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STEP4WIND

Training network in floating wind energy

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1. Introduction

This document collects the literature review provided by the ESRs.

2. ESR 1: Likhitha Ramesh Reddy

With the successful operations of the existing floating wind farms, Floating Offshore Wind Turbines (FOWT) are a promising technology to harness more offshore wind energy by exploiting high wind speeds in regions of deep water. The standardisation of offshore wind systems is difficult due to dissimilar offshore conditions like water depth, wind and wave conditions, seabed properties. An accurate coupled analysis of these systems can lead to the right choice of the sub-system, making it economical. One of the critical design aspects is the accurate prediction of hydrodynamic loading on the substructures leading to the precise estimation of the Fatigue Limit State(FLS) and Ultimate Limit State(ULS), ensuring a safe design of the floater. Numerical methods of varying fidelity are used to predict the physical behaviour of the system and the accuracy of these tools define the correct estimation of ultimate and fatigue loads.

Numerical modelling of floating offshore wind turbines

Irrespective of the substructure type, it is a huge challenge to foresee the floater behaviour in all the metocean conditions expected during its lifetime. It is critical to identify the optimal solution that provides maximum efficiency and endurance at the least possible cost. Engineering models are employed to study the floater performance at multiple scenarios in less time.

Linear wave models based on potential flow theory are used to obtain hydrodynamic coefficients related to diffraction and radiation. These models assume the flow to be inviscid, incompressible, and rotational. This theory is only valid for larger structures compared to the wave characteristics (I and II in Figure 1). Some of the most used frequency-domain tools are WAMIT, NEMOH, and ANSYS-AQWA. These hydrodynamic coefficients are often used in time-domain simulation tools, which models the viscous effects using Morison's equation[1]. In this model, the drag coefficients using empirical relations are accounted for the structural members of the substructure, which is valid only for slender structures. Figure 1 describes the validity of these models based on the wave characteristics and geometrical parameters. The ratio of wave height H, to characteristic length D, is equivalent to the Keulegan-Carpenter(KC) number, while represents the diffraction parameter.

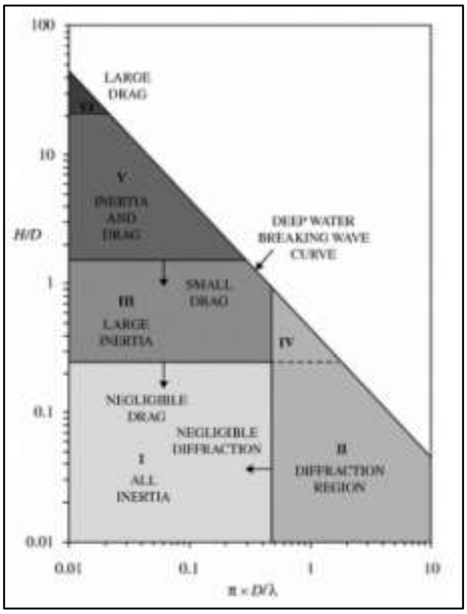

Figure 1: Wave loads according to H, D, and λ[2]

The IEA code comparison campaign OC5 and OC6 demonstrated a persistent under prediction of the non-linear low-frequency responses of the DeepCwind semisubmersible that implied the need for higher fidelity models, (detailed explanation in Appendix 1). In this regard, nonlinear effects are added in the linear potential models by including Quadratic Transfer Functions (QTF) to model the difference-frequency and sum-frequency wave loads. The difference frequency term consists of low-frequency contributions (wave drift force). However, this is just a weak formulation.

Fully non-linear potential flow models are based on Boundary Element Method (BEM), Finite Element Method (FEM), or Finite Volume Method (FVM) [3]–[5]. One possible way to accurately determine and represent the physics is using Navier-Stokes based solver to understand the Fluid-Structure Interaction(FSI) problem in question. Several studies ([6]–[9]) conducted on this front shows that computational fluid dynamics (CFD) better predicts the hydrodynamic loading. Nonetheless, FSI simulations of complex geometries are expensive and cannot be implemented as an industrial solution. Therefore, there is a need to either improve the computational efficiency of CFD models or improve the existing engineering models to account for non-linear and viscous effects.

