Committee V.4: Offshore Renewable Energy

Citation for the original published paper (version of record):

Rawson, C., Abdussamie, N., Abrahamsen, A. et al (2026). Committee V.4: Offshore Renewable Energy. Lecture Notes in Mechanical Engineering: 254-358.
http://dx.doi.org/10.1007/978-981-95-2786-1_4

Committee V.4: Offshore Renewable Energy

Charles Rawson[1(✉)], Nagi Abdussamie[2], Asger Bech Abrahamsen[3], Ivan Catipovic[4],
Thomas Choisnet[5], Toshiki Chujo[6], Jose Gaspar[7], Luca Greco[8],
Ole A. Hermundstad[9], Han-Koo Jeong[10], Shen Li[11], Wengang Mao[12],
Rachel Nicholls-Lee[16], Gabriele Notaro[17], Elif Ogus[13], Freeman Ralph[14],
and Shali Sun[15]

[1] Waldorf, Maryland, USA
`charles.e.rawson@uscg.mil`
[2] Australian Maritime College (AMC), Launceston, Australia
[3] Technical University of Denmark (DTU), Roskilde, Denmark
[4] University of Zagreb, Zagreb, Croatia
[5] BW Ideol, La Ciotat, France
[6] National Maritime Research Institute (NMRI), Tokyo, Japan
[7] University of Lisbon (CENTEC), Lisbon, Portugal
[8] CNR-INM, Rome, Italy
[9] SINTEF Ocean, Trondheim, Norway
[10] Korea Institute of Ocean Science and Technology (KIOST), Busan, Republic of Korea
[11] University of Strathclyde, Glasgow, United Kingdom
[12] Chalmers University of Technology, Gothenburg, Sweden
[13] Middle East Technical University (METU), Ankara, Turkey
[14] C-CORE, St. John's, Canada
[15] Beijing, China
[16] Whiskerstay Ltd, Exeter, United Kingdom
[17] DNV, Oslo, Norway

Committee Mandate. Concern for load analysis and structural design of offshore renewable energy devices. Attention shall be given to the interaction between the load and structural response of fixed and floating installations taking due consideration of the stochastic and extreme nature of the ocean environment. Aspects related to design, prototype testing, certification, marine operations, levelized cost of energy and life cycle management shall be considered.

Keywords: Offshore wind turbine · floating wind turbine · wave energy converter · tidal energy · ocean energy · floating solar photovoltaic · hybrid systems · renewable energy

1 Introduction

This report presents a comprehensive analysis of advancements in offshore renewable energy, including the areas of offshore wind, wave, tidal, floating solar energy, and the hybridization of these technologies. While emphasizing the interaction between environmental forces and structural responses, key aspects of load analysis and structural design

W. Wu and J. Ding (Eds.): ISSC 2025, LNME, pp. 254–358, 2026.
https://doi.org/10.1007/978-981-95-2786-1_4

are the focus of this work. The committee also delves into the latest industry developments, numerical and physical modeling approaches, design standards, and operational challenges associated with fixed and floating offshore renewable energy devices.

The growing global demand for sustainable energy solutions has driven significant technological advancements in offshore wind energy, notably in floating wind turbine and hybrid systems. These technologies have seen rapid development due to increasing investments, policy incentives, and an urgent need to reduce carbon emissions. Bottom-fixed offshore wind turbines remain the predominant choice in shallow waters, while floating wind turbines offer promising solutions for deep-sea deployment, expanding the geographical feasibility of offshore wind farms. Innovations in turbine design, foundation stability, and aerodynamic performance are critical to improving efficiency and reducing maintenance costs.

Beyond wind energy, wave and tidal energy converters, as well as floating solar photovoltaic (FPV) systems, are gaining attention as viable components of the offshore renewable energy mix. Wave energy converters (WECs) harness the kinetic and potential energy of ocean waves, while tidal energy systems capitalize on predictable tidal flows to generate electricity. FPV systems, often deployed in combination with offshore wind farms, present an innovative approach to maximizing energy output within a limited marine footprint. Hybrid energy solutions integrating multiple renewable sources are becoming increasingly viable, offering enhanced energy reliability and grid stability.

This report also examines the role of digital technologies in optimizing offshore renewable energy operations. Digital twin technology, artificial intelligence (AI), and machine learning algorithms are revolutionizing predictive maintenance, structural health monitoring, and real-time performance optimization. Additionally, advanced numerical simulations and experimental testing methodologies are enhancing the accuracy of structural assessments, ensuring robust and cost-effective design solutions.

While this report primarily focuses on structural design and load analysis, it also includes discussions on marine operations, transport logistics, and total cost of energy considerations. The committee explores levelized cost of energy (LCOE) assessments, financing mechanisms, and lifecycle cost management strategies. Transport, installation, and maintenance logistics for offshore renewable energy infrastructure present unique challenges that require innovative engineering solutions and coordinated industry efforts.

2 Bottom-Fixed Offshore Wind Turbines

Bottom-fixed offshore wind turbines (BFOWTs) are mainly concentrated in shallow waters and are predominantly deployed in nearshore, shallow-water zones (<50 km from coastlines) due to cost efficiencies. Their layout follows grid-like patterns to optimize energy output and minimize infrastructure costs. Sentinel-1 SAR remote sensing and Google Earth Engine (GEE) have enabled precise mapping, revealing that 95% of global OWTs are bottom-fixed, reflecting their maturity compared to floating alternatives.

2.1 Recent Industry Developments

Wang, K. et al., (2024a) shows that bottom-fixed offshore wind turbines dominate the global offshore wind energy sector, with 12,412 units identified worldwide as of 2022.

These turbines are concentrated in Northern Hemisphere coastal regions, particularly in Europe (5,915 units) and Asia (6,490 units), while the U.S. lags significantly (7 units). Europe pioneered deployment between 2006–2018, with peak activity during 2010–2015. Europe is the traditional stronghold for offshore wind power, with most OWTs located in the nearshore areas of the North Sea and its surrounding regions. Projects often expanded incrementally, filling gaps between existing turbine arrays. The UK has the largest number of OWTs (2,737), followed by Germany (1,537), Denmark (629), the Netherlands (515) and Belgium (401). Asia, led by China (6,038 units), has experienced explosive growth since 2019, accounting for two-thirds of its installations post-2019 and its OWTs are mainly distributed in the nearshore areas of the Yellow Sea, East China Sea and South China Sea. Vietnam (419 units) and South Korea (33) are emerging players. Asia has rapid acceleration post-2019, driven by China's coastal megaprojects (e.g., Jiangsu and Guangdong provinces). Over 50% of China's OWTs were installed in 2021–2022 alone.

Due to the positive correlation between the construction and maintenance costs of wind turbines and the distance to the port or coast, most wind turbines are built in nearshore areas and distributed in a regular pattern. Therefore, the global wind turbines exhibit a regular distribution in nearshore areas, with numerous turbines aggregated to form a wind farm spatial pattern.

The status of offshore wind, as of Q2 2024, is that 73.1 GW is fully commissioned; with the majority in China (34.8 GW), followed by the UK (14.8 GW) and Germany (8.2 GW). China also has the most under construction (7.7 GW), followed by the UK (5.2 GW) and Germany (2.6 GW). Globally, a cumulative 116.2 GW is post-FID (including operational projects, under construction, and projects in the preconstruction phase).

2.2 Numerical Modeling and Analysis

While the large number of installations of BFOWT worldwide demonstrates a level of technology maturity, cost reduction and operation & maintenance (O&M) optimization of systems are still critical for their design, construction and deployment. Furthermore, the trend towards turbines characterized by higher energy harvesting capacities and greater power per mass ratios to reduce sea occupation and to compete with other sectors of the energy industry is nowadays resulting in larger and more flexible components. Consequently, these units are subject to increasingly demanding logistics concerns, extreme deployment conditions in harsh environments and, in addition, they must withstand aerodynamic, hydrodynamic, gravitational, and geotechnical loads (Jahani, et al., 2022). These aspects must be tackled into a multidisciplinary context involving the interaction among rotary-wing aerodynamics, tower/blades structural dynamics, soil-pile interaction phenomena and control strategies.

2.2.1 Aerodynamic Aspects in Simulations

With increasing maturity of OWT technology and reduced associated commercial risks, the majority of large-scale OWTs share the same features such as horizontal axis of rotation, three blades, upwind, variable-speed, and variable blade pitch. With the state-of-the-art 15 and 18 MW machines now available on the market, research effort on numerical modelling has gradually moved from wind turbine-related aspects to broader topics such as the analysis of the different types of support structures, the development of advanced control systems, new materials and installation and reliability issues.

However, comprehensive wind turbine numerical models with good levels of accuracy and low computational burden are still needed as demonstrated by results from the IEA Task 47 - TURBINIA. This work highlights the limitations of Blade Element Momentum Theory (BEMT), widely used by industry, in predicting blade aeroloads under off-design (unsteady) flow conditions, specifically when the operating conditions are characterized by significant yaw errors or wind shear/veer due to the unprecedented size of modern and next-generation wind turbine rotors. Moreover, many validation exercises on rotor aerodynamics deal only with global rotor loads, whilst it is well demonstrated that the accuracy of these predictions might hide compensating errors on blade local loads.

Among software for design and evaluation is OpenFAST (https://github.com/OpenFAST), an open-source framework for the analysis and simulation of onshore and offshore wind turbines. A real-time hybrid simulation (RTHS) framework couples experimental soil-foundation models with OpenFAST-based analytical substructures for monopile OWTs. Al-Subaihawi et al., (2024) demonstrates improved prediction of foundation nonlinearities under operational and extreme conditions, validating the framework's ability to capture coupled aero-hydro-geotechnical responses.

Further, research on rotor aerodynamics and rotor aeroelasticity is reported to be very limited (especially with respect to similar topics in the field of floating offshore wind turbine applications, see Ch. 3). For instance, Ye et al., (2023) shows a high-fidelity rotor performance analysis conducted using the Finite-Analytic unsteady Navier-Stokes code (FANS). The comparison is performed with the NTNU BT1 wind turbine tested in a wind tunnel in uniform flow conditions and with other state-of-the-art CFD codes over the rotor operating range. The paper shows that CFD predictions correctly match the experimental torque coefficient measurements trend. However, significant underestimation of CT at high TSR values is observed. Differently, local blade loads overestimation is observed on the 2 MW DANAERO rotor, thus demonstrating how the interaction between numerical modelling and experimental tests is fundamental also for the simplest steady axial flow conditions.

Melani et al., (2020) propose a method to extract rotor blades angle of attack from CFD flow fields for Darrieus turbines, comparing three post-processing techniques, 3-Point, LineAverage, Trajectory (see Fig. 1). Results show the LineAverage method achieves the highest accuracy in predicting lift/drag coefficients under stable operational conditions like Figure (TSR = 4.5). The study validates the approach using a pitching airfoil CFD model, demonstrating improved force reconstruction compared to conventional power-law profiles. Boorsma et al., (2023) validate aeroelastic simulation tools (BEM, CFD, free vortex wake) against field measurements from the DANAERO 2 MW turbine under axial, sheared, and yawed inflow. CFD and synthesized airfoil data improve agreement with measurements in sheared conditions, while BEM struggles with skewed wake effects in yawed flows. The study emphasizes the need for

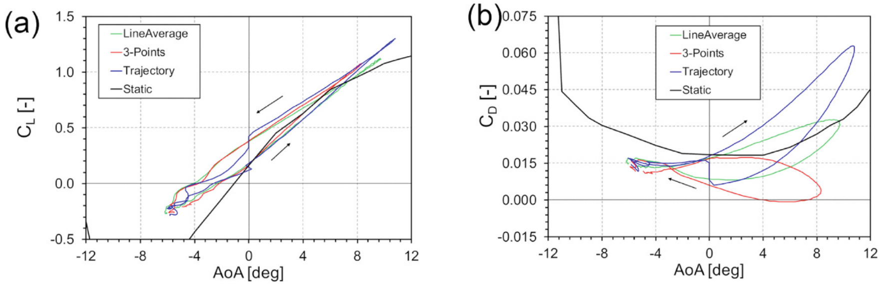


Fig. 1: Comparison of the lift (a) and drag (b) coefficient hysteresis loops obtained with different methods and static airfoil data for TSR = 4.5 (Melani et al., 2020)

turbulence model enhancements and rotational effect considerations. Using URANS and k-ω SST turbulence models, Viré et al., (2020) analyze VIVs for monopiles in supercritical flow ($Re \geq 3.6 \times 10^6$). Results reveal aerodynamic damping transitions between self-exciting and self-limiting behaviors, with lock-in frequencies validated against experiments. Castorrini et al., (2023) couples mesoscale weather models (WRF) with RANS-based CFD to predict offshore wind profiles, validated against LiDAR data. The hybrid approach improves resolution of boundary layer turbulence and wave–wind interactions, demonstrating accuracy in capturing vertical velocity and TKE profiles for large rotors.

2.2.2 Soil-Foundation Interaction (PSI)

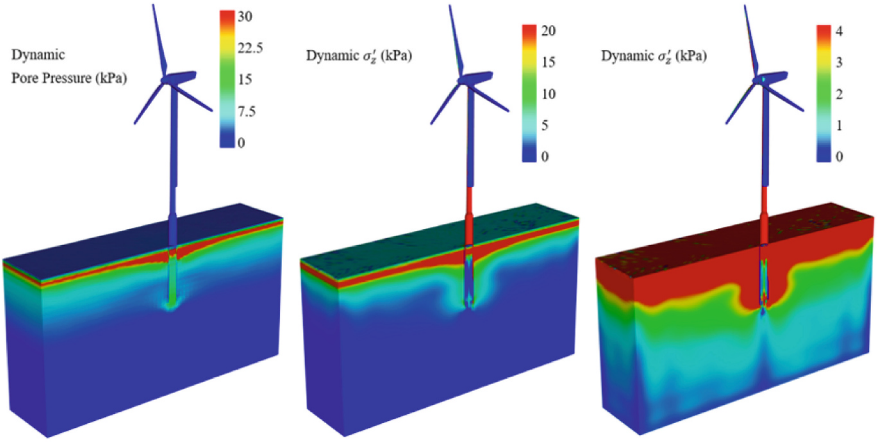
Soil-foundation interaction (PSI) is a vital factor in ensuring structural stability, as demonstrated by Ma, et al., (2024), who analyze the dynamic responses of monopile and jacket-supported turbines using the X-SEA program and finite element analysis (FEA). Their findings emphasize that soil flexibility significantly affects natural frequencies and deflection patterns in turbine structures. By modeling lateral and axial soil resistance through nonlinear soil springs, the study underscores the necessity of PSI in OWT design guidelines to ensure stability across varying soil conditions. Building on this, Wu, et al., (2024) highlight the challenges of PSI in cold sea regions, where combined ice and aerodynamic loads cause greater displacements and reduce natural frequencies, especially in flexible foundations. Using the PISA soil modeling method, they show that accurate PSI modeling is critical for capturing the full impact of ice-induced forces, emphasizing the need for combined load analysis in cold-region OWT standards. Validation and application of integrated numerical models including all the turbine sub-components and aimed at simulating its dynamic response under the fully coupled wind/wave loads, and servo-control commands are widely reported in the literature. As an example, Ma, et al., 2024) show a time-domain analysis of the superstructure of the NREL 5 MW wind turbine by the software framework of Abaqus WT coupled with FAST. The PSI model is based on the nonlinear p-y, t-z and Q-z springs. Based on three-representative wind-wave load cases, it is found that the PSI can significantly reduce the natural frequencies of various WT components, while increasing the tower-top peak motions in normal operational conditions. For parking conditions, the PSI can largely increase the peak motion response and bending moments. This study concludes that the PSI should be considered in the design of offshore wind turbine of a monopile foundation due to its remarkable impact on its natural frequency, dynamic response, and seismic response. Sørum et al., (2022) evaluates fatigue design uncertainties in monopile offshore wind turbines using a sensitivity analysis approach. The authors identify SN curve parameters and environmental conditions as dominant factors influencing fatigue damage, while wave directionality and soil model uncertainties significantly affect dynamic response. The analysis highlights the importance of accurate environmental modeling and interdisciplinary parameter integration for reliability improvements.

Furthermore, Bergua et al., (2022) focus on the integration and verification of a new soil-structure interaction model for offshore wind design. Their work emphasizes the importance of accurately capturing soil-pile interactions to improve the reliability of OWT designs, particularly under complex loading conditions. By incorporating an elastoplastic macroelement model, this study addresses the limitations of traditional SSI methods and provides a less conservative and potentially more cost-effective design framework for OWT foundations. Bergua integrates the REDWIN macroelement model for soil-structure interaction (SSI) into OWT simulations, demonstrating reduced system loads compared to traditional methods. The macroelement's improved damping and stiffness characterization highlights the need for accurate SSI modeling in fatigue and dynamic response analysis.

Chen et al., (2023) investigate the seismic response of OWTs supported by hybrid pile-bucket foundations in liquefiable soils. Their findings demonstrate that soil-structure interactions significantly influence the stability of the turbine structures during seismic events, reinforcing the importance of detailed soil analysis in design standards. He and Ye, (2023) use the FssiCAS software and the Pastor-Zienkiewicz-Mark III (PZIII) elastoplastic soil model to analyze seismic responses of a 1.5 MW monopile OWT. Results show significant seabed liquefaction (5–6 m depth near the monopile) and tower-top horizontal oscillations (up to 2 m), but no cumulative displacement (Fig. 2). Comparisons reveal that neglecting soil plasticity or pore water effects leads to inaccurate dynamic predictions. Ngo and Kim, (2024) compare monopile, suction bucket, and jacket-supported OWTs under seismic loads using finite element modeling in ABAQUS. The monopile exhibits the largest tower-top displacement (0.73 m under El-Centro waves), while the jacket foundation experiences 17–21% higher tower stress due to structural stiffness. Fragility curves indicate monopiles are more vulnerable to displacement, whereas jackets are sensitive to stress and bending moments.

2.2.3 Reliability of Results

A fully coupled aero-servo-hydro-elastic model is developed for a 10 MW monopile OWT using nonlinear Winkler foundation-based soil-structure interaction (SSI). Xi et al., (2021) validate a bladed-style controller in FAST and demonstrates that SSI and time-varying blade-pitch angles significantly affect fatigue damage, with 90% computational time reduction compared to traditional FEA. A hydroelastic model coupling a weak-scatterer potential flow solver with FEM was developed for monopile foundations. Leroy et al., (2021) accurately predicted mudline bending moments under regular waves, matching experimental data better than Morison-based models.



(a) Dynamic pore pressure (b) Dynamic σ_z' (Scale: 0-20 kPa) © Dynamic σ_z' (Scale: 0-4 kPa)

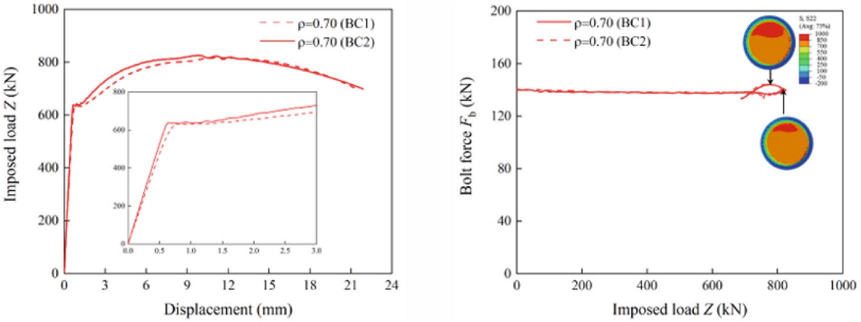
Fig. 2: Distribution of pore pressure and effective stress at t = 300 s (Noted: the initial values are excluded, and the seabed foundation is sectioned by y = 35 m). (He and Ye, 2023)

Barreto, et al., (2022) evaluates the impact of simulation length and flexible foundations on long-term extreme response extrapolation for monopile OWTs. Simulations shorter than 30 min led to significant errors (up to 40% for bending moments), while flexible foundations shifted critical wind speeds (16.5 → 18 m/s) and increased mudline bending moments by ~10% compared to rigid models

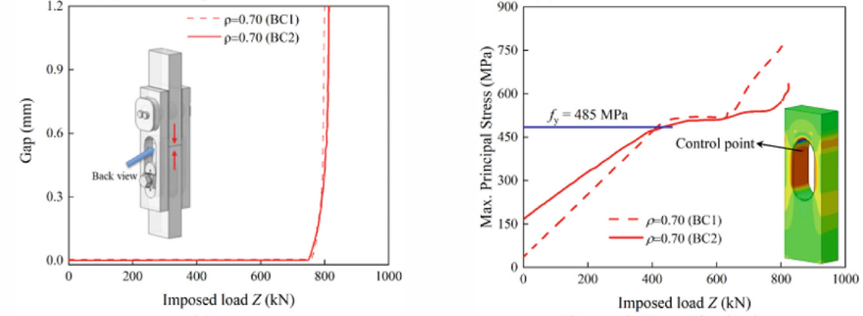
A fully coupled reliability assessment framework was developed for OWTs using surrogate models (Kriging, multivariate regression, and support vector regression) combined with dynamic simulations in OpenFAST. The study highlighted the importance of soil-structure interaction (SSI) modeling and validated the subset simulation (SS) method with Kriging as the most accurate approach for estimating reliability indices. Han et al., (2024) present a generic fully coupled framework for reliability assessment of offshore wind turbines under typical limit states. The framework revealed excessive tower vibrations as a critical failure mode under operational states and emphasized the need for SSI considerations to avoid conservative or unsafe designs. This study emphasizes the importance of soil-structure interaction (SSI) in the reliability analysis, integrating a dynamic simulation tool with surrogate models to estimate reliability indexes efficiently. The framework utilizes various methods, such as the First-Order Reliability Method (FORM) and subset simulation (SS), demonstrating that the use of equivalent coupled spring boundaries can significantly improve simulation accuracy. It advocates reliability-based calibration of partial safety factors and highlights emerging trends like risk-based inspection and digital twin integration for predictive maintenance.

2.2.4 Dynamic Response Analysis and Vibration Control

The NREL 5 MW turbine rotor is addressed by Zeng et al., (2024) where the influence of the wind field and of blade structural models on the turbine response in parked conditions and under the effect of waves is investigated. This work demonstrates that the spatial distribution of the wind speed is crucial for accurately simulating the parked turbine dynamic response where a uniform distribution of the wind field is too conservative. However, the choice of wind speed coherence function shows a weak effect. Furthermore, whilst a detailed structural model is necessary to obtain blade responses, tower structural dynamics is accurately captured with a simplified model in which the blades wind load on these are simplified as a concentrated mass and a concentrated load, respectively.



(a) Load-displacement curves (b) Evolution curves of bolt force



(c) Gap (d) Maximum principal stress

Fig. 3: Comparison between connection types (Cheng et al., 2023)

The mechanical behavior of connections within offshore wind turbine towers is also crucial. Cheng et al., (2023) investigated various connection types using finite element simulations, Fig. 3. Their findings indicate that while traditional bolted connections may present vulnerabilities due to stress concentrations, alternative designs such as the C1 wedge connection offer improved fatigue resistance and overall structural performance. This research informs installation practices, emphasizing the selection of robust connection types to enhance the longevity of OWT structures. Wang et al., (2021) compares the dynamic behavior of conventional and compact gearboxes for a 10 MW offshore wind turbine using a multi-body system (MBS) model. The compact gearbox demonstrated superior performance under torque loads, manufacturing errors, and non-torque loads, validated via decoupled global-local simulations.

An analytical solution for 1:1 internal resonance in wind turbine towers revealed coupled along-wind and cross-wind oscillations. Lenci, (2023) identified pitchfork bifurcations leading to unstable quasi-periodic responses, validated numerically for the NREL

5-MW turbine. Pezeshki et al., (2024) develops a coupled PDE model to analyze gyroscopic effects from rotor-blade rotation on OWT dynamics, including fore-aft, side-side, and yaw motions. Numerical results reveal operational natural frequency shifts and phase differences between torsional and translational responses under wave-wind-blade excitation. They also emphasize the role of gyroscopic moments in altering damping and stiffness characteristics in parked and operational conditions.

Dogru and Yilmaz, (2024) optimized a diffuser-augmented wind turbine (DAWT) using response surface methods and 3D CFD. A wide-angle GOE431 diffuser achieved a speed-up ratio of 1.59, while a six-bladed rotor increased the power coefficient by 93% (from 0.417 to 0.805). Finite blade number effects and Reynolds number sensitivity were critical limitations, with tip losses reduced to one-third of bare turbines. Machado, et al., (2024) introduces a metamaterial-based OWT design using spectral element modeling to suppress low-frequency vibrations induced by wind, waves, and blade rotation. The metastructure achieves 30% vibration amplitude reduction via tunable stopbands, outperforming traditional tuned mass dampers (TMDs). Numerical validation confirms broadband attenuation and highlights the impact of resonator mass ratios (5–30%) on bandgap formation and dynamic response.

Looking at the next generation of wind turbine rotors with increasing size, aeroelastic models considering blades' large deformation are fundamental (see, for instance Li, Z. et al., (2023b) for a FEM-based structural model). Furthermore, the investigation of blades structural integrity is addressed by Ha and Jeong, (2021) where the debonding failure at the adhesive bonded joints between spar caps and shear webs of a blade subjected to extreme bending moments (which represents one of the blade failure modes) is addressed using the 3D FEM composite analysis from the solver ANSYS. The analysis indicates peeling failure possibility of the adhesive structure close to the aft shear web for large blades with double shear webs configurations.

Given the unavailability of data related to real operating WTs, examples of detailed aeroelastic analyses focuses on "virtual" ones, such as the IEA WIND 15 MW Reference Wind Turbine (RWT). The work presented by Lapa, et al., (2023) indicates that blade torsional deformation must be considered when defining the turbine operating curves for an efficient generation of energy. Moreover, the peak shaving process is impacted when torsional deformation is not considered.

In connection with aeroelasticity, the topic of active and passive control strategies is still present in the literature with works on model predictive controllers Pustina, et al., (2022), and studies on the potential of applying viscoelastic dampers to mitigate the vibration of the tower under wind and wave loadings written by Liang, et al., (2024). In addition, Individual Pitch Controller (IPC) techniques have demonstrated their effectiveness in reducing structural loads and dynamic response of the drivetrain, achieving also the stabilization of the power output written by Xie et al., (2022).

2.2.5 Digital Twin Technology

A comprehensive overview of the state-of-the-art digital twin (DT) technology including research and industry perspectives is provided by Stadtmann et al., (2023) where critical research challenges that need to be addressed to fully realize the benefits of DTs are provided based on the industry point of view (standards, data, models and industrial acceptance). Challenges related to predictive DTs, prescriptive DTs and autonomous DTs are identified as the most impacting area of research. In addition, the complimentary role of industry and research for the success of DT technologies is underlined. An example of DT of a bottom-fixed OWT is described by Zhao, et al., (2023) where a component-based Reduced Order Modelling (ROM) is used to synthetize a DT for the modal analysis and structural response starting from a coupled FEM-CFD analysis. This model shows dramatically reduced computational costs with respect to FEM analysis and high accuracy demonstrating that it can provide almost instant predictions of the modes and responses of the turbine structure due to the wind-wave loading as well as projections of structural health conditions (Table 1). A similar strategy is proposed by Cao et al., (2023a) where the DT is fed also with physical asset data and is tailored to rapidly predict and display the distribution of the wake field, structural deformation and stress of fixed OWTs.

