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REVIEW

Floating Offshore Wind Energy: Challenges and Research Needs in Fluid Mechanics

Axelle Viré[1] · Delphine De Tavernier[1] · Dominic von Terzi[1]

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Abstract

Floating wind energy is a relatively new area that consists of harnessing wind energy from wind turbines that are supported by a floating foundation. This enables the installation of offshore wind turbines in deep seas, which means tapping into offshore wind resources that are unreachable with bottom-fixed wind turbines. Up to now, the feasibility of floating wind turbine technology has been demonstrated in small pilot farms. However, floating wind turbines are still subject to unexpected failures. Therefore, a better fundamental understanding of these turbines is needed to improve the technology to accelerate its deployment and reduce the cost of energy. Furthermore, the dynamics of floating wind turbines is different from those of their bottom-fixed counterparts. This presents challenges and opportunities across the different phases of their development and operation. This position paper addresses the fluid mechanics community and presents key challenges and research needs in the field of floating wind energy. Building on the *grand challenges* identified in the wind energy community, the manuscript addresses three focus areas and their interactions: the met-ocean conditions, the wind turbine, and the wind farm. Five groups of fluid mechanics driven challenges are highlighted: unsteady aerodynamics, high-speed flows, non-linear hydrodynamics, flow-induced vibrations, and wake dynamics. In addition, the kind of research methods and infrastructure needed to address these challenges are discussed, including cross-cutting themes such as digitalisation and co-creation across stakeholders and disciplines. Finally, the conclusions provide overarching recommendations to solve the upcoming challenges in floating wind energy and highlight the role that the fluid mechanics community could play.

Keywords Floating wind energy · Fluid mechanics · Unsteady aerodynamics · High-speed flows · Hydrodynamics · Wakes · Flow-induced vibrations · Hybrid testing · Co-creation · Societal challenges

Extended author information available on the last page of the article

1 Introduction

1.1 The Need for Floating Offshore Wind Energy

Wind energy has experienced tremendous growth in the past two decades, increasing from an installed capacity of 24GW worldwide in 2001 to 1023GW in 2023 (GWEC 2024). Despite this growth, wind turbines are not deployed enough to achieve our climate goals of limiting the global temperature rise to $1.5°C$ and reaching net zero emissions by 2050. Wind as an energy source still supplies less than 10% of the world's electricity. The International Energy Agency predicts that, in 2050, wind and solar energy will be equally dominant and will together account for nearly 70% of the global electricity generation, with the latter representing 50% of total energy consumption (IEA 2021). On top of that, wind energy could also play an essential role in producing chemical energy carriers, such as hydrogen, which is set to have a defined coverage in the energy mix in 2050. Affordable green hydrogen is seen as having the potential to bring renewable power into the heat and mobility sectors. This implies that the demand for wind energy could become enormous, requiring the need to harness wind energy in new regions that are unreachable with existing technologies.

While onshore the available land space and wind resources are limited in order to fulfil the demand, offshore wind technology can provide the capacity for electrification as well as the production of chemical energy carriers. As such, it is set to be instrumental in the coming years. It is expected that 2000GW of offshore wind capacity will be needed in 2050 to achieve the world's climate targets, leading to a 30-fold increase compared to today's installed capacity.[1]

A major bottleneck to achieving these offshore wind energy targets is that existing bottom-fixed turbines are economically competitive only in water depths up to about 60 metres and with good seabed quality. This significantly restricts the locations where bottom-fixed wind farms can be deployed. In fact, about eighty per cent of the global offshore wind resources are located in waters deeper than 60 metres (Eurek et al. 2017). In Europe alone, Fraunhofer IWES evaluated that the share of offshore wind energy potential reaches 8000 TWh (corresponding to a capacity of 1600GW) for water depths greater than 50 meters, which is more than twice the current EU-28 electricity demand.[2] For this reason, placing wind turbines on a floating support structure moored to the seabed is a favourable alternative that may allow a reduction in the cost of deep-water offshore energy. It also opens opportunities for many countries to enter the offshore wind industry, where bottom-fixed wind energy is deemed unfeasible. For these reasons, the International Renewable Energy Agency (IRENA) highlighted floating offshore wind energy as a potential game-changer to further reduce the offshore wind farms' levelised cost of energy (LCoE) and unlock new markets (IEA 2016).

Nowadays, floating wind energy only accounts for about 220 MW installed capacity worldwide, but this is set to change in the near future as developments in this area are growing fast. The bubble chart in Fig. 1 shows the installed capacity of floating wind projects, both existing and in the pipeline (IEA 2016), as of 2021 (DOE 2021). It also shows the

[1] https://www.irena.org/News/pressreleases/2022/Nov/Nine-new-countries-sign-up-for-Global-Offshore-Wind-Alliance-at-COP27 (Last accessed: 13 November 2024).

[2] http://www.hiprwind.eu/sites/default/files/HiPRwind_SET-Plan_Nov2011.pdf (Last accessed: 13 November 2024).

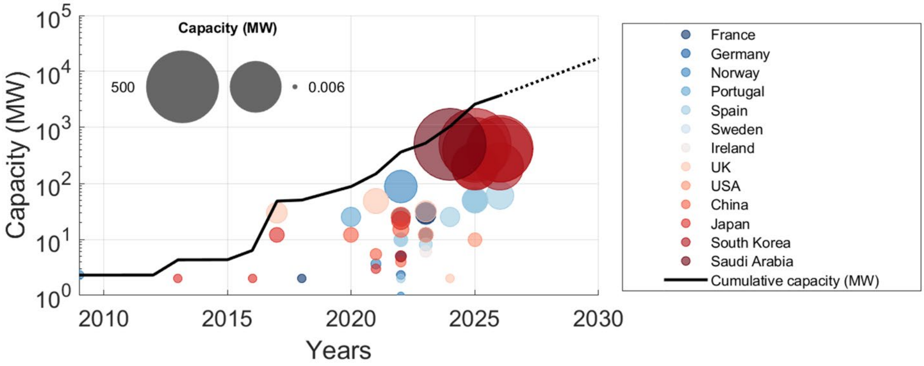
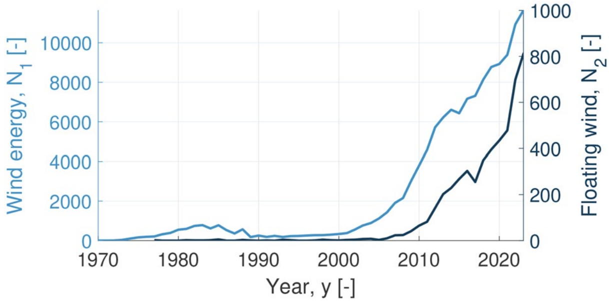


Fig. 1 Existing and planned floating wind projects worldwide: bubbles are projects in the pipeline as of 2021 (data from DOE (2021)), the continuous line shows the cumulative capacity (in MW) of these projects, and the dashed line is the ambitions to reach in Europe alone by 2030 (data from WindEurope)

Fig. 2 Indicative number of scientific publications per year related to wind energy in general and floating wind energy specific (all fields included), as reported by Scopus until 2023



cumulative installed capacity up to 2026 and the ambitions in Europe by 2030.[3] In January 2022, Scotland announced 17 new offshore wind projects with more than half of the installed capacity (i.e. 15GW) being floating wind turbines. Since then, many countries have floating wind energy projects in the pipeline for a total of 160GW in Europe and the UK.[4]

With this rapid growth, there is a need to understand the challenges specific to floating wind energy and adapt the fundamental methods for design, testing, manufacturing, and deployment accordingly. The scientific community has adapted to this need, and the number of scientific publications on floating wind energy has sharply increased in recent years. This is demonstrated by Fig. 2, giving the number of scientific papers per year related to "floating wind energy" in the Scopus database until 2023.

1.2 The Design of Floating Wind Turbines

Floating offshore wind energy involves harnessing wind energy with a wind turbine placed on a floating support structure. So far, more than 20 different platform designs have been

[3] https://windeurope.org/newsroom/news/europe-can-expect-to-have-10-gw-of-floating-wind-by-2030/ (Last accessed: 13 November 2024).

[4] https://www.offshorewind.biz/2023/10/05/global-floating-offshore-wind-project-pipeline-up-by-one-third-in-a-year/ (Last accesswed: 27 March 2024).

tested at sea, either at the stage of prototype, demonstration, or farm scale device (Edwards et al. 2023). And there are currently many more concepts being investigated at an early stage of development (DNV 2022). This variety of design architectures sets floating wind turbines apart from their bottom-fixed counterparts. For the latter, large-scale commercial wind turbines have converged towards horizontal-axis wind turbines and more than 80% of the support structures in Europe are monopiles (EWEA 2021). For such a setup, an optimum sizing of the design can then be achieved using multi-disciplinary design and analysis (MDAO) tools (Mehta et al. 2024). By contrast, it is still unclear what is the best floating wind turbine design architecture suitable for mass deployment and whether this solution is unique. For example, there is evidence that the optimum combination of floater design and suitable O&M strategy may depend on factors such as water depth and distance to port (Baudino Bessone et al. 2025). Floating wind turbines are built from different components: turbine including tower and rotor-nacelle assembly, floater, mooring lines, and anchors. For each component, different layout options are available, and these are summarised in a mix-and-match table (see Table 1). Note that this table is not necessarily complete and that some combinations are infeasible due to the underlying working principle of the component design. Some design options/combinations are also visualised in Figs. 3 and 4. It is foreseen that the number of design options will reduce as the field grows to large-scale industrialisation.

Floater (and mooring lines): As shown in Fig. 4, there are different design categories currently being used for the floating support structure. Each category differs from one another in its designs and its ways of achieving static stability. The tension-leg platform (4a) is stable through high-tension tendons extending vertically to the seabed. This reduces the footprint of the structure on the seabed. However, it also means that the structure is unstable without moorings, which can complicate its installation (Butterfield et al. 2005). In contrast, the semi-submersible platform (4b) is usually composed of three or four columns connected together with braces and attached to the seabed with long catenary mooring lines. Buoyancy is provided by the columns and a combination of large water-plane area and ballasting ensures static stability. The spar-buoy (4c) is a slender support structure which requires a deep and ballasted draft to remain stable. For this reason, this concept is less suited for waters shallower than 100 metres. As for the semi-submersible, it is kept in position with

Table 1 Design options for the rotor and underwater components (floater, moorings and anchors) for floating wind turbines

Component	Design options (not a complete list)			
Rotor	Horizontal-axis:	Vertical-axis:	Air-borne:	Multi-rotor
	- Upwind	- Lift-driven	- Ground-gen	
	- Downwind	- Drag-driven	-Fly-gen	
	- N-bladed	- N-bladed		
Nacelle	Geared drivetrain	Direct drivetrain		
Floater	Semi-submersible	Spar-buoy	TLP	Barge
Moorings	Catenary	Tendons	Un-moored	
Anchors	Drag	Dead-weight	Suction pile	Vertical load

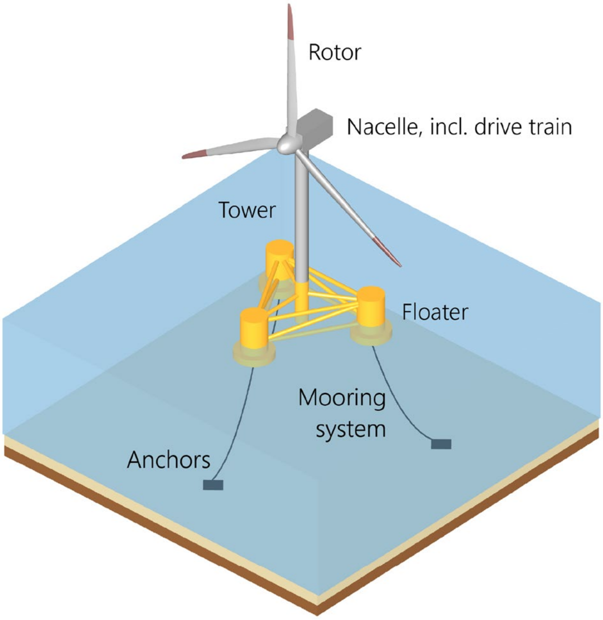


Fig. 3 Components of a floating wind turbine

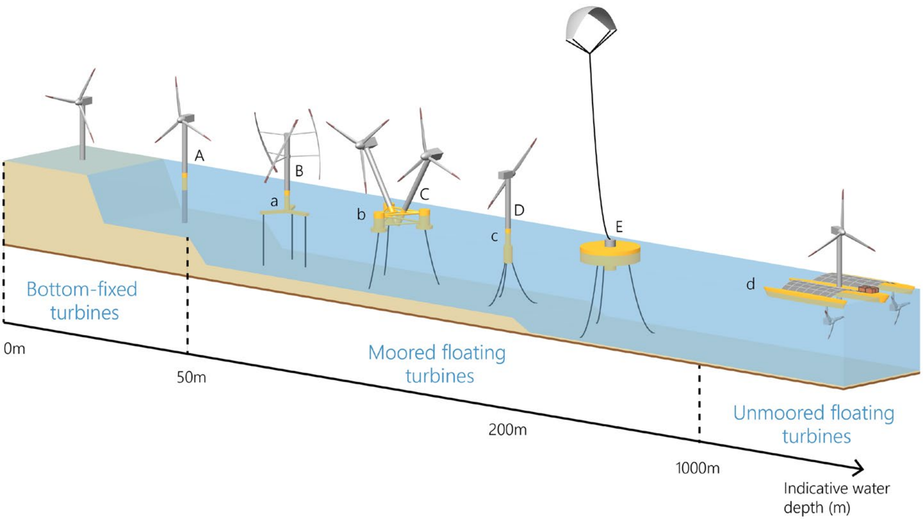


Fig. 4 Examples of alternative rotor and floater concepts. Rotor: (**a**) conventional horizontal-axis wind turbine, (**b**) vertical-axis wind turbine, (**c**) multi-rotor, (**d**) two-bladed downwind turbine, (**e**) airborne wind energy system. Floater: (**a**) tension-leg platform, (**b**) semi-submersible, (**c**) spar-buoy, (**d**) unmoored platform

long catenary mooring lines. Finally, some also distinguish the barge platform design (not shown in the figure). This structure is stable through its large water-plane area and uses catenary mooring lines for station keeping. In the mooring lines options mentioned above, the fairlead positions are distributed around the floating platform and the moorings provide the necessary moments to restore the system motions under wind and wave excitations. This is the most common design option used in today's floating wind turbines. Another option is to use a single-point mooring system, that groups the fairleads at one location and allows the floater to yaw freely (Jiang 2025).