Efforts have been made to improve the currently existing engineering models for the semisubmersible in many ways. One of them is to calibrate or tune the hydrodynamic coefficients like added mass, and damping based on the results obtained from the experiments or CFD. Furthermore, the semisubmersible design incorporates heave plates attached to the base of its columns to reduce the heave motion by providing supplementary added mass. Heave plates also enhance flow separation and vortex shedding effects that produce viscous damping, and these factors call for high fidelity simulation tools that accurately capture the non-linear hydrodynamics[10]. CFD methods found the added mass and damping were largely dependent on the motion amplitude and viscous effects were predominant in the damping term, both of which are incompatible with the assumptions of linear potential flow theory. Some studies [11], [12] extracted the damping coefficients from CFD simulations of free decay motions of a semi-submersible FWT and demonstrated that CFD methods can better quantify the viscous damping characteristics. In addition, Li et al. also modified the QTFs based on the bichromatic wave CFD simulations that provided better estimation of difference-frequence wave loads[13]. Additionally, at the low surge and pitch resonance frequencies, viscous damping generally dominates over the wave radiation damping. In phase 1 of OC6, increase in the transverse drag coefficient increased the low-frequency force better predicting the hydrodynamic loads. Therefore, there was significant focus in the tuning viscous drag coefficients. Böhm et al. tuned the transverse drag coefficient for the columns and the axial/normal drag coefficient for the heave plates for an OpenFAST model of the OC5-DeepCwind semisubmersible using a global pattern search algorithm[14]. Modifications are made for OpenFAST model to account for depth dependent transverse drag coefficient and wave stretching.

Literature Gap

In the literature, the effect of heave plates on the hydrodynamic coefficients is not fully explored. Questions regarding the drag coefficients for different geometries of heave plates and drag force in bichromatic waves needs to be addressed. Moreover, the prediction of the drag force by engineering models in comparison to CFD is yet to be established. Further, though there is information about the non-validity of the engineering models, there is no clarity in the design approach and numerical models required. The use of CFD in the design process is not well-defined. Additionally, certain modified engineering models have been implemented within OpenFAST and other solvers, whose validity domain is not well established.

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3. ESR 2: Ricardo Pinto Elisbão Martins Amaral