Table 1: Computational efficiencies of the high-fidelity FEA model and component-based ROM with and without port reduction for mode shape prediction (Zhao et al., 2023)

		High-fidelity FEA model	Comp.-based ROM	Comp.-based ROM With Port Reduction
Case 1	CPU	205.73 s	26.18 s	0.3878 s
	Time Speed-up	1.00	7.86	530.51
Case 2	CPU	201.26 s	26.61 s	0.3817 s
	Time Speed-up	1.00	7.56	527.27
Case 3	CPU	210.82 s	25.67 s	0.3979 s
	Time Speed-up	1.00	8.21	529.83
Case 4	CPU	206.19 s	25.64 s	0.3786 s
	Time Speed-up	1.00	8.04	545
Case 5	CPU	204.31 s	26.72 s	0.3866 s
	Time Speed-up	1.00	7.65	528
Case 6	CPU	214.25 s	25.62 s	0.4049 s
	Time Speed-up	1.00	8.36	529

Finally, data-driven techniques are also proposed to extend the capabilities of RANS turbulence models for wind turbines under quasi-steady conditions by using synthesized data from high-fidelity LES data. This work introduces a data-driven RANS closure model using LES data to correct turbulence anisotropy and kinetic energy production. The approach, tested on wind-tunnel-scale turbine wakes, significantly improves wake recovery and turbulence intensity predictions compared to baseline – models by Steiner, et al., (2022). An example of the application of DT-based approach to an operational (onshore) wind farm located in Yalova (Turkey) is described that a framework to retrieve and process the temporal data stream from the SCADA units of the turbines aiming at forecasting the wind speed and predicting the generated energy is proposed and successfully validated in a real-life scenario. Zhao et al., (2023) proposes a component-based reduced-order modeling (ROM) approach for real-time digital twinning of monopile-supported OWTs. The ROM framework combines static condensation and empirical port reduction, achieving a computational speedup of 650× compared to finite element analysis (FEA) with $<0.2\%$ error, enabling rapid modal and structural response predictions under wind/wave loads.

Nybø et al., (2021) compares turbulence models (Kaimal, Mann, LES, TIMESR) for a 10 MW turbine, showing TIMESR's low-frequency wind spectra increase tower and blade root moments, while Mann's negative horizontal coherence amplifies yaw moments. Nybø underscores the sensitivity of quasi-static loads to turbulence model choice, particularly in stable atmospheric conditions. Myrtvedt et al., (2020) compares Kaimal and Mann wind models for a 10 MW turbine, showing Mann's lower coherence increases yaw moments, while Kaimal amplifies low-frequency tower bending. Turbulence coherence and atmospheric stability significantly affect fatigue loads, particularly in low-frequency ranges for floating turbines. Kozmar et al., (2022) critiques IEC-standard power-law wind models, showing they underestimate dynamic loads by up to 60% compared to realistic turbulence simulations. Real-world wind conditions increase tower-top displacement variance by 550%, highlighting critical gaps in current standards.

Moving from the analysis of the single machine to the optimization of the whole wind farm, the development of efficient and accurate far wake models is still an interesting topic, especially when turbine off-design conditions such as yaw misalignment or wake steering for farm power optimization are considered. A nonlinear wake model incorporating yaw steering and vertical wind shear was developed using a Gaussian velocity deficit and a "prediction-correction" method Li, Y. et al., (2024). The model showed strong agreement with Garrad Hassan wind turbine experiments and CFD simulations, particularly capturing shear effects and wake redirection. This study validates the Dynamic Wake Meandering (DWM) model against LES for horizontal (yaw) and vertical (tilt) wake steering. Key findings include the importance of filter size in predicting wake deflection and the DWM model's limitations in capturing shear-layer-induced high-frequency wake oscillations assessment of Digital Twins for BFOWTs (Rivera-Arreba et al., 2024). Analytical far wake and mid-fidelity DWM models are addressed in the literature.

2.3 Physical Testing

Empirical research on the structural behavior of large-scale components, such as those used in offshore wind turbines, has been instrumental in validating theoretical and numerical models, especially under unique and often unpredictable load conditions. Physical testing provides insights into deformation modes, material resilience, and structural dynamics that are critical for enhancing the reliability of offshore wind systems.

One notable study by Ren et al., (2023) investigates the deformation behaviors of large-diameter steel tubes subjected to concentrated lateral impact loads. Deformation modes of steel tubes under different impact velocities, showing diamond-shaped dents under concentrated lateral loads like Fig. 4. This research is particularly relevant to

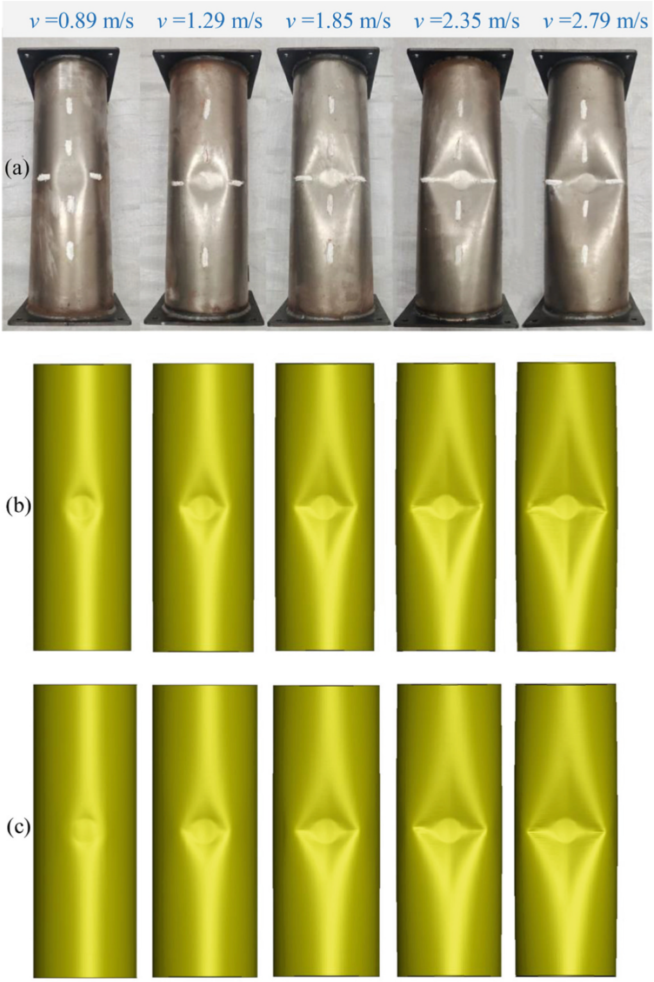


Fig. 4: Deformation modes of steel tubes under different impact velocities: (a) experiment, (b) FEM (without strain rate) and (c) FEM (C = 4000 and p = 5) (Ren et al., 2023).

offshore wind turbine (OWT) foundations, which are exposed to risks such as vessel collisions. Through scaled experiments and high-fidelity numerical simulations using the LS-DYNA software, the study evaluates the response of large-diameter tubes, which differ in deformation patterns from their smaller counterparts under similar loading. The results reveal that larger diameter tubes exhibit localized deformation, manifesting as diamond-shaped dent patterns under high-energy impacts, in contrast to the more uniform deformation typically seen in smaller diameter tubes. These findings underscore the need for tailored analytical models to predict the impact response of large-diameter tubes accurately, as existing models fall short in this regard.

The insights gained from these physical tests serve to refine design assumptions and improve the predictive accuracy of models used in OWT design. By capturing localized deformation characteristics, studies like Ren et al. contribute significantly to developing reliable safety standards and impact-resistant design strategies essential for the structural integrity of OWTs. Such empirical data is invaluable for validating and calibrating complex numerical models, ensuring that theoretical predictions align with real-world behaviors under high-impact scenarios.

It is noted that physical testing of soil resistance and foundation integrity can be challenging, both in terms of physical scale and time for observations. Centrifuge modelling uses scale models subjected to increased gravity to model full-scale nonlinear geotechnical phenomena, enabling reliable and cost-effective investigation of the response of equipment and facilities to real-world conditions; where considerable uncertainties exist in estimating the soil resistance. For bottom founded wind turbines, the performance of the piles driven into the seabed in both dense sands and hard clays can be studied over time to understand the long-term soil resistance behavior. With increased gravity, the correct stress state is achieved in the soil, allowing scaled test results to be converted to full scale field quantities. This avoids uncertainties present in 1 g scaled testing. Being more economic and efficient, a greater number of conditions can be tested to gain greater certainty in complex numerical simulations. No other practical testing is feasibility to verify numerical simulation results. Larger 5.5 m–9 m radius commercial units have the capability to model >22,000 lb and 200 g payloads spinning at 3.5 revs/s (~300 RPM).

2.4 Transport, Installation, Operation and Maintenance

While Transport and Installation (T&I) and Operations and Maintenance (O&M) challenges are often environmental, financial and safety related, there are still many areas in which structural integrity is key. With a growing body of research investigating the use of autonomous systems for T&I and O&M (Jenkins et al., 2024), and the use of digital tools for design, planning, installation and O&M (Ciuriuc et al., 2022), understanding of the industry perspective and how research can assist and improve on this is essential.

2.4.1 Transport and Installation

Jack-up Vessels are used in fixed wind turbine transport and installations. However, for more stable wind conditions and the depletion of near-shore locations, wind farms are moving farther offshore into deeper waters, challenging the current limits of offshore heavy-lift operations. Over time, the design of offshore crane vessels has converged to a semi-submersible crane-vessel (SSCV) type. Fig. 5 shows an open-source crane-vessel.

Although semi-submersibles are known for being sensitive to hanging loads, in comparison to mono hulls, they provide flexible ballasting and enough deck area to accommodate two cranes of large capacity, outreach and lifting heights. In contrast to this, in the offshore wind industry jack-up vessels have been dominating the scene due to higher stability. However, this increased stability comes at a price, which is: operational water depth limit (up to 80 m Next Generation Jack-Up, 2023), dependency on seabed conditions, vulnerability to wind direction changes and jack-up time. The effects of wave and wind loads on the structure need to be considered during transportation, especially in terms of safe transportation strategies in extreme sea conditions.

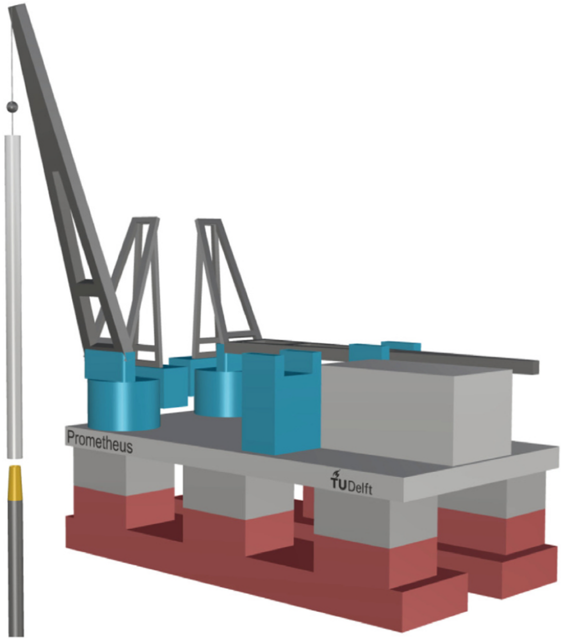


Fig. 5: Prometheus, an open-source SSCV (Domingos et al., 2024)

A comparative study by Domingos et al., (2024) assume an annual operational rate of 39% when considering only transverse waves; annual operational rate is better than sea surface operational rate (24%) due to lower transverse swing (Roll) stiffness and reduced crane acceleration. Operational rate is primarily limited by wave loading, and both wave and wind effects must be considered when evaluating the time window for installation.

2.4.2 Operations and Maintenance

The operation and maintenance (O&M) of bottom-fixed offshore wind turbines (OWTs) face challenges due to harsh marine environments and complex structural dynamics. Recent advancements focus on enhancing reliability and cost-efficiency through innovative monitoring and control technologies.

A comparative study by Wang et al., (2021) highlights the operational benefits and maintenance challenges associated with compact gearbox designs for 10 MW offshore wind turbines. By analyzing conventional and compact gearboxes through a multi-body system (MBS) approach using finite element model (FEM), the study finds that compact gearboxes can reduce fatigue damage and improve dynamic performance, primarily due to their superior load-sharing capabilities. However, the increased complexity of compact designs poses challenges in both manufacturing and maintenance, suggesting that while compact gearboxes enhance load-bearing efficiency, they require more specialized maintenance protocols, which could impact O&M costs over time.

Tuned Mass Dampers (TMDs) are widely employed to mitigate vibrations caused by combined wind-wave loads. Lu, D. et al., (2023) demonstrated that TMDs reduce dynamic responses by up to 40% under typhoon conditions, significantly improving fatigue life. Additionally, semi-active wave compensation systems (e.g., Seaqualize) enhance crane stability during maintenance operations, minimizing mechanical wear. Recent studies emphasize hybrid strategies combining digital twins, robotics, and real-time meteorological forecasting. Domingos, et al., (2024) highlighted that 2-min wave prediction intervals improve maintenance operability by 15%, while Lu, D. et al., (2023) advocated for TMDs coupled with CFD-based wake control to minimize energy losses.

Digital twins integrated with computational fluid dynamics (CFD) and machine learning enable predictive maintenance. Cao et al., (2023) developed a digital twin framework using Bayesian-regularized neural networks, achieving <4% error in stress prediction for tower structures. This approach allows rapid identification of stress concentrations (e.g., 89.44 MPa peaks at tower roots) and optimizes maintenance scheduling. Sentinel-1 SAR and Landsat SWIR time-series analyses address spatial-temporal data gaps in offshore databases. Dadmarzi and Bachynski-Polić, (2022) utilized adaptive Z-score thresholds to achieve 92% precision in turbine detection, enabling retroactive installation-year mapping (2000–2022) for lifecycle assessment. Such remote sensing tools reduce unplanned downtime by prioritizing high-risk components.

Addressing the high computational cost of fatigue assessments, Katsikogiannis et al., (2022) propose a lumping method to optimize fatigue damage predictions in monopile-based OWTs. This approach condenses extensive load cases into a manageable number, reducing computational demands by up to 96% while maintaining an accuracy of 92% to 98%. Such methods are invaluable during early design stages, offering a balance between computational efficiency and prediction accuracy. However, for detailed fatigue assessments, particularly when nonlinear dynamics are at play, fully coupled models remain essential. By significantly lowering computational time, the lumping method also supports efficient fatigue monitoring within O&M frameworks, potentially enabling more proactive maintenance practices.

Collectively, these studies underscore the importance of enhancing transport, installation, and O&M frameworks for offshore wind turbines through targeted design improvements and computational advancements. By refining load-sharing mechanisms in gearboxes and optimizing fatigue modeling approaches, the OWT industry can better address the operational challenges of larger, more powerful turbines, ensuring robust performance and extending their operational life.

2.5 Design Standards and Guidelines

The design of bottom-fixed offshore wind turbines is governed by a combination of international standards, site-specific environmental considerations, and advancements in numerical modeling. Establishing robust design standards and guidelines is critical for the safe and effective deployment of these devices, especially as turbine sizes and environmental loads increase. These standards define structural resilience, fatigue thresholds, and dynamic response characteristics under complex environmental conditions, providing a foundation for reliable and sustainable OWT systems. As highlighted in Table 2, key standards include the IEC 61400 series (e.g., IEC 61400-3 for offshore turbines), DNVGL (ST-0126, ST-0119, ST-0437), ISO19900 series, and CSA C61400; which provide comprehensive guidelines for structural integrity, load calculations, and safety factors. Liu, J. et al., (2024c) emphasize the importance of dynamic response analysis under environmental loads (e.g., waves, wind, and currents) using potential flow theory and Morison equations to simulate hydrodynamic forces.

The IEC 61400 outline numerous standard applicable to wind turbine development. Part 3-1 for fixed wind turbines and Part 3-2 for floating wind turbines deal with issues related design for the harsh marine environment (environmental loads including waves and ice), the specific types of structures (monopile, jacket, spar, semi, TLPs), foundational stability and anchoring given different seabed conditions, access for maintenance given potential storm conditions, safety of marine life and electrical systems including dynamic and static cables and design of substations and storage.

IEC 61400-50 provides standards for wind measurement like wind speed, wind direction and turbulence intensity, and provides use-case independent methodologies and requirements that will ensure consistency, accuracy and reproducibility in the measurement of the wind for the design of OWT. IEC 61400-6 includes tower and foundation design requirements. and consists of Part 50-1 for wind measurement in the application of meteorological mast, nacelle and spinner mounted instruments, Part 50-2 for wind measurement in the application of ground-mounted remote sensing technology, and Part 50-3 about use of nacelle-mounted lidars for wind measurements, respectively. The IEC 61400-50:2022 is developed from IEC 61400-12-1:2017 and IEC 61400-12-2:2013 by separating the wind measurement requirements from them. Although the IEC 614006:2020 specifies the requirements and general principles used to evaluate the tower structural integrity of onshore wind turbine including foundations, its geotechnical evaluation of soils, the flange and connection systems connected to the rotor nacelle assembly including connections to yaw bearings can be referenced in the design of OWT.

Some of these standards reference additional IEC and ISO standards and note that “all or some of their content constitutes requirements”. The IEC 61400-3-1 refers to the ISO 19900 series but some differences between the two sets of standards are worth noting. For example, the IEC 61400-3-1 design cases for ‘parked’ scenarios reference winds and sea states with return periods of 50 years. In ISO 19900, more stringent design criteria are required for manned platforms with hydrocarbon flow and storage. For environmental loads, consideration is given to both the ULS and abnormal limit state (ALS) based on actions with associated return periods of 100 years and (in the case of L1 structures) 10,000 years, respectively.

DNVGL provides a fairly comprehensive set of standards and recommended practices related to general aspects of the design, installation and operation of offshore platforms. The DNVGL offshore wind standards DNVGL-ST-0126, DNVGL-ST-0119, and DNVGL-ST-0437 have design situations and load cases aligned fairly closely with those in the IEC standards. They cover site conditions, design scenarios, load calculation methods, installation and operations guidance for fixed and floating offshore platforms. DNV-CG-0128:2023 provides the methods and principles applicable for the assessment of buckling and ultimate strength limits (ULS) of load carrying column structural members in offshore units.

The Canadian Standards Association (CSA) is accredited to develop and maintain standards in Canada by the Standards Council of Canada. The standard CAN/CSA C61400 Wind turbines - Part 3: Design requirements for offshore wind turbines (R2021) applies specifically to offshore turbines and was adopted from the international standard IEC 61400-3:2009 with Canadian deviations.

Recent studies offer insights into various aspects of these standards, with a focus on soil-foundation interactions, hydroelastic effects, environmental load modeling, and fatigue resilience.

Hydroelastic effects play a crucial role in refining design standards. Leroy et al., (2021) develop a hydroelastic model using Weak-Scatterer potential flow theory, integrated with a Euler-Bernoulli beam structural model, specifically for monopile-supported OWTs. Their model, validated against experimental data, accurately captures dynamic responses under regular wave conditions and shows strong agreement with measured mudline bending moments. While this model has not yet proven more efficient than Morison-based methods, it provides valuable insights into fatigue and ultimate load predictions, particularly in scenarios where hydroelastic effects are significant. This supports the inclusion of hydroelastic considerations in design standards, improving the long-term resilience of OWT substructures.

Environmental conditions such as wave height, wind speed, and soil-structure interaction are critical in design phases. Standards mandate site-specific assessments using JONSWAP wave spectra and Kaimal wind models to simulate extreme conditions. For example, IEC 61400-3 requires a 50-year return period for environmental loads, while DNV guidelines specify safety factors of 1.35–1.5 for ultimate strength checks (Xia and Zou, 2023). Katsikogiannis et al., (2024) investigate the effects of different probabilistic models on extreme load predictions for monopile-based OWTs, finding that the conservative models (like the 3-parameter Weibull model) provide more reliable estimates under extreme conditions. This careful calibration of probabilistic models supports environmental load assessment standards, ensuring that OWT structures can withstand intense marine forces. Additionally, Katsikogiannis et al., (2021) propose an environmental lumping method that condenses load cases using damage-equivalent contour lines, achieving accurate fatigue predictions with a reduced computational burden. This approach balances efficiency and accuracy, offering practical tools for early-stage fatigue assessments and supporting resource-efficient design standards.

Fatigue resilience is a recurrent theme, with studies examining how various factors influence fatigue life. For example, Han et al., (2022) present a half coupling model (HCM) for fatigue assessment in jacket-type support structures, effectively separating aerodynamic and structural responses to enable accurate fatigue predictions under combined wind and wave loads. Validated against spectral methods like Dirlik's and Benasciutti-Tovo (BT), the HCM model offers a computationally feasible solution for early-stage design evaluations, making it instrumental in setting fatigue analysis standards for offshore wind applications. Sørum et al., (2022) extend this focus with a sensitivity analysis that examines the impact of SN curve parameters, wind-related factors, and soil-structure interactions across different turbine sizes. Their findings reveal that soil model choices substantially affect fatigue predictions at the monopile and tower base, highlighting the need for detailed geotechnical parameters in fatigue design standards.

Table 2: Cross-Reference Table of International Standards for Offshore Wind Turbine Structural Design Parameters

Standard Name	Key Design Parameters	Reference Standards	Unique Requirements
IEC 61400-3-1	50-year return period for extreme conditions (wind, waves)	References ISO 19900 series	Excludes hydrocarbon flow/storage criteria
	Parked scenario requirements		Focus on structural resilience
IEC 61400-3-2	Mooring system design	Additional IEC/ISO standards	Seabed adaptation requirements
	Dynamic response analysis		Marine life safety protocols
DNV-ST-0126 & 0119	Safety factors: 1.35–1.5 for ultimate strength checks	Compatible with IEC 61400 series	Includes ice load calculations
	Load case definitions		Offshore oil/gas industry alignment
DNV-ST-0437	Icing scenarios	DNV recommended practices	Specialized installation unit guidelines
	Fatigue design methodologies		
CSA C61400	Local environmental adaptations	Adopted from IEC 61400-3:2009	SCC-accredited deviations

Structural design must account for fatigue life and ultimate limit states, particularly for critical components like monopiles and transition pieces. Finite element modeling (FEM) is widely adopted to assess stress concentrations and optimize geometries, ensuring compliance with DNV's fatigue resistance criteria (Gao, L. et al., 2023a; Domingos et al., 2024). Ataei et al., (2023) highlight the need to address structural flexibility in crane systems during installation, as dynamic coupling between vessels and turbines significantly impacts load distributions.

Structural stability and resonance management are also vital, as seen in the study by Lenci, (2023) on nonlinear coupled oscillations in wind turbine towers. By focusing on along-wind and cross-wind oscillations near a 1:1 internal resonance, the study reveals that nonlinear mode coupling must be considered to avoid instability. Through an analytical model validated with NREL 5-MW reference turbine simulations, Lenci's findings highlight the need for resonance mitigation in design standards to prevent fatigue-induced failures. Moreover, new research has emerged addressing innovative solutions for vibration control in OWTs. Machado et al., (2024) explore the application of metamaterial-based vibration control for OWTs subjected to multiple hazard excitation forces, demonstrating that their approach significantly reduces vibration amplitudes compared to conventional systems. This offers promising implications for improving the operational reliability of offshore wind installations. Additionally, Pezeshki et al., (2024) investigate the gyroscopic effects of the spinning rotor-blades assembly on the dynamic response of offshore wind turbines. Their study develops an analytical solution method to derive partial differential equations governing the motions of the OWT structure, including fore-aft and side-side movements. By incorporating gyroscopic moments into the boundary conditions, the research reveals that these effects can significantly influence the operational natural frequencies of OWTs. The findings highlight the necessity of accounting for gyroscopic effects in dynamic analyses, particularly for floating offshore wind turbines, to ensure accurate predictions of structural behavior.

Seismic dynamics also warrant attention in design considerations. He and Ye, (2023) analyze the seismic response of OWTs and their interactions with seabed foundations, revealing the importance of soil-structure interactions during seismic loading. The insights from their numerical analysis inform design guidelines to enhance structural integrity in earthquake-prone areas. In a related study, Chen et al., (2023) investigate the seismic response of OWTs supported by hybrid pile-bucket foundations, demonstrating improved performance under seismic loads compared to traditional monopile foundations. Their findings emphasize the role of foundation design in ensuring stability and resilience during seismic events. Comparative seismic analysis is further explored by Ngo and Kim, (2024), who conduct a detailed assessment of the seismic performance of various foundation types (monopile, suction bucket, and pile jacket). Their dynamic analysis reveals that while the monopile foundation is more susceptible to large displacements during seismic loads, the suction bucket foundation offers better base stability, and the pile jacket foundation, while stable, experiences higher stress concentrations at the tower base.

Installation safety is governed by marine operation standards (e.g., ISO 19901-6), emphasizing risk assessments for lifting and mating processes. Numerical frameworks integrating digital twins are emerging to optimize real-time decision-making, aligning with ISO 55000 asset management principles

Finally, Sun and Fang, (2023) introduce a novel floating composite anti-collision structure designed to enhance the crashworthiness of OWTs against ship collisions. Their study shows that this structure effectively absorbs collision energy, significantly reducing damage to both the OWT and the colliding vessel, which is crucial for maintaining operational integrity.

Together, these studies form a comprehensive framework for developing robust OWT design standards. By integrating PSI considerations, hydroelastic modeling, probabilistic load assessments, fatigue resilience, and resonance control, these standards support the safe, resilient deployment of offshore wind turbines across diverse marine environments, ensuring long-term sustainability and structural integrity.

3 Floating Offshore Wind Turbines

Floating offshore wind turbines (FOWTs) represent a transformative approach in renewable energy, allowing for wind energy generation in deep-water areas where traditional fixed-bottom turbines are not feasible. This chapter discusses recent industry developments, and the current status of installed and predicted FOWT, advances in structural design through numerical and physical modelling and testing, improvements in transport and installation and operation and maintenance, and concludes with an update of the latest regulatory standards pertaining to FOWT structural qualification. Dynamic power cables are integral to the FOWT system, and have their own unique structural challenges; however, these are discussed in chapter "Uncertainty Modelling in Waves and Wave Responses".

3.1 Recent Industry Developments

By 2030, it is anticipated that 7.3 GW of floating wind projects will have started offshore installation (e.g. pre-lay of moorings or cable installation), translating to roughly 3 GW operational by 2030. By 2040, 70.9 GW of floating projects could reach the offshore installation phase, accounting for 45–50 GW of operational floating wind (4C Offshore, 2024). The UK has an ambition for 5 GW of operational floating wind by 2030, which has been reinforced by the success of Flotation Energy and Vårgrønn's Green Volt project winning in the AR6 Contracts for Difference auction in the UK in 2024 (Flotation Energy, 2024).

FOWT projects that have reached the stage of offshore installation and are either operational or where installation in underway as of Q2 2024 are shown in Fig. 6. There is a total of 235.4 MW of FOW which is currently operational, 123.6 MW under installation and 18.9 MW that have been decommissioned. The majority of this installed capacity is in Europe (301 MW), with 77 MW in APAC and < 1 MW in the Americas (4C Offshore, 2024).

Key operational projects include Hywind Tampen, Hywind Scotland, and Kincardine Offshore Wind Farm (Fig. 7).