Anchors: The anchor selection highly depends on the seabed conditions at the wind farm site. Drag embedment anchors are typically used with catenary mooring systems, as they can withstand large horizontal loads. However, other technologies such as dead-weight anchors can also be considered (Martinez and Iglesias 2022). The high-tension lines of TLPs need to withstand vertical loads, and therefore, the use of a suction pile anchor or a vertical load anchor is preferred. Although all floating wind turbines currently being demonstrated at sea are moored to the seabed, mooring lines and anchors may still be a bottleneck for the installation of floating wind turbines in very deep seas (e.g. > 1000 m) because of the expense of ensuring large load handling capabilities of moorings and anchors, and their increased footprint (Jonkman 2016). To alleviate these limitations, a handful of designs consider the use of an unmoored floating platform (4d), which is either kept in place through thrusters (Alwan et al. 2021) or moved around as a ship (Annan et al. 2020). Freely floating systems could be attractive for different reasons: (i) maximising the energy yield, by dynamically moving to the best resource, (ii) avoiding wake effects, (iii) and accelerating the deployment times by avoiding lengthy permitting processes. However, they raise other challenges, such as their autonomous interactions with other sea users and the energy transport to shore since these systems are operating off-grid. For this reason, it is still unclear which role unmoored systems will have in the long-term landscape of offshore renewables.

Rotor-nacelle assembly: In addition to the variety of underwater components, floating wind turbines can also vary in their rotor design and configuration. The vast majority of floating wind turbines currently developed use a single horizontal-axis wind turbine per floater, with the rotor facing the wind (upwind configuration), and where the wind turbine controller is adapted to floating conditions, as further discussed in Sect. 3. It is foreseen that this will remain the most-adopted design for years to come, and it is therefore the main focus of this paper. However, several alternative concepts are under investigation. For example, some developers are considering the use of downwind horizontal-axis wind turbine, where the nacelle faces the wind, or vertical-axis wind turbines (4B) to lower the centre of gravity of the system and potentially enable smaller floater size for a given rated power of the wind turbine. Independent of the rotor type, some concepts use multiple rotors on a single floating support structure (4C), with each rotor having either its own tower or sharing with other rotors in so-called multi-rotor configurations. In some cases, multiple rotors are also mounted together on a large frame structure. More innovative concepts are also being considered, such as a two-bladed passive pitch rotor that uses a hinge mechanism, so that the lift force of the rotor can regulate the orientation of the rotor blade relative to the wind flow (Krishnan et al. 2022). Another option is airborne wind energy systems (Schmehl 2018) (4E) where wind energy is produced from high-altitude flying devices, where electricity can be generated on-board (fly-gen configuration) or on the ground (ground-gen configuration). Regarding the nacelle, different design options are possible. They are not specific to floating wind turbines but depend on the type of drive train used in the nacelle. In geared drive trains, a gearbox is used to convert the rotation speed of the rotor to a higher value that drives the generator. By contrast, in direct-drive wind turbines, the rotor connects directly to the generator. Although this eliminates the risk of mechanical failures in the gearbox, it increases the size of the nacelle.

1.3 Objective and Outline

Whilst floating wind turbines open up new markets in deeper waters, their design and dynamics are different from those of bottom-fixed wind turbines. Although this brings challenges across disciplines, it also offers opportunities to innovate in numerical methods, experimental techniques, technology, and logistics. This paper aims to present these challenges and opportunities across the lifetime of a floating wind turbine, with a focus on fluid mechanics. The paper is organised as follows. Section 2 characterises the dynamics of floating wind turbines and their impact on the development and operation of these turbines. Section 3 presents the main fluid mechanics challenges associated with floating wind turbines and explains their roles and impacts on the loads, performance and design of these technologies. Section 4 builds on the challenges to highlight areas that are currently unclear or unexplored in the literature and for which there are research needs in associated methodologies and infrastructure where the fluid mechanics community can add value. Finally, Sect. 5 summarises the main findings and presents an outlook for fluid dynamicists in the field of floating wind energy.

2 Characteristics of Floating Wind Turbines

Floating wind turbines vary in type, but independently of the design, these floating machines are subjected to many loads that affect the dynamics of the system. In this section, we highlight the different motions experienced by floating wind turbines, as well as their underlying complexity and impact on the turbine throughout the system's lifetime.

2.1 Floating Dynamics

Due to the compliant nature of floating wind turbines, these systems are non-stationary and experience motions in six degrees of freedom (DOF) under the effect of a variety of loads, such as wind-induced loads, wave-induced loads, ocean currents loads, gravitational loads, aerodynamic loads, sea-ice loads, or loads due to fault or accident (Cruz and Atcheson 2016). All these loads are, in a way, interconnected and are affecting the turbine's dynamics, loads, operations and performance. This dynamic behaviour is one of the floating machines' key characteristics and clearly distinguishes floating turbines from their bottom-fixed counterpart. The floating motions are described by three translations (surge, sway, heave) and three rotations (pitch, roll, yaw), and are highly dependent on the type of moorings, floating support structure and site-specific conditions. The terminology of the different floating motions is indicated in Fig. 5 (top left). It is worth noting that most numerical and experimental studies available in the literature focus on surge, pitch and, to a smaller extent, heave. These are the main degrees of freedom of interest when: (i) wind is purely acting perpendicularly to the rotor plane, (ii) the gyroscopic effects of the rotor are disregarded, and (iii) heave motions are decoupled from the other degrees of freedom (Souza and Bachynski

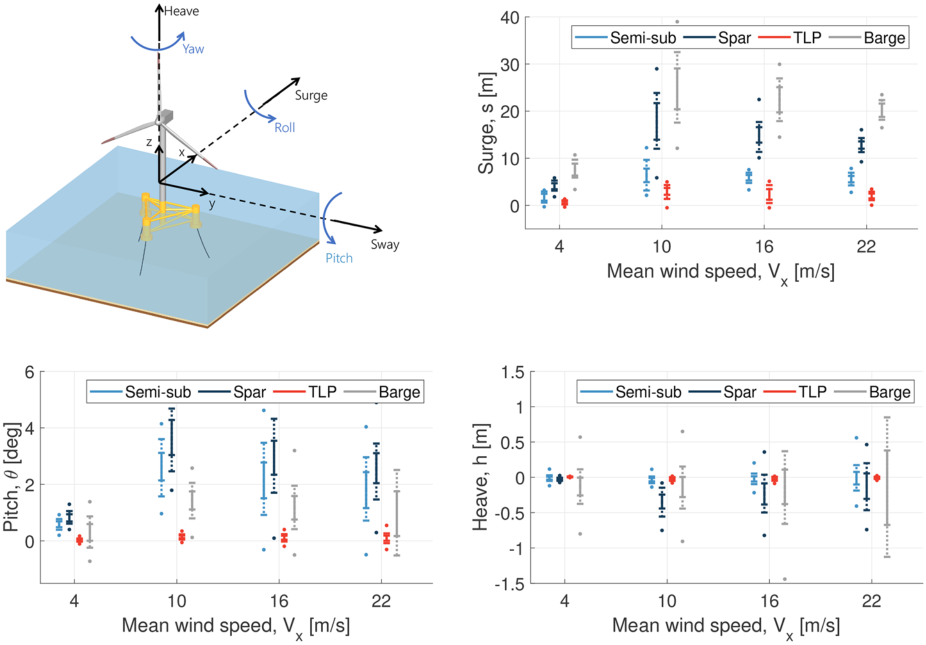


Fig. 5 Terminology of the degrees of freedom (DOF) of a floating wind turbine (top left). floater motion in dominant dof for different floating designs supporting the nrel 5 MW wind turbine: surge (top right), pitch (bottom left), and heave (bottom right); ⌶ 25–75 percentile, ⌶ 10–90 percentile and • the min/max. Simulations are run with OpenFAST in turbulent inflow (Class 1A) and regular waves. Wave height and period are defined depending on the wind speed, according to IEC design load case 1.1

2019). In reality, however, the six degrees of freedom are fully coupled and dynamically interact with external environmental conditions.

The motions experienced by different floating wind turbine configurations have been analysed both numerically and experimentally in the literature. Here, in Fig. 5, the typical floating motions that may be expected are illustrated by showing the results of simulations run with OpenFAST, a state-of-the-art open-source engineering tool for wind turbine simulations.[5] The simulations were run for the NREL 5 MW turbine supported by various floater designs. The NREL 5 MW turbine is a well-known reference turbine (Jonkman et al. 2009), with a rotor diameter of 126 m, that has been extensively studied in the literature over the past years. Only the dominant degrees of freedom are presented, i.e. surge, pitch and heave. The results are obtained in unsteady wind conditions (NTM-A) and subjected to regular waves with significant wave heights varying between 1.1 m and 4.52 m and peak periods between 7.44s and 9.45s. The detailed wave characteristics are prescribed according to the IEC design load case 1.1 for normal operation of offshore wind turbines (IEC 2019) and vary depending on the incoming wind speed. The wind speed at which the turbine reaches its rated power of 5 MW, i.e. the rated wind speed, is equal to 11.4 m/s for the turbine considered here. This is also the wind speed at which the thrust force on the turbine is maximum. Whilst the dynamics of specific commercial concepts might differ from the results presented here, the plots illustrate typical characteristics of the first-order response of these floaters.

[5] https://github.com/OpenFAST/r-test/tree/main/glue-codes/openfast

In particular, the qualitative comparison of the dynamics of the different floater types is expected to hold even under conditions that are different to those investigated here. The figures show that a spar-buoy support structure exhibits large displacements in pitch and surge near the rated wind speed. By contrast, the tension-leg platform (TLP) exhibits little motion across the range of wind speeds. Lastly, the semi-submersible is compliant in both pitch and surge. The barge-type floater shows significant motions in all three directions. The mean displacement of the floater, and its dynamic response, are also highly driven by the mean wind speed. Because the thrust force is maximum at rated wind speed, the turbine also experiences large motions in all degrees of freedom.

Other studies in the literature confirm these findings. For example, the pitch and surge results obtained by wave tank experiments on 1:50 scaled models of each floater supporting a 5 MW turbine (Goupee et al. 2014) are in line with the present results. The response in the other degrees of freedom of a spar and semi-submersible are also reported in the literature, for example Martini et al. (2016), Mahfouz et al. (2020), for both a 5 MW turbine (with semi-submersible floater) and a 15 MW turbine (with spar and semi-submersible). It is shown that a spar supporting a 15 MW turbine can reach about 8° in pitch under extreme wind-wave conditions and up to 7° in yaw, whilst the maximum roll motions are half these values. The semi-submersible has maximum yaw, roll and pitch values of 13.8°, 3°, and 5°, respectively.

There are two main design drivers for floating wind turbines: ensuring a stable system, thus reducing overall motions, and decreasing costs (Edwards et al. 2023). The motion of the system changes the apparent wind speed experienced by the turbine, including the nacelle velocities. Similarly to focusing on platform motions, developers also look at nacelle accelerations. Combined motions may amplify or cancel each other depending on the operational condition. Large translations and rotations could still result in limited nacelle displacements if, for example, surge and pitch are out of phase. Typically, the largest accelerations are found when wind and waves are aligned (Martini et al. 2016). Also, the combination of wave frequency and amplitude is important, as low frequencies generally compensate for large waves. It is worth noting that large wave heights at low wind speed can also lead to large nacelle accelerations, hence indicating the importance of wave conditions on this quantity (Martini et al. 2016).

It is clear that the floating dynamics will significantly impact the turbine response in terms of loads, operations, and performance. The above-mentioned floating platform motions, however, only concern standard operational conditions. As floating wind turbines are not directly mounted on the seabed, their installation process and logistics may differ from bottom-fixed turbines. Floating wind turbines allow for an assembly at port or at a sheltered location, followed by towing to the site. From a dynamics perspective, one may expect interesting behaviours to appear during this installation process, some of which will be detailed further in this paper.

2.2 Fully-Coupled System

As mentioned above, the diverse set of loads acting on floating wind turbines is, in a way, interconnected and affects the turbine's dynamics. While some interactions are typically neglected for bottom-fixed turbines, this is no longer valid for floating turbines. For example, the effect of gravitational loads on the dynamics of wind turbine towers is typically omitted for fixed turbines. However, when the floating turbine moves in pitch and roll, the misalignment between the gravitational force and the tower axis creates a moment on the tower. This can impact the loads on the turbine, and specifically the blade-root edgewise fatigue loads (Singh et al. 2024). Additionally, there are much more interactions between met-ocean conditions and floating wind turbine dynamics than with a bottom-fixed turbine. The importance of wind, wave, and water current characteristics on the motions and loads of a floating wind turbine depends on the turbine rating and the type of floating support structure. It is clear that significant wave height, as well as wind speed mean and standard deviation, are correlated to tower fatigue. Significant wave height is also correlated with the blade root flapwise 10-minute damage equivalent loads for the TetraSpar concept (Singh et al. 2024) and the tower-base loads for spar-buoy and semi-submersible designs, whilst the water current velocity has a large dominant effect on the mooring loads (Ramesh Reddy et al. 2024). Because of the effect of met-ocean conditions on the motions and loads of the system, it is also important to identify the appropriate combination of wind, wave and current characteristics when determining the design probability of failure across different types of load case. Design standards have defined such combinations but there is research work to be done to refine these and ensure that floating offshore structures for wind are neither over-conservative nor unsafe.

The controller of floating wind turbines also needs to be different to that of bottom-fixed wind turbines as it needs to account for platform motions and to avoid system instabilities. The challenges and opportunities in this field is beyond the scope of this paper and is addressed separately in the literature (Stockhouse et al. 2023). Additionally, given the current growth in rotor size, especially for offshore applications, the aeroelastic behaviour of the rotor is non-negligible.

Because different physical excitations impact floating wind turbines in a fully-coupled way, modelling tools should also have the capability to account for these couplings. Suitable simulation tools should integrate the dynamics of each component of a single turbine, i.e. rotor, drive train, nacelle, tower, floater, mooring lines, and control system (Fig. 6), and their possible interactions to produce meaningful results. Note that the orientation of the aerodynamic and hydrodynamic loads is not limited to those shown in Fig. 6.

2.3 Fluid Mechanics Landscape

The coupled dynamics of floating wind turbines in six degrees of freedom give rise to complex fluid mechanics phenomena and interactions that differ from those experienced by conventional bottom-fixed wind turbines. Figure 7 provides a visual overview of these floating-specific challenges and the associated research needs, and spans the entire innovation and supply chain, i.e. from design (phase 1) to manufacturing (phase 2), installation (phase 3), operation & maintenance (phase 4), and end-of-life decommissioning (phase 5).