Offshore wind energy is set to be one of main game-changing pillars of the clean energy revolution that we are experiencing today with the potential to add 5000 GW of capacity in Europe and the UK alone [1]. However, 80% of this capacity is located in deep waters (> 60 m depth) where traditional fixed-bottom wind turbines can't reach in an economically feasible way [1]. This is where floating offshore wind turbines (FOWT) come to play whereby their floater manages to evade most of the cost increase with depth characteristic of fixed bottom substructures. In spite of this promising feature, new challenges arise in the dynamics, structural integrity and control of FOWT. Since the substructure is now free to move and is subjected to hydrodynamic and aerodynamic loads, the whole system, namely the rotor may undergo large motions which in turn can cause large variations in time of the inflow velocity at each point in the blades. Depending on the magnitude of these variations, the rotor may leave the normal operating state to enter much more unsteady states such as the vortex-ring state characterized by the recirculation of the wake's vortices in the blades or even the propeller state where the wind velocity direction relative to the rotor is reversed [2]. These situations go far beyond the simple and practical assumptions like flow steadiness and attachment used to derive computationally efficient engineering models such as the blade element momentum theory (BEMT) [3] and thus, the ability that BEMT-based aerodynamic models have to accurately predict loads and energy yield of FOWT is questionable and needs further investigation. S. Mancini et al. [4] compared different modelling tools to experimental data coming out of the UNAFLOW experiment (Bernini et al., 2018). Each modelling tool was based on different aerodynamic models. From lowest to highest fidelity, these aerodynamic models were: blade-element momentum theory (BEMT), free-vortex wake (FVW), actuator line (AL) and the Reynold-Averaged Navier-Stokes equations (RANS). For a prescribed surge motion amplitude of 8 mm and frequency of 2 Hz, the rotor thrust time-series showed good agreement with the experimental data for all the models. The mean thrust variation showed a good agreement for all the test matrix's entries. Unsteady thrust and power coefficients normalized by the amplitude of the prescribed motion fall into a linear trend confirming the regime to be quasi-steady. Nevertheless, there was no further exploration outside of this range which is where BEMT-based models will likely diverge. Other degrees-of-freedom (DOF) were not explored. T. Tran et al. [5] performed single-DOF simulations using a set of three different BEMT-based aerodynamic models and a RANS-based model. In the simulations, the NREL 5-MW turbine was prescribed sinusoidal pitch motions with different amplitudes and frequencies. The simulations involving BEMT-based models consistently overpredict the rotor power and thrust when compared to the RANS-based model, with one exception for the simulation with the highest amplitude and frequency using one of the BEMT-based models. The other two still over-predict the mentioned physical quantities. Two different aerodynamic models of FAST [6] were compared but for a very low number of cases and other aerodynamic models were active during this comparison which may have skewed the results. Further literature review on this topic suggests that the influence and behaviour of the several aerodynamic models that can be incorporated in a standard BEMT-based simulation tool was not comprehensively investigated nor validated for the many different possibilities of floating motion.

Another relevant topic which is connected to the previous is the assessment of floating turbine performance in controlled conditions. R. Farrugia et al. [3] used a FVW-based simulation tool to assess the performance of the NREL 5 MW Baseline FOWT under prescribed surge motion, steady and uniform inflow and constant rotor speed. In the paper, it is shown that the amplitude of the variations in rotor thrust and power coefficients increases with the amplitude of the surge motion. The average value of the rotor thrust coefficient increases with surge amplitude while the average value of the rotor power coefficient decreases. These variables show similar trends with the frequency of the prescribed motion for different tip-speed ratios (TSRs). The amplitude of the variations in rotor thrust and power coefficients shows a maximum at a given frequency. The average value of the thrust decreases monotonically with the frequency, with one exception for the above-rated TSR. The similar behaviour for different TSRs breaks down when analyzing the average power coefficient. It increases with frequency for above-rated TSR, increases slightly with frequency for rated TSR and decreases with frequency for below-rated TSR. C. Lienard et al. [7] once again analyzed the performance of the NREL 5 MW wind turbine, this time with two simulation tools. The turbine's rotor was rotating at constant speed. Sinusoidal surge and pitch motions with different amplitudes were prescribed to the turbine, at a single frequency. The first simulation tool was RANS-based and it suggested that the average power produced by the turbine would increase with the amplitude of the prescribed motion for both surge and pitch whereas the average thrust would decrease for both cases. Vortex-ring state is forecast for the highest amplitude of surge (16 m) and pitch (8 deg). R. Kyle et al. [2] investigated if vortex-ring and propeller states could occur on the NREL 5 MW turbine under realistic wind and sea-state conditions using RANS-based simulations. The rotor speed was constant throughout all the simulations. Thrust coefficient analysis revealed that under these conditions, the flow states above stated could occur. Z. Chen et al. [8] further analyzed the NREL 5 MW turbine model under prescribed surge, pitch and surge and pitch simultaneously using RANS-based simulations. Mean values of rotor power and thrust seem to be little affected by the amplitude and frequency of the prescribed surge motion. For prescribed pitch, a combination of high amplitude and frequency seems to lead to a significant increase in average power but only a slight decrease in average thrust. For simultaneously prescribed surge and pitch, there is a slight increase in power when the pitch amplitude increases but less steep than the single-DOF pitch motion simulations. Average thrust is almost unaffected. Increasing either the amplitude or frequency in all the three different types of prescribed motion leads to a higher difference between the maxima and minima of power and thrust, which corresponds to an increase in the amplitude of the variations. The literature on this topic is typically restricted to surge and pitch and a very low number of amplitudes and frequencies. Moreover, large turbines in line with the ones currently being employed (around 10 MW) and future ones (around 15 MW) are seldom if never chosen for scientific papers written of this topic.

