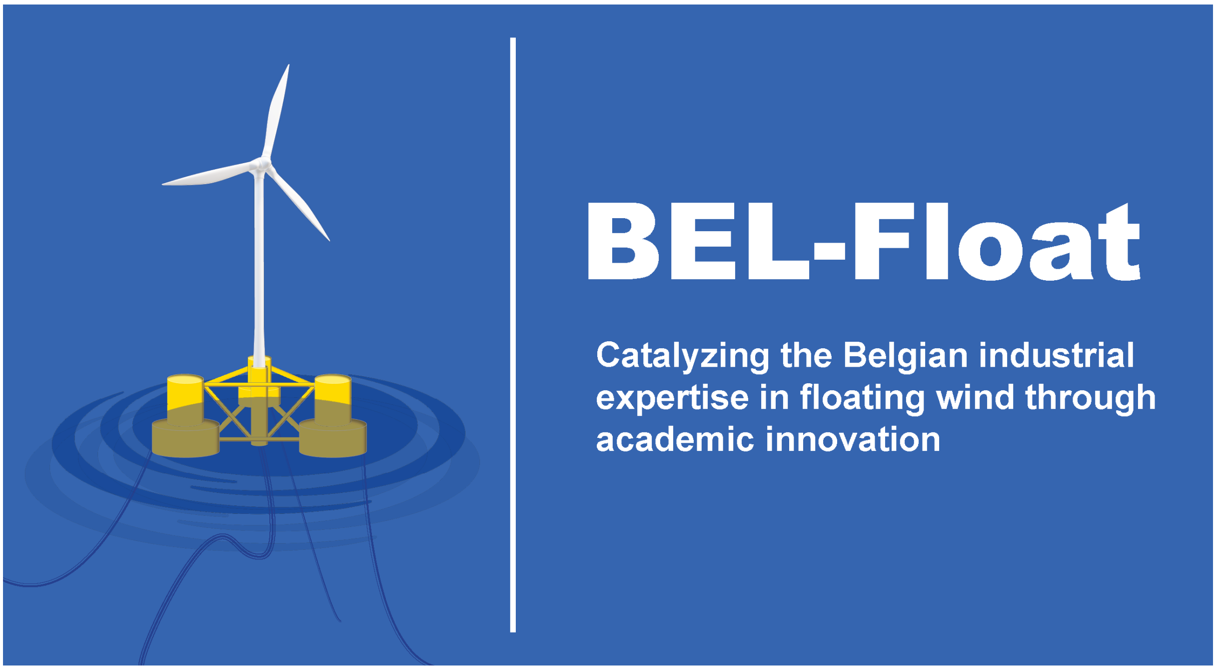

BEL-Float

Topic 4 - Effect of floating platform on turbine loads

Deliverable 1.1.4.1. - Literature review of FOWT loading and performance monitoring

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1 Introduction

The global energy sector is undergoing a transformation towards renewable sources, with offshore wind energy playing an important role. However, conventional fixed-bottom offshore wind turbines are constrained to shallow waters, limiting expansion potential [1]. Floating Offshore Wind Turbines (FOWTs) overcome this limitation by utilising floating platforms that can be deployed in deeper waters where wind resources can be stronger and more consistent [2]. Despite their potential, FOWTs introduce complex challenges, including increased structural loads, platform stability issues, and higher capital costs [3].

Developing more advanced floating platforms that can withstand harsh offshore conditions is necessary, which has led to extensive research into load assessment, performance monitoring, and active control strategies. Ensuring the long-term economic viability of FOWTs requires robust monitoring techniques, such as Structural Health Monitoring (SHM) [4], Supervisory Control and Data Acquisition (SCADA) [5], and AI-based predictive maintenance systems [1].

1.1 Context within BEL-Float

This report summarises the historical evolution of FOWTs, their design advancements, and the challenges associated with structural loading and performance monitoring. The study highlights state-of-the-art strategies to optimise turbine performance, enhance stability, and develop more cost-effective floating wind farms. This represents the first deliverable (D1.1.4.1 - M10) for Topic 4 of the BEL-Float project.

2 Floating Offshore Wind Turbines

2.1 History of Floating Wind Energy

Early offshore wind farms emerged in the 1990s, with the first large-scale offshore wind farm, Vindeby, being established in Denmark in 1991. These were constructed using fixed-bottom wind turbines and deployed in shallow waters, limiting their application to coastal regions with water depths of less than 50 meters. However, as the demand for renewable energy grew, the limitations of fixed-bottom wind turbines in deeper waters became more evident [2].