Fluid mechanics challenges occur throughout all phases of their lifetime. However, they are most prominent in phases 1, 3 and 4. Manufacturing (phase 2) presents some structural mechanics and material science challenges associated, for example, with the manufacturing of very long blades and the mass production of floating support structures. Similarly, decommissioning (phase 5) and the associated circularity aspects of these turbines are crucial but beyond the scope of this paper. Challenges during the installation phase will be addressed here from a fluid mechanics perspective only. There are, of course, many more

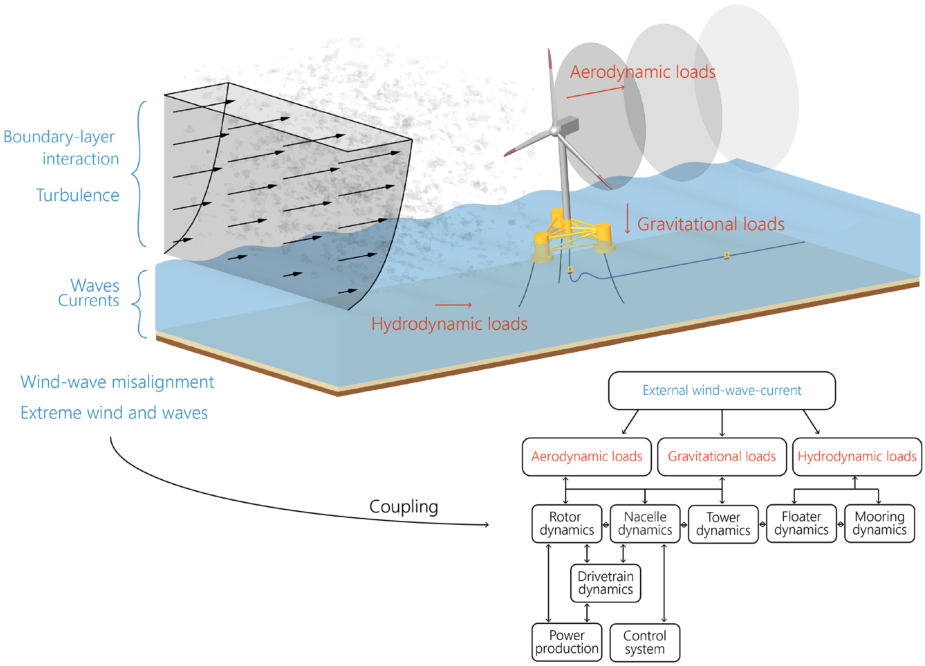


Fig. 6 Coupled loads and dynamics of a floating wind turbine, including the terminology of floating motions

technical challenges during the installation of these turbines that are not directly related to the field of fluid mechanics, such as the need for control and dynamic positioning systems when installing offshore wind turbines (both fixed and floating) from a floating vessel, and the fundamental understanding of soil-foundation system interaction for example during the installation of anchors. Although these topics (and many more) are very relevant to the field, these aspects are beyond the scope of this paper. In the following, in Sect. 3, we describe in more detail the floating-specific fluid mechanics challenges associated with the design, operation, and logistics of floating wind turbines and farms.

3 Fluid Mechanics Challenges for Floating Wind Turbines

In 2022, about a hundred wind energy experts worldwide wrote a series of scientific papers on the grand challenges in wind energy. They identified four generations of wind energy development from the wind and the rotor to the wind turbine system, the plant (or farm) and the grid, and the future energy system (Veers et al. 2022). The authors claimed that in moving along the ladder of generation levels, some scientific challenges were left unsolved, which constituted a barrier to achieving a carbon-neutral future energy system. One of these scientific challenges, as shown in Fig. 8, is floating wind turbines. As highlighted in Sect. 2, floating-specific characteristics bring new challenges across the phases of development and operation of floating wind farms. As such, floating wind turbines and farms have their own set of unresolved research questions.

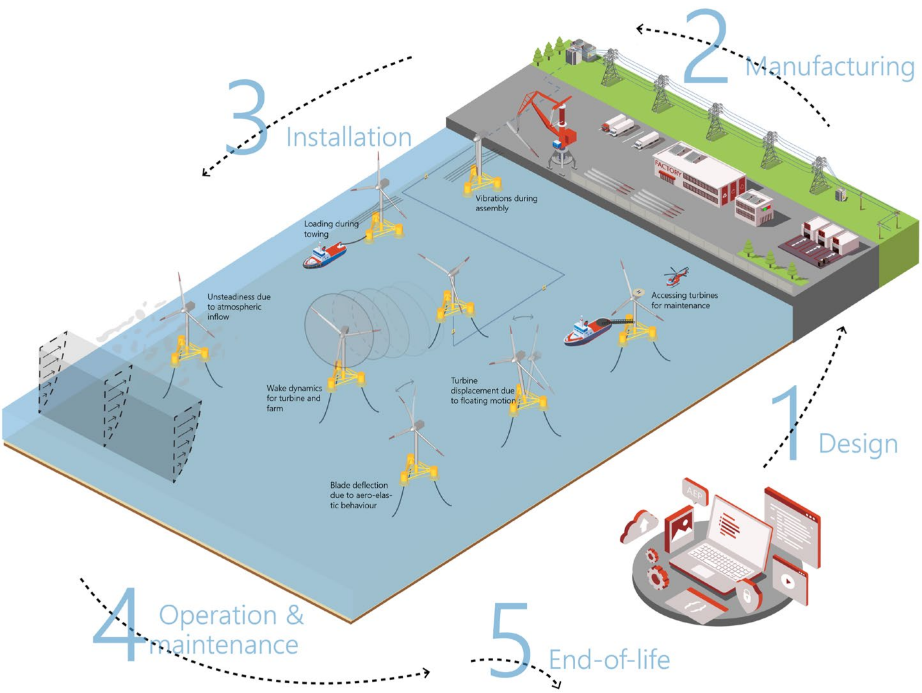


Fig. 7 Examples of fluid mechanics challenges that affect floating wind turbines throughout the phases of their lifetime

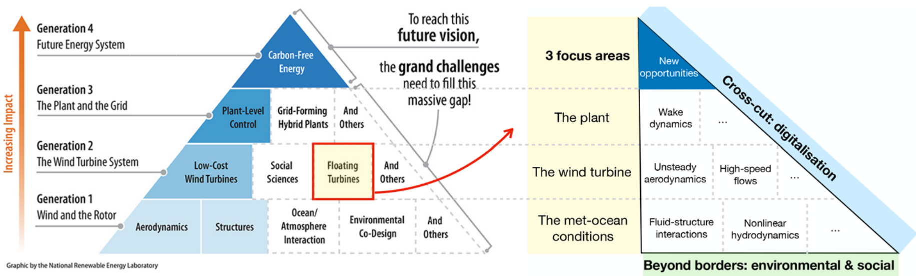


Fig. 8 Scientific challenges to achieve carbon-neutral future energy system: pyramid view from Veers et al. (2022) (left, reproduced with permission) and fluid mechanics challenges associated with floating wind turbines and farms addressed in this manuscript (right)

In this section, we focus on the fluid mechanics challenges. Using the three focus areas of Veers et al. (2022), namely (i) the met-ocean conditions, (ii) the wind turbine, and (iii) the plant, we dive into five fluid mechanics challenges that require further investigations and to which the fluid mechanics community can heavily contribute. Each one of these challenges is addressed in a dedicated sub-section hereafter. Their phase of interest (as defined in Sect. 2.3), scales, roles for floating wind turbines, and impacts on components loads, performance, and design are further explained. The two additional cross-cutting themes of Veers et al. (2022), i.e. digitalisation and looking beyond borders (Fig. 8), are more broadly addressed in Sects. 4 and 5.

3.1 Unsteady Aerodynamics

Phase of interest: Design, installation, operation and maintenance
Scale of phenomena: At airfoil and rotor level
Role for (floating) wind turbines: A rotor blade comprises a series of different airfoils. In bottom-fixed wind turbines, the local relative velocity V_{rel} at each airfoil is a vector sum of a component due to the upstream wind speed and a component due to the rotation speed of the rotor. Based on the conservation of momentum for flow past an actuator disk, the velocity component due to the inflow equals $U_\infty(1-a)$ at the rotor, where a is the axial induction factor that can be related to the thrust force on the rotor and U_∞ is the undisturbed wind speed. The angle of attack, α, is further defined as the angle between the local relative velocity seen by the airfoil, V_{rel}, and the airfoil chord line. When the rotor experiences floating motions, the local relative velocity at the airfoil changes, leading to variations in the angle of attack on the airfoil. Examples of these variations, as a function of the wind speed, are shown in Fig. 9 for a 15 MW wind turbine that is either fixed (blue colors) or floating and subjected to different wind and wave conditions (Allen et al. 2020). The wave conditions are defined as per IEC design load case DLC1.1 (refer to as small waves in Fig. 9) and DLC1.6 (refer to as large waves). It is apparent that the dominant effect on the spread of variations in these quantities is related to the level of turbulence in the wind. These variations lead to changes in the loads on the rotor, which also affect the vortex system in the turbine wake, as further shown in the next section. The change of α due to the change in V_{rel} is considered in the blade-element momentum (BEM) theory commonly used for design. However, another

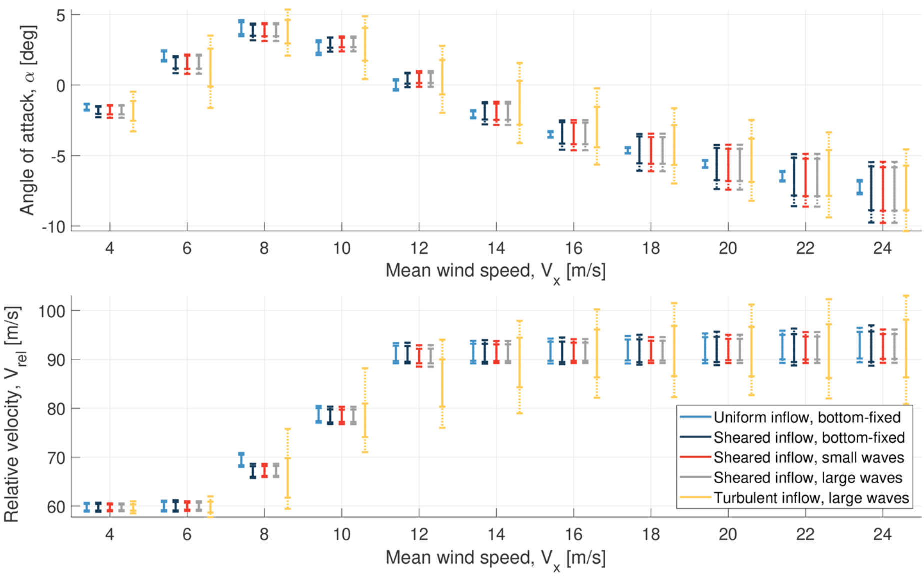


Fig. 9 Operational conditions of a floating IEA 15MW turbine at various inflow (uniform, sheared, turbulent) and sea conditions, small waves corresponding to the iec design load case DLC1.1 and large waves to DLC1.6 ⦙ 25–75%ile and ⌶ 10–90%ile

source of variations in α that is not captured by the BEM theory relates to the fact that the floating motion may cause the blade to interfere with its own wake.

The degrees of freedom that have the largest influence on the rotor aerodynamics are the upwind and downwind motions, i.e. surge and pitch, followed by yaw motions. By contrast, it is reported in the literature that heave, sway, and roll have the least influence on rotor aerodynamics (Jonkman and Matha 2011). If the variations of the angle of attack are fast, the associated changes in lift force will not be immediate. Instead, they will occur at a certain time delay, commonly referred to as dynamic inflow (Theodorsen 1949). The reason is that the loads are still affected by the near wake generated by the previous operating conditions. The wake is the region downstream of the rotor, where the wind speed is reduced and the turbulence level is increased due to the energy extracted by the wind turbine. As time elapses, the "old" wake is convected downstream and a "new" near-wake develops, hence modifying the induced velocities and the loads on the airfoil. As such, the convection velocity of the tip vortices, which is defined as the sum between the far-upstream inflow velocity and the local self-induced velocity, is an important quantity to quantify the occurrence of dynamic inflow. Furthermore, the level of flow unsteadiness is often quantified by a reduced frequency, $k = fl/V_{rel}$, where f is the frequency of motion and l is a relevant length scale. The reduced frequency can be defined either at airfoil scale, $l{=}c$, with c being the airfoil chord length, or rotor scale, $l{=}D$, with D being the rotor diameter. The engineering models used for computing the aerodynamics of floating wind turbines often use dynamic inflow models that are derived for blade pitching motions under non-sheared inflow, rather than floater motions with complex inflow. There is thus a need to evaluate whether dynamic inflow occurs in floating wind turbines and whether current models adequately account for it.

It is not only the frequency of variations of α that is an important parameter, but also their magnitude. If the variations in α are large enough, flow separation occurs on the airfoil leading to stall and a loss of lift force. The cyclic transition into and out of the stall region is referred to as dynamic stall. Similarly to the reduced frequency defined above, a reduced motion amplitude can be defined by dividing the motion amplitude by a characteristic length. In the limit of reduced frequencies and amplitudes tending to zero, the quasi-steady aerodynamics assumption holds. However, as the reduced frequencies and amplitudes increase, the quasi-steady assumption breaks down. This is particularly true for non-dimensional frequencies, $St = fD/U_\infty$, larger than one; see Fontanella et al. (2021), Taruffi et al. (2024), for example.

Consequence on loads, performance and design: Although single degree-of-freedom motions in surge and pitch can have, in certain conditions, a positive effect on the overall power produced by a floating wind turbine (Lienard et al. 2020), (Amaral et al. 2022), the net gain in power due to the increased relative flow velocity at the rotor can also be inhibited by the turbine controller which ensures that the power produced does not exceed the rated value. Additionally, combined two degrees of freedom motions have been shown to be detrimental to the overall power produced by a floating wind turbine, for example, in surge-pitch (Chen et al. 2021), (Ramponi et al. 2023). The yaw amplitude in pitch-yaw motions was further shown to have a negligible effect on power fluctuations (Ramponi et al. 2023). In addition, local flow changes at the blade section can be detrimental to the fatigue loads on floating wind turbine blades.

Overall, in the presence of blade-wake interactions and complex flow phenomena on floating wind turbine airfoils, the validity of engineering tools currently used to design offshore wind turbines becomes questionable and their use leads to uncertainties in the design process. This adds to the underlying uncertainties associated with the stochastic nature of both the met-ocean conditions and the response of the system.