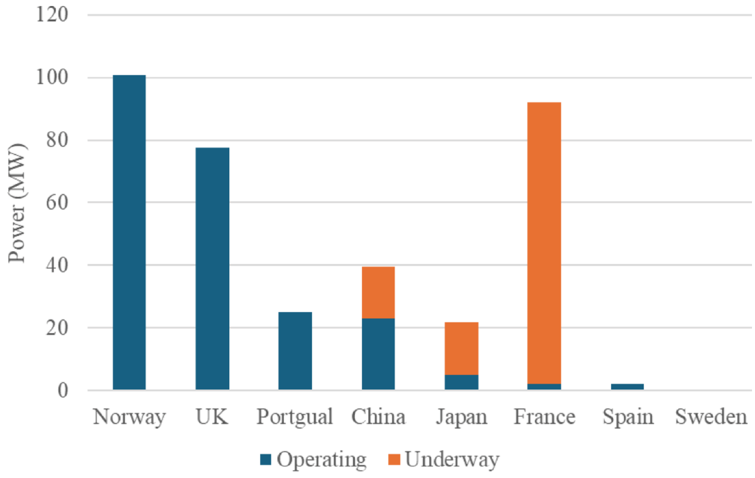


Fig. 6: Floating offshore wind projects that have reached installation globally

Edwards et al., (2024) reviewed 86 past and current, early-stage, platform designs and discuss how FOW substructures were originally influenced by floating platforms

Fig. 7: Kincardine offshore wind farm, showing three of the five 9.5 MW Vestas wind turbines on steel semi-submersible foundations designed by Principle Power (Photo Credit: Flotation Energy)

typically used in the oil and gas industry but have since deviated away from these conventional floater designs to better suit the specific needs of the technology. A previous review covers platforms that have reached at-sea deployment (Edwards et al., 2023), with the latest trend indicating these can be categorised into four types each with its own structural challenges. These four types are semi-submersible, spar, barge and tension leg platform (TLP), and industry trends towards primarily steel, but also concrete designs of each. Of the installed FOW projects globally, 160 MW utilise semi-submersibles, 155 MW spars, 37 MW barges, and 26 MW TLPs.

Floating wind levelized cost of energy (LCOE) has been stated as becoming comparable with its offshore bottom-fixed and onshore counterparts, although this depends on the extent and speed of its evolution (Maktabi and Rusu, 2024). Martinez and Iglesias (2024) mapped the costs of energy for the European Atlantic and Mediterranean and identified that the major drivers of the costs of energy are those directly tied to energy output of the farm, most notably the available wind resource. Other important parameters were the quantity of turbines, rated power, and CAEX of prominently, the turbines and substructures. Regions with the smallest LCOE (~95 EUR/MWh) were those featuring the greatest wind resource: Great Britain, Ireland, North Sea, NW Iberian Peninsula, the Gulf of Lyon and Aegean Sea. One method of reducing LCOE for floating wind, by up to 4%, has been identified as the use of shared anchors for multiple turbines (Housner and Mulas Hernando, 2024). Wake effects have been shown to be a key factor in farm layout and turbine loadings, and ultimately LCOE (Thomas et al., 2024). Sykes et al. (2024) investigated the use of Multidisciplinary Design, Analysis and Optimization (MDAO) as a method of objective assessment, and ultimately reduction, of LCOE for floating offshore wind farms in order to rank foundation designs. Overall, the LCOE related to floating wind is still very volatile, with a study by Helfer et al. (2023) indicating variance from a decrease of 50% to an increase of 100% based on sensitivity scenarios conducted.

3.2 Numerical Modelling and Analysis

3.2.1 Aerodynamics

Rotor aerodynamics is fundamental in understanding the complex behavior of floating wind turbines, particularly due to their dynamic interaction with unsteady wind and wave-induced platform motions. Despite its critical importance, recent years have seen limited research focused explicitly on this area. Most studies tend to address broader aspects of floating wind turbines, such as structural dynamics, control strategies, and mooring systems, leaving rotor aerodynamics somewhat underexplored. This gap is significant because the aerodynamic performance of the rotor directly influences energy yield, load distribution, and overall system stability. Advancing this understanding is essential to optimize designs and improve the reliability of floating wind systems in increasingly challenging offshore environments.

FOWT wake dynamics has emerged as a crucial research topic in the addressed literature, reflecting its significant role in optimizing wind farm performance. Unlike fixed-bottom turbines, FOWTs experience additional complexities in wake behavior due to platform motions induced by wind and wave forces, which can alter wake structure, direction, and recovery rates. Understanding these dynamics is vital for accurately predicting turbine interactions within a farm, minimizing wake losses, and mitigating structural loads on downstream turbines. Current studies deal with wake modeling under unsteady operating conditions including those in which the rotor works under Vortex Ring State (eventually leading to strong Blade Vortex Interactions, BVI).

In (Dong and Viré, 2022) an in-house code using the free wake vortex ring method to simulate the aerodynamic performance of the NREL 5-MW FOWT during a prescribed surge motion is proposed. Their research investigated various characteristics of the rotor as it transitions between different operational states, i.e., windmill working, vortex ring working and propeller working. The aerodynamic load changes corresponding to these states show that the vortex ring state is the most unstable of the three. Moreover, the authors propose two different criteria for the prediction of VRS (based on Wolcowitch and axial induction, respectively) which can be used for the purpose of preliminary analysis.

In Fu et al. (2023), the aerodynamic characteristics of a floating wind turbine are analyzed using *high-fidelity* CFD methods and overlapping grid technology, particularly under platform pitch motion. A detailed analysis of unsteady wake dynamics as well as blade-vortex and vortex-vortex interactions is performed (Fig. 8).

The study shows that, in case of large amplitude, the blade tip periodically enters into the wake (Fig. 8, c4) and there is strong flow mixing of the regular tip vortex and the wake, which potentially leads to faster wake recovering. Moreover, strong blade-vortex

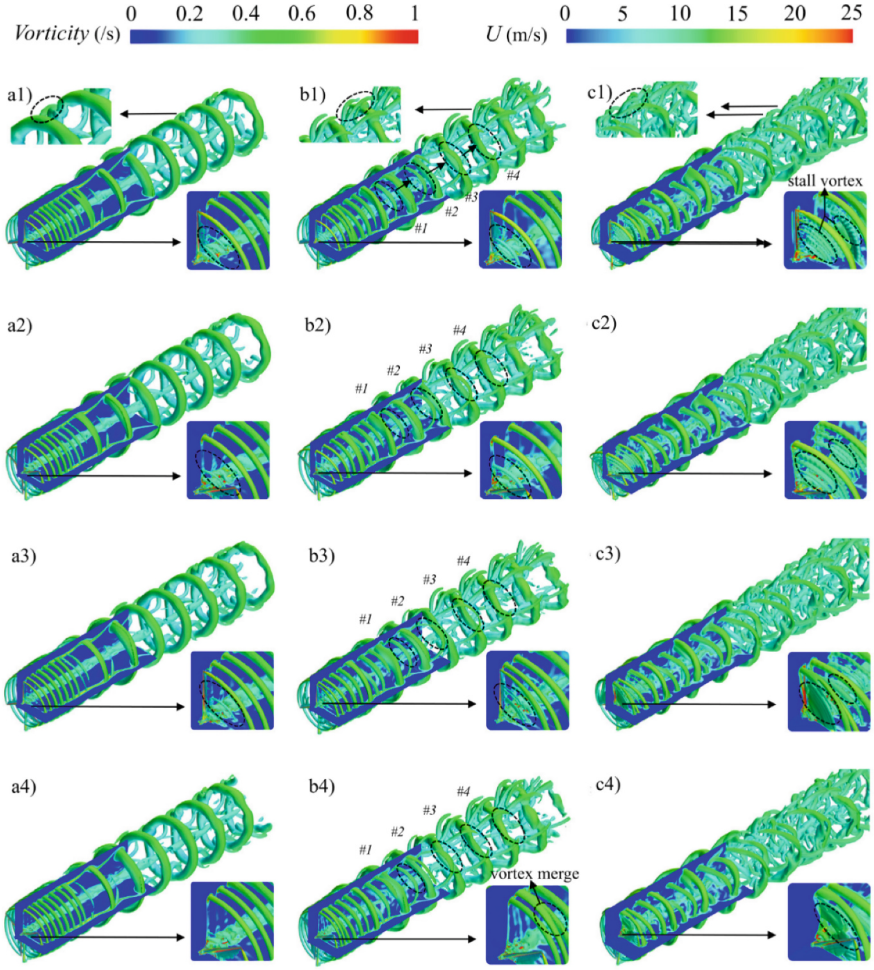


Fig. 8: Instantaneous vorticity contours from the rotor due to the pitch motion: amplitude 1° (a), 4° (b) and 10° (c). 1) $t = 0T$; 2) $t = 1/4T$; 3) $t = 1/2T$; 4) $t = 3/4T$ (T platform motion period) (Fu et al., 2023)

interactions are observed. This affects blade unsteady pressure distribution and, in turn, rotor lifetime. At the same time, more ribbon vortices appear in the wake, which further expands the influence range of the wake. The results conclude that platform motion significantly affects both the aerodynamic performance and the wake of the FOWT, especially when the pitch amplitude is large. FOWT's wake analysis is addressed also by mid-fidelity tools or simplified models. For instance, in Kleine et al. (2022) wake dynamics is investigated through numerical simulations based on linear stability theory (Fig. 9). The study introduces two simplified numerical models to capture the complex vortex behaviours under various turbine motions effectively. The findings indicate that linear theory can predict dominant flow modes when multiple motions or frequencies are involved. Additionally, the general behaviour of the wake can be understood and anticipated using relatively simplified stability models. It is concluded that the highest growth rate in vortex instabilities occurs when the motion frequency is one and a half times the turbine's rotation frequency, with lower frequencies potentially increasing fatigue or causing high amplitude motions in downstream turbines.

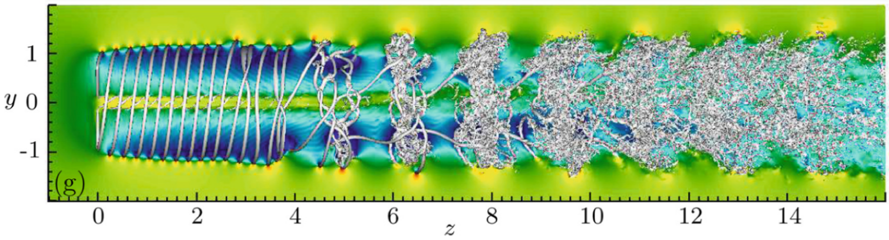


Fig. 9: Instantaneous streamwise velocity along the wake in the yz-plane and 3D iso-surfaces of vorticity magnitude for a surging rotor (Kleine et al., 2022)

Moving from the turbine level to the farm, Ramos-García et al. (2022) propose a numerical investigation on the impact of the wake of a floating IEA wind 15 MW reference wind turbine on downstream machines. Specifically, an aero-hydro-servo-elastic solver coupling free-wake vortex solver (MIRAS) and a multi-body code (HAWC2) are coupled to account for the flexibility of the different turbine components as well as to include the effect of the controller and the dynamics of floater. Moreover, a flow prediction module based on the hybrid filament-particle-mesh approach is used to describe far wake dynamics through the vorticity transport equation. The authors show that the floater motion triggers a faster breakdown of vortex structures with respect to the bottom fixed configuration, thus increasing the power production of a downstream machine. This effect is drastically reduced with the increase of upstream turbulence intensity (Fig. 10). Furthermore, the impact of surge and pitch motion of the upstream turbine on its wake induces higher blade loading on the downstream machine. Overall, the study highlights the importance of an accurate flow and wake modeling for the prediction of turbine-to-turbine interaction in a floating context.

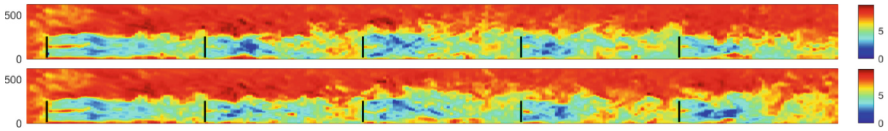


Fig. 10: Instantaneous stream-wise velocity on the extraction XZ plane for a 5-WT farm simulation of five turbines with a spacing of 15R. The fully developed wake is depicted. (Top) Bottom-fixed and (bottom) IEA-15 MW-RWT mounted on the WindCrete platform, wind speed of 15 m/s (Ramos-García et al., 2022)

FOWT farm wake modelling and prediction by a Digital Twin approach is proposed in Zhang and Zhao (2023) using a data and knowledge fusion methodology in which lidar measurements, the Navier–Stokes equations, and the turbine modeling using actuator disk method are integrated via physics-informed neural networks enabling real-time flow characterization and the possibility to retrieve unmeasured flowfield information. In the absence of real-life data, case studies of a wind farm under typical operating scenarios (i.e. a greedy case, a wake-steering case, and a partially operating case) are carried out using *high-fidelity* numerical simulations. The results show a good accuracy of the DT, which an average prediction error about 5% of its range. Nevertheless, local errors, especially downstream rotors, can be more significant, as shown in Fig. 11. Hence, further research on this topic is needed.

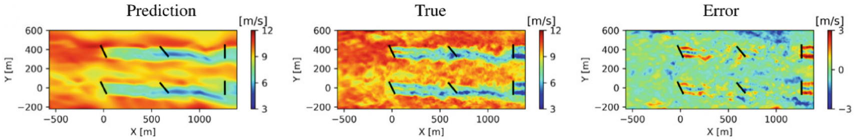


Fig. 11: DT predictions for the wake-steering case (Zhang and Zhao, 2023)

3.2.2 Hydrodynamic Loads and Structural Responses

Floater Loads and Motions For floating wind turbine support structures, assessment of mean forces and slowly varying forces due to waves and current are important in designing the mooring system, for optimizing the turbine control system and ensuring that the nacelle motions and accelerations are within acceptable limits. There is a strong coupling between the wind loads on the RNA/tower and the motions of the floater, but the hydrodynamic phenomena are similar to those for other moored floaters, like e.g. oil & gas semisubmersibles. While some barge-type floaters have been proposed, most foundations for floating offshore wind turbines (FOWT) consist of single or multiple vertical columns that penetrate the water surface, such as spars, semisubmersibles and TLPs. A short overview of the use of simplified methods for design can be found in the introduction section of Høeg and Zhang (2023). Some recent developments of simplified methods for early design stages and optimization analyses are presented later in this section. A *high-fidelity* approach to numerical loads and motion assessment is the use of field methods (CFD), solving the Navier-Stokes equations and capturing viscous effects without resolving to empirical coefficients. However, for structural integrity analysis, long time-series of the FOWT responses in various conditions are needed, and the CFD methods are too computationally demanding to be applied directly in such a process. Instead, they are often used to calculate coefficients to use with simpler methods or to calibrate these methods. They are also used to study special flow phenomena and to compare with experimental results.

Dadmarzi et al. (2022) studied the INO WINDMOOR 3-column semisubmersible using STAR-CCM+, where the VOF technique is used for free surface capturing and turbulence is solved with an improved delayed detached eddy simulation (IDDES). The structure is kept fixed and exposed to Stokes 5th order regular waves. The aim of the study was to define the drag coefficients depending on distance to free surface and

KC (Keulegan-Carpenter) number. Focus was on the single column facing the waves, but interaction effects between the columns were also investigated. Forces on the column simulated by CFD were compared with those from two Morison models; one with coefficients from CFD and one with coefficients from DNV-RP-C205. For large and steep waves, mean and first-order forces from the two Morison models deviated from those from the CFD simulations, but the model with CFD-based coefficients performed significantly better than the one with coefficients from DNV-RP-C205. Since the drag coefficient decreases rapidly with increasing KC number, and determining a representative KC number in irregular waves is challenging, the authors recommend that one should be careful not to select a too high drag coefficient. Califano et al. (2023) analyzed the same INO WINDMOOR in regular waves with the same STAR-CCM+ approach. The simulated surge and heave motions of the platform were reported to be in fair agreement with the experiments. The same floater in regular waves was also investigated with the REEF3D CFD code by Berthelsen et al. (2022), achieving good agreement with experimental surge and heave motions but less good agreement for pitch.

As part of the Reproducible CFD JIP, Wang et al., (2022) performed CFD simulations with the OC6 DeepCwind semisubmersible in 3-h irregular waves and compared with experiments. They concluded that the CFD simulations capture the low-frequency slow-drift motion well but underpredict the low-frequency pitch resonance. Wang and Chen (2022) report from an extensive validation study of CFD simulations with the URANS code ReFRESCO for the OC6 DeepCwind semisubmersible in bichromatic waves and in irregular waves. Compared to experiments, the surge, heave and pitch responses in the wave-frequency regime are well predicted. The low-frequency responses are underpredicted, but the CFD simulations agree better than the results from mid-fidelity tools. Califano et al. (2023), L. Wang et al. (2022a) and Wang and Chen (2022) all point to modelling of incident waves as one of the sources for the discrepancies between CFD and experiments. Hence, appropriate modelling of the waves is important in such validation studies.

The common engineering, or *mid-fidelity,* approach to FOWT wave load analysis is to use radiation-diffraction theory combined with Morison-type drag forces. Mean second order forces are obtained from the first order potential flow solution by including second order terms when calculating the pressure and when integrating it over the wet surface. To assess the difference-frequency and sum-frequency forces, the second order velocity potential must be calculated. These calculations give the quadratic transfer functions (QTF's) relating the difference-frequency and sum-frequency forces to the square of the amplitude of the wave components. To avoid having to calculate the full matrix of QTF's for the difference-frequency forces, Newman's approximation is often used, where only the diagonal terms are needed, and these are obtained from the first order potential. The second-order difference-frequency forces are generally small compared to the first order wave forces, but if their frequency coincides with a natural frequency, they can increase the motions significantly. The lateral motions of a column-based floater usually have low natural frequencies, and for these modes Newman's approximation generally works better than for modes with higher natural frequencies, such as heave, pitch and roll. The approximation works less well when the mode has low damping and the transfer function varies rapidly around the resonance frequency. It also becomes more uncertain when the water depth decreases. Hence, it is becoming increasingly common to calculate the full matrix of QTF's, and several commercially available potential theory solvers have this capability.

Using the full QTF's instead of Newman's approximation, reduces the underestimation of the resonant floater motions, but extensive benchmark studies within the OC5 and OC6 projects indicate that an underestimation is still present even in moderate waves (Otter et al., 2022). Reasons for the underprediction and practical remedies were discussed by Wang et al., (2022), using the OC6 DeepCwind semisubmersible as the case. They focused on ways to include viscous forces more properly, since these contribute to both excitation and damping. Most engineering tools use Morison models, and the results become sensitive to the selection of drag coefficients for the different parts of the substructure. Wang et al., (2022) included wave stretching and found that this makes the surge response more sensitive to the drag coefficients near the free surface and improved the effect of the depth-dependency. For the case studied by Wang et al., (2022) they concluded that the underpredicted surge resonant motion was primarily due to underpredicted excitation rather than overpredicted damping. Using drag coefficients that decrease with increasing depth will increase the viscous surge excitation without increasing the surge damping to the same extent.

Wang et al. (2022) also studied ways of modelling the drag forces on the heave plates at the bottom of each column. The modified model uses a reduced drag coefficient that accounts for flow separation at the plate edges while omitting effects of pressure variations that are already accounted for in the potential-flow solution. This gave better agreement with the experimental low-frequency resonant pitch motions. However, for higher frequencies, reducing the axial drag coefficient for the heave plates gives larger discrepancies for heave/pitch motions, indicating that frequency-dependent drag coefficients would be required. Hence, the reduced coefficient was only applied below a specified frequency. Instead of improving the low-frequency response predictions by modifying the drag coefficients in the Morison model, Li and Bachynski-Polić (2021) modify the QTF's based on results from CFD simulations in bi-chromatic waves. Their simulations were compared with the same OC6 DeepCwind semisubmersible experiments as used in Wang et al. (2022) and it was shown that this alternative approach also significantly improved the predictions of the low-frequency motions.

Fast, Simplified Models to Use in Optimization or Preliminary Design Phase There are many studies on optimization of the rotor nacelle assembly (RNA), but few on optimization of the support structure, as pointed out in a review by Sykes et al., (2023). Optimization requires a set of objective functions that are to be minimized under a set of constraints. Building cost is the most common objective function, but several more are discussed by Sykes et al., (2023). They also review different constraints, design variables and optimization algorithms. An analysis tool, capable of predicting the relevant FOWT responses, is needed in the process, and since many evaluations are required, the tool must be sufficiently fast. These simplified methods are also useful in the initial design process. Frequency-domain methods have often been applied (Hegseth, Bachynski and

Leira, 2021; Ferri and Marino, 2023) while some also use time-domain simulations (Faraggiana et al., 2022).

Simplifications may include the use of quasi-static models for the mooring lines, neglecting higher order potential theory forces, and using linearized Morison-type drag damping (Hegseth, Bachynski and Leira, 2021; Faraggiana et al., 2022; Ferri and Marino, 2023). In the frequency-domain methods of the latter two publications, the linearized model is established for the FOWT's steady state operating point in each weather condition. Instead of using linear hydrodynamics from a panel method, Hegseth et al., (2021) use MacCamy-Fuchs theory to calculate the wave excitation forces on a spar structure, and added mass is calculated by 2D analytic expressions. They neglect radiation damping and viscous wave excitation forces. Compared to mid-fidelity simulations, their linearized model for preliminary design and optimization predicts long-term fatigue damage and short-term extreme structural load effects within 30% agreement.

An alternative simplified method that retains the second order wave loads is presented by Carmo and Simos (2022). Instead of evaluating the loads on the instantaneous position of the body, they speed up the calculations by evaluating the second-order loads on its mean position. Carmo et al. (2023)apply the method on a four-column FOWT in irregular waves. Results are compared with experiments and with calculations using WAMIT and OpenFAST. Satisfactory agreement for long waves is obtained, especially when considering the reduction in modelling and computational cost compared to methods using second-order potential theory solvers.

Høeg and Zhang (2023) present another fast slender-body method that avoids the use of potential theory solvers. Their frequency-domain model is a combination of MacCamy-Fuchs theory and a semi-analytical Morison model, applicable to e.g. semisubmersibles with heave plates. This hybrid method uses the MacCamy-Fuchs model for horizontal wave loads on the cylinders and applies the semi-analytical Morison model for the remaining parts of the hydrodynamic loads. The authors report quite good agreement with potential flow solvers for all frequencies. The Morison coefficients must be determined by model tests or CFD. Interactions between columns are neglected.

Vortex-Induced Motions In the presence of current, or during towing, columns, such as spar-type floating wind turbines, may be subject to vortex induced motions (VIM). This phenomenon can also occur for structures with multiple columns, such as semisubmersibles. The load mechanisms exciting VIM are similar to those involved in the well-known VIV phenomenon, and Morison-type load models are used with various additional load terms. Hence, coefficients derived from physical tests and/or CFD simulations are essential input. These semi-empirical methods are frequency- or time-domain, and focus is mostly on single columns (Passano et al., 2022). With multiple columns there will be interaction effects that increase the complexity, and direct CFD simulations of the floater is a promising method for these more complex structures (F. Jiang et al., 2023a). A systematic review of recent research on VIM can be found in (Yin et al., 2022).

Floater Structural Responses For checking the integrity of the floater structure, one needs to take the pressure distribution from the water into account as well as the forces from the tower and the moorings.

Instead of mapping pressures to a finite element model, one may use the fact that the floater elements are beamlike and that stresses may be derived from cross sectional forces and moments using beam theory. Wang and Moan, (2024a, 2024b) modelled the 10 MW DTU semisubmersible floater using several rigid bodies connected by beam finite elements. Gravitational, hydrostatic, hydrodynamic, drag and inertia loads were appropriately distributed to the bodies. Coupled aero-hydro-servo-elastic time-domain simulations were carried out providing time-series of floater motions and forces/moments in the elements connecting the bodies. Assuming that the different parts of the semisubmersible floater can be modelled by Euler-Bernoulli beam theory, the stresses in the cross sections were calculated based on the forces and moments. Extreme load effects were found using the environmental contour method. The 3D contour surface spanned by the significant wave-height (Hs), the wave peak period (Tp) and the mean wind speed (Uw) is reduced to sets of 2D Hs-Tp contours by selecting a set of wind speeds (corresponding to rated, cut-off and parked conditions). Similarly, by selecting a set of critical peak periods corresponding to the peaks in the RAO's of the relevant load effects (forces/moments), 2D Hs-Uw contours are obtained. The RAO's are calculated from coupled time-domain simulations of the floater with parked turbine in regular waves covering the relevant periods and directions. A similar beam approach was used by Li et al. (2023) in the analysis of the center-column in the 4-column UMaine semisubmersible floater.

An overview of three alternative workflows for floater stress analysis is given in DNV (2024a). All three involve time-domain simulations of the complete turbine/floater/mooring system. The "Direct Load Generation" method is the classical and most general technique, where hydrodynamic pressures and Morison loads are generated in time-domain before they are mapped onto a finite-element model for structural analysis. The added mass and linear damping, and the linear and quadratic transfer functions for the wave-loads are calculated by a frequency-domain panel code. After the complete wind turbine motion simulations, a time-domain potential theory panel code is used to generate time-series of the hydrodynamic pressures based on the time-series of waves and floater motions. This method is flexible and may include local dynamic response as well as nonlinear hydrodynamic forces, but it is computationally resource demanding. A drastic reduction of the computational costs is obtained by using linear transfer functions for the radiation and diffraction pressures from the frequency-domain panel code, instead of recalculating the pressures in the time-domain panel code (Z. Gao et al., 2023b). The disadvantage of this much more efficient "Load Reconstruction" method is that nonlinear hydrodynamic (Froude Krylov) pressures cannot be directly included.

The third and most efficient method is the "Response Reconstruction" method. Instead of using a database of pressure transfer functions, a database of stress transfer functions is used. This stress transfer function database is calculated from FEA with the frequency-domain hydrodynamic pressures. In addition, stresses due to unit anchor line forces at the fairleads as well as unit forces/moments at the tower base must be included. The database may focus on only selected structural members and stress components, and it may later be extended to other members without having to rerun the time-domain simulations of the complete turbine/floater/mooring system (Bredmose et al., 2024). Variants of the method are presented by Lee et al. (2023) and Lim et al. (2023).

3.2.3 Moorings and Anchors

Most recent research uses FEM to estimate the responses of mooring lines. The FEM is usually derived by discretising some of the curved cable or beam theoretical models, (C. Zhang, Wang, et al., 2022a). The models include axial and bending stiffness along with geometric stiffness and can deal with large displacements but with the assumption of small material deformations. If large deformations are included, they are generally applied for axial deformations in cases where synthetic ropes are in question. The mass of the lines can be concentrated in the nodes (a lumped mass approach), or an appropriate mass matrix is derived using the shape functions. Hydrodynamic loads (due to waves and sea currents) that act directly on mooring lines are approximated by Morison's equation, (Guo et al., 2022). The same equation is used to estimate the added mass and drag forces.