Researchers and developers began exploring floating wind turbine concepts to access deeper waters. Initial studies were influenced by floating oil and gas platforms, which demonstrated the feasibility of deeper water operations. Early designs included adapted semi-submersibles, spar buoys, and tension leg platforms, borrowing engineering principles from offshore drilling operations. These studies laid the groundwork for developing full-scale floating wind turbine prototypes [6].

The first MW-scale floating wind turbine, the Hywind project by Statoil (now Equinor), was deployed in Norway in 2009. The 2.3 MW turbine utilised a spar-type floating foundation, marking a significant milestone in floating wind energy development. The project demonstrated the viability of floating wind technology, encouraging further investments and research into optimising floating platforms for offshore wind farms. Over the next decade, other projects emerged, such as WindFloat in Portugal in 2011, showcasing different platform designs and mooring systems [1].

The floating wind energy arises a particular interest with its higher capacity factors when compared with bottom-fixed wind farms, namely for their use of more recent and larger wind turbines [7]. This was further corroborated with the Hywind Scotland, since it went to achieve 56% of capacity factor over the first two years of operation [8], compared to values of around 42% for a wind farm in the same region [9]. The combination of stronger winds, higher than 10 ms^{-1} and reduced wake blockage at greater distances from shore underpins this performance advantage, a trend confirmed by global resource assessments that predicts, in some regions, more than double of the installed capacity in shallow waters [10].

A new commercial milestone was reached in 2023 when the Hywind Tampen project (11 × 8 MW turbines, 88 MW total) delivered first power and became the world's largest floating wind farm. This floating wind farm exports electricity directly to two producing offshore oil and gas platforms (Snorre and Gullfaks) in the North Sea, reducing platform emissions by an estimated 200000 tons of CO_2 per year [11]. Electrification of existing petroleum infrastructure is emerging as an additional driver for floating wind, particularly in regions such as Norway, the UK and California where these type of platforms lie in at least 200 m water depths.

Despite rapid progress, floating wind faces several socio-environmental and technical challenges. One is space-use conflict with commercial fisheries [12]. The introduction of floating wind turbines, adding to a larger occupied area, the mooring lines add a complexity layer for the spacial conflicts with the fisheries vessels. Strategic marine-spatial-planning and adaptive cable-routing are therefore essential to balance energy and fisheries objectives. Another emerging technical issue is inter-farm wake interaction that comes along with larger cluster of wind turbines, as these can provoke annual energy production estimations to drop significantly [13] and increase loading sustained by the wind turbines [14]. The mitigation can occur two-fold: with a proper wind farm layout planning [15] and control strategies [16].

Research institutions and industry stakeholders have collaborated to develop larger, more efficient turbines, with capacities reaching 15 MW and beyond [17]. Additionally, advancements in computational modelling and simulation tools enabled more accurate assessments of floating platform dynamics, allowing for better load mitigation strategies and performance optimisation [18]. Governments and private investors have recognised the potential of floating wind technology to unlock vast offshore wind resources, leading to increased policy support and financial incentives. With ongoing research and development, floating wind turbines are expected to play a role in the global transition to renewable energy, providing a scalable solution for deeper waters wind energy generation [19]. Continued advances in CFD-assisted design, digital-twin monitoring and machine-learning-based control are expected to unlock further cost reductions and maintain high capacity factors.

2.1.1 Floating Platform Designs

Floating offshore wind turbines require specialised platform designs to maintain stability in open waters while minimising structural loads. The choice of platform affects the turbine's performance, maintenance costs, and load distribution. The majority of the current research usually divides into four types: Spar Buoy, Semi-Submersible, Barge, and Tension-Leg Platform (TLP) [1], as shown in Figure 1. However, while the first three types concern the floater design, the last category concerns the mooring line.

