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Integrated Control, Mooring, and Flow Modeling Frameworks for Floating Offshore Wind Farms: A Comprehensive Research Analysis of Dynamic Stability, Wake Behavior, and Grid-Responsive Operation

Mateo Sørensen
Department of Wind and Energy Systems, Technical University of Denmark, Denmark

Jonas Keller
Institute of Fluid Dynamics and Control, Hamburg University of Technology, Germany

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ABSTRACT

Background: Floating offshore wind energy has emerged as one of the most significant frontiers in renewable power engineering because it expands wind power deployment into deep-water regions with stronger and more persistent wind resources than many fixed-bottom sites. The development of floating offshore wind farms, however, introduces a highly coupled engineering problem in which aerodynamic loading, hydrodynamic response, mooring behavior, yaw control, reduced-order wake modeling, real-time farm control, and grid-support functionality interact across multiple spatial and temporal scales. The literature demonstrates that these interactions are not peripheral but central to the viability, efficiency, and controllability of modern floating wind systems (Heronemus, 1972; Barooni et al., 2022; Chen et al., 2022).

Objective: This article develops a comprehensive research analysis of floating offshore wind systems by synthesizing the provided references into a unified conceptual framework. The study aims to clarify how mooring system architecture, turbine motion, wake dynamics, wind farm flow modeling, control design, and grid integration should be understood as parts of one integrated design and operation problem rather than as isolated technical domains.
Methodology: A structured interpretive synthesis was conducted using only the supplied references. The literature was analyzed across six linked dimensions: offshore floating platform and mooring architecture, yaw and weathervaning behavior, dynamic response and aerodynamic-hydrodynamic coupling, reduced-order and control-oriented wake modeling, real-time estimation and forecasting, and grid-responsive wind farm control. The analysis compares assumptions, identifies converging themes, and interprets major research trajectories.

Results: The synthesis shows that floating offshore wind performance depends strongly on integrated system coordination. Single-point mooring systems offer important self-alignment and operational advantages but also introduce complex stability and slow-drift considerations (Nihei et al., 2018; Nihei et al., 2020). Wake-aware wind farm control increasingly depends on dynamic reduced-order models, LiDAR-based estimation, and real-time calibration frameworks (Boersma et al., 2018; Doekemeijer et al., 2018; Towers & Jones, 2016). Control strategies that treat turbulence, inflow variation, and yaw interaction explicitly are more promising than static approaches (Knudsen et al., 2015; Shapiro et al., 2022). Grid integration further requires active power support and operational flexibility rather than simple energy maximization alone (Aho et al., 2012; Ahmed et al., 2020).

Conclusion: The future of floating offshore wind farms lies in integrated, control-oriented, and physics-informed design frameworks that couple platform motion, mooring response, aerodynamic loading, wake interaction, and grid services. Such an approach better reflects the true engineering character of large-scale floating offshore wind deployment.

Keywords: Floating offshore wind, wind farm control, single point mooring, wake modeling, yaw dynamics, grid

integration, reduced-order modeling.

INTRODUCTION

Offshore wind energy has undergone a major conceptual and technological expansion from shallow-water fixed-bottom installations toward floating systems capable of operating in deeper seas. This transition is not simply a matter of extending conventional offshore practice into new water depths. Rather, it marks a shift in the engineering character of wind energy itself. Fixed-bottom offshore turbines are governed primarily by aerodynamic performance, support structure design, marine environmental loading, and electrical integration. Floating offshore wind turbines add another layer of dynamic complexity because the turbine, platform, mooring lines, and surrounding flow field form a coupled moving system whose power production, structural stability, yaw response, and wake behavior must be understood together (Barooni et al., 2022; Chen et al., 2022). As a result, floating offshore wind farms represent one of the clearest examples of multidisciplinary renewable energy engineering in which marine hydrodynamics, atmospheric flow physics, structural dynamics, control systems, and grid operations converge.

The intellectual roots of offshore wind extend back decades. Heronemus (1972) recognized the strategic promise of pollution-free energy from offshore winds long before floating wind technology became a practical development pathway. That early vision is important because it reveals that offshore wind was never merely a geographical extension of onshore generation. It was always connected to the broader ambition of accessing superior marine wind resources while decoupling energy production from many of the land-use conflicts associated with terrestrial wind development. Contemporary work on global offshore wind resources confirms the scale of that opportunity. Zheng et al. (2018) highlighted the spatial significance of offshore wind energy resources worldwide, reinforcing the argument that deeper-water regions may play a central role in future clean energy portfolios.

Yet the expansion into deeper water changes the design problem fundamentally. Fixed foundations become less viable as water depth increases, making floating support systems more attractive. Floating platforms, however, are not passive substitutes for bottom-fixed supports. They introduce motion in surge, sway, heave, roll, pitch, and yaw, each of which can alter turbine aerodynamics, wake orientation, controller performance, and structural loads (Chen et al., 2018; Wen et al., 2022). This motion also couples with mooring system behavior, which becomes a primary determinant of station-keeping, self-alignment characteristics, and overall dynamic stability. In other words, the central design question in floating offshore wind is not simply how to keep a turbine afloat. It is how to design an integrated offshore energy system that remains stable, productive, controllable, and grid-responsive under variable wind and wave conditions.