If used for FOWT research, this kind of FEM is most often coupled with hydrodynamics of the floating support of a FOWT. It is not uncommon that the coupling includes elastic structural models of the tower and turbine blades with associated aerodynamic loads. In some research, even the turbine's control system is included to form fully coupled aero-hydro-elastic-servo-mooring codes. Zhang, C. et al., (2022a) used this approach to investigate the effects of mooring line failure on the global dynamic responses and the internal drivetrain responses of a submersible FOWT. Guo et al. (2022) studied the impacts of catenary dynamics on the global response of a large-sized FOWT under environmental loads. The dynamic stiffness of the investigated mooring system presents itself in a hysteresis loop due to the fluid and structural damping. The hysteretic behaviour becomes more evident with the increase in frequency and amplitude. Yan, X. et al. (2023b) investigated the influences of different water depths and mooring parameters of a 10 MW semi-submersible FOWT. For this purpose, the coupled model was used to validate a simplified quasi-static mooring line model. The simplified model was needed to reduce the computational time since the thirty mooring cases with different water depths and mooring parameters were observed. It was found that mooring elastic stiffness has significant influences on the mooring tension and surge response of the FOWT in shallow water.

Liang, Jiang and Merz (2023) proposed a shared mooring system that would reduce mooring and anchoring costs in a dual-spar FOWT configuration. The hydrodynamic interaction between two FOWTs was ignored in the model because of the large spacing. Compared to the single FOWT, larger horizontal platform motions and higher mooring tension were detected. An open-source code, FAST, was extended in its capabilities to understand better the potential of shared mooring for FOWT farms in Lozon and Hall (2023). The FOWTs coupling (through interconnecting mooring lines) was upgraded to the same high-resolution time step in the MoorDyn module as for an FOWT with a regular mooring system. The study revealed that the shared mooring system satisfies strength constraints without additional strengthening and offers a degree of station-keeping redundancy in the case of mooring line failure.

The coupled models are also used to investigate mooring line failures since industry standards request that dual mooring failure be examined (to ensure that an observed

FOWT will not lose without its self-sustainability), as done in Jia et al. (2023). As an alternative to the models based on the constitutive equations, a machine learning technique can be applied to detect mooring line failures. In Walker et al. (2022), a machine learning model based on kernel regularised least squares methods was used to set up two digital twins of a FOWT. The digital twins were developed to estimate the tensions in mooring lines and detect the failure of mooring lines due to extreme load and fatigue. The training data was from the Hywind Pilot Park. The first twin could predict the mooring tensions under healthy conditions of FOWT. The second twin was used to indicate the near future, of approximately 1–2 min, values of the tensions, which is enough to generate early safety-related warnings if necessary. K. Sun et al. (2023a) developed a neural network as an intelligent early detection damage model for mooring structure damage. The model was able to identify positions of mooring creep from FOWT's yaw response.

Considering the limitations of traditional methods for synthetic fibre rope analysis, a refined numerical model, Syrope, is applied in Xu et al. (2021) to avoid over-conservative mooring design. The model was developed to describe better the tension-stretch and axial stiffness characteristics of synthetic ropes, defining the static and dynamic stiffness in a single model. The model was combined with experimental data to investigate the possibility of expanding FOWT's applicability in shallow waters. The Syrope was compared to the bi-linear model in Sørum et al. (2023b). Laboratory tests were used to set up the models. Afterwards, both models were used for fatigue lifetime and extreme response predictions. The two models predict similar values of extreme tensions, while the bi-linear model predicts a longer fatigue lifetime. François and Davies (2023) developed an approach for polyamide ropes where assumptions and formulations are based on test observations. An improved representation of the non-linear load-strain response is gained using realistic load spectra rather than the usual sinusoidal loading sequences. The stochastic process was assumed to be stationary for around one to six hours. It can include a wave frequency part, a low-frequency part and possibly higher frequencies induced by turbine operation.

3.2.4 Wind Farms and Interactions

To optimize future large-scale offshore wind farms, Arabgolarcheh et al. (2023) utilized a validated actuator line CFD model to explore whether phase lag differences in the surging motions of two tandem rotors affect the load and power performance of the downstream rotor. Their findings indicate that asynchronous surging can increase root bending moment amplitudes by up to 100% in the downstream turbine. They also discovered that fatigue loads can be managed by carefully adjusting the motion phase differences between the turbines. Zhang et al. (2022) carried out a systematic analysis of the interaction of two FOWTs, utilizing the URANS method to assess their impact on the LCOE through a cost model. This work explored critical factors such as the turbines' relative rotating direction and distance, aiming to understand their effects on performance and costs. It is concluded that a tandem layout with a spacing of 9.25D offers the most practical and optimal parameter choice, providing valuable guidance and insights for future wind farm planning.

3.2.5 Applications

The design and analysis of next-generation floating wind turbines requires advanced numerical tools integrating multiple disciplines. Aero-servoelasticity, hydrodynamics, mooring and cables dynamics, controls systems are the essential disciplines to account for complex, coupled interactions between wind forces, wave dynamics, structural vibrations, and mooring tensions that floating platforms endure in harsh offshore environments. As an example, in Patryniak, et al., (2022), it is shown that the representation of the fully coupled system within the optimisation framework requires the introduction of a more complex multidisciplinary analysis workflow.

The topic of the application of widely known integrated numerical models to the analysis larger rotor is heavily represented in the literature of the addressed period. Differently, the validation of those models is much more difficult due to the lack of full-scale experimental data. The accuracy of the widely used integrated tools to address the response of large FOWTs of next generation is still uncertain; hence, literature mainly focuses on numerical assessment or benchmarks (Ramzanpoor et al., 2024) and on validation based on model scale systems tested in a wind tunnel or ocean basins. Combined wind/waves facilities are also used. For instance, Li, C. et al., (2022a) demonstrate how, respect to a concrete one, a steel floater structure with a lower centre of gravity exhibits advantages in platform pitch motion alleviation and is also subjected to lower pitch-induced tower base loads and nacelle acceleration. However, an opposite trend is found in the wave-frequency responses, leading to an insignificant difference of tower base loads and nacelle acceleration between the two structures.

An example of the analysis of an upscaled machine is described in Souza and Bachynski-Polić, (2022). In this work three spar-type 20 MW FOWTs are designed and their structural behaviour is investigated with the non-linear aero-hydro-servo-elastic software SIMA which couples a finite element aeroelastic software for structural analysis of slender marine structures (RIFLEX) and a simulator of marine operations for large bodies (SIMO). Through the integrated model, the authors show that: i) the platforms with larger restoring in pitch present less fatigue damage at the platform, but more at the tower; ii) extreme stresses are largely affected by gravitational loads, such that the designs with larger pitch at rated thrust have the highest extreme stresses at the platform and most of the tower sections; iii) load cases at the rated wind speed often govern the extreme loads, unlike previous studies with 5 MW and 10 MW machines. The same tool is used in Wang et al., (2023) where an effective and robust design method for floating wind turbine platforms, which can provide reasonable internal stress for design checks (such as intact stability, natural periods and buckling) is proposed.

A good example of analysis of the impact of modelling aspects on FOWT response is presented in Papi et al., (2023). In this work, reporting the main outcomes of the H2020 project FLOATECH, QBlade-Ocean, OpenFAST, and DeepLines Wind simulation codes are extensively benchmarked using different floater/turbine configurations, realistic environmental conditions and several DLCs. Results show a good agreement on system dynamics prediction, whilst some differences arise in the analysis of fatigue loads where, depending on the solver, under- or overestimation of lifetime damage equivalent loads is highlighted.

The most represented topic is the application of FAST (or OpenFAST) coupled with different tools for modelling subcomponents (such as the floater), to different types of analysis. For instance, Z. Wang et al. (2022d) propose an identification method applied to the tower top acceleration and root force. This tool uses a deep learning algorithm in which the FOWT response is simulated through OpenFAST to train a neural network and synthetize a Multi-Layer Perception (MLP) model. The identification method describes the coupling between tower forces and motion responses. Different input configurations are analyzed and integration strategies with Smart Health Monitoring (SHM) systems are envisaged. Fig. 12 shows the identified results of the tower top acceleration compared to the simulated values for the DTU 10 MW FOWT model.

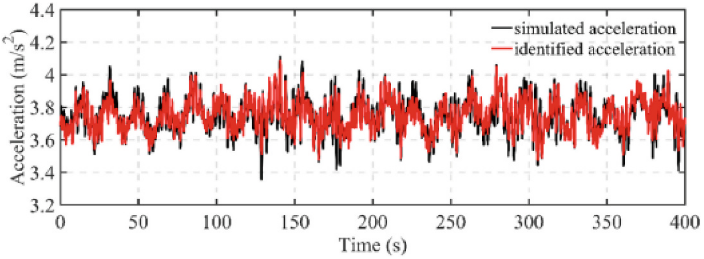


Fig. 12: Identification results of tower top acceleration compared to the true value (Z. Wang et al., 2022d)

Quantitative indicators of the MLP accuracy on acceleration and tower loads are detailed in Table 3 showing an excellent performance. This model appears to be very promising for applications in the field of SHM, which is a very important research topic with critical outcomes for the industry in terms of reliability and costs reduction. For instance, (Gorostidi, Pardo and Nava, 2023) proposes a deep learning algorithm to detect mooring line degradation and failure by monitoring the dynamic response of the DeepCWind OC4 semi-submersible platform. Using OpenFAST, this study implements an autoencoder to predict multiple forms of damage occurring at once, with various levels of severity. The authors show that the proposed algorithm can detect mild anomalies caused by biofouling and anchor displacements, with correlation coefficients up to 98.51% and 99.16%, respectively.

Table 3: Results of evaluation metrics of the trained MLP neural network, from Wang et al. (2022). E_abs, E_max: absolute average and maximum error; R_new: curve fitting degree; MAE: mean absolute error; MSE mean square error. (Z. Wang et al., 2022d)

	E_{abs}	E_{max}	R_{new}	*MAE*	*MSE*
Acceleration	0.568%	0.812%	97.560%	0.444%	3.942%
Shear Force	0.193%	0.208%	98.837%	0.170%	2.487%
Bending Moment	0.618%	0.687%	96.374%	0.826%	4.365%

Other FAST-based applications are reported in T. Wang et al., 2024d) where a Simulink-based coupling strategy between OpenFAST and WEC-Sim is applied to the IEA 15 MW reference wind turbine and UMaine-VolturnUS-S semisubmersible platform for a reference site located at the northern North Sea. Similarly, extreme load responses of a 10 MW FOWT are studied in Xing et al., (2023) and in Gaidai et al., (2023). The latter proposes a novel reliability approach to assess multi-degree-of-freedom nonlinear system failure probability, in the case when only limited system measurements are available. Grid integration aspects using a FAST-based spar buoy FOWT model including generator, converter, and aero-hydro-servoelastic dynamics are addressed in Chen, Yang and Lou, (2024b). The FOWT model is developed using the MATLAB-Simulink cross-platform integration tool and is used to investigate the impact of wind and wave loads on wind power ramp events (WPREs). This study shows that WT power performance is highly unstable within the rated wind speed range, under WPREs within ultra short time period, resulting in failure to meet grid standards, emphasizing the external need for targeted power compensation and power signal processing. Overall, this study highlights the importance of pitch motion and wave load impact for WPRE study of FOWTs .

A few other integrated models are proposed in the literature. For instance, Luo et al., (2024) study a fully coupled floating wind turbine model using the SIMPACK multi-body dynamics environment to integrate the available numerical models of the turbine subcomponents including rotor aerodynamics (Aerodyn), control (based on a widely used FAST library), drive train dynamics, floater and moorings hydrodynamics (Hydrodyn and MAP). The integrated model is applied to investigate the effectiveness of passive 3D pendulum tuned mass dampers (3D-PTMD) and bilinear tuned mass dampers (2TMDs) in controlling the system structural vibrations. The paper shows that, if suitably designed, the TMDs can reduce the platform roll/pitch vibration frequency (mainly driven by the incoming waves). In addition, the combined use of 2TMDs and 3D-PTMD can reduce the vibration frequencies shown by the nacelle displacement. Similarly, a simplified integrated tool based on a nonlinear aeroelastic multi-body dynamic model of a FOWT is used in (Fitzgerald et al., 2023) to examine the effectiveness of TMDIs. This work shows their capability at reducing tower vibrations and improving its reliability when subjected to stochastic wind-wave loading environments. In some cases FAST submodules have been used to be integrated in higher fidelity models of FOWT components. For instance, in Festa et al., (2024) the numerical modelling of the floater, turbine and mooring system was performed using Flexcom, a commercial finite element (FE) software. Flexcom offers fully-coupled aero-hydro-servo modelling using FAST plug-ins INFLOWWIND, AERODYN and SERVODYN. The focus of the work is on FE modelling of the mooring lines to compare the impact of 4 different non-linear stiffness curves on tension reduction and platform motions. Using the IEA 15 MW reference turbine, the authors show that load reduction device stiffness curve types have little effect on out-of-plane platform motions and nacelle acceleration, but lead to an increase in surge when compared to the baseline mooring system. The increase in surge is similar regardless of the load reduction device stiffness curve shape, and is shown to be mainly driven by the length and rated tension of the device.

The analysis of FOWT-ship collision scenarios and the resulting system dynamic response are addressed in Zhang and Hu (2022) where a numerical solver based on LS-DYNA FEM solver to include wind, wave and mooring loads in the collision analysis is proposed. A simplified rotor aerodynamic model is used whereas hydrodynamic loads are based on potential-flow theory coupled with a linear wave kinematic model. In addition, a linearized model for the mooring forces is considered. Detailed FE models of the Hywind Spar-type floater and of the bulbous bow of a colliding offshore service vessel (Fig. 13, left) are built and different collision scenarios considering the influence of velocity, flexibility of tower, deformability of the ship, wind-wave loads are investigated to compute both local structural deformation and floater 6DOF rigid-body motions (Fig. 13, right). It is found that the impact velocity can greatly affect the structural response, and a high-speed impact can directly lead to tower collapse. Differently, tower flexibility influence on collision energy dissipation is more significant for bottom-fixed configurations. Finally, a rigid striking ship can be used for simplicity, anyhow the deformability can significantly influence the structural deformation and energy dissipation (local indention of FOWT is reduced more than 40% in the deformable-ship condition).

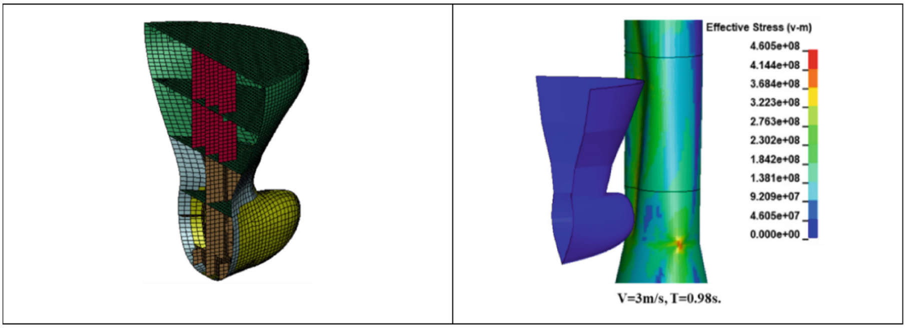


Fig. 13: Ship collision analysis: FE model of vessel bulbous bow (left) and spar deformation (right) (Zhang and Hu, 2022)

The impact of other extreme events, such as typhoons, on the FOWT response is investigated in Zhang, Z. et al., (2024d) where an integrated tools based on the commercial hydrodynamic software ANSYS-AQWA is used to analyze the dynamic responses and mooring forces of different types of platforms, including a novel fully submersible platform with vertical carbon fiber reinforced polymer tendons and circumferential catenary chains. Similarly, Kang et al. (2022) analyze the structural response of semi-submersible floating offshore wind turbine structures in waves generated in hurricane environments.

3.3 Physical Testing

With the development of new technology and components for FOW, physical testing of models and scale prototypes is essential for validation of numerical simulations. Considering the LEG 1 exclusion relating to insurance D'Andrea et al., (2023), physical testing of innovative structures at various scales is essential to improve market confidence. FOWTs are highly complex dynamic systems and therefore coupled testing under wind, wave and current loading is important for development and verification of designs. Primarily carried out in ocean basins, there are challenges with discrepancies between Froude and Reynolds scaling of the substructure and WTG respectively, accuracy of aerodynamic loads at small scale, and scaling highly dynamic components such as moorings and dynamic power cables (Fig. 14) (Holcombe et al., 2025).

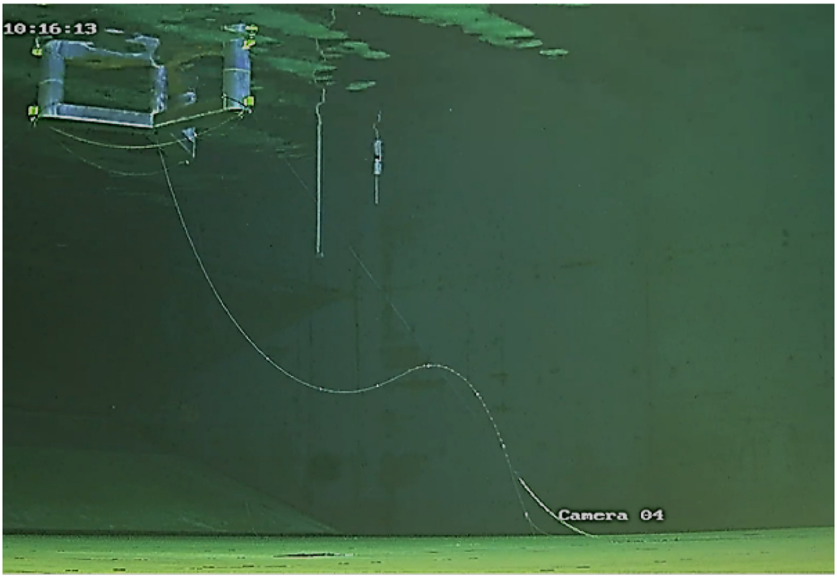


Fig. 14: 1:70 scale testing of the Volturn US platform, moorings and dynamic cable in the COAST ocean basin (Photo Credit: A. Holcombe)

While wind tunnel testing is well understood, techniques are being optimised specifically for generation of accurate aerodynamic loads (Wen et al., 2022; Schulz et al., 2024; Taruffi, Novais and Viré, 2024). Software-in-the-loop (SIL) methods are also becoming increasingly prevalent to assist in discrepancies between Froude and Reynolds scaling (Ransley et al., 2023; Bonnefoy et al., 2024; Jiang et al., 2024). WTG control strategies can also be modelled and assessed as method of load-mitigation (L. Wang et al., 2024b).

Mooring materials and components require validation and testing for long term fatigue performance (Sørum et al., 2023a), effect of breakage (Ren et al., 2024) and structural implications of shared moorings (Lopez-Olocco et al., 2023; Liang et al., 2024).

The tower plays a critical role among a FOWT system, serving as a link between the RNA and the supporting platform. It facilitates the transmission of both aerodynamic and hydrodynamic loads, and the vibrations it undergoes significantly influence the dynamic response of the nacelle and the platform. With turbine designs alternating between soft-stiff and stiff-stiff tower configurations, and floating foundation designs compensating with offset and centrally located turbines, understanding of tower loads is key for design optimisation of floating substructures.

Li, C. et al., (2022a) undertook 1:60 scale, coupled wind-wave, model tests of both a steel and concrete Y-shaped, semi-submersible platform to investigate the effects of different materials. It was found that the steel structure experienced lower tower base loads at the pitch natural frequency with implications for fatigue performance of the tower. Through an experimental study undertaken on a 12 MW semi-submersible FOWT in a wave basin, Guo et al. (2024) systematically investigated the tower load responses. It was determined that the bending moment at the tower top of a FOWT is greater than that of a fixed wind turbine, likely due to the pitch motion of the FOWT, the additional deformations of the tower due to motion, and the significantly amplified inertial load effects. The combination of pitch motion and rotor rotation induced a gyroscopic moment, resulting in the initial yawing of the FOWT.

Full scale FOWT data, from the Wind Float Atlantic wind farm, was used to assist development and validation of a new methodology that explicitly incorporates tower accelerations for the fatigue estimate of FOWTs (Pimenta et al., 2024). The technique was aimed at eliminating the need to install strain gauges on structures. The approach uses tower top accelerations to estimate the tower bending moments and fatigue life consumption, replacing more common data driven approaches based on environmental conditions and/or operation variables by analytical considerations. Feng et al. (2024a) have also undertaken trials of an indirect measurement method to acquire the thrust and pitch moment loads of the turbine without the use of strain gauges and fibre Bragg gratings with a mean relative error of less than 10%.

Measured wave data has been shown to be a potential method for complementary feedforward control of FOWTs though wave tank experiments (Hegazy et al., 2024). Freak wave loading has new impacts on FOWT structures. Experimental investigations into wave slamming effects on a 1:50 scale semi-submersible foundation of the X30 platform with a 5 MW WTG showed strong nonlinearity (Huo et al., 2023). The measured slamming pressures indicated a double-peak phenomenon where the FOWT suffered the second severe slamming after experiencing the initial freak wave slamming.

While many currently leased FOWT farms are in wave dominated regions with lower current, there is always a concern for Vortex Induced Motions (VIM) and the related structural implications. A comprehensive review by Yin et al., (2022) indicated that, while a few experimental investigations of FOWTs have been carried out, VIM model tests on integrated models (floater–mooring–subsea power cables) at small/moderate Reynolds numbers under representative sea states was an area that was lacking detail.

Structural and hydrodynamic performance validation of new FOWT designs is essential on the path to certification. Recent model tests of the WindCrete platform have indicated good performance to the design basis (Somoano et al., 2024). The OUCwind design was assessed through coupled testing in a wave basin with the data currently being used to compare and validate numerical models (Bai et al., 2024).

With regard to mooring and anchoring system validation and verification, Sect. 2.3 provides some discussion on the testing anchor/seabed interaction effects and system integrity.

3.4 Transport & Installation, Operation & Maintenance

While these items as they relate to FOWT are similar to that described in Chapter 2.4 for BFOWT, there are notable differences as well.

3.4.1 Transport & Installation

Despite the compelling environmental and economic prospects of floating wind technology, its implementation is challenging; complex installation procedures, associated high costs, and evolving regulations can hinder widespread adoption. Installation operations often utilise several vessels at one time (Fig. 15) with dynamic load regimes proving challenging for the WTG nacelle, blades, tower and FOW platform itself.

Fig. 15: One of the Kincardine floating wind turbines being towed to site illustrating the multiple vessels required for a relatively small FOWT (Photo Credit: Flotation Energy)

Hong et al. (2024) discuss the technical, operational, and economic aspects of floating offshore wind farm installation, providing a comprehensive overview of the current state-of-the-art. Critical research areas include foundation design optimisation, not least materials and structural design to optimise for fabrication and installation, and anchor design and installation considering novel anchor concepts and the anchor-seabed interaction. A novel multi-bucket foundation, aimed at improving installation and structural reliability, using integrated transportation, has been proposed by J. Li et al. (2024a). Initially numerical assessment using SESAM_ABAQUS indicated the roll and pitch of the foundation do not exceed 2.5° and the stresses in all parts of the structure during installation are below 250 MPa at 2.5 m significant wave height and 11 s peak period, which is an improvement on more conventional installation methods.

Environmental loads are key to successful installation operations, with recent research into the wind loads during transport and installation of a 10 MW turbine investigated through wind tunnel tests (Sim, 2023). The wind load coefficients at each stage of fabrication, transportation, and installation are presented for use during concept design assessment for FOWT installation.

Mooring attachment and hookup are key aspects of installation that many are endeavouring to optimise. With short weather windows and a need to be able to reach a level of integrity at which the FOWT can be left if the installation vessel needs to retreat to safety, learnings from the oil and gas industry are proving essential in the development of smaller, lighter and more cost-effective solutions for FOW. Atallah (2024) presents a case study from a recent successful mooring hook up and tensioning operation for a Floating Production Unit (FPU) where they evaluated an optimized strategy for the installation of a typical wind farm. The case study demonstrates quick connection and re-tensioning capabilities, and a need for innovation in design to increase the weather windows for mooring installation for operational success.

One area of limited research is that of quayside mooring and load requirements. With FOW platforms and WTGs increasing in size, WTG integration and subsequent mooring of the whole FOWT system in port is proving challenging, with bollards and quayside loading not rated for the larger dynamic loads present – this is an area that recent stakeholder engagement has indicated may be assisted through collaboration between industry and academia.

3.4.2 Operation & Maintenance

Chitteth Ramachandran et al. (2022) reviewed the various marine operations challenges towards the commercialization of floating wind in the context of spar-type, semi-submersible and tension leg platform (TLP) technologies. Many of the recommendations are related to cost savings and improving safety, and while OPEX is often the key driver for optimisation of O&M activities, structural health monitoring and assessment is imperative for formulation of proactive O&M strategies. Access to platforms is often required to undertake maintenance tasks and retrieve data from monitoring equipment, Fig. 16, therefore predictive and remote monitoring is an integral area for improvement.

Failure Mode and Effect Analysis methods are often used to identify key failure modes in FOW farms (McMorland et al., 2022; Y. Sun et al., 2023b; Ågotnes and Eik, 2024; Busby, Thethi and Fulton, 2024; Q. D. Feng et al., 2024a; Saetren Nornes et al., 2024). Many of these failure modes are structural in nature, with accurate prediction of structural loads and responses being a primary driver for improvement of O&M philosophies.

Robotics are being considered for integration into O&M planning and assessment of FOW structures offshore (Khalid et al., 2022, 2024). Unmanned aerial inspection of assets such as the WTG and blades can show areas where damage is occurring (K. Zhang et al., 2024c) to enabling prompt action to be taken before failure occurs.

Digital Twin (DT) technology is an area in which much progress has been made, despite the challenging computational and instrumentational requirements (B. Q. Chen et al., 2024a). DTs are based on simulated models and or Machine learning models, thereby improving predictions throughout the life of the asset (Mousavi et al., 2024).

Fig. 16: A worker accesses the base of the tower on one of the Kincardine FOWTs (Photo Credit: Flotation Energy)

Surrogate models are being considered for fatigue estimation of FOWTs (Liu et al., 2024). DTs have also been developed for assessment of specific areas of concern such as protective coating systems enabling corrosion to be minimised (Momber et al., 2022). While in their infancy, with a true digital twin requiring a phenomenal amount of computational hardware, and structural monitoring equipment, even the emerging DTs require validation through comparison with both model and dull scale trials (Branlard et al., 2024; Lotfizadeh, 2024).

Two key areas of concern that have recently been addressed through research are those of moorings and tower response and failure. The failure performance of different mooing configurations, and shared anchors, was assessed by the Offshore Renewable Energy Catapult's Floating Wind Centre of Excellence (Apollo and DOF, 2024; Weller et al., 2024). Chain catenary, semi-taut and taut mooring systems were considered comprising 3, 6 and 9 mooring lines. The key implications of redundancy provision were explored via the identification of candidate designs (based on a commercial-scale turbine), followed by ALS simulations and lifecycle analysis. It was recommended that the number of failures could be reduced by improving the reliability of mooring components, and/or reducing the system complexity buy reducing the number of components. Coraddu et al. (2024) have continued development of a DT specifically aimed at mooring line integrity and maintenance. Complementary methods of mooring integrity assessment and monitoring include; the use of autoencoders which can detect various issues including those related to marine fouling (Gorostidi et al., 2023), improved convolutional neural networks for machine learning (Sharma and Nava, 2024), and recurrent neural networks which indicated a very high rate of prediction accuracy of 98% over various scenarios (Saetren Nornes et al., 2024). Collision loads, based on the coupling of wind-wave-mooring loads, during maintenance operations were investigated through the use of Star-CCM+ and ABAQUS and assisted in informing weather windows and safe operational conditions, alongside structural design improvements (Zong et al., 2023).

