to reduce the required number of optimization steps, while still robustly modeling critical dynamic couplings.

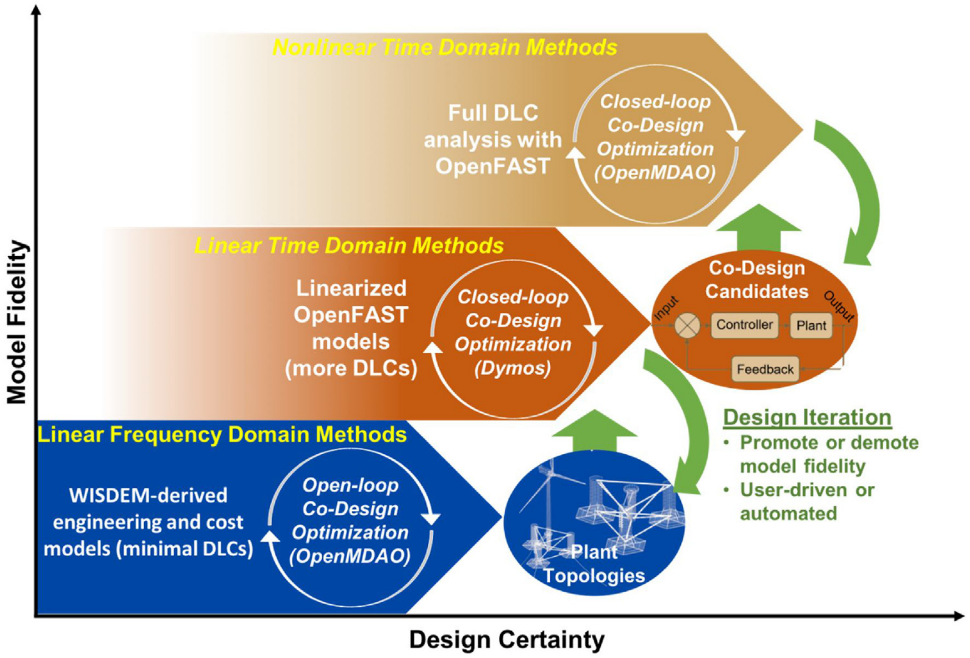

FIGURE 10

Design iteration over model fidelity envisioned for WEIS.

The first, and lowest level of fidelity, involves the use of linear, frequency-domain engineering models, derived from new functionality to be introduced in NREL's WISDEM tool set, coupled with full plant and lifecycle cost models. This level of fidelity enables conceptual design optimization over a trade-space to survey different plant topologies. This trade-space might be narrower for some users, those with existing designs, whereas others might want a complete survey of feasible floating offshore wind turbine topologies, with design options that are quite distinct from one another. Therefore, a set of models that evaluate extremely quickly, within seconds or minutes, through a limited number of design load cases (DLCs) is appropriate. At the same time, the models must also be able to represent the core physical environment to identify feasible and higher performing designs versus infeasible and/or more costly designs. When the user or optimizer arrives at a promising configuration, the analysis moves to the next level of fidelity.

The middle-fidelity tier is where the bulk of the CCD optimization occurs. This level of fidelity operates in the time domain and uses linearized models and a core set of DLCs to streamline the computational approach such that optimization loops and design iterations are tractable. These linearized models come from new functionality to be introduced in NREL's OpenFAST tool, and the linearization takes place around the design point of the configuration promoted by the lower fidelity optimization. In this way, the linearized models are valid for small variations of design parameters around the immediate design space (the trust region), while at the same time being a basis for state-space controls design. If the optimization ventures beyond this region of validity, new linearized models are generated. Nevertheless, these linearized models still capture real-world physics more accurately than the low-fidelity frequency-domain models. Therefore, it is possible that a candidate configuration will be revealed to be infeasible or too costly when interrogated at this level of fidelity. In this case, the design loop would return to the conceptual phase with updates to design constraints, so that the lower-fidelity models can work around the physics that they cannot fully resolve.

The highest level of fidelity within WEIS is the complete IEC and user-defined DLC assessment with the fully nonlinear physics-based models of OpenFAST. At this level of fidelity, the evaluation of a candidate plant and controller over the full list of DLCs is expected to require many hours. Therefore, running an extensive optimization with hundreds of analysis calls is intractable. Instead, optimizations performed at this level will involve narrow design variable bounds. If a final spot check reveals a constraint that is not fully satisfied, then the design process iterates again at the middle tier, with updated constraint values and an expanded set of DLCs. If the spot check and final controller tuning do not uncover any problems, then the WEIS design process is complete.

At each level of fidelity, the WEIS optimizations will be driven by OpenMDAO and its optimal control library, Dymos. OpenMDAO, designed by NASA Glenn Research Center, is an open-source software package built in the Python programming language that integrates complex models for multidisciplinary analysis that might include sensitivity analysis, design of experiments, metamodeling, uncertainty quantification, or optimization. Advanced optimization techniques—such as adjoint-based design, uncertainty quantification, and mixed-integer solvers—are already available, as are plug-ins to other numerical libraries [92]. Dymos extends OpenMDAO for simultaneous closed- and open-loop optimal control and plant optimization. Dymos casts continuous optimal control problems, such as trajectory optimization, into nonlinear programming problems so that they can be solved with traditional optimization approaches [93].