A recent study by Corniglion et al. (2022) showed that the variations in local velocity associated with a prescribed surging motion dominate the variations in the axial induced velocity, hence leading to marginal changes in the velocity induced by the tip vortex helix. Therefore, even if the motion largely modifies the local flow, there is no delay between the changes in loads and the motion dynamics. It is worth noting that a floating turbine will change its blade pitch and rotor speed to adapt to the floating motions, and these two changes will lead to dynamic inflow. Thus, although the floating motions do not seem to be the prime source of dynamic inflow, they will indirectly lead to it.

3.2 Wake Dynamics

Phase of interest: Design, operation and maintenance
Scale of phenomena: At rotor and wake level
Role for (floating) wind turbines: The wake of a wind turbine is defined by the vortex system created by the force field of the rotor. According to the vorticity equations for incompressible, inviscid flows, vorticity can only be created by a change in the force field, i.e. at the locations where the curl of the force field is non-zero. As such, vorticity is a time- and space-dependent parameter. Following this definition, the force field of a floating wind turbine is, per definition, different than that of a bottom-fixed turbine due to two reasons. First, the additional velocity component caused by the turbine's motion triggers an unsteady rotor loading, as described in the previous section. Second, the force field is no longer stationary but moves in space due to the floating motion. These two effects evolve into a significantly different vortex system for floating turbines. In Figs. 10a, the vortex system of a 2D uniformly steady-loaded actuator disk is presented, where the blue dots show the center of the vortex cores. Simulations results are obtained for a disk of diameter $D=1$ under a uniform wind speed of 1 m/s. In a sense, this may represent a simplified version of the vortex system of a bottom-fixed turbine in steady inflow conditions. Figure 10b and 10c, on the other hand, present as a comparison the vortex system of a sinusoidally pitching actuator disk and an unsteady loaded disk, respectively. Both phenomena cause a harmonica effect in the vortex system resulting in wake roll-up and wake mixing. The impact of prescribed wind turbine motions on wakes was further shown in the literature, for example by highlighting the presence of motion frequencies in the wake of a moving turbine (Fu et al. 2019), (Raibaudo et al. 2022) and showing the effect of motion frequency on the stability of tip vortices as they propagate downstream (Kleine et al. 2022). In the example presented in Fig. 10, the floating motion velocity remains smaller than the wake propagation velocity. Here, the vortices are released behind the turbine in a rather steady behaviour. However, as shown in the previous section, for some combination of wind and wave conditions, the blades may move into their own wakes resulting in strong blade-wake interactions.

It is not only the vorticity being generated that is altered by the floating motions, larger-scale wake dynamics can also change. As wakes are convected downstream, they exhibit random unsteady oscillations with respect to the time-averaged wake centreline, both in

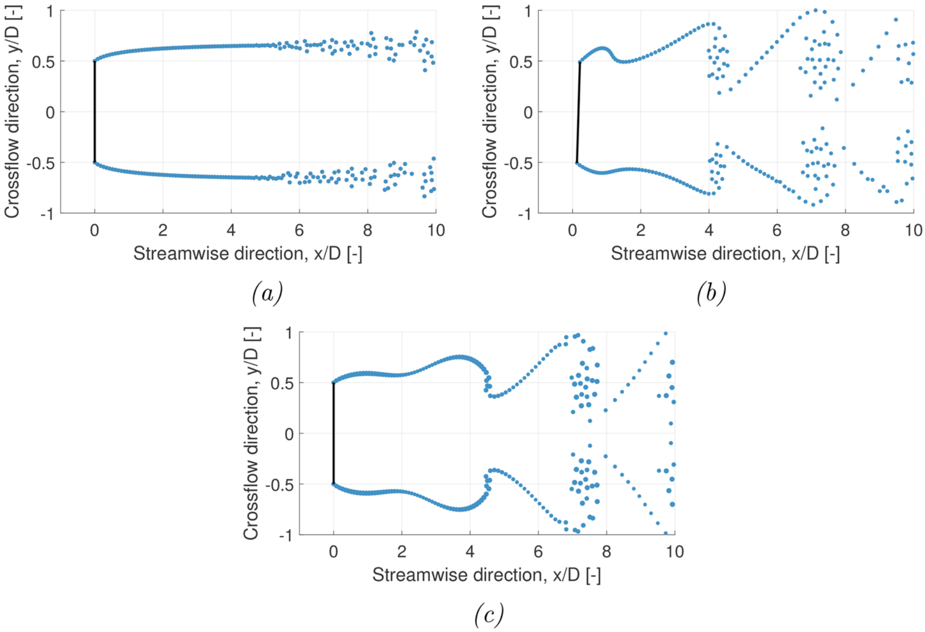


Fig. 10 Visualisation of the vortex system (blue dots are the centers of the vortex cores) for an actuator disk with a mean thrust coefficient of 0.7: (**a**) bottom-fixed steady-loaded 2D actuator disk, (**b**) pitching, steady-loaded, 2D actuator disk (sinusoidally, $A = 5\text{deg}$, k=0.25), and (**c**) bottom-fixed unsteady-loaded 2D actuator disk (sinusoidally, A=0.1, k=0.25)

the lateral and vertical directions (Agel et al. 2020). This is commonly referred to as wake meandering. For bottom-fixed wind turbines, wake meandering can be triggered by both the selective amplification of disturbance in the inflow and the intrinsic shear instability of the wake when turbulent eddies become larger than the wind turbine diameter (Heisel et al. 2018), (Yang and Sotiropoulos 2019), (Lin and Porté-Agel 2024). For floating wind turbines, two questions are of interest: does the floating motion impact the wake meandering process, and vice-versa, does wake meandering affect the dynamics of downstream floating wind turbines? To partly answer the first question, literature shows that pitch motions influence vertical meandering (Wise and Bachynski 2020) and that the motion frequencies present in the far-wake can trigger a pseudo-lock-in phenomenon when approaching the wake meandering frequency (Gupta and Wan 2019). There is also evidence that even small side-by-side motions (i.e. roll, sway) of less than $0.01D$ can be an additional source of onset of meandering when the inflow turbulence is low (Li et al. 2022). The answer to how wake meandering affects the dynamics of downstream floating wind turbines is addressed hereafter.

Consequence on loads, performance and design: The effect of the near-wake on the loads and performance of the turbine has already been discussed in the previous section. Here, the focus is on how the wake dynamics develop at farm level and the consequences for floating wind turbines located downstream. Wind turbine wakes are characterised by a reduced mean wind speed and an increased turbulence intensity compared to an undisturbed wind field. As the distance from the rotor increases downstream, turbulent mixing re-energises the wake by bringing undisturbed wind flow into the wake region, hence progressively decreasing the velocity deficit. Understanding the dynamics of wind turbine wakes is important to maximise both the power produced by farms and the lifetime of individual turbines.

For bottom-fixed wind turbines, the speed at which wakes fully recover depends on the inflow conditions, the characteristics of the atmospheric boundary layer, and the wind turbine control strategy. When the turbine floats and the motion frequencies are present in the wake, momentum transport from the surrounding flow increases. This suggests a faster wake recovery than without floating motions, which would be beneficial for the overall performance of floating wind farms and the lifetime of individual turbines. These findings are consistent with the results obtained experimentally with an actuator disk under prescribed surge motion (Schliffke 2021) when the motion surpasses a certain threshold, and a scaled turbine under side-by-side and fore-aft motions with laminar inflow and low wind turbulence intensities that are characteristic of stable atmospheric conditions (Messmer et al. 2024). It is worth noting that the presence of inflow turbulence is likely to affect the process of wake recovery, as this has been shown for both bottom-fixed (Hodgkin et al. 2023), (Parinam et al. 2024) and floating wind turbines (Li et al. 2022), and could thus reduce the impact of turbine motions on the recovery process. It has also been shown in the literature that wake meandering can increase the yaw motion of downstream floating wind turbines (Wise and Bachynski 2020). This adds complexity to the dynamics of the system and shows the importance of incorporating multiple scales and fidelities when analysing these systems. Finally, since each degree of freedom has a different effect on the vortex dynamics in the wake, the wake recovery process depends on the motion characteristics of the turbine and the natural frequencies of the floater.

3.3 High Speed Flows

Phase of interest: Design, operation and maintenance
Scale of phenomena: At airfoil and rotor level
Role for (floating) wind turbines: Due to system design trades, state-of-the-art offshore wind turbines are large, with long and flexible blades (Mehta et al. 2024). These substantial wind turbines are characterised by high-speed flows at the blade tips, ensuing new aerodynamic challenges. For wind turbines with a rotor radius in the order of $120m$, the flow velocity perceived by the blade tips approaches $100m/s$. These high relative wind speeds dictate high Reynolds numbers, on the one hand, and increased Mach numbers, on the other hand. More specifically, the (chord-based) Reynolds numbers *Re* easily exceed 10×10^6 for a blade length in the order of $120m$. For the IEA 15 MW and 22 MW reference wind turbine, in particular, *Re* values above 10×10^6 occur at the outer ≈75% of the span at rated conditions. The maximum chord-based Reynolds number equals $Re = 15.3 \times 10^6$, and is reached at a radial position of 70% for the IEA 15 MW, and equals $Re = 17.6 \times 10^6$ at 50% radial position for the IEA 22 MW. Contrary to a 5 MW turbine, which was the reference nearly 10 years ago, the Reynolds numbers are more than 25% and 45% higher, as illustrated by Fig. 11. While airfoil-based Reynolds numbers are generally of major interest for airfoil aerodynamics, a rotor-based Reynolds number has been introduced for wind turbines. Here the characteristic length is defined as the rotor diameter, and the characteristic flow velocity is the incoming wind speed. For the IEA15MW turbine, the diameter-based Reynolds number equals 1.69×10^8 at an inflow wind velocity of $10m/s$, while for a 5 MW turbine

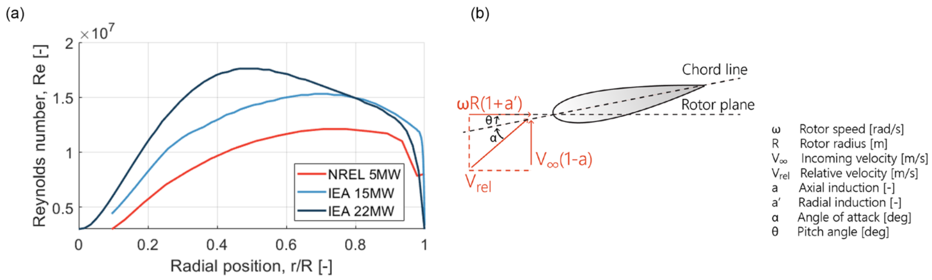


Fig. 11 (**a**) Chord-based Reynolds number along the span of the blade for the NREL 5MW, IEA 15MW, and IEA 22MW reference turbines at rated wind speed. (**b**) Wind velocity triangle

this would be roughly 40% lower, assuming that the power is linearly proportional to the diameter squared.

High subsonic (compressible) or even transonic flows remain mostly ignored in the wind turbine literature, as they have been considered irrelevant for wind turbines. However, recent work shows that local Mach numbers larger than one may appear on the IEA 15 MW reference turbine (De Tavernier and von Terzi 2022) leading to the emergence of supersonic flow on near-future (floating) offshore wind turbines. For wind turbines with a rotor radius in the order of 120m, the Mach number in steady design conditions remains (well) below M=0.3. Unsteadiness due to the presence of turbulence, wind gusts, blade-wake interaction from the aero-hydro-elastic response of the turbine, and the floating motion, however, may cause inflow Mach numbers to rise above 0.3. This implies that the incompressible flow assumption is in question. Moreover, the flow over the airfoil surface is accelerated. At high angles of attack, the local flow can be several times faster than the inflow velocity, depending on the pressure peak. Due to this combination, transonic conditions were identified in normal turbulent inflow conditions near the cut-out wind speed (De Tavernier and von Terzi 2022), as also presented by Fig. 12. At high wind conditions, wind turbines operate at their maximum rotational speed while the blades are pitched out to reduce the rotor torque. Here, negative angles of attack up to −15deg are reached, at which the pressure peak reaches its maximum for wind turbine airfoils.

Consequence on loads, performance and design: In terms of lift and drag, favourable effects on the airfoil performance are expected at high Reynolds numbers. For typical wind energy airfoils, an increase in maximum lift coefficient is to be anticipated, as well as a decrease in the minimum drag. For a typical wind turbine airfoil, this may be in the order of an increase of 25% and reduction of 20%, respectively, according to the experimental campaign executed during the AVATAR project (Schepers 2017) at $Re = 3 \times 10^6$ and $Re = 15 \times 10^6$. The width of the (laminar) drag bucket is expected to reduce with increasing Reynolds numbers, and thus consequently also, the efficiency of the airfoil in terms of lift-to-drag ratio drops. While the maximum lift-to-drag reduces with increasing Reynolds number, also a flattening of the Cl/Cd_{max} peak is observed. In tripped conditions, this may reverse. The overall effect of the Reynolds number can be explained from the point of view of the boundary-layer thickness. Two basic effects can be identified. Generally, we expect thinner boundary layers due to a higher Reynolds number. On the other hand, the rapid forward movement of the transition location tends to thicken the boundary layer. The exact

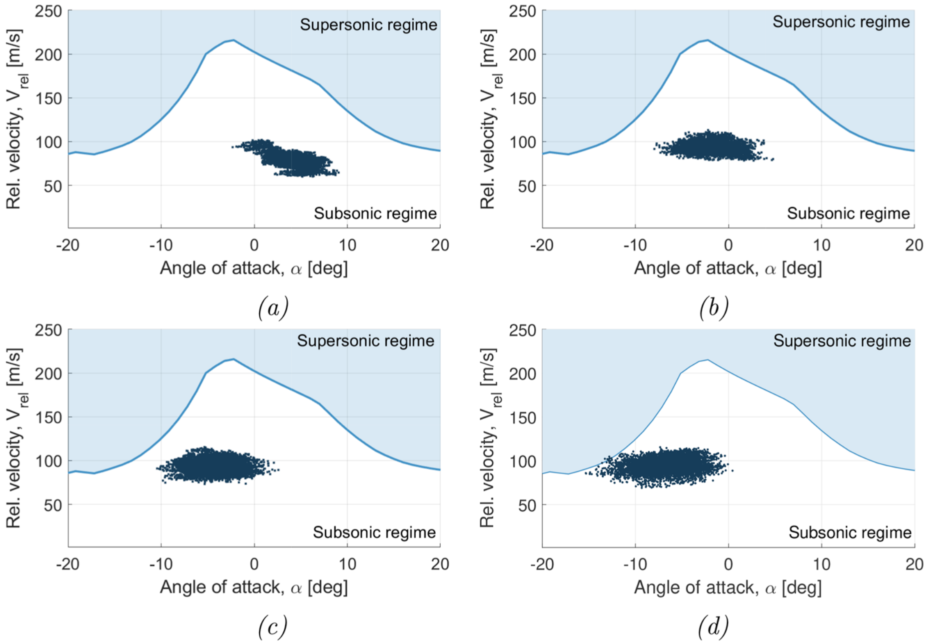


Fig. 12 Operational conditions of IEA 15MW turbine at $r/R = 0.97$ in normal turbulent wind of class a at (**a**) 10 m/s, (**b**) 15 m/s, (**c**) 20 m/s and (**d**) 25 m/s. The supersonic boundary is derived for tip-airfoil FFAW3211 at $Re = 10 \times 10^6$. From De Tavernier and von Terzi (2022)

location of transition from laminar to turbulent flow depends on the pressure and skin friction distributions and, hence, on the airfoil shape.