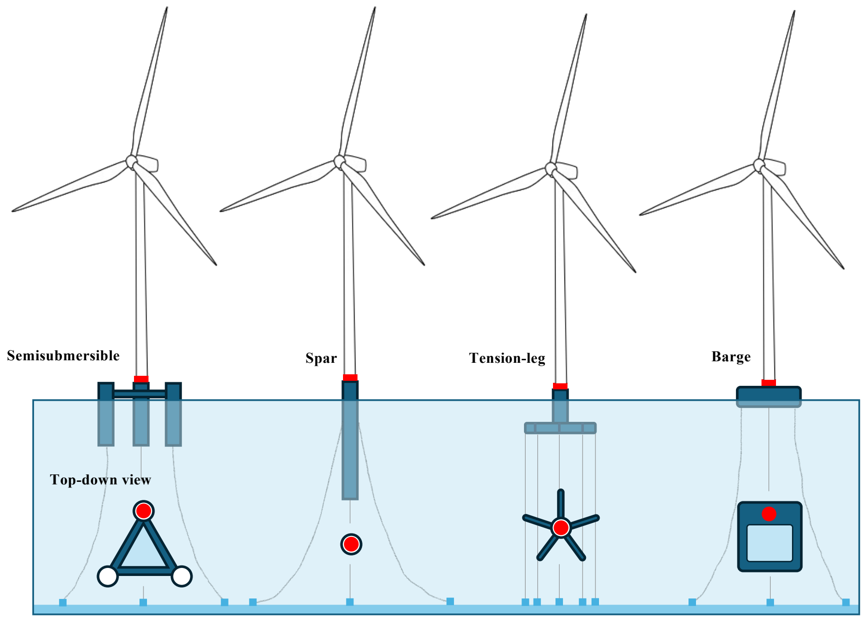

Figure 1: Floating wind platform design concepts. Based on similar schematic in [20].

Spar Buoy Platforms are characterised by a long, cylindrical structure that extends deep below the water surface. Stability is achieved through ballast weighting, which keeps the turbine upright despite wave and wind forces. The Hywind series has successfully demonstrated the feasibility of spar-buoy designs in deep waters (200+ meters)

[21]. However, spar buoys require deep-water deployment, making them less suitable for mid-depth regions [5].

Semi-Submersible Platforms are among the most widely tested designs due to their versatility and ability to be deployed in shallower waters compared to spar buoys. These platforms consist of multiple buoyant columns connected by pontoons, offering improved stability through distributed buoyancy and ballast. WindFloat Atlantic successfully deployed this design, showing its capability to support large wind turbines (8+ MW capacity) [3]. However, semi-submersibles require extensive mooring systems to reduce motion [22].

Barge Platforms are flat structures that float on the water surface and are stabilised through large waterplane areas. While more cost-effective, they are negatively impacted by significant wave-induced motion, making them less practical for high-wind environments. Research from DeepCwind has examined barge-type FOWTs, highlighting the need for advanced motion dampening strategies [5].

Tension-Leg Platforms (TLPs) use taut mooring lines anchored to the seabed, significantly reducing vertical movement, and they can be applied to different floater designs. Unlike catenary mooring lines, these rely on tension forces rather than ballast for stability. The GustoMSC Tri-Floater [23] and BlueH [24] have explored this platform type. TLPs offer high stability but introduce complex mooring requirements, making them more expensive to deploy [2, 23].

2.2 Load Assessment in Floating Wind Turbines

Floating offshore wind turbines experience loads due to the interactions between wind, waves, and mooring forces. The aerodynamic loads imposed by wind vary significantly depending on atmospheric conditions, while hydrodynamic forces from waves and currents induce additional stress on the turbine structure. Unlike fixed-bottom turbines, FOWTs are particularly susceptible to inertial loads resulting from platform oscillations. These six degrees of freedom motions of the platform can amplify aerodynamic loads, presenting a challenge for structural design and long-term reliability [3].

Design Load Cases (DLCs) are essential to assessing these loads. The IEC 61400-3-2 standard defines scenarios under which FOWTs must be tested, including normal operation, extreme wind and wave conditions, fault scenarios, and mooring line failures [25]. These conditions are simulated to ensure the structural integrity of the turbine under both operational and extreme environments. Additionally, computational tools such as FAST (NREL) and HAWC (DTU) have been developed to better model the coupled aero-hydro-servo-elastic response of FOWTs [1, 26].

Empirical validation remains an essential aspect of load assessment. Despite the sophistication of numerical models, full-scale experimental data are still scarce. Research initiatives like DeepCwind have contributed valuable insights by conducting wave basin tests to analyse real-world turbine responses. However, discrepancies between experimental results and computational models highlight the need for further improvements in simulation accuracy [21]. Experimental tests, such as those by DeepCWind and MARIN, have helped refine aerodynamic and hydrodynamic load calculations. Nevertheless, floating platforms remain complex systems with intricate coupling between aerodynamic, hydrodynamic, and structural loads, making full-scale testing essential for improved validation.

Mooring systems help mitigate the platform motion and distribute loads more evenly. Advanced mooring configurations, including tensioned mooring lines and adaptive control strategies, have been investigated to enhance stability and reduce wave-induced fatigue. These optimisations help to extend the operational life of FOWTs while improving energy efficiency [1].