All in all, it is necessary to assess the effect of the whole diversity of aerodynamic models that can be used in engineering-level simulation tools, typically BEMT-based, which represent the state-of-the-art tools used in academia and industry when the turbine has an added motion due to the floater; it is necessary to assess the impact on the turbine performance of the floater motion in the whole range of possibilities for all six DOFs and it is necessary to validate or refute the use of these models to FOWT performance assessment by means of higher-fidelity tools such as large-eddy simulations.

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4. ESR 3: Deepali Singh

Topic: Probabilistic surrogate modelling of floating offshore wind turbine loads

It is necessary to push the technological boundaries in the renewable energy sector to cope with the rising energy demand worldwide while meeting the aggressive climate goals set by many countries to tackle climate change. Offshore wind energy has shown tremendous potential in recent years. The International Energy Agency's offshore energy outlook in 2018 estimates the offshore and floating offshore sites worldwide to generate as much as 160-350 GW of wind power by 2040 in Europe alone. The emergence of floating wind technologies is the next big step in wind energy. It opens access to offshore regions with >50m water depth, typically unsuitable for fixed bottom structures. Floating offshore farms benefit from higher capacity factors and lower hourly fluctuations in energy production thanks to consistent, high-quality wind conditions. Depending on the type of floating platform, the wind turbine can also be towed to the location, potentially reducing installation costs. The installation noise emissions impacting marine life are lower for FOWTs as most of the turbine assembly is done onshore [1]. FOWTs do not face the same opposition fixed offshore or land-based wind turbines face concerning obstructing views or aeroacoustic disturbance to the human population. As a result, they can be much larger, with future wind turbines as large as 240m in diameter.

The design of such mega-structures comes with new technological challenges. FOWTs are complex machines with various new components such as the floating platform, mooring lines, and dynamic cables. They are subject to irregular waves and turbulent wind loads, resulting in a 6 degree of freedom motion, unsteady aerodynamics, and complex control systems. As such, the loads and performance of the wind turbine are a combined function of the aerodynamic and hydrodynamic forces and the structural response of the component's material. The numerical design and conception of FOWTs are incredibly complex and expensive. It is due, in part, to the coupled aero-servo-hydro-elastic simulations, longer simulation duration, and the additional cases that need to be simulated to include wind-wave misalignment and extreme weather conditions (IEC61400-3-2). For instance, simulations made at every 2m/s as dictated by the certification guidelines lead to 10 simulations in the wind speed dimension. With n such parameters significantly impacting fatigue loads, the total number of simulations can quickly scale up to 10^n [2]. It is necessary to carry out the high fidelity simulations as it is a strict requirement for certification. However, surrogate models can help minimize the computational overhead either in the conception or the site-selection phase.

A surrogate model is a simpler and computationally inexpensive representation of the full-order model that emulates the outputs as a function of the inputs. The full-order model is typically a computational code, but it can also consist of real-life measurements. Surrogates are typically used as an engineering tool to do preliminary design calculations, optimization, or real-time control, where accuracy can be traded for computational efficiency. System-identification methods or data-driven surrogate models derive the dynamical system's behaviour based on the relationship between the inputs and the outputs. In this approach, the computer code is assumed to be a black box and the physics unknown to the user. It has the advantage of the ease of implementation in very complex systems where analytical closed-form solutions are intractable.