The amount of research performed on wind turbine airfoils in compressible and transonic conditions is very limited, to say the least. How the flow will react when entering, in an unsteady manner, into these flow conditions remains elusive. However, experience from aerospace-related studies shows that sudden separation of the boundary layer could be expected at the point where supersonic flow is reached. This has drastic consequences for the aerodynamic airfoil performance, as it can lead to full separation and stall of the profile, higher drag and even shock buffeting. Particularly, the high unsteadiness of wind turbines needs to be considered, as the hysteresis effects may significantly affect the airfoil's behaviour in compressible and/or transonic flow conditions.

It is obvious that using appropriate polars is vital in determining the loads and performance of the turbine, as well as its aero-elastic response. However, obtaining credible polars at high-speed flows, both high Reynolds and Mach numbers, remains challenging. Typical wind tunnels for airfoil testing operate in Reynolds numbers between 1×10^6 and 3×10^6, while more recent tunnels can reach Reynolds numbers up to 8×10^6. To reach Reynolds numbers above 10×10^6, a unique and rare pressurized or cryogenic wind tunnel is required which is only available at a handful of locations. Because of the rare availability of experimental facilities, only a few experimental studies for wind turbine applications are executed at Reynolds numbers above 10×10^6, for example Llorente et al. (2014), Pires et al. (2016). While these studies are performed at reasonably high Reynolds numbers, they do not consider the high Mach numbers. Transonic or even supersonic wind tunnels are available but they are not yet used to study compressible, transonic wind turbine airfoil characteristics, except in the study of Aditya et al. (2024), albeit at much lower Reynolds numbers below one million. Vitulano et al. (2024) has numerically identified the necessity of studying both high Reynolds numbers and high Mach numbers at the same time.

The experienced Reynolds and Mach numbers, representative for large-scale floating wind turbines, are well beyond the reach of the available experimental data, and hence, beyond the validation regime of the design and performance assessment tools. As a result, simulation tools are poorly validated in these flow regimes, questioning their applicability. As an example, the physical mechanism of flow transition from laminar to turbulent is very dependent on the Reynolds number regime but, to a lower extent, also on the Mach number. Determining the exact location of transition is shown to be extremely challenging, leading to a wide spread in the results of various models that rely on different existing transition models. While the Reynolds number will mostly affect loads and performance, the impact of transonic flow physics on the turbine level may be significant, also concerning a drastic turbine lifetime degradation leading to a large number of blade replacements in the field at exorbitant costs or even total loss of turbines at sea. However, at this stage, it is impossible to quantify this further.

3.4 Nonlinear Hydrodynamics

Phase of interest: Design, installation, operation and maintenance
Scale of phenomena: At floater and moorings level
Role for (floating) wind turbines: The dynamics of floating wind turbines are excited at different amplitudes and frequencies by wind, wave, and current loads impacting the floater and moorings. Generally speaking, wave loads on an offshore structure can be split into: (i) excitation loads driven by incident and scattered (diffracted) waves due to the structure, (ii) radiation loads driven by the structure motions and proportional to both velocity and acceleration of the structure, and (iii) nonlinear drag loads driven by viscous effects. These loads induce motions of the floater. The floater response to linear irregular waves is in the wave frequency range and can be computed through a linear superposition of the responses to the diffraction and radiation problems considered separately. However, nonlinear waves also induce motions at the sum- and difference-frequencies of the incident wave component, which can interact with some of the floater's natural frequencies. Linear or nonlinear potential flow methods are typically used to compute these wave-structure interactions. However, these methods omit viscous and rotational effects that can have a non-negligible impact on the floater loading. Empirical relations exist to compute the viscous drag force on a floating support structure, but their accuracy is questionable when dealing with complex floater geometries as used in floating wind energy. Another option is to use computational fluid dynamics (CFD) models and solve the Navier-Stokes equations. This requires the addition of an advection equation for tracking the evolution of the air-sea interface. However, the use of CFD-based models to study the dynamics of floating structures subjected to waves is the exception rather than the rule due to their high computational cost. The accurate prediction of wave propagation over long distances using CFD models is also non-trivial, even in the absence of a structure, as this requires accurate discretisation schemes that conserve energy (i.e. non-dissipative), local values (i.e. non-diffusive), and the travelling speed of waves (i.e. non-dispersive). Additionally, for any wave propagation simulation in a numeri-

cal wave tank, absorption zones of several wavelengths need to be used close to the domain boundaries to limit spurious wave reflections. While this is somewhat effective in achieving this goal, it also increases the computational domain size, and hence, the computational cost. Instead, the use of generating-absorbing boundary conditions can alleviate the need for these absorption zones, whilst keeping the same level of accuracy at reduced computational costs (Ramesh Reddy and Viré 2022). It is worth noting that air-sea interactions also affect the level of ambient atmospheric turbulence, which is an important design parameter for wind turbines, and impact on the wake dynamics, making it a multi-scale challenge. Efforts to derive accurate wave phase-averaged and wall-stress parametrisations of wind-wave interactions should also continue as an alternative to exascale computing for wave phase-resolved simulations that are still lacking (Deskos et al. 2021).

Consequence on loads, performance and design: Floating support structures are designed such that their natural frequency falls outside the first-order wave frequency range, in order to avoid large linear responses of the structure. For example, in the context of semi-submersible floaters, heave plates are commonly used to increase the floater's natural period in heave and avoid overlapping with regions of large wave energy. These plates introduce additional viscous effects that require corrections to the nonlinear potential flow models, as mentioned above (Wiley 2021), (Ramesh Reddy et al. 2022). Floaters used for floating wind turbines are also subjected to second-order hydrodynamic loads at the sum- and difference-frequencies of the incident wave components, thus outside of the first-order wave frequency range. These loads are typically smaller in magnitude than first-order wave loads. However, they can induce large motions because of their proximity to some of the floater's natural frequencies. Figure 13 illustrates the typical wind and wave spectra, together with the natural frequencies in the six degrees of freedom of three different floater designs (Moan et al. 2020). It is clear that TLPs are sensitive to the sum-frequency wave loads, especially in

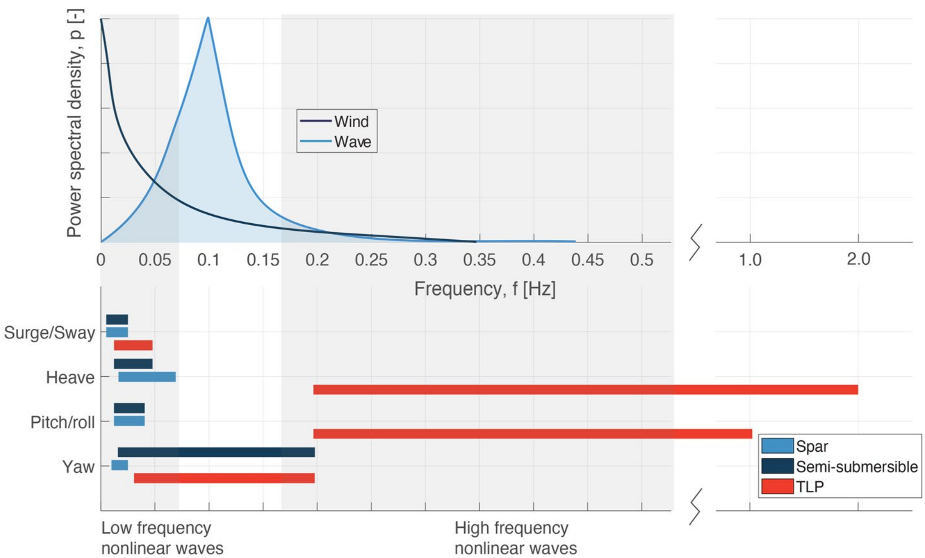


Fig. 13 Illustration of typical wind and wave spectra and the interference of nonlinear wave frequencies with floating wind turbine degrees-of-freedom (dof) for three different floater types: spar, semi-submersible, and TLP. Data on natural frequencies are obtained from Moan et al. (2020)

heave and pitch, whilst semi-submersibles are the most affected by second-order difference-frequency wave diffraction loads that can excite the six degrees of freedom. These observations are further confirmed in the literature, for example by Bayati et al. (2014) and Goupee et al. (2014). Additionally, the nonlinear viscous effects on a semi-submersible floater can lead to an under-prediction of the hydrodynamic loading by about 20% when compared to wave-tank testing (Robertson et al. 2020) and affect both added mass and damping coefficients of the floater (Ramesh Reddy et al. 2022). This prompts the need for higher-fidelity computational methods to study these wave-structure interactions, as further described in Sect. 4.

3.5 Flow-Induced Vibrations

Phase of interest: Design, installation, operation and maintenance
Scale of phenomena: At blade, rotor, tower, floater and mooring lines, and electrical cables level
Role for (floating) wind turbines: Flow-induced vibrations (FIV) are structural vibrations that can be triggered by vortices being shed in the wake of a structure when a fluid flow passes around it. Although flow-induced or vortex-induced vibrations are the most commonly used terminologies, the term flow-induced motions is also used when the structure is rigid which is also of relevance here. Under certain conditions, the frequency of these vibrations can be close to the vortex shedding frequency, leading to potentially large amplitude motions and reduced structural lifetime. This dynamic behaviour of the structure depends on the Reynolds number, the mass ratio defined as the mass of the structure divided by the mass of the displaced fluid, and the damping ratio defined as the ratio between the structural damping and its critical value. For given mass and damping ratios, the amplitude of motion of the structure is often quantified in terms of a reduced wind speed, defined as $U^{\star} = U/(\omega_n D)$, where U is the characteristic flow speed (i.e. free-stream wind speed for FIV on blade, rotor, and tower; and current speed for FIV on the floater, moorings, and electrical cables), ω_n is the structural natural frequency, and D is the characteristic length of the structure of interest.

The fluid mechanics community has widely studied flow-induced vibrations. However, it is worth noting that these studies are mostly limited to low Reynolds numbers in the sub-critical regime, for which the boundary layer remains fully laminar and the drag coefficient is nearly constant with the Reynolds number. As explained before, large wind turbine blades experience much larger Reynolds numbers in the super-critical regime ($Re \geq 3.6 \cdot 10^6$), for which the boundary layer is fully turbulent. Flow-induced vibrations have been reported on wind turbine blades for bottom-fixed wind turbines, dominantly during idling conditions, e.g. Horcas et al. (2020). Flow-induced vibrations can also occur on wind turbine towers, that are subjected to both transitional flow regimes ($1.5 \cdot 10^5 \leq Re \leq 3.5 \cdot 10^6$), where laminar separation bubbles can exist and the drag coefficient is reduced, and super-critical flow regimes. Flow-induced vibrations on towers are particularly critical during the wind farm installation phase. When the tower does not yet support the rotor-nacelle assembly, the tower acts as a beam clamped at one of its ends and subjected to a wind flow. Because of the vortex shedding developing in the tower wake, the tower may start to oscillate. For bottom-fixed wind turbines, this occurs when the tower stands on the quay-side, is transported offshore on a vessel, and is installed on the offshore foundation in the absence of the rotor-nacelle assembly. For the current bottom-fixed wind turbine towers, tower diameters in the range of $4.5\mathrm{m} \le D \le 6.5\mathrm{m}$ and first bending frequency $0.4\mathrm{Hz} \le \omega_{bm1} \le 1.1\mathrm{Hz}$ are most critical for the occurrence of FIV (Viré et al. 2020). However, this depends on the tower's natural frequency, which changes with the tower thickness, material, and geometry (including tapering).

Because the installation phase of floating wind turbines is different from that of fixed turbines, the risk of FIV occurring on floating wind turbines is expected to also be different. Currently, floating wind turbines are assembled in ports or sheltered locations, and then towed to site. Once the rotor is placed on the tower, it modifies the natural frequency of the system. Thus, the presence of the rotor during towing might reduce the risk of FIV on the tower of floating turbines during installation. Nevertheless, the installation of one of the spar-buoy floating wind turbines in the Hywind Tampen farm seemed to reveal vortex-induced motions in the direction lateral to towing, leading to noticeable roll motions. It was informally reported that the latter could be suppressed by changing the towing velocity. It is, however, unclear how much these fluid-structure interactions generally develop during the installation phase of floating wind turbines and how they differ per concept and towing strategy.

Additionally, during both installation and operation, FIV can occur on the submerged part of the floater under the effect of sea currents. Amongst the different floating foundations, the spar-buoy is the most prone to FIV due to its deep draft. The structure can be considered as a rigid cylinder experiencing a current velocity varying with water depth (i.e. in the spanwise direction) and a Reynolds number of the order of $Re = UD/\nu = 15 \cdot 10^6$, where D is the spar diameter. It is worth noting that, whilst FIV in hydrodynamics has been analysed for risers and moorings, the Reynolds-number regime experienced by a floating support structure is much higher due to the larger diameter of the structure. Additionally, floaters are characterised by a relatively small aspect ratio (ratio of length over diameter), which also sets them apart from the vast body of literature on FIV for infinitely long cylinders. Considering a typical spar diameter of $D = 10m$ subjected to a maximum current velocity of $U = 1.5m/s$, the frequency of oscillation of the spar in the cross-flow direction under critical conditions would be of the order of $f = 0.03Hz$, assuming a Strouhal number of the vortex shedding equal to St=0.2. Note that this simple reasoning neglects the fact that the current velocity, and hence also the vortex shedding frequency, changes along the water column. Moreover, the first natural frequencies of floating wind turbines are significantly lower than those of bottom-fixed turbines (Fig. 13). The first mode of a spar-buoy floating turbine is a horizontal translation mode of the tower at a frequency of about 0.01 Hz, whilst the second mode is a rigid body tilt rotation at a frequency of 0.035 Hz followed by a vertical translation mode at about 0.037 Hz (Larsen and Hanson 2007). Whilst the mooring lines positively damp the first and third (translation) modes, the tilt rotation is not and receives little damping from the hydrodynamic loads. Recently, a study showed that the spar exhibits flow-induced motions in the cross-flow direction, as a combination of sway and roll, leading to a cross-flow pendulum motion (Passano et al. 2022). The spar can also move in the in-line direction at a frequency twice larger (Carlson and Modarres-Sadeghi 2018).