The tower of a wind turbine is the primary load transfer path of the WTG loads to the floating structure and vice versa. Adaptive control methods of blade pitch, turbine yaw etc. can be used to improve corrosion-fatigue of tower fixings, such as bolts (Heng et al., 2024; J. Zhang et al., 2024b), and LIDAR assisted feedforward strategies to improve fatigue performance of both the blades and tower (Russell et al., 2024). Zhu, Z. et al., (2023b) developed a DT for wind turbine towers based on joint load-response, but including rotational effects, estimation which showed good correlation to laboratory tests. Sensor optimisation based on the effective independence method and modal assurance criteria methods has been investigated to utilise as much structural information as possible to predict progressive failures through identification of tower top accelerations and forces and moments at the tower base (Z. Wang et al., 2024e).

3.5 Design Standards and Guidelines

Further to the standards summary provided in Sect. 2.5 for fixed offshore installations, this section outlines the updated design standards and guidelines for FOWTs for the period 2022–2024, integrating recent advancements and industry best practices to ensure the safe, efficient, and reliable operation of these systems. There are several industry standards providing the framework for FOWT design, related to structures and structural performance. Table 4 summarizes the main design criteria specified in these standards:

Table 4: Design load criteria specified in different industry standards

Standard	Mooring Redundancy	Stability Structures	Damaged Stability	Type of Criteria	Materials	References
IEC	Optional, Increased safety factor	Optional	Quasi-static or dynamic-response-based	LRFD or WSD	Not specified	(IEC, 2020, 2021)
ABS	Optional, Safety factor increase 20%	Yes, in 1YRP	Quasi-static or dynamic-response-based	LRFD	Steel, concrete	(ABS, 2024)
BV	Optional, Safety factor increase 20%	Optional	Quasi-static or dynamic-response-based	WSD, LRFD optional	Steel	(BV, 2024a, 2024b)
DNV	Optional, Safety factor increase 15% to 25%	Optional	Quasi-static or dynamic-response-based	LRFD	Steel, concrete	(DNV, 2023b, 2023a, 2024e, 2024a, 2024f)
LR	Optional, Safety factor increase 50%	Yes	To IMO MODU or other	LRFD	Steel, concrete	(LR, 2024a, 2024b)
ClassNK	Mandatory, 1YRP check	Yes	Quasi-static	LRFD	Steel	(ClassNK, 2022)

Design loads for FOWTs are largely based on the fixed offshore wind turbine standard IEC 61400-3-1 (IEC, 2020), with additional considerations for floating structures (IEC, 2021). Key additional load cases include:

- Compartment damage;
- Mooring line damage;
- Stoppage and maximum operating conditions; and
- Robustness under extreme conditions (e.g., turbine still producing electricity beyond its specified operating threshold).

These additional load cases are explicitly included in IEC, DNV, and BV standards. While not specifically listed in ClassNK, LR, and ABS documents, these standards require verifications of damaged mooring and compartment conditions. There are two key design methodologies prevalent for the structural aspects of FOWTS: Loads and Resistance Factors Design (LRFD) and Working Stress Design (WSD). Table 4 indicates which of these are relevant to each society's regulations.

Loads and Resistance Factors Design (LRFD):

- Preferred for its practicality in real-world projects.
- Involves dividing material strength by a safety factor and multiplying design loads by a load factor.

Working Stress Design (WSD):

- Offered as an alternative by BV and IEC.
- Applies a global safety factor on stresses depending on material, loading condition, and failure mode.

As has been discussed in previous sections in this chapter, the two main materials used for FOW substructures deign are steel and concrete. Steel is covered across all standards and is common in the offshore industry due to its strength and durability. Concrete is only included in guidance form DNV, ABS and LR, and is seen as an emerging material for the construction of FOW substructures, primarily due to facilitation of economy of scale of manufacturing facilities and ports.

Since 2022, further advancements in FOW technology and design standards have been made. These include:

1. Updated Mooring System Guidelines:
   (a) Emphasis on redundancy and robustness to handle extreme weather conditions.
   (b) New materials and technologies for mooring lines to enhance durability and reduce maintenance.
2. Enhanced Stability and Control Systems:
   (a) Advanced dynamic response models to better predict and mitigate risks associated with floating structures.
   (b) Integration of real-time monitoring systems for continuous stability and damage assessment.
3. Sustainability and Environmental Impact:

(a) Increased focus on minimizing environmental impact during installation and operation.
(b) Guidelines for the use of eco-friendly materials and sustainable construction practices.

DNV have also recently updated the vessel standards which directly relate to T&I and O&M operations, and should be noted regarding coupled loading, collision risk and weather loading on FOWT structures (DNV, 2024d, 2024b, 2024c).

While the design standards and guidelines for floating offshore wind turbines from 2022 to 2024 reflect significant advancements in technology and industry practices. By harmonizing these standards, the industry ensures the development of safe, efficient, and reliable FOWTs. These guidelines support stakeholders, including engineers, designers, project developers, and regulatory bodies, in creating robust and sustainable wind energy solutions. Some independent research has been undertaken with suggested improvements to the standards: Wang, S. et al. (2022b) investigated wind and wave loading to floating wind turbine drive train damage, Kozmar et al., (2022) critiqued wind load assessment in offshore engineering standards and Gudmestad & Schnepf (2023) considered the critical aspects requiring inclusion in the Design Basis.

4 Wave Energy Converters

4.1 Recent Industry Developments

Wave energy convertors (WECs) have various types of power generation system and many kinds of WECs has been studied and developed. In these years, EMEC (European Marine Energy Centre), located off Scotland, PLOCAN (Oceanic Platform of the Canary Islands) located off Canary Islands and other areas were used for on sea trial projects.

Table 5 is a summary of on sea trial projects conducted in recent years (Ocean Energy Systems, 2023). There are some types of the installation as well as power generation types. The installation types are classified into a floating type, a sea bottom fixed type and a breakwater fixed type. Most of projects are still at the R & D stage which includes technological demonstration, and a few projects are in the commercial operation.

The classification of WEC type in Table 5 is according to Fig. 17 and based on EMEC and descriptions in the developers' web sites.

Small power generation WECs is the most in Table 5. Most of them supply electricity to marine equipment which includes ROV, marine observation sensors and so on. WECs which supply electricity to the land have about 200 kW power generation.

The directions of research and development are diverse, including response characteristics of floating structures, power generation performance, optimization of power generation control, mooring, coupling of multiple analysis methods, and reliability. The following section summarizes the R&D trends.

4.2 Numerical Modeling and Analysis

Wave energy converters have various types of power generation mechanics, shapes, and installation methods. Furthermore, many of the WECs have moving parts. Therefore,

Table 5: Major sea trials in recent years

Project	Foundation	Site	Power Generation	WEC type
xWave	Floating	USA	100 kW	Point absorber
SeaRay	Floating	USA	2 kW	Attenuator
PB3 PowerBuoy	Floating	USA	3 kW	Point absorber
Triton-C	Floating	USA	100 kW	Point absorber
C4 WEC	Floating	Portugal	300 kW	Point absorber
Blue X	Floating	UK	10 kW	Attenuator
Waveswing	Floating	UK	16 KW	Pressure differential
Mutriku	Breakwater	Spain	16*18.5 kW	OWC
DIKWE	Breakwater	France	800 kW	OWC
SEATURNS	Floating	France	200 kW	Rolling Mass
Exowave	Bottom	Belgium	–	Pendulum
Wavepiston	Floating	Spain	200 kW	Surge convertor
Slow Mil	Floating	Netherland	40 kW	Point absorber
ISWEC	Floating	Italy	250 kW	Gyroscopic
Wave Rudder WEC	Bottom	Japan	45 kW	Pendulum
Intelligent wave absorber	Breakwater	Japan	19.5 kW	OWC
Zhoushan	Floating	China	500 kW	Pendulum
Penghu	Floating	China	60 kW	Pendulum
Yongsoo	Bottom	Korea	250 kW	OWC
UniWave200	Bottom	Australia	200 kW	OWC

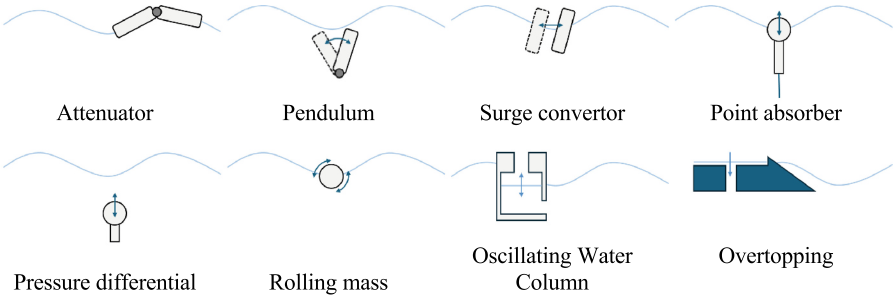


Fig. 17: Classification of WEC types (Esteban et al., 2017)

load and motion response of floaters are studied in many research works. In addition to the conventional analysis of the floating response, many studies have combined the optimization of power generation and the development of control algorithms. There is also an increasing number of studies combining multiple analysis methods.

4.2.1 Power Take Off and Control Algorithm Analysis

Parsa et al., (2022) estimated the power generation performance of the OPT PB3 Power Buoy for waves with multiple components by separating the spectra for each component. The estimation results were verified through simulation of the power simulation of the OPT PB3 Power Buoy at a point off Chile and show the effectiveness of this method for WECs with strong wave period dependence (Fig. 18).

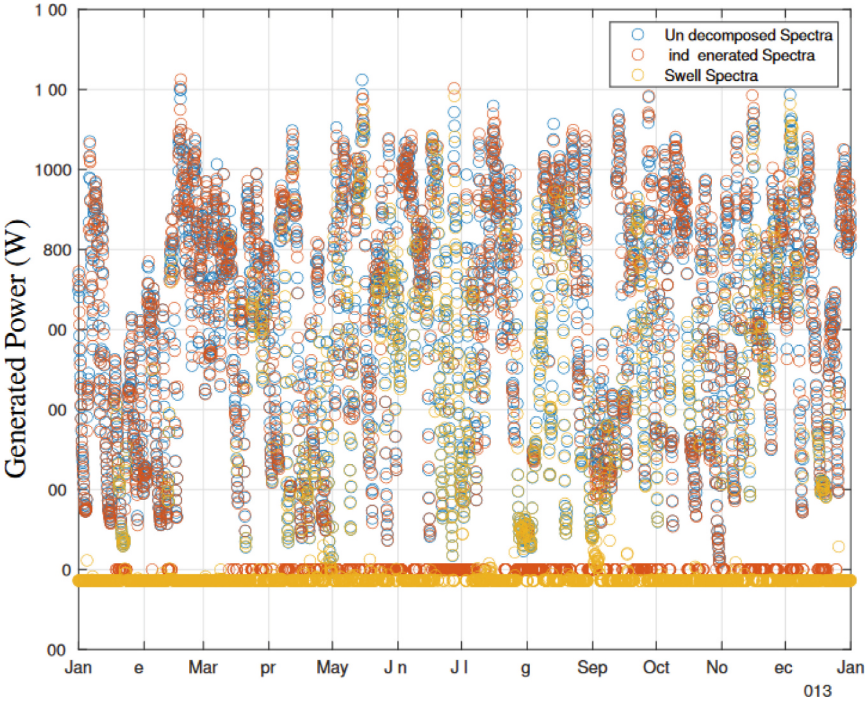


Fig. 18: Power estimates for un-decomposed and component spectra, based on simulations run on hindcast spectra for a site offshore Chile

Rahimi et al., (2022) introduced a new mechanism for a mechanical power take-off (PTO) system that can be used in a variety of wave energy converters (WECs). The mechanism uses two ball screws to convert the relative linear motion of the WEC bodies into unidirectional rotary motion. Guerrero-Fernández, J. L. et al., (2022) used WEC-Sim with a detailed Nonlinear model predictive control (NMPC) approach based on the real time iteration (RTI) scheme and revealed that RTI-NMPC clearly outperforms a simple resistive controller. Marley & Skjetne, (2023) introduced novel feedback control strategy which they called control barrier functions (CBFs). They simulated the effectiveness of CBFs against the Bolt Lifesaver point absorber WEC developed by Fred. Olsen Ltd. The control strategy mitigated the large force oscillations in power take off unit which were observed during initial on sea trials (Fig. 19).

Fig. 19: Bolt Lifesaver pictured outside Falmouth Bay, England, where she was deployed in 2012. Courtesy Fred. Olsen Ltd.

Faedo et al., (2022) introduced a nonlinear moment-based energy-maximizing control solution for WECs under non-ideal PTO behavior. The point absorber type WEC was studied and the nonlinear moment-based energy-maximizing control showed better absorbed energy than a benchmark PI controller. Umeda et al., (2024) proposed a data-driven reactive control strategy for a point absorber type WEC using Gaussian process regression and validated its efficiency through a tank test. The validation results confirmed that the proposed data-driven reactive control strategy effectively controlled the WEC and improved its performance using the Gaussian model. Moreover, performance was improved under different wave conditions compared to those used during training.

4.2.2 Hull Forms

Ghigo A., et al., (2022) proposed the optimization results for a cylindrical point absorber in the Mediterranean Sea. The optimization parameters were shape, dimensions, mass properties, ballast and draft. Huang, S., et al., (2023a) introduced the optimization method using NSGA-II and optimized results for heaving buoy type WEC in bimodal wave spectrum.

Ahmed et al., (2023) proposed a new bulbous-bottomed buoy designs for an optimal oscillating body type WEC (Fig. 20). The optimization was carried out under the condition which the radius, mass, and volume were equal. The optimized body showed about 12% enhancement of the performance (Fig. 21).

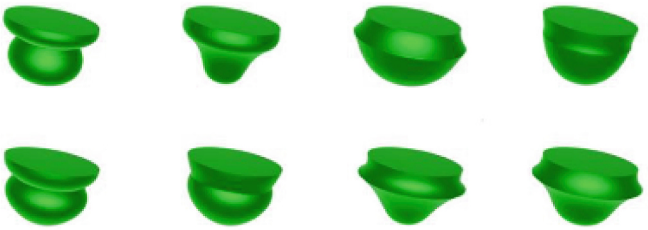


Fig. 20: The variants of the first generation (geometry definition-I)

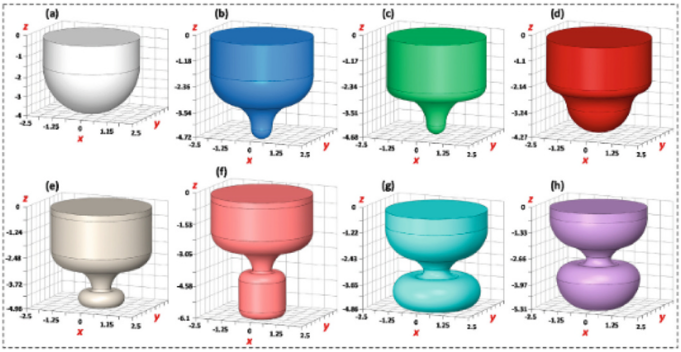


Fig. 21: The state-of-the-art buoy geometries (a) Cylindrical-hemispherical (C-HS) reference buoy (b) S-1 buoy (c) S-2 buoy (d) S-3 buoy (e) SB-1 buoy (f) SB-2 buoy (g) SB-3 buoy (h) SB-4 buoy.

4.2.3 Moorings

Yim, et al., (2022) proposed a combined nonlinear mooring-line and umbilical dynamics with bending capability (MUDB) model. The developed model was combined with WEC-Sim, and they simulated mooring lines and dynamic cable. Shahroozi, et al., (2023) proposed a neural network approach for the minimization of mooring tension of a point absorber type WEC in survival conditions. The simulation and experimental results showed that the deep neural network could reduce the mooring line tension. Gubesch et al., (2023) introduce the experimental results of a response of a floating OWC type WEC in extreme waves. A TLP (Fig. 22) and a taut mooring were the mooring setups considered in the experiment, and several differences in tension characteristics were observed between them.

4.2.4 FEM and CFD/Coupled Analysis

Huang et al., (2023b) introduced the simulation results with CFD and FEM coupled analysis for a flexible tube WEC. The nonlinear behavior of Natural Rubber is considered by using YEOH hyper-elastic model and fluid-structure interaction responses of the WEC were compared considering the impact of incident wave speed on the performance of the device. Shao et al., (2023) introduced simulation results with CFD and FEM

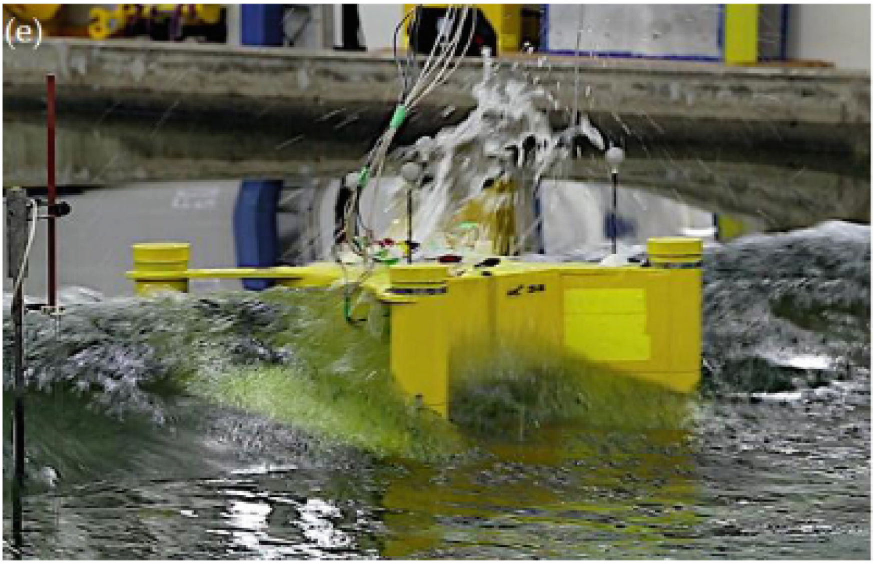


Fig. 22: Focused wave slammed into the TLP WEC

coupled analysis for a heave-point buoyant WEC called NoviOcean. They compared 2 commercial software packages. Yue et al., (2023) introduced the analysis results of a semi-submergible WEC which is called “Penghu”. The FEM analysis was carried out with the wave load estimated by 3-dimensional potential flow theory, Fig. 23.

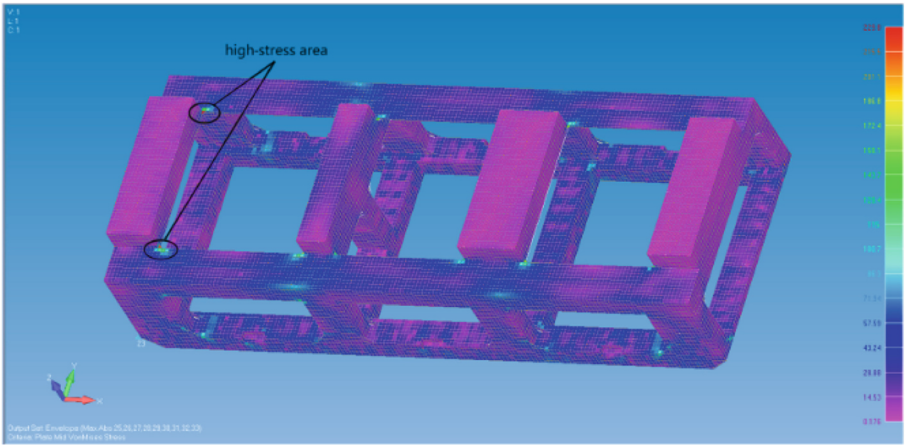


Fig. 23: Results of von Mises stress distribution of the hull.

Li, X. et al., (2022c) introduced the analysis method of coupling CFD and multi-body dynamic (MBD) for arrayed point absorber WEC (Fig. 24). The coupled simulation method was combined with CFD and MBD, and they introduced the power take off performance.

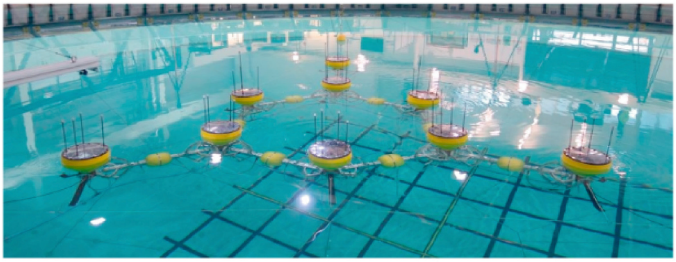


Fig. 24: Hex WEC array with sub structures

4.2.5 Reliability

Bao, X. et al., (2023) proposed a turbine fault diagnosis of the OWC WEC based on a correlation analysis of ensemble empirical modal decomposition (EEMDCA) and the fusion of multi-lead residual neural (MLRN) networks.

4.2.6 CFD

Prakash, R., et al., (2022) simulated of the motion of floats which shapes were rectangular, trapezoidal, and hemisphere with CFD solver. The results showed that the trapezoidal shape with fin found to be optimum float shape. Katsidoniotaki, E., et al., (2022) introduced the floater motion of point absorber type WEC using by CFD and a model experiment. The CFD results were well agreed with the experimental results. Li, M. et al., (2022b) introduced the optimized floater shapes of OWC type WEC using by CFD analysis. The power generation performance was compared with several types of floater shape.

4.2.7 Field Layout

Zeng, X., et al., (2023) proposed the optimized layout of the array of WECs based on the genetic algorithm (Fig. 25). From the results, the influence of introducing other degrees of freedom, besides the heave mode, on the performance of arrays was investigated.

He, et al., (2022) proposed the optimized layout of the square array of heaving buoy type WECs based on the differential evolution algorithm. The simulation results showed that the array of WECs has a large effect on the power generation performance. Abdulkadir & Abdelkhalik, (2023) introduced the results on the power generation performance with several dimensions of WECs. The studied parameters were a radius and a draft of a single float. The generic algorithm was applied to this study and the maximum 40% advantage of the power generation performance was acquired with the algorithm.

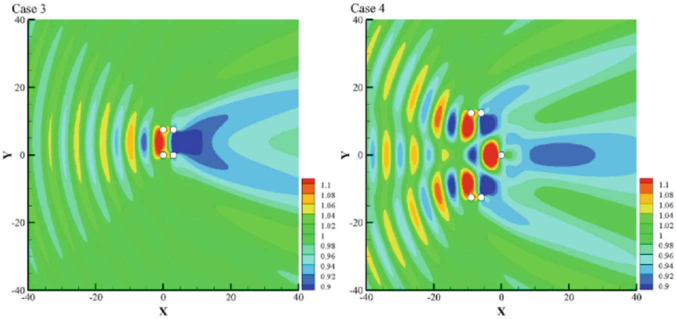


Fig. 25: Optimal layouts and the corresponding free surface amplitudes for case 3 & 4.

4.3 Physical Testing

Since there are a variety of WEC types and single installation and installation with arrays are considered, no dominant system has been found at this time. Therefore, in addition to numerical simulation studies, tank tests are also conducted. This section introduces studies of several types of tank tests.

4.3.1 Laboratory Study (Tank Tests)

Stansby et al., (2022) conducted a tank test and numerical simulations for an attenuator type WEC, M4 WEC which consists of 6 floats with 2 hinges. This model was moored to a single point buoy with elastic mooring cable. In the experiment, the floats showed occasional deck submergence (dunking) limiting relative angular motion as wave height increases, in effect providing a passive end stop, for very large waves.

Fig. 26: Aerial photo of WEC with mooring in the wave basin

Ahmed et al., (2023) conducted a tank tests for a point absorber type WEC with S shaped buoy (Fig. 26). Various types of buoys were tested through the tank tests and S shaped buoy showed a 34% greater RMS heave response than the cylindrical hemispherical buoy.

Niosi et al., (2023) introduced a tank test and numerical simulations for a Pendulum Wave Energy Converter (PEWEC) with 1:25 scale ratio carried out at the University of

Naples Federico II (Fig. 27). The experiments consist of free decay and static pull out tests to assess the inertial properties of the model and mooring system; tests in operative and extreme regular and irregular waves to fully characterize the mooring system and the device dynamics.

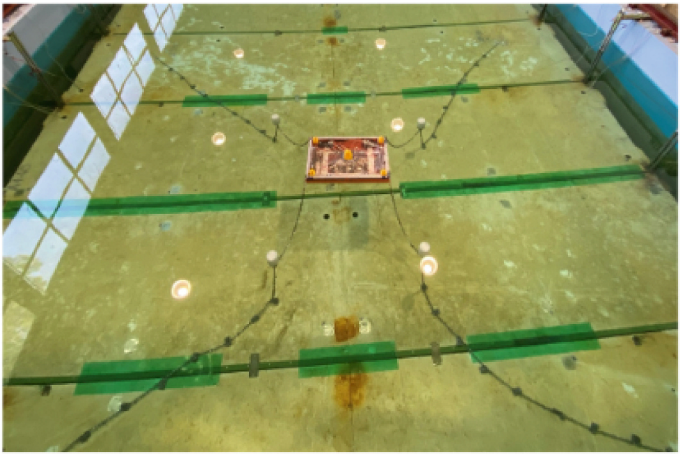


Fig. 27: PEWEC Mooring system 1:25 scaled model.

Meyer et al., (2023) studied a relationship between mooring types and a potential of power generation of point absorber arrays by a tank test. They conducted a tank test with 3 types of mooring types (a taut line mooring, a vertical tension leg mooring, and a conventional slack catenary mooring).

4.3.2 Field Tests

Although several sea trials have been conducted, not many studies have introduced measurement data in real sea areas. However Gato, et al., (2022) introduced the results on sea trials of biradial and Wells turbines at Mutriku WEC power plant (Fig. 28). They conducted on sea trials with 30 kW biradial turbines at 3 sites, IST variable flow test rig, the shoreline Mutriku wave power plant and the offshore IDOM MARMOK-A5 spar buoy device in EU H2020 OPERA project. The mean time averaged peak efficiency by the biradial turbine at Mutriku WEC power plant showed 37% higher results than with the Wells turbine.

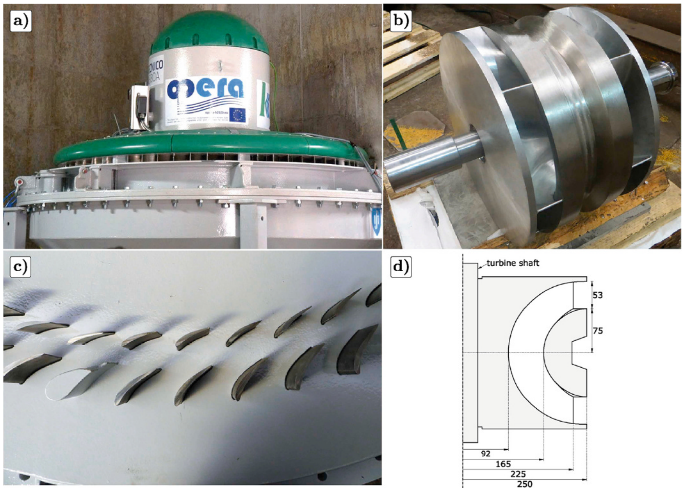


Fig. 28: a) OPERA's 30 kW biradial turbine at Mutriku's wave power plant. b) Biradial turbine rotor and c) guide vanes. d) Main dimensions of tested turbine rotor (in mm).