With the recent advancements in machine learning, many data-driven methods have been explored for fatigue load prediction. Zwick et al. [3] use piecewise linear regression and linear statistical models to fit fatigue loads as a function of the wind speed. Artificial neural networks (ANNs) are also prevalent due to their ease of implementation, robustness, and scalability. Mueller et al. [4] use ANNs to model fatigue load response surfaces for FOWTs but concluded that the ANN regression could not fit the data satisfactorily due to excessive noise in the responses. Schroeder et al. [5] predict blade root flapwise damage-equivalent loads using ANNs for the DTU−10MW offshore wind turbine under aerodynamic loading and indicate excellent performance in terms of accuracy and robustness. Dimitrov et al. [6] reproduce blade root and tower base load time series using SCADA measurements of rotor speed, power production, wind speed, pitch angles, and tower top accelerations sufficiently well using ANNs.

Non-parametric approaches like the Gaussian process regression (GPR) have been evaluated by Texeira et al. [7] for the uncertainty quantification of fatigues loads on offshore wind turbines with wind and wave input. Abdallah et al. [8] use hierarchical Kriging by first training a Kriging model on low-fidelity training data. The low-fidelity Kriging model is then used as a model trend to fit a Hierarchical Kriging model on high-fidelity data. The motivation is to reduce the epistemic uncertainty associated with the choice of the simulation fidelity and develop a framework to search for the best Kriging parameters(hyperparameters, correlation family, etc.) that are not known a priori. They compare the performance of the hierarchical Kriging vs. the standard Kriging tuned on engineering judgment to find notably better predictions by the hierarchical model. Zhu et al. [9] treat the response as a random variable and introduce a joint polynomial chaos expansion- generalized lambda distribution (PCE-GLD) algorithm to model the probability density function (PDF) of the response. The parameters of the lambda distribution are calibrated from the data using the maximum likelihood estimate. The model is shown to accurately predict the PDF for a simple test case of a fixed-bottom wind turbine with aerodynamic loading. The main advantage of this method is that it does not assume a Gaussian distribution for the responses and accounts for the heteroscedasticity in the noise. A few authors also compare different data-driven approaches, both parametric and non-parametric. Gasparis et al. [10] compare linear regression, ANNs, and Gaussian process regression for modelling power and fatigue loads, showing a superior performance by the GPR. Similarly, Dimitrov et al. [11] evaluate importance sampling, nearest-neighbour interpolation, polynomial chaos expansion (PCE), GPR, and quadratic response surface (QRS), to conclude a better performance again by the GPR despite a computational penalty.

There exists a research gap in the literature as data-driven, especially probabilistic data-driven models, have not yet been widely investigated for FOWT loads prediction.

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5. ESR 4: Matteo Baudino Bessone

Floating wind is a promising source of renewable energy, as floating foundations enable the exploitation of wind resource in deep waters, where conventional bottom-founded offshore wind turbines are no-longer economically attractive [1]. This enables to reach new markets [2], exploit more abundant, far offshore wind resource, and reduce the environmental and visual impact of the wind farm [3]. Forecast for floating wind foresee a tremendous growth of the installed capacity, together with a significant reduction of the cost of floating wind [1], [4].

At the same time, floating wind is still a relatively novel field, and there is no large-scale floating wind power plant in operation or under construction. However, we can infer the complexity of the design process for floating wind farms by comparison with the related fields of bottom-founded and onshore wind. Similarly, the design of a floating wind farm will involve dealing with several subsystems, such as the floater [5], [6], the station keeping system [7], or the power collection system [8], and procedures, such as the definition of the layout of the farm [9], or the operation and maintenance (O&M) strategy [10].

Although the interest in the design of wind farms has considerably grown in the last decade, there are only a few works dealing with the design of floating wind farms, most likely due to the novelty of the field and the lack of large-scale floating wind farms in operation.