Finally, mooring lines and dynamic electrical cables are also prone to FIV. They experience smaller Reynolds numbers (order of $Re \approx 3 \cdot 10^5$), as their characteristic diameter is of the order of $D = 0.2m$. However, their flexible motions in two directions complicate the fundamental understanding of the fluid-structure interactions at play. This is further exacerbated by the fact that mooring lines and dynamic cables are inclined with respect to the incoming flow, which also modifies the FIV phenomena. For electrical cables, although the high damping and viscoelastic behaviour of their dynamic bending stiffness can help prevent the onset of FIV, the risk of FIV is real when the cable is not laying on the seabed (free spans regions) and subsea currents are present (Hedlund 2015), (Delizisis et al. 2022). In that case, FIV needs to be taken into account in the planning and design phases to avoid cables' fatigue failure.

Consequence on loads, performance and design: Flow-induced vibrations can be very detrimental as they can lead to unexpected structural failures, hence potentially putting the whole floating wind turbine at risk. These vibrations affect both the extreme and fatigue loadings on a series of components of the floating turbine. However, it is still unclear how to best incorporate flow-induced vibrations in the design process of floating wind turbines (Yin et al. 2022). The resolution of FIV requires nonlinear time-domain simulations. This is because flow-induced vibrations grow due to the vorticity in the shear layers near the structure (Menon and Mittal 2021) and the nonlinear behaviour of the structure can also be important (Passano et al. 2022). Thus, the modelling of FIV requires an accurate resolution of these boundary layers, which is computationally expensive for the Reynolds numbers encountered in the aero- and hydro-dynamics of floating wind turbines. Such simulations can be achieved for a handful of design load cases, but cannot yet be incorporated in the design process. This leads to opportunities to embed high-fidelity physics into design tools, as further discussed in Sect. 4.

Additionally, there are open questions regarding the fundamental physics associated with FIV for floating wind turbines and their mitigation. For example, there is still limited literature on FIV at high Reynolds numbers under both cross-flow and in-line motions, as experienced by floating wind turbines. In terms of mitigation strategy, the efficiency of strakes has been reported both with wave basin tests and computational modelling (Yin et al. 2022).

Finally, it is important to note that floating wind turbines are designed for a lifetime of about 25–30 years. The blades, floater and mooring lines are therefore affected by corrosion, as well as other degradation and marine growth, all of which change the characteristic of the boundary layer and potentially the growth process of FIV. More research is needed in this area to understand how this impacts both the development of FIV and their mitigation.

4 Research Methods and Infrastructure Needed

The previous sections have shown that floating wind energy presents challenges across phases of development and across system components and scales. These challenges are either new to wind energy or existing – but different and likely more challenging – than for bottom-fixed wind turbines. Importantly, they bring needs in terms of research methods and infrastructure. These needs are also opportunities for the fluid mechanics community to impact on this field and help accelerate the transition to a climate-neutral economy. This section brings forward some of these overarching needs and opportunities. It also presents the associated research questions that need to be answered to fill the knowledge gaps related to the fluid mechanics phenomena described in Sect. 3. These needs can be split into the following three categories and are further presented in the subsections below.

- **Experimental** testing and, in particular, the development of novel **hybrid testing** infrastructures.
- **Computational modelling** including advances in high-fidelity, multi-scale, multi-physics and fast engineering tools and the application of machine learning techniques.
- **Co-creation across** multiple **disciplines and** integration of perspectives from a variety of **stakeholders**.

Importantly, these three categories of needs all require data from full-scale testing on installed floating wind turbines. The collection and availability of high-quality full-scale datasets for floating turbines is very limited. However, it has enormous value to the research and design communities.

4.1 Experimental and Hybrid Testing

Model-scale experimental testing is an important step in fundamental research and technology development for both bottom-fixed and floating wind turbines. As extensively discussed in this paper, a key challenge associated with floating wind turbines and their logistics is that these technologies strongly interact with their surrounding environments in complex nonlinear ways. These interactions lead to physical phenomena that require new, or updated, lab-scale facilities, some of which are indicated in Table 2.

An additional difficulty is to accurately and fully integrate knowledge from different fields in experimental laboratories. In particular, existing lab-scale research infrastructures fail to adequately represent key physics experienced by full-scale floating wind turbines. This arises for two main reasons.

Firstly, the physics at play are driven by a range of non-dimensional numbers that cannot be matched simultaneously at lab-scale. This includes: (i) the Reynolds number Re, which can be interpreted as the ratio between viscous and convective time scales in a fluid flow, (ii) the Froude number Fr, which is the ratio between inertia and gravitational forces, (iii) the Mach number M, which is the ratio between flow velocity and the local speed of sound, and (iv) dimensionless frequencies that characterise dominant oscillations in flows (e.g. the Strouhal number St for vortex shedding). A reciprocal of the Strouhal number, also often used in hydrodynamics, is the Keulegan-Carpenter KC number that represents the ratio between drag forces and inertia forces for bluff bodies in an oscillatory fluid flow. To experimentally analyse incompressible aerodynamic flows, Reynolds-based scaling is typi-

Table 2 Types of experimental facilities needed to address the fluid mechanics challenges outlined in Sect. 3

Fluid mechanics challenges	Experimental facilities
Unsteady aerodynamics	Wind tunnel with moving airfoils, blade segments, or rotors, including the emulation of wave and current excitations Active grid for complex turbulent inflows
Wake dynamics	Boundary layer wind tunnel Thermally-stratified wind tunnel
High speed flows	Transonic wind tunnel, e.g. pressurised wind tunnel
Nonlinear hydrodynamics	Wave-current basin with wind excitations
Flow-induced vibrations	Wind tunnel, wave-current basin, dynamic test rig

cally used since the influence of the external gravitational field can be neglected (i.e. in the limit of high Froude numbers). By contrast, Froude scaling is the norm for scaling down the hydrodynamics of floating structures since viscous dissipation can be neglected (i.e. in the limit of high Reynolds numbers). However, these two scaling laws do not match. This means that a turbine rotor scaled geometrically with a setup matching Froude scaling will experience a Reynolds number that is much lower than reality. Conversely, a floater scaled geometrically with a setup matching Reynolds scaling will experience a Froude number that is larger than required. A similar mismatch exists for high-speed flows, where transonic flow facilities reach Reynolds numbers that are too low for offshore wind energy applications. This mismatch between scaling laws of different physics encountered by floating wind turbines is a challenge for their lab-scale testing.

Secondly, it is difficult to combine all realistic environmental conditions in a single facility that is large enough to study both single turbine and farm effects. Although this is an active field of research (Bossuyt et al. 2023), such full physical testing facilities are almost nonexistent and still present uncertainties due to the mismatch in scaling laws.

Hybrid testing alleviates these issues by emulating, in a given facility, the effect of the missing physics through actuators driven by numerical models. As such, only some components of the system are built and tested at scale, whilst the effects of the missing components are modelled numerically. These so-called hardware-in-the-loop (HIL), or software-in-the-loop (SIL), strategies are illustrated in Fig. 14. The left-hand-side image illustrates a HIL technique in a wind tunnel, where a scaled wind turbine rotor is placed on a hexapod. The motion of this hexapod in six degrees of freedom is driven by a numerical model, which computes the response of the floating support structure given, as inputs, a representative wave-current excitation and the aerodynamic thrust force and moments acting on the scaled rotor due to the wind flow. This type of setup can be used to investigate the aerodynamics of floating wind turbines, assuming that the numerical model is able to assimilate measured data and instantaneously compute the system response accordingly. Similarly, the hydrodynamics of the turbine can be investigated in a wave tank (with or without currents) by equipping a scaled floater with an actuator emulating numerically the rotor thrust forces and torque, aerodynamic yaw and pitch, as well as higher-frequency loadings when possible. As

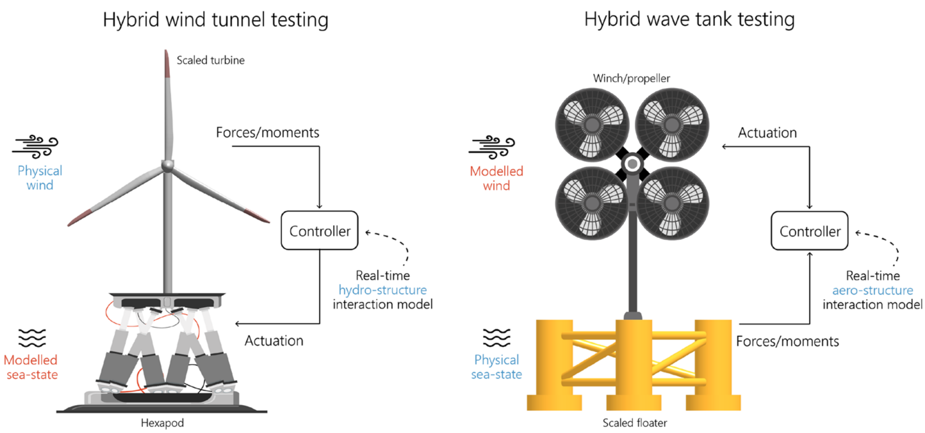


Fig. 14 Illustration of the hybrid testing strategies using hardware-in-the-loop in a wind tunnel (left) and in a wave tank (right)

illustrated in Fig. 14 (right), this can be achieved with dynamic winch systems (Bachynski et al. 2015), although simpler systems such as propellers have also been used with some success (Otter et al. 2020). Again, a requirement of the hybrid setup is that the actuator should react instantaneously to the physical hydrodynamic loads acting on the floater.

Hybrid testing has been identified as the preferred technique to study experimentally the performance and loads associated with floating wind turbines because of the versatility, practicality and relatively low cost of this approach compared to full-scale testing (Otter et al. 2022). The HIL technique can be applied across the system, from grid integration to component testing. A limitation, however, is that the numerical models used to control the actuators need to react instantaneously to the changes in the physical scaled model. Therefore, simplifications (e.g. assuming linear dynamics) are made and can lead to inaccuracies and uncertainties. There are thus still many research questions to answer to ensure reliability, accuracy, and repeatability of such hybrid tests. Some of these questions are outlined hereafter.

How do the results of hybrid testing compare across facilities? There exist different strategies for actuating the missing physics at a lab-scale, each having its own advantages and drawbacks. Additionally, these actuators have so far often been built specifically for the purpose of conducting hybrid testing for floating wind turbines, as actuators covering the range of velocities and accelerations required for this application are mostly not commercially available. On the one hand, there is thus a need to cross-compare results of hybrid tests across similar facilities, for example, testing different HIL strategies in a given facility as well as testing a given strategy in facilities of different sizes (e.g. different wind tunnels). This will help identify how scaling effects influence the results of hybrid testing and assess how small hybrid facilities can be. On the other hand, there is a need to compare results across complementary facilities and learn from one another. For example, the aerodynamic results of HIL tests in a wind tunnel can be used to calibrate the aerodynamic numerical model used in HIL tests in a wave tank, and vice-versa. This leads to hybrid testing facilities re-inforcing one another, with the goal of increasing the level of accuracy and fidelity in the digital emulation of loads. When these results are compared with full-scale data, further calibrations of the lab-scale setups can be done. It is also possible to identify which physics is most critical for conducting accurate hybrid tests, as further explained below.

What level of physics is required in the numerical emulations used in hybrid testing, and what are the associated needs in terms of computational modelling? Because HIL numerical models need to react instantaneously to the physical loads acting on the scaled models, these numerical models need to be computationally inexpensive. This leads to simplified approaches – sometimes linearised – which are in stark contrast with the complex nonlinear characteristics of the dynamics at play. Increasing the level of physics and realism in hybrid testing is, therefore, an important topic. On the one hand, the type of load cases and the associated turbine dynamics should be accurately captured in the labs. Having numerical models that can reproduce instantaneously the nonlinear aerodynamic and hydrodynamic phenomena discussed in Sect. 3 is required. The comparison of results across facilities (including full-scale data) can help make informed decisions on the level of physics required to have acceptable results and the associated level of uncertainties. It can also help calibrate numerical models for higher-order physics, for example to incorporate the aeroelastic behaviour of large rotors in wave tank tests, something that has not yet been investigated to the best of our knowledge. Machine learning techniques can further help automate the learning process across facilities and full-scale data.

It is worth noting that the questions outlined above are relevant across the range of disciplines involved in floating wind energy, even beyond the scope of fluid mechanics. For example, performing hybrid testing with sufficient accuracy is required to study anchor-soil interactions or the integration of electrical power into the grid, just to name a few examples. Also, several additional fundamental questions exist of relevance to hybrid testing itself, such as the need to reduce system latency between the different steps in the HIL process (e.g. simulation, actuation, sensing, feedback) and to increase the repeatability of sensing methods. However, these fall outside the direct application in fluid mechanics and are therefore not further discussed here. Similarly, the use of hybrid testing is not restricted to floating renewable energy systems. It is useful for emulating any dynamic loading on a scaled structure, and is therefore also relevant for example when investigating the combined effects of aero- and hydro-dynamics excitations on bottom-fixed offshore renewables and in other fields like scaled flight testing.

4.2 Computational Modelling

Computational models offer a good complement to experimental and full-scale testing because of the detailed insights they provide under controlled conditions. However, the phenomena associated with floating wind turbines are both multi-physics and multi-scale, with fluid-fluid interactions, fluid-structure interactions, and vortex transport evolving from a millimetre scale in the blade boundary layer to kilometres at the farm level. Resolving simultaneously all key physics and relevant scales at play will remain a challenge for years to come. On the one hand, advances in high-fidelity computational methods are needed to increase our ability to predict local unsteady phenomena and provide a new fundamental understanding of their causes and consequences. On the other hand, there is a need for fast prediction tools – that do not capture all the physics – but are accurate enough for design assessment, design optimisation, and real-time control. These low-fidelity models can be validated based on the results of high-fidelity models. The range of model fidelities and their possible interactions is illustrated in Fig. 15. Research opportunities in this field include: (i) understanding where high-fidelity information is needed, (ii) developing high-performance

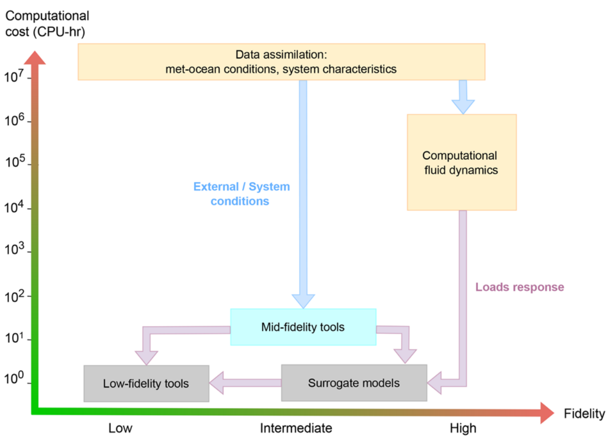


Fig. 15 Illustration of computational model fidelities and cost, and their possible interactions

tools to get accurate and reliable data, and eventually (iii) having methods that use this data and integrate it into fast prediction tools. This is further detailed in the rest of this section by highlighting some of the main overarching research questions.