Floating offshore wind research

Once the system optimization tools are developed, a research plan can be executed that applies the tools to highlight effective cost reduction pathways. This will be accomplished by quantifying the cost-benefit trade-offs of individual building blocks (e.g., alternative substructure materials) and also different system or industrial strategies (e.g., standardized floating turbine models for different metocean condition classes). The new framework will be used not just to optimize the whole system and present a result, but more importantly to conduct trade-off and sensitivity studies such that the results are widely beneficial to the broader community. Some of the research studies include:

Novel substructure designs: To move beyond the standard three classical designs (Figure 3), a mixed-integer optimization of floating substructure components will be explored. The optimizer will be allowed to mix-and-match components and size them appropriately for a given turbine design to arrive at novel hybrid configurations. This is similar to the approach of Karimi et al. [94], but more extensive as the full lifetime LCOE will be considered. For example, the framework will be able consider designs that lower installation costs and reduce O&M costs by making access easier.

Novel anchoring methods: Current floating offshore turbine anchors are installed slowly, which becomes costly when considering the number of mooring lines requiring anchors across the entire plant. Significant cost savings might be possible through automated anchor installation methods and strategies to reduce the number of anchor points, such as sharing common anchors among multiple turbines. This would create an anchor and mooring network at a plant level that could reduce material and installation costs, as well as the scope of geotechnical investigations [95]. Challenges to this approach include the multi-directional loading dynamics on a single anchor and, perhaps, increasing wildlife impact challenges as well. An initial cost-benefit trade-off of this idea could be evaluated within the systems framework.

Stiffer structures versus lower weight in substructure: To date, floating substructures have been designed to minimize tower-top motion to support turbine designs imported from fixed-bottom installations that had not been designed to tolerate such dynamics. This has led to substructure designs that offer considerable stiffness, with the penalties of higher mass and higher tension in the mooring lines. With an integrated design of the substructure, tower, rotor, and control system, lower tower-top motion may be achieved while reducing overall system mass and cost. Essentially, some of the burden of minimizing tower-top motion may be shifted to the controller and away from the substructure, which would reduce overall mass. Additional actuation, such as tuned mass-dampers or active tendon tensioning, may also be economical. Mass-dampers have been proposed and analyzed in the literature [96,97], and some laboratory tests have been conducted, but they have not yet been implemented in commercial turbines. An optimized floating wind turbine will be designed to withstand the fatigue load environment, including turbine top motion, but will also minimize the energy production sacrificed to control loading and tower top motion.

Alternative materials: Currently, proposed and tested designs for floating wind substructures use steel and/or concrete. Trade-offs between these two alternatives could be quantified by a system framework, as they offer different advantages and disadvantages for manufacturing, assembly, overall mass, structural stiffness, longevity, and durability at sea. Additionally, other materials such as carbon fiber composites should be explored. Allowing an optimizer to choose between different materials for each element in a design, while adhering to the same structural requirements, would be a worthwhile feature.

Cost uncertainty and sensitivity studies: In exploring novel engineering designs in the context of LCOE, many of the cost elements are uncertain. This includes the cost to manufacture, assemble, install, and operate novel designs, especially since there is little industry experience in floating offshore wind energy. Some of these unknown costs will lead to significant uncertainty in LCOE, while others will have a minor effect. Conducting a system-wide sensitivity study that accounts for this uncertainty can guide future efforts to conduct research and gather information to reduce floating offshore LCOE uncertainty.

Value of towability: Two of the criteria mentioned above (*Deployability* and *Maintainability*) call out the ability to tow a fully assembled floating turbine to and from a port as a pathway to reducing costs. This criteria comes from prior experience and other modeling efforts, but can be better evaluated with this new framework. Designs that are constrained to be stable for towing will be compared to designs that do not have this constraint. The system trade-offs between the cost savings during installation and maintenance for the towable design will be compared to the expected improved operational performance (and perhaps lower capital cost) of the alternative.

Trade-offs between deep drafts and port availability: For substructure designs that can be towed, the compatibility of a design with a given port is chiefly dependent on the depth of the draft. Deeper drafts give better operational stability, but are more limited in the ports that they can use. Having to use ports that may be further from station adds to installation and maintenance costs. This system trade-off between deeper drafts and port compatibility will be quantified from a geo-spatial and LCOE perspective. In many regions, deep draft substructures may be a major barrier, forcing full assembly at sea, whereas in other regions perhaps port upgrades may be possible (at a substantial cost).

Floating plant controls: Floating turbines placed in arrays have not been studied extensively in terms of wake behavior, characteristic loading, or energy production. Because floating turbines have a soft coupling with the sea bottom, there are six extra degrees of freedom that may not be tuned out by the turbine controls system. Of these, yaw motion control will likely need the most significant redesign compared to fixed-bottom systems. Active yaw control systems will need different algorithms to accurately correct yaw errors and optimize yaw position for the wind plant as a whole system. New control strategies also need to be developed to maximize plant output without introducing new loading.