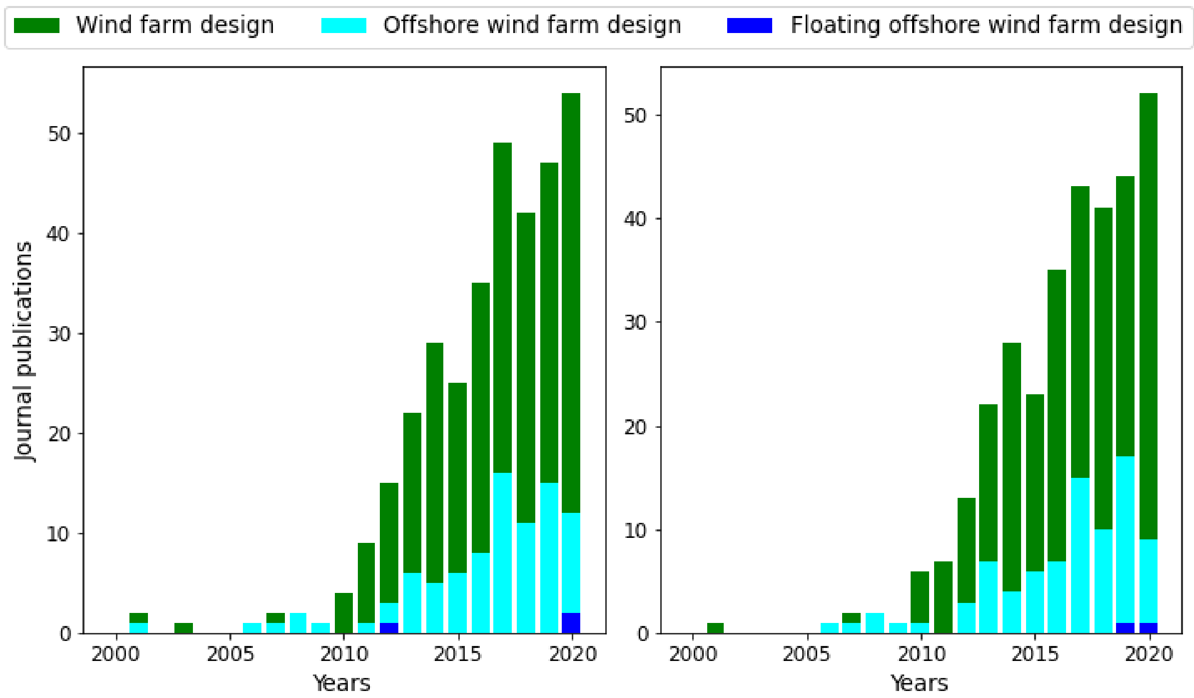

Figure 1: Number of Journal publications related to wind farm design based on Scopus and Web of Science databases

A preliminary work was carried out by Castro-Santos et al. [11], who compared different power collection configurations, installation and maintenance strategies for floating wind farms. Forinash and DuPont [9] optimised the layout of an offshore floating wind farm by minimising costs and maximising revenues from energy production, and compared the result with an optimised onshore wind farm, observing that both the onshore and floating offshore case achieved a similar performance, although in the floating offshore wind farm more turbines were implemented to offset the larger costs. Connolly and Hall [12] introduced different configurations for shared-mooring, pilot-scale floating wind farms, concluding that there is potential for cost savings from shared-moorings from 400 m water depth onwards. Both the works of Kheirabadi and Nagamune [13] and Wu et al. [14] leveraged on the possibility to modify the layout of the floating wind farm in real-time, taking advantage on the non-fixed foundations. Kheirabadi and Nagmune investigated the potential of passive Yaw and Induction-based Turbine Repositioning (YITuR) control strategy, while accounting for parameters such as mooring length and orientation, and anchoring position. Wu et al., instead, individuated the optimal layout of a floating wind farm for every month of the year by maximising its economic benefit. Lerch et al. [15] optimised the power collection system of a floating wind farm and compared a cable configuration where both dynamic and static cables were installed for the power collection system, and a configuration with only dynamic cables. They showed a reduction of cable cost and cable losses when compared to the reference topology presented in LIFES50+, and that the configuration with only dynamic cables is superior to the mixed configuration.