5 Tidal and Ocean Current Turbines

5.1 Recent Industry Developments

Tidal energy, due to its predictability, is considered vital for energy mix and security. The authors Coles et al., (2023) explored the impacts of tidal stream energy on overall energy system security using the Isle of Wight as a case study. The findings revealed that, compared to the best-performing solar and wind system, adopting tidal stream energy reduced the magnitude of maximum power shortages and surpluses by 11% and 24% respectively. Additionally, the adoption of tidal stream energy reduced the total land/sea space required by 33%. Furthermore, the energy storage capacity and charge/discharge capacity requirement for an additional inter-seasonal energy storage system to absorb curtailed energy were reduced by 21%. Assuming a 100€/MWh Levelised Cost of Energy (LCOE) by 2030, the analysis by Grattan and Jeffrey, (2023) indicated that the UK tidal stream sector could achieve commercial deployment by the early 2030s, reaching around 1GW by the mid-to-late 2030s, and ultimately deploying 6GW by 2050.

An overview of key achievements in ocean energy, including tidal stream, was summarised in the annual report issued by International Energy Agency – Ocean Energy System (Stratigaki et al., 2023). Notably, Sustainable Marine delivered the first floating in-stream tidal power to Nova Scotia's grid, harnessing the tidal currents in Canada's Bay of Fundy (Fig. 29) (Garanovic, 2022b). Altum Energy, formerly MAKO Tidal Turbines Pty Ltd., received financial support to advance their modular tidal turbines for slow-flowing tidal and river sites, with a demonstration currently underway in northwestern Australia. In the UK, Orbital Marine Power's flagship device, the O2 (Fig. 30), has been in continuous operation at EMEC since 2021, achieving a peak power of 2.5 MW. MeyGen Phase 1, operational since 2018, installed four 1.5 MW turbines and delivered over 45 GWh to the local Shetland distribution network as of October 2022. In France, Sabella's D10-1 MW tidal turbine was redeployed in the Fromveur passage, and the company connected a small electrolyzer to experiment with green hydrogen production (Garanovic, 2022a). In Sweden, Minesto completed commissioning of the Dragon 4 (100 kW) tidal power plants in Vestmannasund, Faroe Islands. In China, the tidal stream energy demonstration project at Zhoushan installed and connected a new turbine to the grid in 2022, achieving a total installed capacity of 3.3 MW. The new turbine, Endeavour (Fig. 31), with a total weight of 325 tons, a rated power of 1.6 MW, and a designed annual power generation capacity of 2 million kWh, is expected to reduce carbon dioxide emissions by 1,994 tons annually.

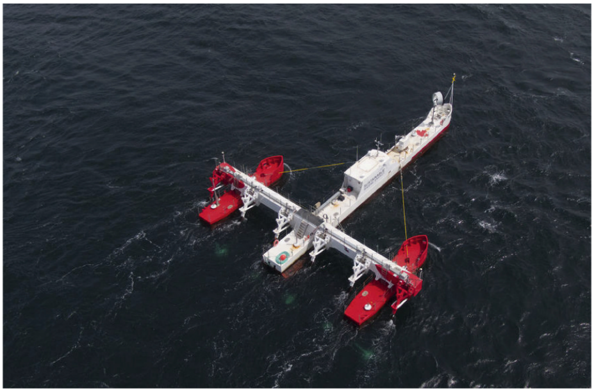


Fig. 29. Sustainable Marine's floating tidal platform (Garanovic, 2022b)

Fig. 30. Orbital Marine Power's O2 turbine (Stratigaki et al., 2023)

Several review articles discuss the state-of-the-art developments in tidal energy technologies and future R&D trends. For example, Chowdhury et al., (2021) examined current trends, ecological effects, and prospects for tidal energy technology. A review of tidal current energy converters' developments in China was presented by Si et al., (2022),

Fig. 31. China's Endeavour tidal stream turbine (source: https://www.seetao.com/details/141111.html)

concluding that the development in China has diverged into large-scale turbines for grid connection and small-scale turbines for diverse applications in marine environments such as multi-energy complementary systems, in situ power supply, seawater desalination, and mariculture. The UK's Engineering and Physical Sciences Research Council funds the *Co-design to deliver scalable tidal stream energy* (CoTide) programme grant research (*Co-design to deliver Scalable Tidal Stream Energy*, no date). The CoTide program aims to develop integrated tools and design processes for tidal stream energy to reduce costs by eliminating unnecessary redundancy and improving engineering solutions' confidence. This initiative seeks to significantly contribute to achieving climate change objectives by 2030–40.

5.2 Environmental Conditions

Regarding the characterization of environmental conditions, a comparison was presented by McIlvenny et al., (2023) concerning field measurements of flow speeds in tidally energetic channels using large-scale particle image velocimetry (LSPIV) and dense optical flow techniques with the Gunnar-Farnback algorithm. Compared against underway Acoustic Doppler Current Profilers (ADCP), LSPIV was recommended due to the optical flow technique's underprediction of high velocities (>1 m/s). The authors of Thiébot et al., (2022) investigated the long-term variability of the tidal stream energy resource associated with the 18.6-year lunar cycle. Three sites in north-western Europe with strong potential for tidal array development were considered: the Alderney Race (English Channel), the Fromveur Strait (western Brittany), and the Ramsey Sound (Irish Sea). Results based on harmonic analysis and predictions of depth-averaged tidal currents indicated comparable variability in predicted annual power densities at the three locations. A numerical investigation by Spicer et al., (2023) examined the influence of a hypothetical tidal stream turbine array on barotropic tidal processes in the Piscataqua River - Great Bay estuary, potentially producing 44.7 GWh annually with 180 tidal turbines. Simulation results showed that tidal turbines can reduce tidal elevation and current magnitudes, diminishing tidal asymmetry due to reduced water storage over tidal flat regions at the estuary. Weakened ebb dominance keeps depths from the mouth to mid-reaches deep enough to minimize shallow water and frictional effects on storage mechanisms, with upstream shallow regions' frictional mechanism reduced by 10% due to the turbines. Environmental considerations such as sediment transport, water quality, and ecology are also discussed. Sea level rise (SLR) can change estuarine tidal energy. A systematic review by Khojasteh et al., (2022) on factors related to sea level rise categorized them into primary (e.g., tidal prism, range, current, asymmetry), secondary (e.g., sediment transport), and tertiary (e.g., shifts in estuarine shape/landform) factors. High uncertainty regarding SLR impacts on tidal energy resources exists due to spatial variability of estuaries. SLR may strengthen or weaken tidal ranges or currents, depending on estuarine shape and boundary conditions (e.g., levees, low-lying areas).

5.3 Tidal Turbine Loads and Response Analysis

5.3.1 Numerical Methods

An integrated floating energy system combining wind and tidal/current energy generators was investigated in Yang et al., (2023). An integrated analysis tool was developed to consider aero-hydro-servo-elastic coupling effects under wind, wave, and current loadings. It was shown that increasing the number of tidal turbines led to smaller pitch motion of the platform, and the presence of tidal turbines had an insignificant effect on fatigue damage at the tower base. Additionally, the total power of the integrated platform with three tidal turbines was expected to increase by 9.46% compared to the floating wind turbine alone. The authors of Zhang, J. et al., (2022) applied a continuous array optimization approach based on the open-source coastal ocean modeling framework Thetis to derive optimal configurations for four turbine arrays around Zhoushan Islands, Zhejiang Province, China. Different optimization scenarios were tested to investigate interactions between turbine arrays and their hydrodynamic footprint. The analysis showed that optimizing all turbine arrays simultaneously minimized array competition effects (which otherwise led to an average power decrease of 42.2%) and reduced the cost of energy. Computational fluid dynamics simulation by Mercier and Guillou, (2022) investigated spatial and temporal variations of flow characteristics at a tidal stream power site. The analysis indicated that flow characteristics are highly variable in space, especially laterally. Turbine positioning should thus be optimized locally with precision between 10 to 100 m. Longitudinal velocity can vary significantly over short periods, with average power of the flow reaching a turbine varying by a factor of 2 in less than a minute. The authors of Gao et al., (2022) employed the CFD-DPM (Discrete Phase Model) approach to study lift and drag coefficients of turbine blades under multiphase flow, considering fluid–particle interactions. The numerical analysis was validated by experimental tests of a 120-kW tidal turbine, showing small diameter particles can improve tidal current turbine power while large diameter particles can reduce power. Impact loads to tidal turbine blades from sea animals were analyzed by Gavriilidis and Huang, (2021) using Finite Element Modeling software ABAQUS, where an adult killer whale was modeled to study its impact on the blade. Various magnitudes and trajectories of animal entry into the blades were analyzed. Results indicated that equivalent plastic deformation of the blades is lower for carbon steel materials than for stainless steel. Based on 45 consecutive impacts, it was concluded that turbine blades' ultimate strength is sufficient to withstand impact loads from animals, but plastic accumulation in the blades requires further study. Increasing tidal turbine structures can lead to fatigue failure of turbine components due to load variations. The authors of Zhang, Y. et al., (2022h) applied a bidirectional fluid-structure coupling method to analyze the hydrodynamic performance and structural response of tidal-stream turbine blades. Results showed that structural responses of blades are minimally influenced by water depth but significantly affected by turbine speeds, which are critical for determining structural safety. Maximum stress responses occur near the blade root, but fatigue life remains a concern for tidal turbine blades. The structure dynamics of Horizontal Axis Tidal Turbines (HATTs) was also studied by Wang et al., (2024), analyzing inflow turbulence and unsteady force excitations on a three-blade HATT using Large Eddy Simulation. Distribution of unsteady loads on blades, the relationship between upstream and downstream flow velocities, and unsteady blade characteristics were analyzed. Under 10% turbulent intensity, HATT blades' hydrodynamic fluctuations reached 57.44%, with maximum loads located between 0.7R to 0.8R section of the blades. Middle and tip sections contributed to third-order blade passing frequency harmonics. The authors of Borg et al., (2021) developed a FEM solver for a full-scale ducted, high-solidity tidal turbine rotor made of fiber-composite, investigating structural performance under unsteady blade-resolved computational fluid dynamic analysis with configurations from aligned and yawed flows. Three internal blade designs were used for fluid-structure interaction analysis to study structural deformation, with maximum axial deflection-to-blade span ratio of 0.04 and maximum strain of 0.9%. Fatigue life assessment ensured sufficient operational time.

5.3.2 Laboratory Tests and Field Measurements

Static and fatigue tests were presented by Glennon et al., (2022) for composite tidal stream blades. Design, material selection, and manufacturing of candidate blades were carried out by SCHOTTEL Hydro (Germany) and Sustainable Marine Energy (UK): a 3 m length blade for a 6.3 m diameter rotor and a 2 m length blade for a 4.0 m diameter rotor, both resin-infused carbon fibre blades. Tests demonstrated survival of both blades in fatigue at lifetime-equivalent load, confirming structural strength and design life of the SCHOTTEL HYDRO blade. An experimental study was conducted by Zhang, J. et al., (2022) on a twin-rotor horizontal axis tidal stream turbine tested various approaching velocities and yaw angles. Results showed increased approaching velocity significantly boosted thrust and its fluctuation range. Yawed inflow reduced thrust gradually with increasing yaw angle, with thrust fluctuation range rising as yaw angle increased from 10° to 30°, then decreasing beyond 30°. Increased approaching velocity accelerated wake velocity recovery and enhanced turbulence intensity. Higher yaw angles resulted in long strip-shaped wake flow velocity distribution, reduced near-wake flow velocity deficit, and faster wake merging but negatively impacted further downstream wake recovery. Array spacing effect on wake interaction of tidal stream turbines was experimentally investigated by Zhang, Y. et al., (2023b) using a wave-current flume. Tests on single- and twin-turbine piled systems with three mid-passage distances (1.2D, 1.5D, and 2D, where D = rotor diameter) for the twin-turbine case indicated that a staggered layout with a 2D spanwise distance is preferred over an aligned layout due to better wake recovery.

5.4 Design Standards and Guidelines

Design rules and standards relevant to tidal and current turbines include the following:

- DNV-ST-0164, 2021. Tidal turbines (Det Norske Veritas, 2021b).
- DNV-SE-0163, 2021. Certification of tidal turbines and arrays (Det Norske Veritas, 2021a).
- BV Guidance note NI 603 DT R01 E, 2015. Current and tidal turbines (Bureau Veritas, 2015).
- IEC TS 62600 (International Electrotechnical Commission, 2019).

DNV-ST-0164 provides principles, technical requirements, and guidance for the design, construction, and in-service inspection of tidal turbines, covering structures, machinery, safety, controls, instrumentation, and electrical systems. DNV-SE-0163 defines specific certification requirements and respective deliverables for tidal turbines. The BV Guidance Note NI 603 DT R01 E sets requirements for fully submerged Current and Tidal Turbines (CTT) installed on the seabed, addressing support structures, turbine components (blade, hub, nacelle, duct), and electrical installations. The International Electrotechnical Commission (IEC) offers comprehensive design requirements to ensure the engineering integrity of marine energy converters (e.g., tidal energy), aiming to protect against hazards that could cause catastrophic failures in structural, mechanical, electrical, or control systems.

6 Floating Solar Photovoltaic Systems

6.1 Recent Industry Developments

The first developments of floating photovoltaic (FPV) systems started during the late 2000s, and since then, the cumulative installed capacity has doubled year on year (Friel et al., 2019). Some early FPV projects reported an improved energy yield of more than 10% over ground-mounted photovoltaic (PV) systems due to the cooling effect of water on PV panels, increasing their efficiency. In some cases, spurred by the high cost or limited availability of land, the PV industry has started to look into using water bodies for PV applications (World Bank Group, 2019). The FPV sector is still a fast-growing segment in the global PV industry, with more than 3 GWp of installed capacity by the end of 2021 (Zhao et al., 2023). Various floating technologies have emerged in the market. They can be categorised into four types: pure floats, floats with metal structures, membranes or mats that are directly installed on the water surface, and semi- or fully-closed platforms.

The deployment of FPV systems at sea is limited due to harsh environmental conditions, mainly induced by wind and waves. The vast majority of the available technology and projects in operation are located in inland freshwater bodies. It was found that the most common type of floating structures used inland is unsuitable for marine deployment (Oliveira-Pinto and Stokkermans, 2020). Furthermore, installing the FPV system in offshore environments is complicated, including lifting, towing, manoeuvring, and positioning heavy structures (Vo et al., 2021). This novel sector faces many challenges, including the unavailability of FPV-specific standards and technical guidelines, water body data, FPV plant component safety, and long-term reliability. Despite the difficulties, several projects installed at sea showed promise for offshore FPV systems worldwide.

Thus, research activities for marine FPV systems should focus on developing new concepts for FPV for the ocean instead of scaling up existing technologies. There is momentum in the sector to develop FPVs to be deployed in marine environments (Oliveira-Pinto and Stokkermans, 2020). Recent research has focused on FPV installations in coastal sites and sites with natural or artificial barriers that reduce severe wave impacts (World Bank Group, 2019). The research aims to standardise and optimise the used technology to provide commercial use of the marine segment of FPVs.

In 2021, Det Norske Veritas released the world's first Recommended Practice (RP) for floating solar energy projects, DNVGL-RP-0584, 2021 (DNV GL, 2021). The RP was released following a joint industrial project involving 24 industry participants. It applies to maritime locations close to the coast (which are reasonably protected) where significant wave heights up to 2 or 3 m are expected. These recommendations can also be used for FPV systems in protected and inland water bodies.

The analysis of the different FPV technologies revealed that pontoon-type systems will probably play a major role in the transition to the marine environment (Claus et al., 2022). These systems use joints between the floats. Truss structures are applied to this type of floating support to keep the modules safe. Also, thin-film-based designs have great potential for offshore applications. These systems minimise stress by allowing deformation and could be cheaper than pontoons at the cost of harvesting fewer resources. Integration with offshore wind, using the existing power grid, provides all types of FPVs with cheaper deployment (Ghosh, 2023).

Environmental loads, like wind and waves, are the primary loads on marine FPV systems, for which estimations are referred to the standards for relatively mature marine engineering, such as those of the oil and gas industry (Shi et al., 2023). The robust design of connections between floats is essential for the reliability of modular FPV platforms. So, different methodologies are applied to assess the structural response of FPV systems to environmental loading. However, since the dynamic response of FPV plants cannot be ignored in the marine environment, rigid solid dynamics or hydroelastic methods are applied (Claus et al., 2022). A mooring system proved to be much more critical for FPVs than traditional floating structures. With FPVs, the mooring system plays an essential part in the structural integrity of the whole system, so recent research is focused on coupled models (Catipovic et al., 2022).

Further improvements in FPV technology are needed to fully realise its potential, particularly in floating structure design, instrumentation, and monitoring systems. Addressing safety concerns, standardisation issues, and policy considerations will be crucial for widely adopting FPV systems (Ramanan et al., 2024).

6.2 Numerical Modelling and Analysis

As noted, most of the FPV installations are made of connected multiple floating bodies, i.e. made as modular structures. Incoming waves will cause structural loads on the floats, the connections between floats, and tensions in associated mooring lines. The wave loads can be determined by methods based on the potential flow theory. These methods are already well developed for the needs of the oil and gas industry, except that they have not yet been applied and tested extensively for structures with relatively large numbers of floating bodies, as current and undoubtedly future FPVs will have. One way to accommodate many floats is to use a hydroelastic approach, as presented in (Michailides et al., 2013), to analyse a modular-type floating structure with flexible connectors to determine motions and connection loads. The model was assumed linear, so the numerical results were obtained in the frequency domain. A simplified hydroelastic approach was used in (Jin et al., 2023), which presented a lightweight and high-stiffness floating platform composed of an ultrahigh performance concrete surface panel and an expanded polystyrene geofoam bottom panel as a large area bi-layered structure. The mechanical performance parameters of the upper layer are designed by adopting the representative volume element method.

The hydroelastic approach is also well suited for floating thin membranes as carriers of PV panes at sea. For example, Ma, et al., (2020) combined SPH and the linear FEM to study the structural response of the membrane. The SPH method has an advantage over the potential flow methods since it can model waves with large amplitudes. As a non-linear method, it was solved by time domain simulations. Further, due to large angular displacements, non-linear membrane response was studied in Xu and Wellens, (2022) to estimate the influence of such response on the strain-stress relation.

Some recent research is oriented on single-float support for FPVs but with the assumption that the float is rigid instead of being hydroelastic. A parametric study using a simplified approach based on the potential flow of a single floater regarding its dimensions and incoming wave characteristics is a good example (Al-Yacouby et al., 2020). A more advanced approach used for single support, including Froude-Krylov, radiation, diffraction, and viscous drag forces determined by Morison's formula, was presented in Friel et al., (2020). The response of the structure and the mooring lines was determined by FEM.

The assumption that the floats are rigid is also commonly used when dealing with multi-float support. In these studies, the connections between the floats are part of the numerical models, so more realistic, i.e. the coupled response of the floats is gained. In Catipovic et al., (2023), the ball connections between floats are considered in a frequency-domain seakeeping model. An additional stiffness matrix is presented, which introduces the influence of ball connections on multiple-float motions. The matrix can also be used to estimate the loads due to waves that occur in the connections. In Shi et al., (2023), the floating support structure is discretised into an array of floats connected by equivalent elastic beams based on Euler–Bernoulli beam theory. The corresponding structural stiffness matrix is assembled using coordinate transformations and matrix reorganisation techniques. Afterwards, the vulnerable area of the structure can be assessed using the equivalent stress based on the von Mises stress theory. A combination of rubber rings and anti-collision pads as connecting elements was proposed in Kang et al., (2023) for two triangular floats carrying PV panes. The forces in these connections were determined by time-domain simulations based on the potential flow. A similar time-domain numerical model was used in Zhang et al., (2024) to include non-linearities in the model tests and prototypes, for example, the viscous effects from waves, drag forces from currents, and the non-linearities from mooring lines and fenders. Flexible joints, whose stiffness was derived from the structural tests, were considered model constraints. The model was used for the design and verification of the recently deployed world's largest 5 MW nearshore floating PV farm in the coastal region of Singapore. The previous models include the hydrodynamic interaction between the floats, which can be computationally demanding for a large array of floats. So Zhang, D. Q. et al., (2023a) proposed a hydrodynamic interaction cut-off scheme for the multi-body potential solvers to save computational time. An optimal cut-off radius can be determined from an acceptable truncation error, so the interactions between bodies reaching outside the radius can be neglected, making the calculation less extensive.

More advanced methods for determining the wave loads were also used for multiple-float supports. The SPH method was used on a structure composed of 10 individual modules that were connected by rings in Wu et al., (2022). It was established that wave-breaking, which potential solvers can not detect, causes a significant increase in the loads, possibly making forces in the connections and tensions in mooring lines above design values. A safety analysis procedure that is composed of CFD simulations and FEM analyses with validations by experimental data was presented in Choi et al., (2023). The procedure was used to estimate the stress distribution on an FPV system for various incoming angles of the winds and waves. The Arbitrary Lagrangian-Eulerian (ALE) method is used for the fluid-structural analysis of yet again modular FPV system under wave action in Sree et al., (2022).

Wind loads make a significant part of the environmental loads of FPV structures because installed PV panels have large surfaces that are exposed to the wind. To define these loads, measurements in a wind tunnel were conducted in Chung et al., (2018), where a stand-alone PV array was put in a uniform flow with a given average air speed and turbulence intensity. The study was done for rooftop PV panels. Also, for the rooftop panels, Su, et al., (2020) applied CFD simulations to determine the wind resistance and uplift coefficients. Several turbulence models were compared with the wind tunnel experimental results, and the SST k-ω model has proven to be the most accurate. Hsu and Su, (2020) also used CFD simulations to get the wind-pressure coefficient of a PV panel under extreme conditions when the wind and wave are in the same direction. In such cases, the PV panel is subjected to a more concentrated non-uniform pressure near its edges compared to cases without waves. The SST k-ω turbulence model was used in simulations conducted by Bei et al., (2022) to resolve wind loads on a large-scale FPV system. The results show that the upstream PV modules facing the wind have an occlusion effect on the downstream PV modules. Stress analysis of the PV unit revealed that the maximum stress is mainly concentrated in the upper part of the supporting columns connecting the floating support and the PV modules. A structural response under the action of winds in combination with waves was investigated in Yang and Yu, (2021) for a single-float FPV. CFD modelled the pressure distribution on the PV panels due to wind action. The total loads were used to estimate the tensions in the associated mooring system.

An offshore PV system with 420 mooring lines was studied in Ikhennicheu et al., (2021). A quasi-static analytical analysis was applied to estimate the tensions of mooring lines so that the first-order wave loads were omitted. Waves drift loads were computed using Maruo's formula. The sea current loads were estimated based on drag and shielding coefficients. The analyses established that the mooring lines must be homogenously placed over the FPV system, i.e., non-uniform load distribution between mooring lines is a design problem. The mooring system was also studied in Song et al., (2022) for an FPV system made in a 10 × 10 assembly of floating supports that were connected by hinge joints. A catenary mooring system made of 80 steel wire ropes was observed. The lumped mass approach was used to model the mooring lines in combination with Morison's equation for hydrodynamic forces acting directly on the lines. It was found that the floaters' response was amplified in extreme wave conditions due to the resonance effect caused mainly by the stiffness of the catenary mooring. A similar number of lines in a mooring system was studied in Kanotra and Shankar, (2022). Here, the lines were made of chain and polyester, with different lengths and anchor positions to accommodate the bathymetry of the site and the water level changes. Such a large number of mooring lines was necessary to ensure that the expected load on each line was well below the structural capacity of interconnecting pins and fairleads. In Claus et al., (2023), an FPV plant was structurally assessed for marine environmental conditions. This work aimed to compare several chain sections for its mooring system. It was found that the heavier chain sections are better from the stationkeeping point of view and may prevent instantaneous chain wrenches that could result in snaps.

6.3 Physical Testing

The paper by Jiang et al., (2023b) presented an innovative floating photovoltaic (FPV) concept designed to endure harsh offshore conditions, including extreme wave heights exceeding 10 m. The FPV array employed semi-submersible floats constructed from lightweight circular materials, connected via ropes to form a soft-connected lattice structure. This design ensured modular motion with minimal wave overtopping and prevents contact between adjacent modules under extreme conditions. The study utilized a 1:60 scale model of a 2 × 3 FPV array, tested in a wave tank at the Canal de Ensayos Hidrodinámicos of the Universidad Politécnica de Madrid. The tank's dimensions were 100 m in length, 3.8 m in width, and 2.245 m in depth, equipped with a single flap wavemaker and a wave absorption beach. The experiments involved testing nine regular wave conditions (WR1 to WR9). These wave conditions represented typical wind-generated ocean waves with periods ranging from 7.8 to 12.8 s and wave-heights ranging from 1.9 to 5.1 m. The wave amplitudes were adjusted to specific wave steepness values. An additional survival condition (WR10) was included, having a higher wave height of 15.3 m to simulate extreme conditions. For irregular waves, the Pierson-Moskowitz Spectrum was employed. Three conditions (WIRR1, WIRR2, and WIRR3) represented different sea states with significant wave-heights ranging from 1.2 to 7.2 m and significant wave-periods ranging from 6.7 to 10.9 s. Moreover, Calm water free-decay tests were conducted to determine the natural frequencies and damping coefficients for the heave, roll, and pitch motions of the floats. Natural frequencies and damping coefficients for heave, pitch, and roll were determined to be 2.19 s (23%), 2.03 s (17%), and 1.78 s (14%), respectively.

Schreier and Jacobi, (2022) investigated the interaction between waves and a thin, flexible floating sheet. This study was motivated by the increasing interest in flexible floating structures for offshore applications, such as floating solar installations. The main objective was to understand the hydroelastic behavior of a floating sheet with a high length-to-height ratio in regular long-crested head waves. The experiments were conducted in the Ship Hydromechanics Lab at Delft University of Technology. The tank dimensions are 80 m long and 2.75 m wide, with a water depth of 1.00 m. The model is a closed-pore neoprene foam rubber sheet with dimensions of 4.95 m in length, 1.02 m in width, and 5 mm in thickness. The model was moored at the center of the tank using four mooring lines connected to the sidewalls. The surface deformation of the floating structure was measured using the Digital Image Correlation (DIC) technique. Regular waves were generated with a wavelength ranging from $L/\lambda = 5$ to $L/\lambda = 20$ and wave steepness in the range of 0.02 to 0.05 however, the researchers reported the results of only two specific conditions $L/\lambda = 5$ and $L/\lambda = 10$. The floating sheet mainly followed the local wave elevation, with a reduction in motion amplitude observed over the length of the structure. The wave condition $L/\lambda = 5$ showed increased hydroelastic interaction compared to $L/\lambda = 10$ which indicates stronger three-dimensional effects for shorter waves. The elevation amplitude of the model was found to be larger than the amplitude of the incoming wave, suggesting significant hydroelastic interaction. Claus et al., (2024) investigated hydrodynamic response of an innovative floating photovoltaic (FPV) system HelioSea under regular and irregular wave conditions. The HelioSea device features a pole-mounted solar platform with a double-axis tracker, supported by a tension-leg platform (TLP). HelioSea comprised a solar platform mounted on a pole with a dual-axis tracker which was supported by a tension-leg platform (TLP) to maintain stability. The experiments were conducted at the wave basin of the University of Porto, featuring a $12 \times 28 \times 1.2\ \mathrm{m}^3$ basin equipped with piston-type wave paddles. A 1:30 scale model of HelioSea was tested. Regular waves with nine different periods ranging from 0.73 to 5.11 s and three target wave heights (4–6–8 cm) were generated to establish the Response Amplitude Operators (RAOs) of the structure. Additionally, irregular wave tests using the JONSWAP spectrum were performed to evaluate the device's response under more realistic sea conditions. Both long-crested and short-crested irregular waves were tested with peak wave periods of 2.19 and 3.65 s and a significant wave height of 4 cm. Directional spreading functions were applied to generate short-crested waves. In all degrees of freedom, the HelioSea device showed a modest amplitude response for wave periods under 20 s, with surge responses reaching up to 4 m/m and yaw responses reaching up to 1 deg/m. Regular wave tests showed negligible sway, heave motions and a dominating surge motion. The anchoring mechanism significantly limited the pitch and roll movements, resulting in amplitudes below 0.5 deg/m. The yaw motions were consistently below 1 deg/m under normal wave conditions. The highest surge motion observed in the prototype scale was 1.8 m, which corresponds to a mooring line angle of 2.3°.