The literature provided for this article shows that the field has evolved along several interrelated pathways. One pathway concerns platform and mooring innovation. Single-point mooring and weathervaning concepts have attracted strong attention because they allow floating turbines to align more naturally with the incoming environment, potentially reducing yaw system burden and altering the dynamic load environment (Iijima et al., 2013; Nihei et al., 2018; Netzband et al., 2020). Studies of single-point moored floating offshore wind turbines have examined motion characteristics, slow-drift damping effects, stability under combined wind-current fields, and comparative weathervane behavior across alternative system concepts (Iijima et al., 2015; Hashimoto et al. as reflected in the provided list through related entries; Nihei et al., 2020; Liu et al., 2018). At the same time, related marine mooring literature on buoy systems, CALM and SALM arrangements, subsea connectors, and single-point mooring dynamics provides additional insight into how offshore station-keeping design influences system reliability and hydrodynamic behavior (Pecher et al., 2014; Jin et al., 2022; Li et al., 2023; Yu et al., 2020).

A second pathway concerns aerodynamic and hydrodynamic coupling. Floating turbines do not experience the same flow environment as rigidly fixed turbines because platform motion changes rotor inflow conditions, blade-relative velocities, and the orientation of the rotor relative to the mean wind. Chen et al. (2018) compared dynamical characteristics for a semisubmersible floating turbine using different blade concepts, illustrating how aerodynamic design choices intersect with floating response. Wen et al. (2022) examined aerodynamic loading effects for a spar-type floating wind turbine experimentally, showing that aerodynamic loading cannot be treated as a static overlay on hydrodynamic design. Chen et al. (2022), through their review of model experimental methods, confirmed that aerodynamic simulation for floating offshore wind turbines remains a technically demanding field because correct scaling and coupled representation are difficult to achieve in laboratory contexts. These works collectively show that floating wind performance emerges from dynamic coupling rather than from separate aerodynamic and hydrodynamic subsystems.

A third pathway concerns yaw systems, weathervaning, and turbine orientation. Large horizontal-axis wind turbines rely on yaw systems to orient rotors into the wind, but the problem becomes more nuanced offshore and even more so in floating applications. Kim and

Dalhoff (2014) outlined the concepts and challenges of yaw systems, while Yang et al. (2021) reviewed control strategies for large turbine yaw systems. In floating concepts employing single-point mooring or passive self-alignment, yaw control and platform weathervaning may interact or partially substitute for each other, but not necessarily without trade-offs (Netzband et al., 2020; Nathanial et al., 2018). This line of inquiry matters because yaw misalignment in floating systems affects not only power capture but also wake direction, platform loads, and downstream wind farm behavior.

A fourth pathway involves the evolution of wind farm flow modeling and reduced-order methods. Large wind farms, especially floating arrays, cannot be managed effectively if each design or control decision depends on full high-fidelity computational fluid dynamics at every step. Consequently, reduced-order, control-oriented, and data-driven flow models have become indispensable. Annoni and Seiler (2016) proposed an input-output reduced-order approach for wind farm flow modeling. Hamilton et al. (2018) developed a generalized framework for reduced-order modeling of turbine wakes. Iungo et al. (2015) and Iungo et al. (2016) emphasized reduced-order and data-driven wake prediction strategies, while Boersma et al. (2018) introduced WFSim as a control-oriented dynamic wind farm model. These studies do more than reduce computational burden. They redefine what it means to model a wind farm by prioritizing representations that support control, estimation, and real-time decision-making.

A fifth pathway centers on wind farm control itself. The literature shows a strong transition from static, energy-only thinking toward active control of farms as dynamic systems. Fagiano et al. (2013) framed advanced control applications in wind energy as a field of growing importance. Knudsen et al. (2015) surveyed wind farm control with attention to both power and fatigue optimization, making clear that control objectives extend beyond simple maximization of instantaneous output. Shapiro et al. (2022) further emphasized the role of turbulence and control in wind farms, underscoring that wake behavior and control action cannot be disentangled. Doekemeijer et al. (2020) demonstrated closed-loop model-based wind farm control under time-varying inflow conditions, revealing the importance of dynamic adaptation in realistic atmospheric environments.

A sixth pathway concerns measurement, estimation, and forecasting. Wind farms are exposed to time-varying inflow conditions that cannot be controlled unless they are estimated with sufficient accuracy and speed. Towers and Jones (2016) addressed real-time wind field reconstruction using LiDAR and state estimation. Doekemeijer et al. (2016, 2017, 2018) contributed Kalman filtering, ensemble estimation, and online model calibration strategies for wind farm flow models. Iungo et al. (2013) demonstrated the value of field wake measurements using lidars, while Iungo (2016) emphasized experimental wake characterization through both wind tunnel and wind LiDAR methods. At a larger forecasting scale, Louka et al. (2008) and Cassola and Burlando (2012) showed that Kalman filtering can improve wind speed and wind energy forecasts by refining numerical weather prediction outputs. These estimation and forecasting studies are crucial because they connect atmospheric uncertainty to real-time farm operation.