Similarly to what was mentioned for the complexity of the field, much could be learned about the design process of floating wind farms by drawing a parallel with conventional, bottom-founded wind power plants. The design process for conventional offshore wind farms can be defined sequential, or partitioned [16], [17], with different companies or offices undertaking a portion of the design process. Although this approach has underpinned the growth of the offshore wind industry to these days, it inherently overlooks the interactions embedded at the interface between the different subsystems. At the same time, there is a growing evidence that applying a more comprehensive, systems engineering approach to the design of offshore wind farms leads to improved results when compared to a conventional approach. Pillai et al. [18], [19], presented a comprehensive approach to optimise the layout of an offshore wind farm, accounting for both energy production and costs dependent on the layout of the farm, such as the cost of the power collection system and the cost of the foundations, wrapped into the Levelised Cost of Energy (LCoE) metric. The framework was then applied to the optimisation of Middelgrunden offshore wind farm [20]. Hou et al. [21] developed a methodology to optimise concurrently the layout of the wind farm, the substation position and the power collection system. They showed that the simultaneous optimisation results in a larger improvement of the Levelized Production Cost (LPC) for the Norwegian centre for off-shore wind energy (NORCOWE) reference offshore wind farm than a traditional approach based on optimising first the layout and then the power collection system. Sanchez Perez-Moreno et al. [17] applied the Multidisciplinary design Analysis and Optimisation (MDAO) technique to optimise the Borssele III wind farm, accounting for wind farm layout, foundation design, substation location and power collection system design. They showed that the application of MDAO enables to exploit the trade-offs between different subsystems, yielding a lower LCoE than a sequential approach.

Although there is a growing evidence that comprehensive design methodologies yield better farm design than traditional sequential approaches in the case of bottom-founded offshore wind, and that applying there is no application yet of a systems engineering methodology, such as MDAO, to floating wind systems can have an higher impact than for bottom-founded wind [22], there is still not application of this methodology to the design of a floating offshore wind farm, nor indication of the most relevant trade-offs that should be considered to yield a better design.

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6. ESR 5: Felipe Miranda Novais

Hardware-in-the-Loop Experiments of Floating Offshore Wind Turbines

Due to the complex dynamics involved in Floating Offshore Wind Turbines (FOWT), whose motions are a compound interaction of turbine, wind, current and waves, there is a necessity of a comprehensive understanding of the servo-aero-hydro-elastic codes utilized during the design and certification processes, demanding the validation and calibration of such tools through high-fidelity simulation or representative data. A common practice utilized by the maritime industry for research and development of floating structures is to make use of scaled models, an approach that allows, under a safe and controlled experimental environment, to investigate the behaviour of the system at a lower cost and shorter time span under different defined external loading conditions [1].

Model test of FOWTs has been a valuable tool at this early stage of the industry as means to understand the overall dynamics of the system, identify the presence of any unforeseen phenomena, evaluate the system's response under extreme environmental conditions as well as to provide a baseline for validating numerical models and calibrating hydrodynamic coefficients [2]. Indeed, code comparison campaigns, such as the OC5 Phase II [3], made a significant effort to compare different engineering tools utilized by both the industry and the academia, noticing an underprediction of ultimate and fatigue loads by several medium-fidelity simulation codes when compared to physical experiment, reinforcing the importance of model testing to mitigate risks and uncertainty involved on the development of the technology.