Floating turbine classes: Land-based commercial turbine models are generally designed to suit one or two wind speed classes at time. This standardization by class has allowed manufacturers to gain economies of scale in production and still achieve some site-specific gains in efficiency. Floating offshore turbine and substructure designs must account for more than just wind speed, however. Designing a single turbine and substructure model that suits all metocean conditions and ports is one option. Customizing unique designs for every installation is another extreme. Understanding that cost-benefit trade-off space could be facilitated with a system-level tool.

Some technology building blocks associated with the turbine are worth exploring within this new framework as well. Some of these technologies have perhaps not found success with land-based or fixed-bottom installations, but are worth revisiting in a floating context. Others are in the early stages of research and development and may offer tangible benefits to a floating wind system. Cost-benefit trade-off studies for these building blocks include:

Downwind rotors: Downwind rotor blades can be made more flexible (and lighter) than upwind rotors because blade deflections are away from the tower under high thrust loads, allowing blade stiffness requirements to be relaxed. For this reason, downwind turbines can have longer blades, lower specific power, higher capacity factors, and higher energy yield. Downwind machines can also relax yaw drive requirements, which are already more challenging in the floating environment, because rotors tend to be more stable downwind by acting as a natural weathervane. Finally, downwind turbines allow for pitch-based wake steering by tilting the rotor shaft, which is potentially more effective in increasing energy yield than yaw-based wake steering [63]. Historically, downwind rotors have been avoided because blades passing through the tower wake create infrasonic noise, but this will be less of a drawback in a remote offshore environment.

Two-bladed rotors: Two-bladed designs may reduce weight by the elimination of one of the blades. In addition, a two-bladed rotor can operate at higher tip speeds with lower solidity, reducing exposure to extreme loading and torque. Two-bladed rotors can be assembled as a single component onshore or offshore and installed as one piece to provide more flexibility in rotor installation. They also enable easier transport in height-constrained areas, such as under a bridge or near airports. Two-bladed configurations have increased cyclic loading over three-bladed configurations and have been aesthetically unpopular in land-based turbines. However, they are less visible offshore and the weight reduction at the rotor could propagate throughout the entire load path to lower cost.

Lightweight components: The cost increases from using more advanced materials in the system components may be offset through weight reductions in the substructure and throughout the load path. The tower, hub, nacelle bedplate, and much of the proposed substructure designs could substitute lightweight alternative materials such as fiberglass or carbon fiber composites for heavy steel. Reducing the mass above the waterline would lower the center of mass and relax the stability requirements. Designers may also consider higher carbon fiber content in the rotor to make the blades ultralight and stiff.

Novel generator technologies: Research is under way to develop generator magnets with higher flux densities to reduce weight with perhaps some cost penalty. New technologies such as superconducting permanent magnets or pseudo-direct-drive generators [98] are also being considered as a possible weight reduction pathway for direct-drive generators. The cost per unit energy of superconducting generators has a positive impact on scaling, becoming more attractive at larger turbine ratings. Relevant analyses include weight, cost, and scaling trade-offs.

Direct current (DC) generation: Due to the distance from shore and size of offshore wind plants,high-voltage DC transmission of energy from the plant electrical substation to the grid connection on land may be a prudent design choice for many applications. However, conventional turbine designs use alternating current (AC) generators requiring AC-to-DC conversion either at the substation or at the base of the turbine. One proposed alternative that has not yet been proven out is to avoid conversion losses by shifting the whole plant, including the turbines, to operate purely in DC. This would have system impacts on the generator, the power electronics suite in each turbine, and the array cabling and substation.

High-speed, low-torque rotors: Rotor speeds have been reduced for land-based turbines to reduce blade aerodynamic noise at the cost of energy production, efficiency, higher input torques, and heavier drivetrains. This trade-off has been necessary onshore, but offshore wind plants feature rotor tips speeds up to 100 m/s while relaxing noise requirements. The optimization of floating wind turbines may encourage further speed increases to reduce torque and lower drivetrain weight while balancing leading edge erosion challenges. Lower torque and higher speed will also improve turbine up-scaling potential by enabling higher speed direct-drive generators and gearboxes.

Conclusions

The resource and market potential for offshore floating wind turbines is enormous and the cost reduction potential is very promising. However, current engineering design tools are insufficient for the design of the next generation of floating wind systems that are cost-competitive with fixed-bottom installations. These systems are likely to have more flexible substructures, optimized turbine features, and transforming geometries to accommodate a wider range of conditions. Due to the complexity of the problem, a multidisciplinary, multifidelity, systems modeling approach with uncertainty quantification is required to reduce the number of viable technologies and identify the most impactful solutions. With focused effort and a solid foundation of existing models, the authors plan to develop this tool and use it to help the industry design the next generation of cost competitive floating wind turbines.

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