A seventh, and increasingly important, pathway is grid support and system integration. Wind farms are no longer treated merely as variable generators to be absorbed passively by the grid. Aho et al. (2012) demonstrated how wind turbine control can support grid frequency through active power control. Ahmed et al. (2020) reviewed the grid integration challenges of wind energy broadly, reinforcing that large-scale wind deployment requires controllability, flexibility, and power quality awareness. In floating offshore wind farms, these issues are especially significant because power production variability, wake interaction, and platform motion may affect the controllability envelope within which the farm can deliver grid services.

Taken together, the provided references indicate that floating offshore wind research is no longer adequately described as a sequence of separate problems in platform design, wake modeling, or turbine control. Instead, the field is moving toward a more integrated systems perspective. Platform motion influences yaw behavior. Yaw behavior influences wakes. Wakes influence farm-level controllability. Farm control depends on reduced-order modeling and state estimation. Grid support depends on reliable farm-level dynamic control. Mooring architecture influences self-alignment, stability, and operational constraints across the entire chain. This interdependence is the central intellectual challenge of floating offshore wind engineering.

Despite the richness of the literature, an important gap remains in how these strands are synthesized. Many studies focus deeply on one technical layer while holding others relatively fixed. Mooring studies may emphasize stability and motion without exploring downstream implications for farm control. Wake modeling studies may focus on reduced-order aerodynamic representation without accounting for the consequences of floating support motion. Grid integration studies often discuss wind energy broadly without addressing the distinctive control and uncertainty issues that characterize floating farms. As a result, there remains a strong need for integrative scholarship that places these domains into one analytical frame.

The present article addresses that need by developing a comprehensive research analysis based strictly on the supplied references. It advances the argument that future floating offshore wind systems must be designed and operated according to integrated control-oriented principles rather than isolated subsystem optimization. The article examines floating wind technology across several coupled dimensions: resource logic and offshore transition, mooring and weathervaning architectures, aerodynamic-hydrodynamic interaction, wake and flow modeling, estimation and forecasting, farm-level control, and grid-responsive operation. In doing so, it aims not only to summarize the literature but to interpret its deeper convergence. The core proposition is that floating offshore wind farms should be understood as dynamic, model-based, wake-coupled, mooring-constrained, grid-participating energy systems. That systems perspective provides the conceptual foundation for the analysis that follows.

Methodology

This study employs a structured interpretive synthesis methodology using only the references supplied by the user. The purpose of the methodology is to transform a broad, technically diverse body of literature into a coherent research article that identifies conceptual patterns, methodological convergences, and major unresolved tensions in floating offshore wind engineering. Because the references span multiple domains—including floating platform design, mooring dynamics, wake modeling, wind farm control, LiDAR-based estimation, wind forecasting, and grid integration—the chosen method is not a narrow literature summary but a cross-domain analytical synthesis.

The first methodological principle of the study is bounded evidence discipline. No external references, contemporary reports, or additional sources were introduced. Every analytical claim is derived from or supported by the supplied reference list. This ensures consistency with the task and maintains direct traceability from the article's claims to the user-provided literature. Such a strategy is particularly appropriate for review-based academic writing in which the study objective is conceptual integration rather than numerical meta-analysis.

The second principle is multidimensional thematic coding. The references were read and organized across six interconnected analytical dimensions. The first dimension was floating offshore structural and mooring configuration. This included studies dealing with floating offshore wind turbines broadly, semisubmersible and spar-type systems, single-point mooring architectures, motion characteristics, connector behavior, and self-alignment concepts (Barooni et al., 2022; Chen et al., 2018; Iijima et al., 2013; Nihei et al., 2018; Nihei et al., 2020; Li et al., 2023). The second dimension was yaw, weathervaning, and directional response, including literature on yaw systems, passive self-alignment, fixed-yaw concepts, and reviews of yaw control strategy (Kim & Dalhoff, 2014; Yang et al., 2021; Nathanial et al., 2018; Netzband et al., 2020). The third dimension was aerodynamic-hydrodynamic coupling and experimental representation, including studies on blade concepts, loading effects, laboratory methods, and dynamic response of floating systems (Chen et al., 2022; Wen et al., 2022; Liu et al., 2018).

The fourth dimension was wake, flow, and reduced-order modeling. This included field measurements, input-output representations, control-oriented dynamic models, stochastic turbulence modeling, and reduced-order wake frameworks (Annoni & Seiler, 2016; Iungo et al., 2013; Hamilton et al., 2018; Boersma et al., 2018; Bhatt et al., 2023). The fifth dimension was estimation, forecasting, and online model adaptation, incorporating LiDAR-driven reconstruction, Kalman filtering, online calibration, and improved wind prediction (Louka et al., 2008; Cassola & Burlando, 2012; Towers & Jones, 2016; Doekemeijer et al., 2016; Doekemeijer et al., 2018). The sixth dimension was control and grid integration, covering wind turbine active power control, wind farm control, turbulence-aware control, and grid-facing operational challenges (Aho et al., 2012; Fagiano et al., 2013; Knudsen et al., 2015; Ahmed et al., 2020; Shapiro et al., 2022).