2.3 Performance Monitoring Techniques

Monitoring the performance of floating wind turbines assists in ensuring long-term reliability and efficiency. Structural Health Monitoring (SHM) systems track the condition of key components such as blades, the tower, and mooring lines [4]. Advanced sensor technologies, including strain gauges, fibre optic sensors, and accelerometers, enable real-time data collection, allowing for early fault detection and predictive maintenance [21].

Supervisory Control and Data Acquisition (SCADA) systems are widely used to track operational parameters such as power output, rotor speed, and environmental conditions. These systems provide insights that can be used to optimise turbine performance and diagnose potential issues before they escalate. Recent advancements in artificial intelligence and machine learning have also been integrated into SCADA systems to enhance predictive maintenance capabilities [5, 27].

Experimental validation is key to ensure the accuracy of performance monitoring methods. In [1], a detailed analysis of real-time monitoring using smart sensors is made. They found that combining SHM with SCADA systems significantly improves early detection of mechanical failures. Moreover, AI-driven diagnostics can predict maintenance needs, reducing operational downtime and maintenance costs.

2.4 Control Strategies for Load Mitigation

Control strategies play a fundamental role in mitigating excessive loads and improving the overall stability of FOWTs. Blade pitch control is one of the most effective techniques for managing aerodynamic loads and platform motion. Individual Pitch Control (IPC) adjusts each blade independently to counteract asymmetric loads caused by wind shear and turbulence, reducing fatigue stress on the structure. Collective Pitch Control (CPC), on the other hand, adjusts all blades simultaneously to regulate rotor speed and power output [28]. However, the pitching introduces further vibrations to the tower and blades, which lead to further fatigue loads [29].

Other control methods have been investigated, in [5], a detailed review is made, including active damping systems and hybrid mass dampers. These control strategies dynamically adjust system parameters in real-time, mitigating excessive oscillations caused by aerodynamic and hydrodynamic forces. Additionally, active mooring system control has been explored to stabilise floating platforms. Adaptive mooring tensioning techniques dynamically adjust line tension in response to environmental conditions, improving platform stability and reducing wave-induced motion [30, 31]. Active ballast control is another promising approach that redistributes weight to counteract tilting forces and maintain optimal turbine orientation [32].

The integration of Control Co-Design (CCD) principles has gained traction to optimise turbine control and structural design simultaneously. CCD incorporates control strategies into the initial design phase, allowing for a more holistic approach to load mitigation and performance enhancement. Research has shown that co-designed control systems can significantly reduce platform motion and structural stress, leading to increased efficiency and longevity [33].

Recent studies have also investigated using AI-driven control algorithms to enhance turbine stability. Machine learning-based controllers can adapt to changing environmental conditions in real-time, optimising pitch and yaw adjustments to minimise loads. Implementing these advanced control techniques has demonstrated potential for improving turbine performance while reducing maintenance requirements [5, 24].

3 Conclusion

The development of Floating Offshore Wind Turbines (FOWTs) represents a significant breakthrough in offshore wind energy, enabling deep-water installations where stronger, more stable wind resources are available. However, several challenges must be addressed to enhance cost efficiency, structural integrity, and energy capture performance.

One of the primary concerns in FOWT deployment is structural loading, as these turbines experience complex interactions between wind, waves, and mooring forces. Advanced computational modelling tools such as FAST, OpenFAST, and HAWC2 have enabled more precise load assessment, yet full-scale validation remains necessary to improve model reliability. Additionally, innovative floating platform designs, such as Spar, Semi-Submersible, and Tension-Leg Platforms (TLPs), continue to evolve, balancing stability, mooring efficiency, and scalability.

Performance monitoring ensures turbine longevity and minimises maintenance costs. Integrating Structural Health Monitoring (SHM) and SCADA systems allows for real-time tracking of operational parameters, while emerging AI-driven fault detection techniques improve predictive maintenance. Enhanced machine-learning-based control strategies optimise blade pitch adjustments, mooring system dynamics, and ballast weight redistribution to reduce turbine fatigue.

Future research should focus on:

1. Hybrid platform innovations that improve stability while reducing costs.

2. Integration of AI and digital twin technologies for real-time turbine diagnostics.

3. Advancements in co-designed control strategies to mitigate extreme environmental loads.

4. Scaling commercial floating wind farms to achieve competitive Levelized Cost of Energy (LCOE).

By addressing these challenges, floating wind technology will become a cornerstone of global renewable energy expansion, unlocking vast deep-water wind resources and supporting the transition toward a sustainable energy future.

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