6.4 Design Standards and Guidelines

As noted in Sect. 6.1, the only design recommendation for floating solar projects was released in 2021, DNVGL-RP-0584 (DNV GL, 2021). Its scope is limited to significant wave heights of “up to 2–3m”, which makes it inapplicable to most offshore sites. A number of demonstrators are being developed and tested (e.g. Merganser and Sun’Sete projects) yet there is still no offshore standard available. The recommended practice consequently needs to be extended to more severe environments.

The floating photo-voltaic structures expected to be installed are of considerable dimensions, potentially causing hazards to the surrounding sea-spaces and shores in case of a mechanical failure. The first demonstrators and prototypes will need to be designed following a goal- and risk-based approach to confirm that risks are taken at an acceptable level. It would be more desirable that certification schemes and standards would be available, but the maturity of these systems and the limited understanding of their behaviour still prevents it.

Indeed, most of the research so far focused on hydro-elastic modeling of the modular structures that will support the panels, and addressed specific aspects of loading and/or response (the influence of the stiffness of connections, non-linear breaking wave loads, diffraction of waves within the array, wind load/motion coupling etc.). This research helped identify the shortcomings of simulations and test models. These findings still need to be combined into complete higher fidelity models that will be required before standards can actually be issued. More recommended practices or guidance notes would be needed to guide designers in the estimation of design loads, coupling between modules, the type of dynamic simulations to be investigated, etc.

Important aspects of the structural strength of FPV systems have been so far scarcely investigated and will require further work and guidance: mooring systems and in general the long-term structural strength of these systems. A number of designs currently consider that arrays of solar panels will need to be moored by means of a large number of mooring lines, which poses the question of the safety of these systems which loads are shared between many non-linear members. In addition, limited research was made on the long term behaviour and resistance of these structures. A number of modules consider using polymer materials, which will need to be qualified in the marine environment. Elastic members connect modules; again made of polymer materials which long term behaviour (resistance, stiffness, creep, etc.) will need to be ascertained.

There is hence significant research to be undertaken before mature standards can be issued. In the interim, specific guidance notes on the testing and qualification of polymer load-bearing components, mooring system analysis as well as hydro-aero-elastic modeling would be very useful to the industry.

7 Other Offshore Renewable Energy Technologies and Hybrid Solutions

This chapter reviews the most relevant contributions regarding load analysis and structural design of floating and fixed offshore renewable energy devices. It also considers aspects related to prototype testing and the levelized cost of energy (LCoE). The review is structured into three main engineering design steps, the design requirements (e.g. LCoE), conversion methodologies (e.g. load analysis, structural design), and design specifications (e.g. structure architecture).

7.1 Ocean Thermal Energy Conversion

The Ocean Thermal Energy Conversion (OTEC) device removes and transfers seawater heat to a second fluid, which evaporates and acts on a turbine connected to an electrical generator (Fig. 32). OTECs may be located onshore and offshore (Fig. 33) and used as hybrid systems for district heating and cooling, desalination of seawater hydroponic cultivation, aquaculture, and extraction of seawater minerals. OTEC has been proposed to provide energy and extend the service life of unmanned underwater vehicles (UVV) (Jung et al., 2022).

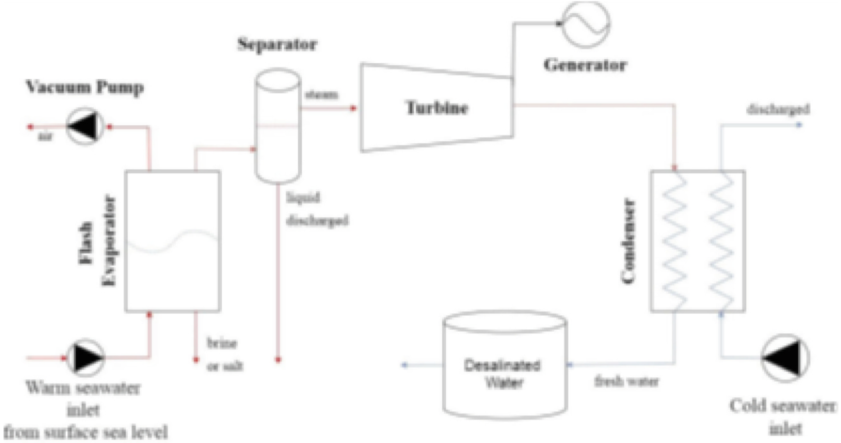


Fig. 32. Conventional open cycle OTEC system. Adapted from (Aresti et al., 2023).

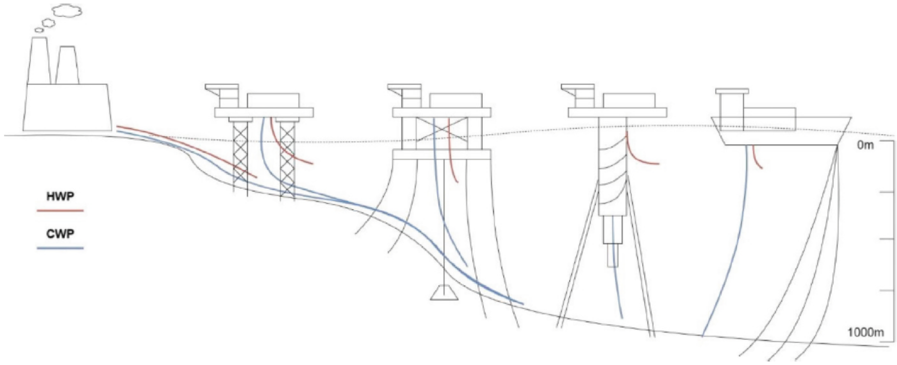


Fig. 33. OTEC positioning. Adapted from (Aresti et al., 2023).

Early development stage projects examine and propose the OTEC requirements. LCoE is the most used and important requirement. It is currently the major drawback of

OTEC devices since it is comparatively higher than conventional and other renewable energy systems (about 0.05 to 0.45 USD/kWh) (Aresti et al., 2023)

Thus, it is hard to attract research funding from investors. Hence, OTEC LCoE is used to study upscaling scenarios to make it feasible (Langer et al., 2022), and control systems are identified as a potential and important LCoE modulator since OTEC technological requirements are not focused on control as an enabling technology (Ringwood, 2022). For example, a proportional-integral controller has been designed to control the OTEC-generated net power and numerical simulations have confirmed the effectiveness of the proposed control system (Matsuda et al., 2023).

Other scenarios include hybrid solutions to improve LCoE, like integrating OTEC with solar and solar wind renewable technologies (Dezhdar et al., 2023; Hoseinzadeh et al., 2023). The OTEC system utilizes solar and wind energy to enhance its feasibility. Also, OTEC integration with Pumped Thermal Energy Storage (PTES) technology has been proposed but with a different requirement to improve, the Levelised Cost of Storage (LCOS) (Ghilardi et al., 2024)

The design specifications are related to OTEC energy harvesting performance and conversion efficiency (Langer et al., 2022, Aresti et al., 2023), LCoE (Langer et al., 2021; Langer, et al., 2022) and LCOS (Ghilardi et al., 2024).

OTEC requirements for conversion methodologies are proposed but without producing design specifications related to OTEC platform structures, since these parametric studies are performed on onshore applications, to determine OTEC energy harvesting system specifications (Dezhdar et al., 2023; Hoseinzadeh et al., 2023).

7.2 FPV Combined with Floating Wind Turbines and WECs

Floating photovoltaic (FPV) is used to exploit large water surfaces for energy generation, such as the ones in the free area between wind-floating platforms, to increase the production of energy per area of the sea bed used. (Fig. 34) (Solomin et al., 2021; Garrod et al., 2024). This technique can also be combined with WECs and the same floating structure, as illustrated in Fig. 35.

The LCoE is one of the most important indicators for assessing system performance; yet, the scientific community is divided on the best way to evaluate this metric and others (Solomin et al., 2021). Furthermore, system structural needs are not included in the list, indicating that these notions are substantially unknown and developed. Fig. 36 illustrates the only known hybrid offshore wind-solar power installation.

The harsh sea climate will drive the creation of structures capable of supporting these features, which will be done first for pilot plants (Garrod et al., 2024). Thus, it is predicted that a methodology for evaluating the structural integrity of FPV hybrid structures would be established from the single FPV mature methodologies, like the one by Claus and López, (2023) (Fig. 37)

7.3 WECs Combined with Floating Breakwater

Using WECs with a breakwater combines renewable energy production with coastal protection, against erosion and waves, resulting in more effective space usage and cost

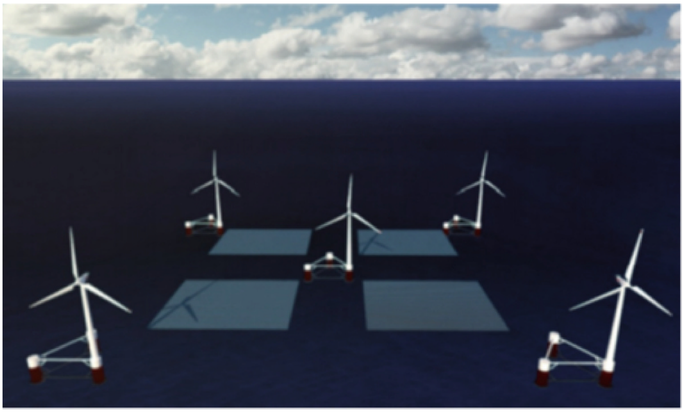


Fig. 34. Combined floating wind and solar energy farm. Adapted from (Solomin et al., 2021).

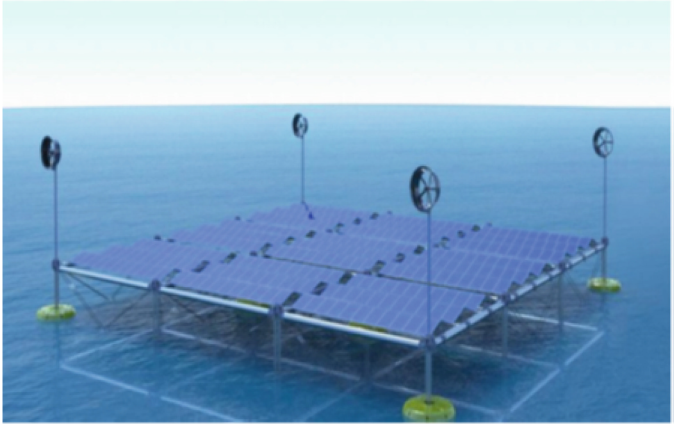


Fig. 35. Conventional open cycle OTEC system. Adapted from (Solomin et al., 2021).

savings (e.g., construction and maintenance). WECs are located inside or in front of the breakwater, which can be either floating (Fig. 38) or stationary (Fig. 39).

WECs used in these applications are Oscillating Water Column (OWC) (Guo et al., 2021; Han and Wang, 2021; Cheng, Du, et al., 2022b; Ram et al., 2022; Mayon et al., 2023) and point absorber type (Cheng et al., 2021; Ji, et al., 2021; Cheng, Fu, et al., 2022a; Cheng, Xi, et al., 2022c; Ji and Jiao, 2021; Yang et al., 2023; Jeong and Koo, 2023; Ji and Chen, 2023; Cheng, Du, et al., 2024b; Wei et al., 2024; Cheng, S. et al., 2024; Peng et al., 2024). Also, a hybrid WEC, consisting of an OWC and a horizontal floating cylinder (HFC), is proposed by Shahabi-Nejad and Nikseresht, (2022).

Most of these studies are dedicated to studying and improving the WEC hydrodynamic performance. Very few include structural safety, and the analysis is mostly simplified. They evaluate the loadings on the system and moorings caused by the WEC

Fig. 36. Hybrid offshore wind-solar power plant. Adapted from (Garrod et al., 2024).

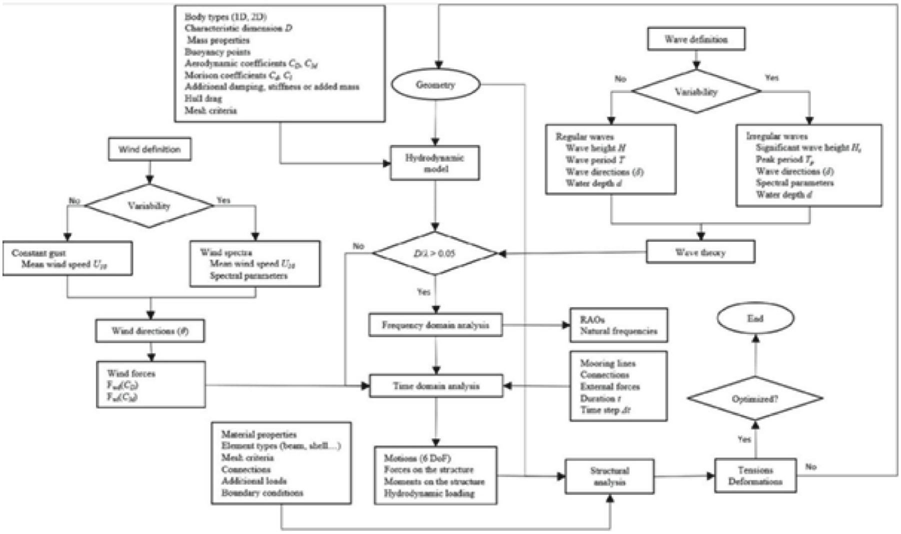


Fig. 37. Design methodology for FPV systems. Adapted from Claus and López, (2023).

motions and give indications about their impact on structural integrity without quantifying them with dedicated parameters (Guo et al., 2021; Ji and Chen, 2023; Cheng, Du, et al., 2024b). Consequently, no structural-related, requirement conversion methodologies and design specifications are presented; however, these few studies offer guidance for future research in this area.

Some of these indications include the influence of WEC Power Take-Off (PTO) damping force on the system survivability in extreme waves (Ji and Chen, 2023) and

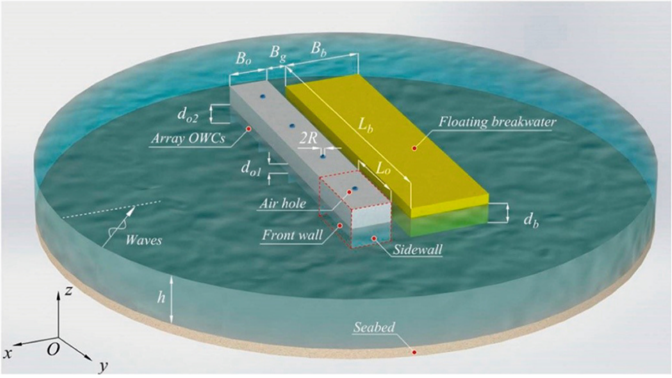


Fig. 38. OWCs in front of the floating breakwater. Adapted from (Cheng, Du, et al., 2024b).

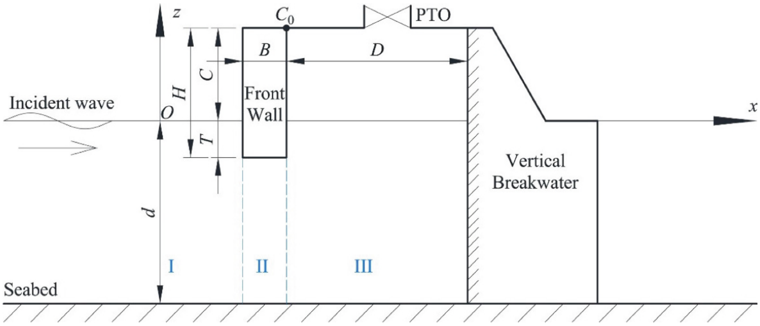


Fig. 39. OWC mounted breakwater integrated system. Adapted from (Guo et al., 2021).

the need to adjust system parameters to reach an optimal state in terms of WEC energy conversion ability and system structural safety (Guo et al., 2021).

7.4 WECs Combined with Floating Wind Turbines

Floating offshore wind turbine (FOWT) platforms are subjected to combined cyclical wind and wave interactions, rotor-induced forces, and control operations, making them susceptible to large oscillatory motion responses, undesirable resonant motions, and fatigue loads, especially in rough sea conditions systems (Uzunoglu et al., 2016).

Wind and waves cause cyclic loads on the tower and platform, resulting in significant wear damage at the tower's base and top (blades, rotor shaft, yaw bearing, gearbox, generator). This impacts the structural behavior, fatigue life, safety, and operating circumstances (Aboutalebi et al., 2023; Aboutalebi et al., 2024; Ahmad et al., 2023; Chen et al., 2022; Tian et al., 2023; Wang, Y. et al., 2022c). Thus, extreme oscillatory vibrations lead to reduced energy efficiency, greater maintenance and repair costs, and economic losses due to irreversible and inadvertent structural defects, resulting in downtime, shortened lifetime, and revenue loss (Aboutalebi et al., 2024); (Ahmad et al., 2023; M'Zoughi et al., 2023; Tian, et al., 2023).

(a) (b) (c) (d)

Fig. 40. FWWPs. (a) Spar–torus WEC, (b) Semi-OWC (Oscillating Water Column), (c, d) Semi–torus WEC. Adapted from (Chen et al., 2024; Hallak, et al., 2023; Jaya Muliawan et al., 2012; Sarmiento et al., 2019; Zhu et al., 2023).

These have a detrimental impact on the levelized cost of electricity (LCoE) and undermine wind turbine upscaling to reduce LCoE, as oscillatory motions are increased with turbine upscaling (greater height and mass), resulting in higher accelerations and loads (Stansby and Li, 2023; D. Zhang et al., 2022b). These issues have a significant impact on structural design. A 5 MW HAWT (Horizontal Axis Wind turbine) blade's sectional modulus is enhanced by 50% to prevent fatigue failure caused by a 10% increase in external load at 5° pitching (Dong et al., 2022; Zhu, H. 2023; Zhu et al., 2024). Thus, the wind turbine must be strengthened, resulting in increased weight. This results in structural design needs such as increased displacement, structural reinforcements to resist larger bending moments, additional stability to counteract turning moments, and regulated motion response to minimize significant accelerations and dynamic loads on the turbine (Hallak et al., 2018).

Furthermore, this issue is more significant with a 20 MW HAWT because the rotor diameter is approximately twice the 5 MW HAWT (Kamarlouei et al., 2022). Then, suppressing platform motions for structural load reduction should be sought to extend the life of the overall structure while enhancing power output and lowering maintenance and monitoring costs (Ayub et al., 2023; da Silva et al., 2022). Thus, WECs for controlling FOWT motions are presented. The basic goal is to build these hybrid systems, also known as Floating Wind-Wave Platforms (FWWPs), to share infrastructure and, thus, increase LCoE. However, the research trend is now committed to the preliminary design of FWWPs for controlled platform motions, as rated power is delivered mostly by the wind turbine (Cao et al., 2023; Zhu et al., 2024).

Several FWWP configurations are proposed, each with unique WECs, arrays, layouts, and controls (Gaspar et al., 2021). Furthermore, many modeling and simulation approaches are proposed, as merging these technologies raises the complexity of platform dynamic analysis (M'Zoughi et al., 2023; Zhu et al., 2024).

7.4.1 Design Requirements

The design requirements can be divided into two categories: functional (FR) (features and functions) and non-functional (NFR) (architecture traits or "ilities"). In this context, FWWP feasibility is linked to economic viability and profitability, and both are related to other system characteristics such as reliability, efficiency, capacity, and maintainability.

LCoE (Yi et al., 2024) is used to assess feasibility, while the platform's structural integrity and associated metrics such as FOS (Factor of Safety) (Yi et al., 2024), ULS (Ultimate Limit State), FLS (Fatigue Limit State), ALS (Accidental Limit State) (Jaya Muliawan et al., 2012), and DEL (Damage Equivalent Load) (Chen et al., 2022) are used to assess reliability, survivability, and maintainability. The system capacity is measured using WEC CWR (Capture Width Ratio) (Shi et al., 2022). Other metrics, such as platform pitch and heave, are employed to assess the impacts of motion on structural integrity (Yi et al., 2024), but they do not provide a quantitative measure like the ULS, FLS, ALS, and DEL.

7.4.2 Conversion Methodologies

The FWWP requirements for design specification conversion methods include the integration of hydrodynamics, aerodynamics, mooring and station-keeping systems, structural dynamics, and PTO systems, among others. Thus, researchers use diverse techniques, including code and software, given the numerous disciplines involved. These combinations, known as numerical frameworks, consist of several interconnected software components that perform calculations in all required domains at each timestep. FAST@, OpenFAST@, AeroDyn@, HydroDyn@, and MoorDyn@ packages, as well as ANSYS AQWA@, Nemoh@, WAMIT@, and WEC-Sim@, are commonly utilized in these frameworks (Gaspar et al., 2024).

7.4.3 Design Specifications

The conversion methodology models are based on engineering parameters, which are WEC-measurable qualities. WEC parameters are grouped into categories, depending on its subsystems, such as PTO and PTO two-step damping and PTO spring-damping for the control system (Cao et al., 2023; Chen et al., 2022; da Silva et al., 2022; Tian et al., 2023; Zhu et al., 2024), buoy radius and draft for the absorber (Ghafari et al., 2022; ZHU1 and piston area, motor displacement, accumulator pre-charge pressure, accumulator initial gas volume and throttle valve orifice size for oil-hydraulic PTOs (Y. Wang et al., 2022).

7.4.4 FWWP Geometries

System architectures are involved in the FWWP requirement conversion approaches (e.g., geometries in Fig. 40 Approximately 77 distinct FWWP designs have been proposed over the previous 13 years (Gaspar et al., 2024). Since 2020, research on this topic has increased, with 7 studies in 2020, fully dedicated to semi-submersible hybrids, 12 in 2021, mostly dedicated to semi-submersibles and very few papers to barge and spar hybrids, 11 in 2022, dedicated to semi-submersible hybrids, and 23 in 2023, mostly dedicated to semi-submersible hybrids and very few to spar types (Gaspar et al., 2024).

Furthermore, continuous growth in these investigations is noticeable in 2024, almost reaching the same number as the previous year, with 17 research till the end of May, most dedicated to semi-submersibles and one to TLP hybrids (Gaspar et al., 2024).

Because semi-submersible FWWPs outnumber other platforms, a comparative analysis is conducted by counting research for each platform type each year and adding them up over time. Fig. 41 shows that contributions to semi-submersible FWWPs have increased exponentially since 2019, while contributions to other FWWPs have remained low and consistent (Gaspar et al., 2024).

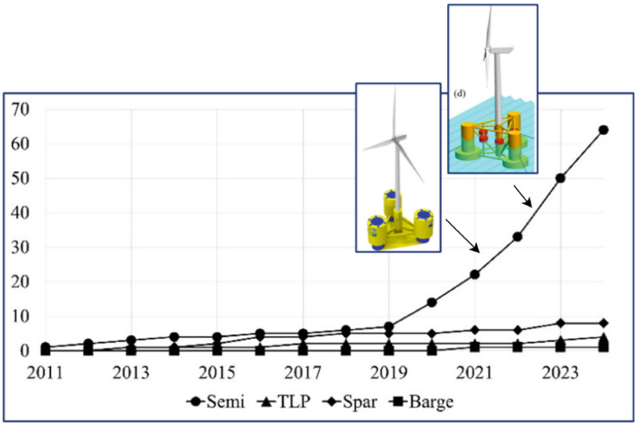


Fig. 41. Cumulative studies over the years per platform type. Adapted from (Gaspar et al., 2024).

The same approach is used for semi-submersible platform waterplane layouts, and it is revealed that only waterplane layouts 2, 3, and 4 are meaningful, as shown in Fig. 42, with contributions increasing exponentially since 2019. Layout 2 consists of one central column with a wind turbine (TCL) on top, and three exterior columns (CL). These are based on DeepCWind (OC4) (Fig. 40b–d). Layout 4 uses the same column configuration but fewer connecting pontoons (i.e., braceless platforms). Layout 3 likewise features three outer columns distributed in the same triangle pattern, but not a central one. One of these columns supports the TCL. It is based on modifications to the WindFloat and OC4 platforms. Furthermore, semi-submersible Layout 3 is catching up with Layout 4 and may overtake it by 2024.

The last analysis is performed on waterplane configurations of WEC absorbers utilized in semi-submersible FWWPs. The results are shown in Fig. 43, which demonstrates an exponential and relevant trend for type 3 absorbers (A) positioned outside the platform waterplane layout against absorbers located inside (types 1 and 5) or at the platform waterplane's boundaries (type 2). Overall, FWWP designs are moving toward more spread and less concentrated waterplanes.

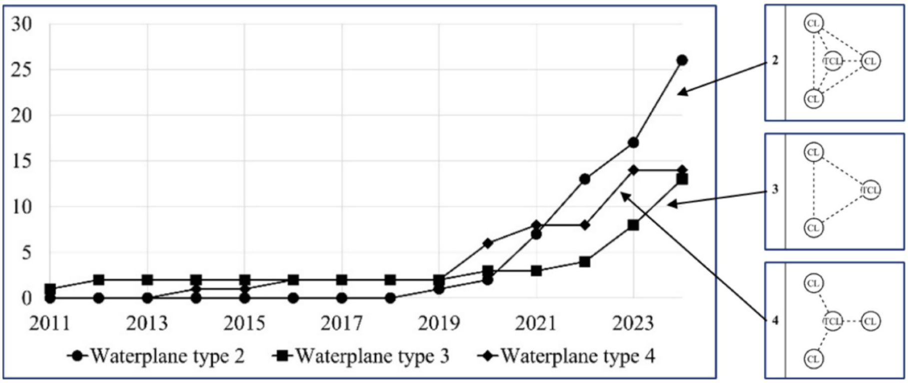


Fig. 42. Cumulative studies by SSB waterplane layout. Adapted from (Gaspar et al., 2024).

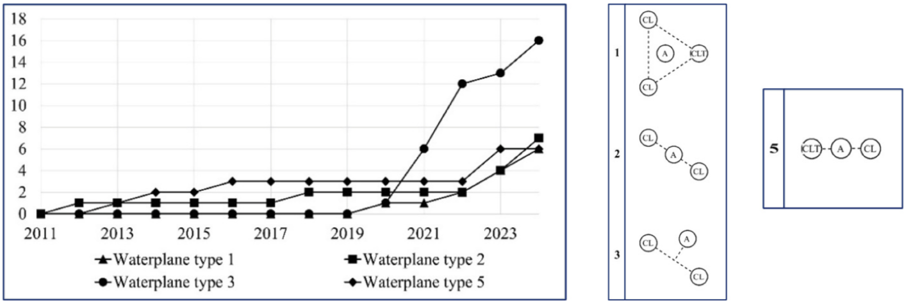


Fig. 43. Cumulative studies by SSB absorber waterplane layout. Adapted from (Gaspar et al., 2024).