The third methodological principle was comparative interpretation rather than isolated study description. A reference was not treated as important solely because of its recency or technical specificity. Instead, each work was interpreted according to how it contributes to a broader systems-level argument. For example, Nihei et al. (2018) was not read only as a mooring mechanism study, but as evidence for how floating support architecture shapes operational alignment and possibly downstream control considerations. Similarly, Boersma et al. (2018) was not read only as a dynamic model paper, but as a sign of the field's transition toward real-time control-capable wind farm representations.

The fourth principle was convergence mapping. Where different studies from different subdomains pointed toward a similar conclusion, that conclusion was treated as especially robust. For instance, the importance of dynamic environmental variability appears in forecasting research, LiDAR reconstruction, closed-loop farm control, and turbulence-oriented control reviews (Louka et al., 2008; Towers & Jones, 2016; Doekemeijer et al., 2020; Shapiro et al., 2022). Likewise, the need for reduced-order yet physically informative models appears across wake prediction, farm flow representation, optimization-related modeling, and stochastic dynamical turbulence studies (Annoni & Seiler, 2016; Hamilton et al., 2018; Iungo et

al., 2016; Bhatt et al., 2023). This triangulation strategy helps reduce the risk of overemphasizing any single specialized contribution.

The fifth principle was contextualized interpretation of "results." Since this is a research article built on supplied literature rather than on newly generated experimental data, the results section presents analytically derived findings from the synthesis itself. In other words, the "findings" are the patterns, relationships, and implications that emerge from structured comparison of the literature. This is consistent with rigorous scholarly review writing, especially in multidisciplinary technical fields where theory integration and methodological clarification are necessary contributions in their own right.

The sixth methodological principle was analytical attention to coupling. A recurring weakness in segmented engineering literatures is the treatment of interfaces as secondary. This study instead places interfaces at the center. The interaction between mooring and yaw, between wake modeling and control, between forecasting and grid support, and between floating motion and aerodynamic response were treated as primary analytical sites. This reflects the engineering reality of floating offshore wind farms, where failure to understand interfaces often leads to incomplete design or unrealistic control assumptions.

Finally, the study acknowledges limitations intrinsic to the method. No new experiments, simulations, or field measurements were performed. The article does not rank technologies numerically or report unified benchmark outcomes. The supplied references themselves vary in form, detail, and domain specificity. Some are conference papers or reports, while others are full journal articles or reviews. Nevertheless, the methodology remains robust for the present purpose because the study's objective is not to compute a pooled effect but to construct an academically rigorous, publication-ready synthesis of an integrated engineering domain.

Results

The literature synthesis reveals that floating offshore wind farms are best understood not as static power-generation assets but as dynamically coupled marine energy systems whose performance emerges from the interaction of resource availability, floating support architecture, mooring configuration, yaw behavior, wake development, control logic, and grid-facing operational requirements. Across the provided references, six major findings emerge.

The first major finding is that floating offshore wind energy owes its strategic importance to resource access, but its practical viability depends on integrated system engineering rather than resource abundance alone. Offshore regions offer strong and often more stable winds, and global resource studies reinforce the magnitude of this opportunity (Heronemus, 1972; Zheng et al., 2018). Yet resource richness does not automatically translate into high-performing floating wind farms. Barooni et al. (2022) make clear that current and future prospects for floating offshore wind depend on how effectively the sector manages the combined challenges of structural response, cost, installation, operation, and design complexity. This means the central engineering problem is not simply where offshore wind is available, but how to convert deep-water wind resources into stable, controllable, and economically meaningful energy production systems.

The second major finding is that mooring system architecture is not merely a support detail; it is a primary determinant of floating turbine behavior and therefore of overall wind farm performance. Studies on single-point mooring, buoy systems, and related offshore station-keeping concepts consistently show that mooring configuration shapes motion characteristics, self-alignment potential, damping behavior, and the balance between stability and flexibility (Iijima et al., 2013; Nihei et al., 2018; Jin et al., 2022). Single-point mooring systems are especially significant in the literature because they introduce the possibility of natural or semi-natural weathervaning. In principle, such systems can help a turbine align with wind and current directions, reducing dependence on active yawing and potentially altering load pathways. Nihei et al. (2018) present research and development related to single-point mooring mechanisms for offshore wind turbines, while Nihei et al. (2020) examine the influence of slow-drift damping on the weathervaning of such systems. These studies show that self-alignment is not a trivial passive property but a dynamic phenomenon sensitive to damping, environmental loading, and mooring design details.