Which physics needs to be resolved and at what level of accuracy? A key question is whether the simultaneous resolution of all the physics and scales present in floating wind turbines and farms is needed, or whether some effects can be decoupled or simplified. The answer to that question depends on the outputs of interest. For example, the flow physics in the boundary layer of the rotor blades will have a limited impact on the development of the far-wake and its interaction with downstream floating turbines. By contrast, boundary layer flow physics will be important when calculating the local blade loads and response. Sensitivity analyses have been conducted to understand the importance of various inputs on fatigue and ultimate loads for floating wind turbines (Wiley et al. 2023), (Ramesh Reddy et al. 2024). These works show that wind turbulence, or the standard deviation of wind speed, is the dominant input for both ultimate and fatigue loads on a 5 MW wind turbine rotor supported by a semi-submersible floater. Other wind characteristics and hydrodynamic parameters, such as sea current speed and significant wave height, also have an influence on fatigue loads on the rotor, but to a lesser extent. However, they do influence the mooring lines and tower loads, respectively. Such studies are important to assess which features need to be reproduced or modelled most accurately when predicting loads on floating wind turbines. They also indicate which on-site measurements are needed to perform these predictions.

How can we model nonlinear dynamics accurately and cost-effectively, in both space and time? Once it is known which inputs need to be known accurately, high-fidelity models can be used to compute them. This can be for estimating the inflow conditions and predicting the associated system or component dynamics. For the latter, a fluid-structure interaction (FSI) framework is needed whereby computational fluid dynamics (CFD) and computational structural dynamics (CSD) models are coupled. This can be used for predicting the dynamics of the whole turbine or only investigating the dynamics of certain components, for example for investigating flow-induced vibrations or structural deformations on turbine components below- and above-water. There are multiple strategies for modelling the dynamics of structures immersed in a fluid. These approaches differ in: (i) the way the fluid and structural dynamics equations are solved, (ii) the numerical representation of the fluid-structure interface, and (iii) the numerical scheme used to exchange information between solvers. For floating wind turbines, both monolithic and partitioned coupling have been used. In a monolithic approach, the fluid and structural dynamics equations are solved simultaneously in one solver. This avoids a time staggering of the solutions to the fluid and structural dynamics equations. However, identical numerical schemes are required for the fluid and structure. By contrast, in a partitioned approach, the fluid and structural dynamics equations are solved using two distinct solvers that are coupled together. This enables the spatial and temporal numerical schemes of each solver to be tailored to the specific needs of each component. However, this means that the two sets of equations are solved in a staggered way, rather than simultaneously. In this context, bridging different time step restrictions from the two different solvers is difficult. Methods exist in the literature to address this challenge, for example with the quasi-Newton waveform iteration method that provides a fast – yet high-order – coupling method in time (Rüth et al. 2021). However, these types of methods have yet to be applied to the simulation of floating wind turbines and could be important for capturing nonlinear dynamics.

For both monolithic and partitioned approaches, the structure can either be excluded from the fluid-dynamics mesh or immersed in it. The former is commonly referred to as an Arbitrarily Lagrangian-Eulerian (ALE) formulation, whereby the boundaries of the fluid mesh at the FSI interface coincide with the boundaries of the structure. This enables the fluid-structure boundary conditions to be applied directly on the mesh boundaries. However, it forces the mesh to deform at each time step, in order to follow the structural motions, which can lead to ill-shaped mesh cells for large structural motions. In this context, research in new dynamic meshing techniques remains important. Another approach consists in immersing the structure in the fluid mesh and tracking its position (or that of its boundaries) using a scalar field. The cells of the fluid mesh where the scalar field is non-zero indicate where the FSI boundary conditions are applied. Although this requires the resolution of an additional scalar field, it simplifies the meshing process and its motion. However, attention must be paid to imposing the boundary conditions accurately at the immersed fluid-structure interface. These methods are commonly referred to as immersed-boundary or immersed-body methods (IBM), depending on whether the structure boundary or the whole structure is represented by the scalar field. Interestingly, these methods can also be used to simulate flows in porous media. This is an interesting avenue for further research, as porosity could be used to mimic the effect of marine growth on the floater or mooring lines, which is of relevance for floating wind turbines.

Finally, research efforts to reduce the computational cost of high-fidelity FSI approaches should continue. This includes the development of high-order and scalable numerical schemes, code portability on new computing architectures (e.g. GPU), and flexible and easy-to-use coupling libraries are all contributing to this. An example of such an open-source library is preCICE (Chourdakis et al. 2022), which enables partitioned multi-physics simulations by coupling different high-fidelity software packages. Another way to decrease the computational cost of high-fidelity numerical simulations is to use machine learning techniques, as further explained hereafter.

How can we embed high-order physics into fast prediction tools to perform better design assessment, optimisation, and control? Whilst high-fidelity modelling has the potential to incorporate more physics in the computations and improve the fundamental understanding of the dynamics at play, there is a need to learn from high-fidelity data and correct more economical models accordingly. This is particularly relevant for features that have a dominant influence on the system response, as explained above. Machine learning approaches offer the possibility to bridge model fidelities and embed high-order physics into simplified models. Broadly speaking, machine learning techniques can be categorised into: (i) physics-based approaches, which are based on physical laws and their key features, and (ii) data-driven methods that are oblivious to the physics but instead learn system behaviours based on data observations. There is a growing interest in both these techniques in various areas of wind energy research. For example, data-driven models have been used at wind farm level to calibrate wake models, e.g. Göçmen and Giebel (2018), Hulsman et al. (2020), van Beek et al. (2021), or perform wind farm control such as in Munters and Meyers (2016) and Vali et al. (2019), or improve Reynolds-Averaged Navier-Stokes turbulence models, e.g. in King et al. (2018) and Steiner et al. (2022). At turbine level, machine learning techniques, either deterministic or probabilistic, have also been used to help predict fatigue and extreme loads at a given site (Singh et al. 2022), (Ghazali Bin Muhammad Amri et al. 2024). Their application to floating wind turbines is been considered but, overall, this field is rather unexplored. For example, questions such as the accuracy, reliability, training process and generalisation of these approaches for forecasting of loads on floating wind turbines, including local aerodynamic effects, are still unanswered.

Enhancing low-cost models with high-order physics has applications for both the control and design of floating wind turbines and farms. Indeed, both processes require computationally-efficient tools that represent the right physics. For example, embedding nonlinear fluid dynamics into a closed-loop control framework can help mitigate the undesirable unsteady aerodynamic effects on the rotor and blades. Similary, surrogate models can be embedded in multi-disciplinary design analysis and optimisation (MDAO) frameworks for accelerating the process of finding the best preliminary designs. This can be done, for example, to replace the frequency-domain analysis of the floater hydrodynamics, which can be prohibitively expensive when the hydrodynamics coefficients are computed using radiation-diffraction analysis software (Baudino Bessone et al. 2024). As mentioned in Sect. 4.1, machine learning techniques can also be used to control actuators in hybrid testing facilities, with the aim to increase the level of fidelity and reduce the computational cost in digital load emulations.

4.3 Co-creation Across Disciplines and Stakeholders

Since the floating-specific challenges span the entire innovation and supply chain, designing the best floating wind farm needs to account for the coupling between all disciplines. Additionally, in order to adequately address the societal challenges associated with the energy transition, there is an increasing need to develop methods and technologies that encompass both technical and non-technical aspects. For example, there is a long-term benefit in including environmental metrics in the design of wind turbines, instead of focussing purely on minimising costs (Canet et al. 2023). We use the terminology co-creation to describe the active collaboration across stakeholders and disciplines, leading to the inclusion of multiple disciplines and viewpoints in methods and technologies. Involving multiple stakeholders (including citizens) in the development of renewable energy technologies is also important to increase social acceptance and adoption, which can otherwise constitute major barriers to the large-scale development of these technologies. There is also a need to achieve the energy transition together with other offshore transitions, such as the sustainable offshore food production and the ecological transition (Dutch government 2022). Finding solutions that can benefit multiple transitions at once is therefore attractive. It is still an open question whether floating wind turbines can have an additional benefit for achieving this.

Multi-disciplinary design analysis and optimisation (MDAO) workflows can help perform multi-stakeholder optimisations. These workflows couple a set of computational tools that represent each component of the system, as well as the different phases of its development and operation. It can be used to perform design optimisation with respect to given metrics, sensitivity analyses, or uncertainty quantification. It is also useful to identify trade-offs between different aspects of the system. A typical design structure matrix for the MDAO of floating offshore wind farms is illustrated in Fig. 16, where the framework can optimise and analyse different components of the system (represented in grey) based on a set of input variables and given metrics. From a computational point of view, these frameworks require a set of computationally-efficient models that represent each component of the system. This leads to an opportunity to bridge models of different fidelities, as already mentioned in the

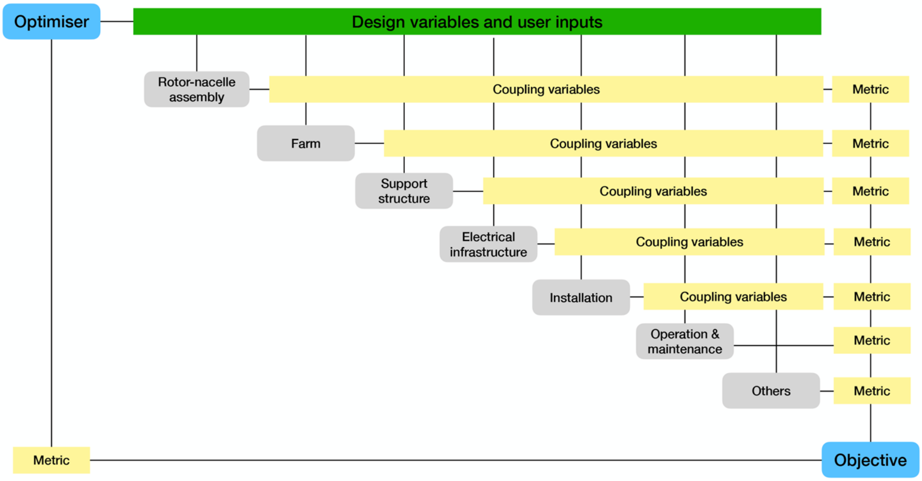


Fig. 16 Sketch of a typical design structure matrix for floating offshore wind farms

previous section. Hereafter, we outline some of the overarching questions that these MDAO frameworks can help answer from a multi-stakeholders' point of view.

What type of data is needed, and can be monitored, to better inform stakeholders across society? Acquiring large amounts of diverse categories of data is already playing a key role in offshore renewable technologies. It can be used, for example, to drive wind turbine controllers, to improve the scheduling of operation and maintenance strategies, or to track birds and mammals around wind farms. Whilst the need to monitor data is clear to gain feedback on the technology and its ecosystem, it can also be used to actively engage stakeholders, such as policy makers and citizens. This is particularly important for floating wind turbines, as these technologies are spatially distant from citizens and, therefore, face the risk of being perceived as less urgent, disconnected, and too big or abstract to be influenced by individual choices (McDonald et al. 2015). Technologies such as virtual environments have the capacity to reduce such psychological distance (Fox et al. 2020). Engaging citizens in the monitoring of real-life data, for example, by supporting ecologists during offshore monitoring, can help increase their feelings of psychological ownership. This can eventually improve citizens' and stakleholders' usage of, and willingness to pay for, renewable energy. Digital twins can also help train workers to learn new skills and support them in transitioning from other sectors to renewable energy. There is an opportunity for fluid dynamicists and data scientists to contribute more broadly to these societal needs, which will be key to successfully achieving the energy transition in a timely manner.

Can floating wind turbines enhance the offshore nature and food transitions? An open question is whether floating support structures can be used to produce offshore food sustainably, in a nature-inclusive and profitable way, and restore marine biodiversity. A floating structure can function as reef and sessile organisms such as mussels, barnacles, anemones can grow underneath these structures. From a fluid mechanics perspective, sessile organisms are often considered unwanted fouling, as they can enhance drag on the structure and reduce buoyancy by increasing the structure's weight. However, these organisms are also ecologically valuable reef builders that provide habitat and food for many other marine organisms, including fish, birds, and marine mammals. Floating structures often also function as fish aggregation devices, as fish tend to hide underneath them to be out of sight of birds. Not only the biodiversity attached to, or underneath, floating structures will change, also the seafloor below is expected to adapt, most likely in a positive sense. Additionally, the impact of flow turbulence and stratification on birds and fishes is an active research area. There is thus an opportunity for fluid mechanics researchers to work more closely with, for example, ecologists and non-governmental organisations to understand these phenomena and co-create technologies that could benefit multiple transitions at once. Adding these objectives in existing MDAO frameworks and analysing the impact on the optimal designs is still largely unexplored but very much needed to address the societal challenges lying ahead.

5 Recommendations and Conclusions

The urgency to transform the energy system worldwide is clear, both for tackling the climate crisis and for gaining energy independence. However, the targets set to achieve the energy transition are huge. Offshore wind energy will continue to play a big role in achieving this transition, but both technical and non-technical challenges lie ahead. Floating offshore wind energy brings opportunities to widen the deployment of offshore wind energy and install wind turbines in new regions. Although it comes with its own set of challenges, it also offers opportunities to innovate across the chain of development and to benefit other offshore transitions. Embracing these challenges and opportunities with long-term solutions will create positive impact, not only on floating offshore wind energy, but also on other offshore renewable energy technologies at large. This section summarises the three main overarching needs that will help the fluid mechanics community to contribute to a long-term and sustainable growth of our energy system.