8 Power Infrastructure at sea

8.1 Necessity and Application of Power Infrastructures

The main function of offshore renewables remains to feed onshore grids (International Energy Agency, 2023). This comes with the challenge of connecting to the shore a large numbers of remotely located electricity generators. This connection uses infrastructures which includes essentially cable systems that connect energy generators within an array, export substations that converts the inter-array electricity to export voltage, and subsea cables routed from the substations to shore (Feltes et al., 2012). Substations typically handle several hundreds of MW, which make these structures and the export cables critical not only for the farms but also for the grid (Boakye-Boateng, et al., 2021).

Robak and Raczkowski, (2018), Jump et al., (2021) and MacDonald, et al., (2018) list essential functions of offshore substations. These can be summarised as follows:

(i) interconnection of array to the export system,
(ii) raising voltage to its export threshold,
(iii) compensating cable capacity losses,
(iv) connecting to the export cable,

(v) allowing monitoring, maintenance and operation in general.

There is no example of normally manned substation; hence unlike most hydrocarbons production facilities, export substations are manned only when maintenance takes place. There is a single example of a floating offshore substation, installed on the Fukushima Forward site in Japan; all other substations have been installed on fixed structures, anchored to the seabed.

Previous work on cables confirmed the feasibility of high voltage dynamic cable systems, whereas certain electrical equipment suppliers (Hitachi ABB, 2021) already propose a range of equipment for floating substations. Hence the only barrier to floating substations remain their economic performance and risk profile (perceived or actual). Jump et al., (2021) compare fixed and floating substations, concluding that floating substations can be cost-competitive to fixed substations from water depth in the range of 55-60 m. shallow draft "barge-like" floaters being more competitive than semi-submersible floaters.

Offshore renewable energy being competitive in a number of places, it is also possible to use the electricity produced offshore to an energy carrier or other products needed in e.g. chemical processes in Power-to-X applications (Wulf, et al., 2020). This use of offshore renewables is expected to grow (Bossmann et al., 2018).

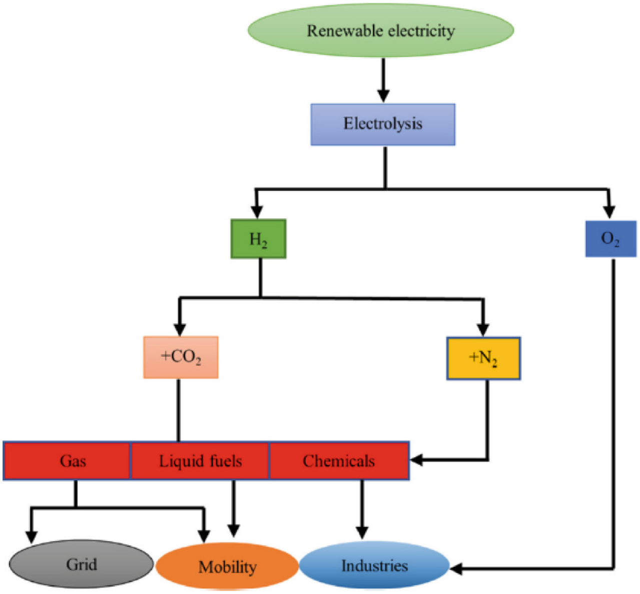


Fig. 44: Schematic of the P2X conversion pathways (Dahiru et al., 2022)

The initial feedstock of all Power-to-X projects is hydrogen that is generated by water electrolysis using renewable electricity. The flowchart in Fig. 44 from Dahiru, et al., (2022) shows a variety of pathways of Power-to-X processes. Both Singlitico, et al., (2021) and (Groenemans et al., 2022) found that hydrogen generation from offshore wind is economically viable. However, Groenmans found that the most competitive solution is to distribute electrolysers on individual wind turbines, whereas Singilitco found that centralised offshore production for a farm/group of farms is a better trade-off. Both options are however only 25% off in levelized cost of hydrogen, which is remarkable for such early-stage studies. It is hence probably worth considering both options for further development.

The first production of hydrogen from an offshore site combined Lhyfe's electrolyser and BW-Ideol's floating wind turbine. In this case, the electrolysers are located off the coast of France. Another approach followed by Dolphyn was to install the hydrogen production equipment on a barge, moor it in a sheltered site and deploy it offshore at a latter stage. No information was found on the results of these early experiments.

Little information was made available on the modifications required to operate electrolysers and all related equipment at sea. This data is proprietary to Lhyfe and Dolphyn. It can however be expected that fixed structures would need no modifications compared to onshore processes, and that centralized production on floaters would be less challenging than distributed production on floaters as the support structure would be larger on a centralized production unit.

These early experiments on hydrogen production addresses the first steps of the Power-to-X processes, but there is more to be done. In particular, (i) for direct hydrogen export; designing and qualifying hydrogen compression/export/offloading solutions (ii) for hydrogen use; designing and qualifying e.g. ammonia or methanol production platforms (iii) for designing and qualifying storage; export and offloading solutions for the produced hydrogen carrier (e.g. ammonia, methanol, etc.).

Structures currently installed and under construction deal with electricity generation, which makes electrical cable systems critical. We propose in the next subsection a state of the art of power cables design and issues. We will review in the following sections how large structures (substations or Power-to-X platforms) are (or could be) designed.

8.2 Cable Systems

Techno-economic studies help quantify the criticality of power cable systems for electricity generation; globally, around 149,300 km of cable is expected to be installed for offshore wind projects by 2035. Haq Duggal, (2024) estimates at around 150,000 km the length of cables to be installed by 2035 for offshore wind systems, leading to around 2200 cable failures between 2024–35. The Global Underwater Hub, (2023) concludes that these failures can lead to up to EUR 20.5 billion repair cost for the same period;[40% for inter-array and 60% for export cables].

Scrutiny to failure causes and claims reveal that the highest insurance settlement costs are linked to Cable Protection Systems and manufacturing faults (Marcollo and Efthimiou, 2024). This relates to the top four causes of cable failure: installation, mechanical failures, external aggression (T. Zhang, Du, et al., 2022f; T. Zhang, Li, et al., 2022g) and cable design (4C Offshore Limited, 2020; Haq Duggal, 2024). Failure rates of static subsea cables were estimated at around 0.00165–0.0213 failures/km/year (Harvey et al., 2024; Marcollo and Efthimiou, 2024), which is several orders of magnitude higher than the target failure rates [10^{-4} for the whole cable system].

Some research was made on the modelling of installation loads (Kuang et al., 2022; Li et al., 2024; Okkerstrom, 2021; Hansen, 2023) to identify critical phases, and analyse the typical loads that impact cable installation to determine the parameters affecting the process. This allowed to determine the optimal environmental conditions for cable installation through the moonpool of a vessel to minimise structural damage were determined.

Another track followed by Jordal et al., (2023) is to test cable strength. They presented a novel axial compression test rig to investigate combined bending/compression of cables. The rig captured adequately the bend curvature and axial compression behaviour of cables by testing.

Large scale mechanical testing of dynamic subsea power cables is essential for qualification, but also enables the determination of key properties and validation of numerical models (Ringsberg et al., 2023; Thies and Georgallis, 2024). These large-scale tests are the first step of a cable system analysis: material tests provide the mechanical properties of the cable, which are used as a basis to global dynamic analysis which itself feeds local strength verification (Marcollo and Efthimiou, 2024). The global models are used as part of the design process to provide a holistic picture of the hydrodynamic response of the cable and estimates of the fatigue life (Liu et al., 2024; Yan et al., 2023) and derive cable cross section loads. These global models can be complemented by local structural modelling to determine the load path through the different layers of the cable, which gives access to stiffness properties as well as the hysteretic behaviour of the cable (Skeie et al., 2023). Nicholls-Lee, et al., (2021) coupled global and local models to improve the understanding of the response of the cable and the influence of local parameters to the behaviour of the whole cable system.

The case of dynamic cables gains attention as more floating structures are being installed. Dynamic cables were found (Harvey et al., 2024) to be potentially subject to failure rates an order of magnitude higher than static cables because of their exposure to fatigue loads. Key to deriving the fatigue damage of each cable layer, various methods have been investigated to improve the understanding of the response of the complex layup of power cables to cyclic loads (Beier et al., 2023; Beier et al., 2024; Beier, 2023; Martinez-Puente et al., 2024; Sobhani, 2021; Sobhaniasl et al., 2020; Svensson, 2020).

The focus has primarily been on copper conductor analysis, which ensure the cables' main function of energy transmission (Bakken, 2020; Poon et al., 2023; Poon et al., 2024; Wan et al., 2022). Another area of focus has been on the water-tight barrier that protects higher voltage conductors from degradation by water. Cables with voltage ratings in excess of 132 kV utilise a metallic lead alloy sheath to do so (Moreno et al., 2021;.Viespoli, 2020; Viespoli et al., 2020; Viespoli et al., 2021), which is prone to work hardening under small strain cycles. The strength of these components is a concern for the industry with the advent of floating offshore substations requiring very high voltage dynamic cables (Guignier et al., 2020; Hung and Yang, 2023), or inter array cables being considered at 132 kV. A solution leading to acceptable performance was to use corrugated-copper instead of lead-based watertight sheathing (Guignier et al., 2020).

The dynamic environment also poses the threat of Vortex Induced Vibrations (VIV) on the cables (Marcollo and Efthimiou, 2024). Numerical investigations have indicated that there may be preferable orientation for the cables, depending on local metocean conditions, to minimise fatigue caused by VIV (Börü, 2021; Delizisis et al., 2022; Shim et al., 2023); however, it has been noted that more information is required for appropriate values, such as Strouhal Number, to improve modelling accuracy. Experimental investigations of a flexible dynamic power cable in lazy wave configurations found that the peak frequencies usually aligned with a Strouhal number of 0.15 for most of the cases (Elrick and Venugopal, 2023; Moideen, et al., 2024).

The industry proposes novel cable designs to overcome these issues. These novel cable structures pose new modelling challenges. Fig. 45 compares conventional cable structures and a novel design where structural members are made of aramid fibres laid with the conductors. This differs from conventional cable structures where the load bearing members are steel wires helically laid around the conductors in so-called tension armours.

Conventional dynamic subsea power cable design (Technip FMC, 2024)

Novel dynamic subsea power cable design (NKT, 2024)

Fig. 45: Current subsea power cables designs

This novel design improves the fatigue performance of the cable by using aramid tension members and reducing the diameter of the copper wires that make up each conductor. The construction also improves the thermal dissipation from the cable which eventually reduces the risk of overheating. Research in understanding these novel material combinations will be required to allow the development of internationally-recognized standards.

With structural health being of paramount concern for dynamic subsea power cables, monitoring and fault identification is key to enable prompt action and reduce farm downtime, and hence revenue. Typical monitoring methods, such as Time Domain Reflectometry, Distributed Strain and Temperature Measurement and Partial Discharge Measurement, heavily depend on thresholds and residual trace analysis, imposing conservative limits or can be easily deteriorated by possible errors leading to an incorrect cable system assessment that does not correspond to the failure condition (Caruso, 2020). Newer monitoring system are being developed, such as SSTDR, that have the potential to detect defects and degradation in the cable and pin-point the fault location to within one meter, but can also provide real-time data streamed to shore for potential development and optimization of a digital twin of the dynamic cable system (Nicholls-Lee et al., 2022).

Digital twins have the potential to help predict failures and optimise operation and maintenance strategies, lowering farm downtime and lost revenue (Jin et al., 2022; Yin et al., 2024).

8.3 Design Standards and Guidelines

As any offshore structure, offshore substations are subject to national requirements. In addition to these regulations, classification societies, which usually act as project certifiers, have issued requirements for these. ABS has issued Requirements for Offshore Substations and Electrical Service (American Bureau of Shipping, 2023) which specifically cover fixed and floating substations. This standard calls for offshore oil and gas rules when it comes to structural strength, floating stability, mooring system design or performance assessment.

Another approach proposed by LR as part of project certification LR-GN-007 Guidance Notes for Offshore Wind Farm Project Certification (Lloyd's Register, 2024a) is to verify the structures of the substations per the same approach as the wind turbines' substructures. In this case, the primary design standard is the family of IEC 61400 standards (International Electrotechnical Commission, 2024), complemented by relevant rules for offshore units (Lloyd's Register, 2024b). Bureau Veritas approach is in the Guidance Note for the Certification of Fixed Offshore Substations for Renewable Energy Projects (Bureau Veritas, 2022), is that the structural design should comply with ISO 19900-series (International Standards Organisation, 2019), which are international oil and gas production standards.

DNV adopts a mixed approach where the safety principles, structural load cases and partial safety factors are defined in the standard for Offshore Substation ST-0145 (DNV, 2020), while the material factors, failure modes, etc. are taken from the offshore structures standards. This leads to having ABS, BV and DNV standards designing against the 100-year return period whereas LR asks to design against the 50-year return period with a different set of safety factors. Each of these classification societies consequently proposes a different design approach with its own safety factors and principles, although eventually accept to design against ISO 19900 series as an alternate. Although these standards explicitly deal with the design of mooring system as well as offshore installation, they do not cover the cable systems.

The Carbon Trust floating offshore wind joint industry project recently reviewed standards related to submarine dynamic power cables, primarily focussing on mechanical, electrical, and fatigue testing (Harvey et al., 2024). The review covered 62 publications from multiple regulatory bodies, including DNV, ISO, API, IEC, CIGRE, ABS, and BV. The standards were categorised based on three criteria:

- Type of cable (static/dynamic)
- Field of application (oil and gas/offshore renewable energy)
- Type of component (cable/ancillaries)

The review identifies CIGRE TB 862 (CIGRE, 2022) as the only directly applicable recommendation to dynamic subsea cables in the renewable energy sector; however, this covers only mechanical testing. The other standards still used are primarily related to the oil & gas industry and bring inherent levels of conservatism that may not be applicable to the floating wind industry. Cable ancillary qualification is still very focused on the API standard RP 17L2 (American Petroleum Institute, 2021).

Power-to-X platforms will include additional systems for the production and processing of hydrogen. Flexible and rigid pipe standards can effectively deal with properties of hydrogen and other products such as methanol or ammonia; only the safety of the installations need to be addressed. Owing to the nature of these fluids, it is likely that extensive explosion, collision and accidental leak load cases should be considered. Material selection will also need to be revised to prevent embrittlement or corrosion of the materials by these products (Hydrogen can embrittle materials (Findley, et al., 2022), ammonia can trigger stress corrosion cracking (National Association of Corrosion Engineers, 2021) while methanol is a solvent for a number of polymers (American Chemical Society, 2013)). In addition, current process piping standards for these products which are mostly used in an onshore environment may need to be revised to reflect the larger volumes handled in a production facility. It is likely that the first installation would be designed by a goal-based approach, and the provisions taken will gradually be reflected in rules. The subjects of the chemical compatibility of offshore construction materials as well as accident-related loads should then be studied to support the revision of standards and the first projects due to be started.

9 Life-Cycle Cost and Operational Management of Offshore Renewable Energy

Offshore renewable energy sources, such as wind farms, wave, and tidal energy, are essential to the global transition to sustainable energy systems. These technologies offer the potential for significant energy generation, contributing to energy security and reducing greenhouse gas emissions. However, the financial viability and operational management of these projects are complex, requiring a thorough understanding of life-cycle costs (LCC) and effective strategies to manage operations throughout the project's lifespan. This report explores the LCC and operational management of offshore renewable energy, focusing on offshore wind farms, wave, and tidal energy. It also provides relevant capacity and cost data to contextualize these discussions. Table 6 summarizes lifecycle cost and operational management aspects of offshore wind farms, wave energy, and tidal energy based on 2023–2024 data.

9.1 Offshore Wind Farms

As of 2023, global installed offshore wind capacity exceeds 75 GW, with substantial expansion expected, particularly in Europe, Asia, and the United States. Offshore wind farms generally have higher capacity factors (40–50%) than onshore wind farms, leading to more consistent energy generation. The costs for offshore wind have been decreasing due to technological advancements and economies of scale. According to the 2024 Global Offshore Wind report by GWEC, the average LCOE (Levelized Cost of Energy) for offshore wind in the second half of 2023 was 114 USD/MWh in the UK and 95 USD/MWh in Germany, with the most competitive projects deployed in China achieving LCOE below 50 USD/MWh. For the US, the 2023 NREL's report provided the LCOE values for the 2022 representative fixed-bottom and floating offshore wind systems (12 MW unit) are estimated at $95/MWh and $145/MWh

- **Capital Expenditure (CAPEX):** Offshore wind farms require significant upfront investment, including costs for turbines, foundations, electrical infrastructure, and installation. The CAPEX for offshore wind projects typically ranges from $2,500 to $4,000 per kW installed.
- **Operational Expenditure (OPEX):** O&M costs are a major component of LCC for offshore wind, often ranging from $80,000 to $150,000 per MW per year. These costs are influenced by the distance from shore, water depth, and the availability of maintenance infrastructure.
- **Decommissioning Costs:** Decommissioning offshore wind farms involves dismantling turbines and foundations and restoring the site. Estimated costs for decommissioning range from $200,000 to $600,000 per MW.

9.2 Wave Energy

Wave energy is an emerging technology, with global installed capacity currently less than 1 GW. The potential for wave energy is significant, particularly in regions with strong wave climates like the North Atlantic, the Pacific Northwest, and parts of Australia. The LCOE for wave energy remains high, ranging from $300 to $500/MWh, reflecting the nascent stage of the technology.

- **CAPEX:** Wave energy projects involve significant CAPEX due to the innovative nature of the technology and the harsh marine environment. CAPEX for wave energy systems can range from $5,000 to $10,000 per kW.
- **OPEX:** O&M costs for wave energy are high due to the technical challenges of maintaining devices in harsh ocean conditions. OPEX can be around $200,000 per MW per year.
- **Decommissioning Costs:** Decommissioning costs are currently difficult to estimate due to the limited number of projects that have reached end-of-life. However, these costs are expected to be high due to the need for specialized vessels and equipment.

9.3 Tidal Energy

Tidal energy, like wave energy, is at an early stage of development, with installed capacity also under 1 GW globally. However, tidal energy is more predictable than wind or wave energy due to the regularity of tidal cycles. The LCOE for tidal energy is currently between $200 and $400/MWh, with expectations of significant reductions as the technology matures.

- **CAPEX:** The CAPEX for tidal energy systems is high, often ranging from $4,000 to $8,000 per kW, due to the engineering challenges posed by underwater installations and the need for robust materials to withstand corrosive environments.
- **OPEX:** O&M costs are influenced by the accessibility of the tidal installation, with OPEX ranging from $150,000 to $250,000 per MW per year.
- **Decommissioning Costs:** Similar to wave energy, decommissioning costs for tidal energy are expected to be significant, reflecting the technical challenges of removing underwater infrastructure.

9.4 Floating PV Systems

Floating Photovoltaic (FPV) systems present a promising renewable energy solution for such applications, especially in regions with limited land availability and extensive water bodies. According to the Solar Energy Research Institute of Singapore (SERIS), as of the end of 2023, global installed FPV capacity had reached approximately 7.6 GWp, marking an increasing global adoption of this technology. Notable global projects in this field include the world's first offshore FPV farm in Leiden in 2019, the 181 MWp offshore solar project in Taiwan, and the 1 MW PV-bos project at Valencia harbor in Spain in 2024. The increase in FPV installations, along with the advancements in technology, has brought down FPV CAPEX cost from a median of 2.41 USD/Wp in 2015 to 1.05 USD/Wp in 2023

9.5 LCC Optimization Strategies

For all offshore renewable energy types, optimizing LCC involves:

- **Design for Reliability:** Integrating reliability into the design phase to minimize maintenance needs and extend operational life.
- **Predictive Maintenance:** Utilizing real-time monitoring to anticipate and address maintenance issues before they lead to costly failures.
- **Modular Design:** Adopting modular approaches to facilitate easier maintenance and upgrades, thereby reducing both OPEX and downtime.

Operational Management of Offshore Renewable Energy

Operating offshore renewable energy installations poses several challenges, including harsh environmental conditions, high maintenance costs, and logistical difficulties. Effective operational management is crucial for overcoming these challenges and ensuring the longevity and profitability of the project.

Remote Monitoring and Control

- **Real-Time Data Collection:** Advanced sensors and data acquisition systems are essential for monitoring performance, detecting anomalies, and optimizing energy output.
- **Automated Control Systems:** These systems enable remote adjustments to operational parameters in response to environmental changes, ensuring optimal performance and safety.

Maintenance Strategies

- **Preventive Maintenance:** Regularly scheduled maintenance activities are essential to prevent equipment failures and extend the life of the installation.
- **Corrective Maintenance:** Rapid response to operational issues minimizes downtime and ensures that energy production is restored quickly.
- **Condition-Based Maintenance:** Leveraging data from monitoring systems to perform maintenance only when needed, reducing unnecessary costs.

Supply Chain and Logistics

- **Logistics Planning:** Efficiently managing the supply chain and logistics, particularly for remote or hard-to-access sites, is crucial to minimizing delays and costs.
- **Inventory Management:** Maintaining a strategic inventory of spare parts and critical components ensures that repairs can be carried out promptly without extended downtimes.

Technological Innovations

- **Digital Twin Technology:** Creating digital replicas of offshore installations allows for simulation and optimization of operational strategies.
- **Autonomous Maintenance Systems:** The use of drones and autonomous underwater vehicles (AUVs) for inspection and maintenance is reducing human intervention and improving safety.
- **Integrated Energy Systems:** Integrating offshore renewable energy with other systems, such as hydrogen production or battery storage, enhances energy efficiency and provides greater flexibility in managing energy output.

The life-cycle cost and operational management of offshore renewable energy systems, including wind, wave, and tidal energy, are critical to the economic viability and long-term success of these projects. As the offshore renewable energy sector continues to grow, ongoing innovation in technology and management practices will be essential to overcoming the challenges posed by the harsh marine environment. By optimizing LCC and implementing effective operational management strategies, stakeholders can ensure that offshore renewable energy projects contribute significantly to global energy goals while maintaining financial and environmental sustainability.

Table 6: Summarizing lifecycle cost and operational management aspects of offshore wind farms, wave energy, and tidal energy based on 2023–2024 data.

Aspect	Offshore Wind Farm	Wave Energy	Tidal Energy	Floating Solar
Installed Capacity	>75 GW globally	<1 GW globally	<1 GW globally	>7 GW globally
Capacity Factor	40–50%	25–35%	25–45%	18–25%
LCOE	\$50–\$70/MWh	\$300–\$500/MWh	\$200–\$400/MWh	\$60–\$120/MWh
Capital Expenditure (CAPEX)	\$2,500–\$4,000 per kW	\$5,000–\$10,000 per kW	\$4,000–\$8,000 per kW	\$1,000–\$2,500 per kW
Operational Expenditure (OPEX)	\$80,000–\$150,000 per MW/year	\$200,000 per MW/year	\$150,000–\$250,000 per MW/year	\$25,000–\$50,000 per MW/year
Decommissioning Costs	\$200,000–\$600,000 per MW	High (limited data)	High (limited data)	\$50,000–\$150,000/MW
Key Maintenance Strategies	Preventive, Corrective, Condition-Based	Preventive, Corrective, Condition-Based	Preventive, Corrective, Condition-Based	Preventive, Corrective, Condition-Based

(*continued*)

Table 6: (*continued*)

Aspect	Offshore Wind Farm	Wave Energy	Tidal Energy	Floating Solar
Monitoring & Control	Real-time data collection, automated control systems	Real-time data collection, automated control systems	Real-time data collection, automated control systems	Real-time monitoring, automated cleaning systems
Supply Chain & Logistics	Complex due to remote locations and large components	Complex due to specialized equipment and harsh conditions	Complex due to underwater installations	Moderately complex
Technological Innovations	Digital twins, autonomous maintenance, integrated energy systems	Autonomous maintenance systems, digital twins	Autonomous maintenance systems, digital twins	Floating array optimization, hybrid systems, anti-fouling coatings
Operational Challenges	Harsh marine conditions, accessibility, high O&M costs	Harsh marine conditions, high O&M costs, early-stage tech	Harsh marine conditions, accessibility, early-stage tech	Biofouling, water-body regulations, storm resilience
Regulatory Compliance	Established frameworks, evolving environmental regulations	Evolving regulations, less established than offshore wind	Evolving regulations, less established than offshore wind	Emerging frameworks, less established than offshore wind

10 Main Conclusions and Recommendations for Future Work

This report documents the significant progress made in offshore renewable energy technologies while highlighting key challenges that must be addressed for further advancement. Offshore wind energy, particularly bottom-fixed and floating wind turbines, continues to be the most mature sector, benefiting from ongoing innovations in turbine efficiency, structural integrity, and digital monitoring. The development of wave, tidal, and floating solar photovoltaic (FPV) systems is also gaining momentum, offering additional renewable energy sources to complement offshore wind farms.

One of the primary takeaways is the critical role of digital technologies in enhancing the performance, reliability, and economic viability of offshore renewable energy systems. Digital twins, artificial intelligence (AI), and predictive maintenance strategies are proving to be invaluable in optimizing operations, reducing unplanned downtime, and extending the lifespan of offshore installations. The integration of real-time data analytics with structural health monitoring further ensures that maintenance and operational strategies remain efficient and cost-effective.

From a structural perspective, the industry must address challenges associated with extreme environmental loading, fatigue life, and material performance. Offshore renewable structures are exposed to highly dynamic and unpredictable forces, including wind, waves, currents, and seismic activity. Innovations in structural materials, including advanced composites and corrosion-resistant alloys, are essential in ensuring the longevity and reliability of offshore installations. Additionally, improvements in foundation design, mooring systems, and hydrodynamic modeling are critical in mitigating structural fatigue and optimizing load distribution. Additional research into mechanical behavior of connections within offshore wind turbine towers is also crucial.

The ongoing development of floating renewable energy systems presents unique structural challenges, particularly in the areas of stability, dynamic response, and mooring integrity. Advanced numerical simulations, coupled with large-scale physical testing, are critical in validating design methodologies and ensuring the successful development and deployment of floating structures in deep-water environments. Hybrid solutions that integrate wave and wind energy must also be carefully engineered to balance load interactions and maximize efficiency without compromising structural integrity.

The committee believes that future investigation of digital twins integrated with computational fluid dynamics (CFD) and machine learning is key. Such integration enables predictive maintenance extending service life and wider financial viability, and further optimisation and improvements of structural health monitoring will reduce the fundamental differences between numerical models and operation reality.

Economic and logistical considerations play a pivotal role in the viability of offshore renewable energy projects. These topics extend beyond traditional marine structural design but are addressed here due to their critical impact on the practical implementation and economic feasibility of offshore renewable energy systems. Future work should explore these interdisciplinary aspects further, and their impact on the unique design features of offshore renewable energy devices.

Looking ahead, the offshore renewable energy industry must focus on expanding research and development efforts, scaling up successful pilot projects, and fostering international cooperation to accelerate the transition to a cleaner and more resilient global energy system. By leveraging technological innovations, improving economic strategies, and refining regulatory frameworks, offshore renewable energy can become a cornerstone of sustainable energy production for future generations.

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