This finding is strengthened by comparative weathervane studies and passive alignment research. Iijima et al. (2015) compare performance between different FOWT systems moored to single-point moorings, indicating that not all weathervaning architectures behave similarly. Netzband et al. (2020) discuss passive self-aligning floating offshore wind turbines, pointing toward design strategies that may simplify directional control but also require careful evaluation of stability and response characteristics. Nathanial et al. (2018) analyze a fixed-yaw weathervane offshore wind turbine with single-point mooring, further illustrating that directional behavior in floating systems may differ fundamentally from land-based or fixed-bottom yaw paradigms. The broader result is that mooring design directly influences not only survivability and station-keeping but also aerodynamic alignment strategy.

The third major finding is that aerodynamic and hydrodynamic coupling is a foundational design challenge in floating wind systems. Unlike fixed-bottom turbines, floating turbines move under environmental forcing, and this motion feeds back into aerodynamic loading. Chen et al. (2018) show that the dynamical characteristics of a semisubmersible floating offshore wind turbine depend in part on blade concept, indicating that aerodynamic design cannot be fully separated from platform response. Wen et al. (2022) provide experimental evidence that aerodynamic loading materially affects a model spar-type floating wind turbine. Chen et al. (2022), in their review of experimental methods focusing on aerodynamic simulation of floating offshore wind turbines, confirm that the challenge is not merely one of testing platforms in water tanks or turbines in air, but of achieving physically meaningful coupling between the two domains.

This body of evidence suggests that any optimization or control framework that treats platform motion and rotor aerodynamics as weakly related is likely to be incomplete. The implications extend beyond component design. Platform pitch or yaw excursions can alter effective inflow angles, power capture, and wake direction. Such changes may cascade into farm-level interactions if multiple floating turbines operate in array configurations. Liu et al. (2018), through their analysis of DeepCwind response characteristics under single-point mooring, reinforce that motion behavior is not an abstract structural issue but one that shapes operating conditions directly. In effect, floating wind systems convert environmental disturbances into aerodynamic variability in a way that fixed-bottom systems do not.

The fourth major finding is that yaw control in floating offshore wind farms must be understood as part of a wider directional response ecosystem involving turbine yaw mechanisms, passive or active platform alignment, wake orientation, and downstream control consequences. Kim and Dalhoff (2014) provide an overview of yaw systems and their challenges, while Yang et al. (2021) review control strategies for large horizontal-axis turbine yaw systems. In floating environments, however, these yaw systems operate within a more complicated directional context. If the platform itself can rotate or align through mooring-mediated weathervaning, the traditional boundary between nacelle yaw control and support-structure directional behavior becomes blurred. This creates both opportunities and complications. On one hand, passive or assisted alignment may reduce actuator burden. On the other, the dynamics of such alignment may be slower, less precise, or more coupled to current and wave effects than conventional yaw systems.

The result emerging from the literature is that directional optimization in floating wind farms cannot be reduced to rotor-wind alignment alone. It must account for how directional decisions affect platform dynamics and wake steering. This is particularly important because wake direction is central to wind farm control. A turbine that misaligns slightly might reduce its own power but could redirect its wake beneficially. In floating contexts, such misalignment may arise from a mixture of controller action and platform motion. Therefore, the directional state of a floating turbine is both an aerodynamic control variable and a marine dynamic outcome.

The fifth major finding is that wake and wind farm flow modeling has shifted decisively toward reduced-order, control-oriented, and data-informed representations. This trend is one of the strongest across the literature. Full high-fidelity simulation is valuable for analysis, but it is too computationally demanding to serve as the sole basis for real-time control or repeated design iteration. Annoni and Seiler (2016) propose an input-output reduced-order model for wind farm flow, illustrating how system-theoretic thinking can be brought to aerodynamic field representation. Hamilton et al. (2018) provide a generalized reduced-order wake framework. Iungo et al. (2016) emphasize reduced-order modeling for power optimization, while Iungo et al. (2013) and Iungo (2016) root such abstractions in field and experimental wake measurements.

Boersma et al. (2018) make a particularly important contribution through WFSim, a control-oriented dynamic wind farm model. The significance of such work lies in its intended use. A control-oriented model need not reproduce every detail of the flow; rather, it must preserve the dominant dynamics relevant to estimation and control. This changes evaluation criteria. The best model for farm control is not necessarily the most physically elaborate, but the one that best balances interpretability, fidelity to actionable dynamics, and computational tractability. Bhatt et al. (2023), through stochastic dynamical modeling of wind farm turbulence, further suggest that reduced-order models must increasingly grapple with uncertainty and turbulence variability rather than deterministic averages alone.

The sixth major finding is that real-time wind farm control depends fundamentally on measurement assimilation, state estimation, and online model adaptation. This theme appears repeatedly across the literature and represents one of the clearest pathways toward operationally intelligent wind farms. Towers and Jones (2016) reconstruct wind fields from LiDAR measurements using a dynamic wind model and state estimation, demonstrating that remote sensing can be integrated into control-oriented inference. Doekemeijer et al. (2016) use enhanced Kalman filtering with a two-dimensional CFD-based wind farm flow model. Doekemeijer et al. (2017) extend this through ensemble Kalman filtering for wind field estimation, while

Doekemeijer et al. (2018) investigate online model calibration for a simplified large-eddy-type model to enable real-time closed-loop control. Together, these studies show that the future of wind farm control lies not in open-loop precomputed settings, but in adaptive frameworks that continuously update their internal understanding of the flow.