5.1 Infrastructure for Multi-Disciplinary and Multi-Scale Research

Given the coupled nature of floating wind turbines, there is a strong need to ramp up collaboration across fields, both to unlock innovative technological solutions to the challenges mentioned above, as well as to improve our ability to simulate and test these technologies in a realistic way. Integrating the different disciplines and physics at play should be done in a structured and long-standing way. For example, networks of large-scale infrastructures comprising hybrid experimental facilities, simulators, and offshore demonstration sites, that all learn from one another, will help accelerate our ability to test these technologies at lab-scale in a reliable and accurate way. In such a network, as illustrated by Fig. 17, data monitored offshore in real full-scale conditions can be used to calibrate and enhance the accuracy of numerical models. This learning and enhancement process can be supported by artificial intelligence (AI). Offshore data can also be used to validate numerical models of different fidelities, which can then be used to provide additional data in the learning process. The data- or physics-enhanced models, when computationally fast, can be used to drive hybrid testing facilities and enable lab-scale testing at increasingly high accuracy and reliability, hence bridging the gap between lab-scale and full-scale environments. Having such a network of infrastructures (full-scale, lab-scale, and digital), closely working together, can be

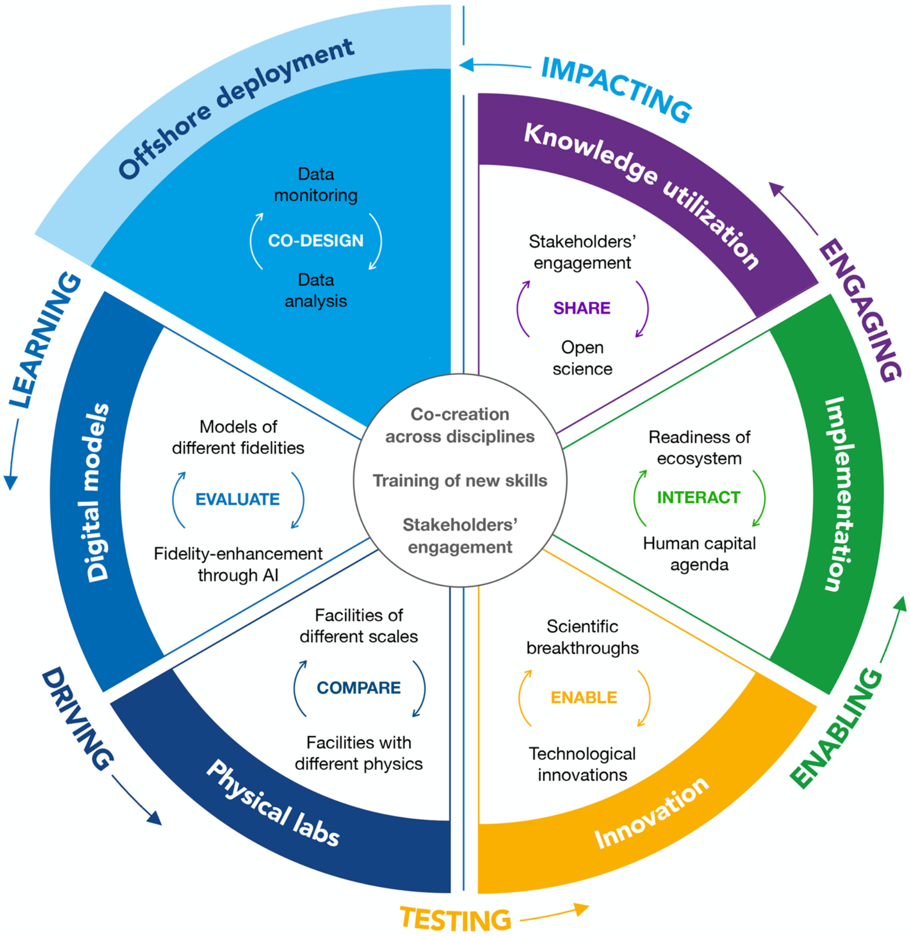


Fig. 17 Overall vision of how co-creation across disciplines, training to new skills, and active stakeholders' engagement can be used to accelerate the development and implementation of innovations in floating wind energy

used to test innovations of both technological and scientific nature, with the vision to alleviate the need for expensive and lengthy full-scale demonstrators. Indeed, at the moment, full-scale demonstrators are needed for testing new products in real conditions and for certification purposes. However, these demonstrators might still be prone to failure or require new design iterations. Increasing the realism of lab-scale facilities could eventually reduce this need, and hence, accelerate the overall development and deployment times of new floating wind technologies. Key to such a network is the co-design of monitoring campaigns, scaled models, and numerical methods, so that: (i) lab-scale facilities can truly learn from full-scale data, and (ii) cross-comparisons between several facilities and numerical models can be achieved, across different scales and different physics.

It is worth noting that cross-comparisons between large-scale facilities are not entirely new. However, national or international co-design initiatives that also include full-scale testing is rather new and should be strengthened in the future. The numerical methods and experimental facilities developed by the fluid mechanics community can be used or adapted for this purpose. There is thus an opportunity for fluid dynamicists to work together with other disciplines in this co-creation effort and enhance the impact of their knowledge to the emerging field of floating renewable energy.

5.2 Learning Communities for Floating Wind Energy

The technical infrastructure for testing innovations, as described above, is a required step in the development of new technologies. Additionally, the successful implementation of these innovations necessitates increasing the readiness of the surrounding ecosystem. This includes addressing supply chain challenges, assessing the impact and adoption of new technologies, and training the workforce to the skills needed to interact and work with these innovations. On the one hand, the range of challenges outlined in this paper sparks the need for more people with diverse skills to work in the field of offshore wind energy. Figure 18 shows examples of expertise needed across disciplines, and in fluid mechanics specifically, for addressing the challenges in floating wind energy. On the other hand, bringing these expertises together in diverse teams is not enough to ensure the successful co-creation described above. There is also a need to clarify terminologies between fields and train professionals and students to co-development across fields, so that all disciplines and stakeholders can be truly included in the co-creation process. A promising instrument to achieve this is the creation of learning communities, in which a wide range of stakeholders work together to solve challenges of societal relevance. These stakeholders include students from different education levels and backgrounds, researchers, lecturers, industry professionals, policymakers, and citizens. The co-creation process also implies sharing knowledge and best practices between stakeholders, which will benefit the design, development, and operation process of new technologies. Actively engaging stakeholders in these processes is needed. For example, gamification of multi-disciplinary design analysis and optimisation tools can

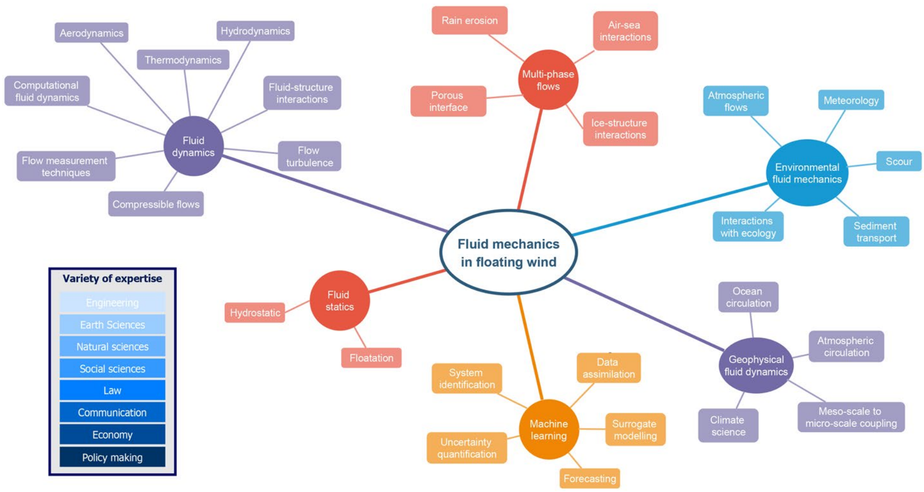


Fig. 18 Fluid mechanics disciplines involved in the challenges associated with floating wind turbines and farms

be used with policymakers and citizens to illustrate design choices and their impact on the ecosystem. Actively engaging citizens in offshore monitoring campaigns, for example, by livestreaming measurement results on widely accessible platforms (e.g. mobile phones) and training citizens to participate in some of the monitoring processes, can also have a positive impact on social adoption and awareness. These activities can also help attract more workforce to the various fields, hence addressing the human capital agenda in the longer term. Thus, stakeholder engagement through outreach, open science, and citizen science activities should be strengthened to ensure a long-standing and wide societal impact. Simultaneously, education programmes should incorporate both technical and non-technical skills.

5.3 Innovations Enabled by Floating Wind Technologies

Although floating wind energy technologies are still at an early stage of deployment, tens of gigawatts of floating wind projects are currently in the pipeline worldwide (Renewable UK 2023). The feasibility of the technology has been demonstrated up to pilot floating wind farms. However, the appetite to massively scale up the technology is still fragile, and the remaining research questions are numerous, both to improve the technology (e.g. increased lifetime, increased benefits on the ecosystem) and to accelerate its deployment (e.g. faster testing and scale-up of innovations). Because floating wind turbines are different from their bottom-fixed counterparts, they offer opportunities for breakthrough innovations of fundamental and applied nature. For example, being able to control the unsteady aerodynamics of floating wind turbines is an active topic of research with the aim of limiting the impact of floating motions on power and load fluctuations. To this end, closed-loop control strategies that assimilate data (measured or computational) can be used to minimise the difference between the current state of the wind turbine controller and the one that compensates for upcoming undesirable effects (see Fig. 19). The controller can be a conventional blade pitch controller that changes the pitch angle of the blade, or it could be a local actuator that adapts the blade shape. Several smart rotor concepts exist for aeronautical applications to minimise noise and vibrations, minimise losses in aerodynamic efficiency and/or improve manoeuvrability (Concilio et al. 2018). However, smart structures have only been scarcely investigated in wind energy, with limited efforts for trailing edge flaps and active flow control devices (Barlas and van Kuik 2010), (Lachenal et al. 2013). Such control strategies that use the structural behaviours of wind turbine blades could be promising in the context of floating wind turbines. Another possibility to control floating wind turbines is to act on their position. This can, in principle, be done in different ways, such as adapting the magnitude and direction of the aerodynamic thrust force on the rotor (Kheirabadi and Nagamune 2020), changing the mooring line length (Rodrigues et al. 2015), or using thrusters (Bguyen and Sørensen 2009). Dynamic positioning of a floating wind turbine without mooring lines has also been investigated, either by continuously moving the system (Annan et al. 2020) or by keeping the turbine in a fixed position with thrusters (Alwan et al. 2021). To this end, the potential of wave feedforward control strategies has been recently investigated in wave basin experiments (Hegazy et al. 2024). Whilst the method was found to be somewhat successful in reducing the generator power oscillations, the effectiveness of the control strategy diminished with increased wind turbulence intensity and was inconclusive for varying wave characteristics. Additionally, it was found that the amount of actuation required to minimise the platform pitch motion was unfavourable for that objective. All these control strate-

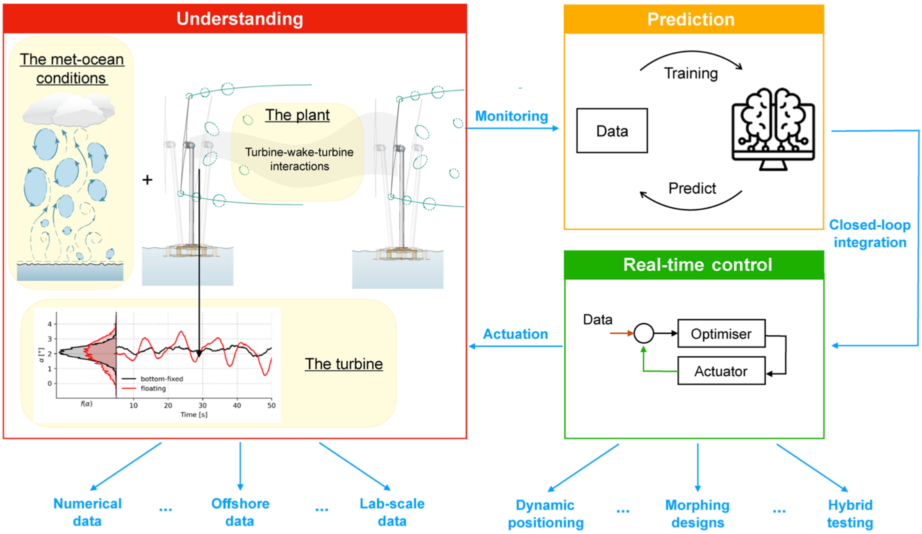


Fig. 19 Innovative methods require a fundamental understanding of the nonlinear interactions between met-ocean conditions, on the one hand, and floating wind turbines and farms, on the other hand. Data of different natures (numerical, lab-scale, offshore) need to be monitored and used to develop fast prediction tools that can be integrated into a closed-loop control framework to mitigate undesirable effects on the system

gies require good knowledge and prediction capabilities of the state of the system, which depends on the surrounding met-ocean conditions. There is, thus, a strong need for fluid mechanics experts to contribute to this research field and collaborate with control engineers.

Floating wind turbines are currently used to produce electricity and feed it into the electrical grid. However, in sight of the possibility of dynamically repositioning floating wind turbines during operation, it also becomes necessary to produce energy off-grid. In this context, producing and storing chemical energy carriers such as hydrogen on board a floating wind turbine is attractive. Additionally, for far-offshore installations, the cost of transporting hydrogen can be significantly smaller than that of transporting electricity. At locations far away from demand, using floating wind turbines to produce hydrogen should, therefore, be favoured over electricity production. This brings additional opportunities at the interface between fluid mechanics and chemistry, for example, to better understand the impact of floating motions on the electrolysis process.

5.4 Conclusions

To summarise, co-creation between disciplines and stakeholders is a pre-requisite to address the interdisciplinary challenges of floating offshore wind farms. This emerging field is expected to grow significantly and could be a gamechanger to significantly increase our share of renewable energy in the coming decades. Although it brings a range of challenges, it also offers opportunities to innovate from both fundamental and technological points of view. This paper focusses on the main fluid mechanics challenges and the opportunities for fluid dynamicists to contribute to this research area. It provides recommendations to structurally accelerate the development of these novel technologies, as well as new fundamental methods and understanding. This co-creation process requires investments in large-scale infrastructures, both physical and digital, as well as human capital. Although initiatives in this direction already exist, they are still insufficient to address the wicked interactions (technical and non-technical) faced by floating wind turbines. Further growing these initiatives at national and international level is necessary to fulfill short-term industrial needs as well as ensure long-term societal impact.

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Declarations

Competing Interests The authors declare no competing interests.

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Authors and Affiliations

Axelle Viré[1] · Delphine De Tavernier[1] · Dominic von Terzi[1]

✉ Axelle Viré
avire@tudelft.nl

Delphine De Tavernier
d.a.m.detavernier@tudelft.nl

Dominic von Terzi
d.a.vonterzi@tudelft.nl

[1] Wind Energy Section, Flow Physics and Technology Department, Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, Delft 2629HS, The Netherlands