This result is especially important under time-varying inflow conditions. Doekemeijer et al. (2020) demonstrate closed-loop model-based wind farm control using FLORIS under changing inflow, reinforcing that static wake models and static control assumptions are insufficient. The atmosphere evolves, wakes shift, and farm control must respond accordingly. Shapiro et al. (2022) deepen this conclusion by connecting turbulence and control directly. In a turbulent, spatially distributed farm environment, the relevant control problem is not merely setpoint allocation but dynamic interaction management.

The seventh major finding is that forecasting and estimation operate on multiple timescales and must be integrated. Some studies focus on second-to-minute scale wind field reconstruction, while others improve broader wind speed and energy forecasting through Kalman filtering of numerical weather prediction outputs (Louka et al., 2008; Cassola & Burlando, 2012). These are not separate concerns. Short-horizon flow estimation supports turbine and farm control, while longer-horizon forecasting supports scheduling, reserve planning, and grid interaction. A mature offshore wind farm therefore requires layered predictive intelligence. The literature indicates that the same methodological families—state estimation, filtering, model correction—are valuable across both timescales. This suggests a future architecture in which forecasting, state estimation, and control operate as a coordinated digital system rather than as isolated analytical tools.

The eighth major finding is that wind farm control objectives are inherently multi-criteria. Knudsen et al. (2015) emphasize both power and fatigue optimization. Fagiano et al. (2013) describe advanced control applications broadly, implying a move away from single-metric design. Shapiro et al. (2022) highlight turbulence-aware control, which may improve some operational outcomes while complicating others. Aho et al. (2012) show that wind turbines can support grid frequency through active power control, which means that generation maximization may at times be subordinated to grid-support objectives. Ahmed et al. (2020) reinforce that wind energy integration raises issues of stability, variability, and system response beyond raw energy output. These studies collectively demonstrate that wind farm control should not be defined narrowly as extracting the maximum possible energy under all circumstances. Instead, it involves balancing energy capture, structural loading, flow interaction, predictability, and grid service capability.

The ninth major finding is that floating offshore wind systems increasingly invite hybridization and multifunctionality, which further broadens the design problem. Chen et al. (2025) present a novel SPM wind-wave-aquaculture system, while Liu et al. (2022) examine an aquaculture ship integrating a wind turbine and internal turret mooring. Zhang et al. (2022) analyze a hybrid floating offshore wind turbine and oscillating water column system. These studies suggest that future offshore energy systems may not be single-purpose turbines but integrated marine infrastructure platforms. This trend heightens the importance of mooring and dynamic analysis, because the support system must now accommodate multiple operational functions and interaction modes. It also reinforces the central argument of this article: floating offshore wind engineering is evolving toward integrated marine energy systems rather than isolated turbine technology.

The tenth major finding is that reference platforms, reports, and demonstration-oriented designs remain crucial in structuring the field's technical development. Reports such as Robertson (2014) and concept/demonstration works such as Schnepf (2019) provide practical design baselines and transition mechanisms between theoretical research and implementation. The importance of such work lies in standardization, comparability, and technology transfer. Floating offshore wind remains an engineering field in which validated reference concepts are essential for accumulating knowledge coherently.

Overall, the synthesis results show that floating offshore wind farms are governed by a network of interactions that make subsystem isolation increasingly untenable. Mooring affects alignment. Alignment affects wakes. Wakes affect farm control. Control depends on reduced-order models, estimation, and calibration. Grid integration depends on controllability and forecast quality. Hybridization expands the design space further. The most important result of the synthesis is therefore that the future technical frontier is not any one component but the integration logic that coordinates them.

Discussion

The literature analyzed in this article indicates that floating offshore wind has reached a stage where its most difficult and most intellectually significant problems are no longer purely component-specific. Earlier phases of technological development understandably concentrated on proving that floating turbines could be stabilized, moored, and operated at sea. That work remains essential, and many of the references supplied here continue to address motion response, mooring concepts, aerodynamic loading, and

experimental representation in focused ways (Iijima et al., 2013; Chen et al., 2018; Wen et al., 2022). Yet the field is now moving into a more demanding stage in which the key challenge is integration. The decisive question has become how multiple subsystems—platform, mooring, rotor, yaw mechanism, wake field, flow estimator, farm controller, and grid interface—can be coordinated into a coherent operational whole.

One of the clearest implications of the literature is that the traditional separation between marine engineering and wind turbine engineering is becoming increasingly untenable in floating systems. In fixed-bottom wind energy, it was possible, at least to some extent, to optimize aerodynamic performance and structural support along relatively distinct lines. In floating wind, such separation becomes much less defensible because support motion feeds directly into rotor inflow, loading, directional alignment, and wake orientation. This is why the experimental and numerical studies on floating aerodynamic-hydrodynamic coupling are so significant. Chen et al. (2022) make clear that representing these interactions in model testing is itself a complex research problem, while Chen et al. (2018) and Wen et al. (2022) show that platform dynamics and aerodynamic loading are intertwined in practice. These studies together imply that future floating turbine design cannot simply import control assumptions or load models from fixed-bottom experience without adaptation.

This point becomes even more important at the wind farm scale. A floating turbine does not merely respond to waves and wind as an individual machine. Its motion may alter the spatial development of its wake. That wake then affects downstream turbines. If multiple turbines in an array are simultaneously moving, yawing, or self-aligning, the wind farm becomes a distributed dynamic flow system with moving sources of wake generation. The supplied literature does not yet provide a complete unified framework for floating-array wake interaction, but it provides many of the necessary conceptual building blocks: wake measurement, reduced-order representation, stochastic turbulence modeling, dynamic control-oriented simulation, and time-varying closed-loop farm control (Iungo et al., 2013; Annoni & Seiler, 2016; Boersma et al., 2018; Bhatt et al., 2023; Doekemeijer et al., 2020). The logical implication is that future research must more explicitly connect floating support motion to array-scale wake and control models.

The discussion around mooring systems further highlights how deeply subsystem choices affect broader operational logic. Single-point mooring is especially important in this respect. It is attractive because it may enable weathervaning and self-alignment, potentially simplifying directional control and reducing yaw actuator burden (Nihei et al., 2018; Netzband et al., 2020). However, the literature also shows that such benefits are conditional. Weathervaning depends on damping, environmental forcing, and detailed mooring behavior, not merely on the nominal presence of a single-point arrangement (Nihei et al., 2020). Comparative system studies show that different single-point moored concepts can behave differently even under similar broad design intentions (Iijima et al., 2015). This should caution against treating self-alignment as an automatic advantage. A system that passively aligns may still introduce oscillatory behavior, lag, or control ambiguity. Thus, the most mature interpretation is that single-point mooring offers a promising but highly design-sensitive directional response mechanism.

Related marine literature on CALM, SALM, buoy systems, and connector dynamics strengthens this conclusion by showing that mooring systems are themselves sophisticated dynamical devices rather than fixed restraints (Pecher et al., 2014; Jin et al., 2022; Li et al., 2023). This matters because floating wind discussions sometimes reduce mooring to a question of holding position. The references supplied here suggest a broader view: mooring defines the physical envelope within which alignment, damping, platform motion, and hybrid operational functions occur. When wind turbines are embedded in multi-use systems, such as wind-wave-aquaculture concepts or turbine-equipped aquaculture vessels, the mooring problem becomes even more central because it must satisfy multiple dynamic and operational criteria simultaneously (Liu et al., 2022; Chen et al., 2025).

Another major discussion theme is the growing centrality of model-based control. The wind energy control literature represented here reflects a significant shift away from purely local turbine regulation toward farm-level dynamic coordination. Early emphasis on advanced control applications and wind farm control surveys already signaled this transition (Fagiano et al., 2013; Knudsen et al., 2015). More recent work makes the transition operationally concrete through closed-loop model-based farm control under time-varying inflow, online model calibration, and flow field estimation through Kalman filtering and LiDAR-assisted reconstruction (Towers & Jones, 2016; Doekemeijer et al., 2018; Doekemeijer et al., 2020). These developments suggest that the future wind farm is increasingly a cyber-physical system in which sensing, estimation, prediction, and control are tightly integrated.

That shift has important consequences for model design. In many engineering domains, a strong temptation exists to equate better models with more detailed models. The wind farm flow modeling literature suggests a more nuanced criterion. For real-time control, the best model is not the one that resolves every turbulent structure, but the one that captures the dominant actionable dynamics

while remaining identifiable, updateable, and computationally fast (Annoni & Seiler, 2016; Boersma et al., 2018). Reduced-order and control-oriented models therefore represent not a compromise of necessity alone, but a distinct epistemic strategy. They are built to be useful in decisions, not merely descriptive in hindsight.

This perspective also helps explain why estimation and forecasting are so prominent in the literature. A controller can only exploit a model if it has credible information about the current and near-future state of the environment. LiDAR reconstruction, Kalman filtering, ensemble estimation, online calibration, and forecast correction through filtering all address different aspects of the same challenge: atmospheric uncertainty is operationally meaningful and must be inferred continuously (Louka et al., 2008; Cassola & Burlando, 2012; Towers & Jones, 2016; Doekemeijer et al., 2017). In floating wind farms, this challenge may be even greater because platform motion and wake displacement can make the local operating environment more variable and harder to characterize using static assumptions.

A related issue is the role of turbulence. Shapiro et al. (2022) explicitly place turbulence and control together, which is conceptually important. Turbulence is not just a background disturbance degrading ideal control performance. It is one of the defining conditions under which wind farms operate. Bhatt et al. (2023) similarly highlight stochastic dynamical modeling of wind farm turbulence. These studies imply that deterministic control logic may be inadequate for the next stage of large offshore wind farms, especially floating arrays. Instead, control design may need to become more probabilistic, adaptive, and robustness-oriented. This does not mean abandoning model-based control. It means expanding it to accommodate variability as a governing feature rather than an external nuisance.

Grid integration introduces another layer of interpretive complexity. Wind energy discussions often draw a distinction between plant-level optimization and system-level integration, but the supplied references suggest that such a separation is increasingly artificial. Aho et al. (2012) show that wind turbine control can directly support frequency response through active power control. Ahmed et al. (2020) show that grid integration challenges are broad and consequential. Taken together, these studies imply that a floating offshore wind farm should not be designed solely for maximum energy capture under free operation. It should be designed for controllable participation in a larger power system. That shift matters because it changes what counts as good control. A controller that maximizes power but offers little flexibility or predictability may be inferior, from a system perspective, to one that reserves capability for support services.

The literature also suggests that future floating offshore wind development may be shaped by hybridization and multi-use offshore platforms. Zhang et al. (2022), Liu et al. (2022), and Chen et al. (2025) indicate that floating wind technology can be integrated with wave energy or aquaculture systems. These concepts expand the design problem substantially. Energy, food, and marine infrastructure functions may be colocated, creating potential synergies but also much more complex dynamic, operational, and regulatory interactions. The implication for wind engineering is profound: the future offshore platform may be evaluated not only as a turbine support but as a node in a broader marine production ecosystem. If that future materializes, the value of integrated modeling, mooring design, and supervisory control will increase further.

Several limitations in the current research landscape are also evident from the literature. First, although many references address important individual couplings, fewer provide truly unified frameworks linking floating motion, array wake control, and grid services in one model. Second, while reduced-order and control-oriented models are advancing, the question of how much physical complexity must be retained for floating arrays remains unresolved. Third, experimental methods for floating turbine aerodynamics continue to face scaling and representation challenges (Chen et al., 2022). Fourth, although forecasting and estimation tools are sophisticated, the integration of short-horizon flow estimation with longer-horizon grid-aware scheduling remains underdeveloped in the literature provided.

Despite these limitations, the overall trajectory is clear. Floating offshore wind farms are becoming more model-based, more dynamically controlled, more estimation-driven, and more integrated with broader marine and grid systems. The field is not moving toward a single “best” platform or one canonical control law. Instead, it is moving toward a layered engineering framework in which structural design, mooring configuration, flow representation, state estimation, and control logic are co-developed. This is a demanding direction, but it is also the one most consistent with the actual complexity of floating offshore energy deployment.

Future research should therefore prioritize several linked goals. One is stronger coupling between floating support dynamics and wake-aware farm control models. Another is the development of estimation frameworks that integrate LiDAR, SCADA-like operational data, and reduced-order dynamic models for floating arrays specifically. A third is the incorporation of grid-service objectives into floating farm control design from the start rather than as an afterthought. A fourth is more explicit treatment of multifunctional offshore platforms, where wind generation interacts with other marine uses. Finally, standard reference architectures and benchmark

scenarios for floating farm control would help unify a field that currently remains technically rich but somewhat fragmented across subdomains.

Conclusion

The literature synthesized in this article demonstrates that floating offshore wind farms must be understood as deeply integrated dynamic systems rather than isolated collections of marine structures and wind turbines. The field has progressed far beyond the initial problem of demonstrating that turbines can be floated offshore. Today, the decisive engineering issues concern how platform dynamics, mooring architectures, yaw and weathervaning behavior, aerodynamic loading, wake evolution, reduced-order flow modeling, state estimation, closed-loop control, and grid-responsive operation can be coordinated into a unified framework.

A central conclusion of this study is that mooring and directional response are foundational to floating wind performance. Single-point mooring and passive alignment concepts are attractive because they may support self-orientation and operational flexibility, but their benefits are strongly dependent on damping characteristics, dynamic stability, and detailed system design (Nihei et al., 2018; Nihei et al., 2020; Netzband et al., 2020). A second conclusion is that aerodynamic and hydrodynamic coupling is not a secondary complexity but a defining feature of floating wind systems, with direct consequences for performance, loading, and control (Chen et al., 2018; Wen et al., 2022; Chen et al., 2022).

A third conclusion is that the future of wind farm operation lies in dynamic, reduced-order, and control-oriented modeling supported by continuous estimation and online calibration. Wake-aware farm control under variable inflow is increasingly feasible because of advances in LiDAR-assisted reconstruction, Kalman filtering, stochastic flow modeling, and computationally efficient dynamic models (Towers & Jones, 2016; Boersma et al., 2018; Doekemeijer et al., 2020; Bhatt et al., 2023). A fourth conclusion is that wind farms, including floating offshore arrays, must increasingly be designed as controllable grid participants rather than passive variable generators (Aho et al., 2012; Ahmed et al., 2020).

Overall, the most promising direction for future floating offshore wind research is the development of integrated frameworks that combine marine dynamics, aerodynamic interaction, wake-aware control, real-time estimation, and grid service capability in one coherent design and operation paradigm. Such a paradigm best reflects the technical reality of floating offshore wind and offers the strongest foundation for scaling the technology into a mature and reliable component of future energy systems.

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