In order to perform a scaled model test of a FOWT, it is necessary to simultaneously reproduce both wind and wave loads. However, a challenge is set since the aerodynamic and hydrodynamic components follow different scaling principles. While ocean basin tests are commonly based on the Froude scaling for representing wave and gravity forces, the blade aerodynamics requires a high Reynolds number to be able to represent a full-scale rotor [4]. Nonetheless, there is a clear conflict when trying to apply both scaling approaches at the same time as they follow different physical laws, demanding each a divergent length scale parameter. Therefore, the incompatibility of downscaling components with two different fluid-structure-interaction must be compensated, otherwise, it might compromise the ability of the model to represent the true-to-scale wind loads [5].

Several approaches have been proposed to overcome the Froude-Reynolds scaling issue. One solution has been to instead of geometrically downscale the turbine's blade, utilize a low-Reynolds numbers airfoil with increased chord length, and by doing so, achieve a better agreement with respect to the desired thrust force, which is the main driver of the coupled rotor platform-dynamics, a re-design process that is usually referred to as performance scaling [6][7].

Changes to the physical setup can also be utilized to circumvent the dissimilitude of scaling laws, passive methods such as using a wire with constant horizontal force or a drag disk combined with wind fans could be utilized to emulate a steady mean thrust. However, these simplified techniques neglect important aerodynamic effects [2]. Another method is to utilize a software-in-the-loop approach, also referred to as hybrid testing, where the experiment is conducted by performing the real-time coupling between physical measurements and numerical simulation, applying a set of actuators to impose the calculated forces, or desired motion, on the model.

In a wave basin, the hybrid approach consists of substituting the rotor-nacelle-assembly by an actuator system. [7] performed a test campaign utilizing controlled ducted fans, which were used to emulate the varying rotor thrust, and a simulation, which was used to calculate aerodynamics loads and rotor's response, was being fed in real-time with the displacements and velocities of the platform measured by a set of sensors. In [8] a cable-based hybrid approach was validated against an experimental setup with a physical rotor. Different kinds of actuators have also been utilized to conduct test campaigns in different facilities, as tendons [9], winches [10] and a multi-fan system [11][12]. The main bottleneck of utilizing this sort of emulation technique is related to the choice of the actuator, in [13] performances requirements are discussed for the selection of the actuation mechanism. In [14] an analysis was conducted to evaluate the effect over that simplifying some of the aerodynamic physics involved would cause to the platform motion. Recently, hybrid testing was also utilized as a method for the validation of control strategies, testing a pitch individual control and a generator torque controller combined with a gain-scheduled collective blade pitch controller [15].

The utilization of hybrid modelling has also been adapted to be utilized in a wind tunnel. The floating structure response, hydrodynamic loads and mooring lines dynamics are now simulated numerically, and the aerodynamic loads are physically generated. Politecnico di Milano developed an approach by placing the hybrid setup at the atmospheric boundary layer test section of the GVPM wind tunnel, firstly employing two hydraulic actuators to emulate the pitch and surge dynamics of the platform [16] and more recently utilizing a parallel kinematic robot, the HexaFloat, which was developed within the scope of the LifeS50+ project [17], and is able to represent the motion over the 6 degrees-of-freedom. The model has already been utilized on several occasions and for different testing purposes, the fact that the facility has the capability of generating a high-quality controlled wind field and the actuator device could be utilized to impose motions within a certain amplitude and frequency, allows the investigation of complex phenomena involved in FOWTs, such as wake dynamics[18][19], validation of numerical aerodynamic models [20], evaluation of the effects of the unsteady behaviour of the turbine rotor aerodynamics [21]. Tests were also conducted in closed-loop, using the HexaFloat's hardware-in-the-loop system to emulate a semisubmersible OO-Star platform, feeding the numerical model with measurements extracted from a 6-components force transducer placed at the base of the setup's tower, and that way, feeding the numerical model with the measured loads and setting the set-point for the actuator system [22]. A comparison study between wind tunnel and wave basin hybrid testing was conducted in [23], proposing also recommendations for combined use.

Despite the significant development that model testing of FOWTs has achieved in recent years, there are still many challenges to overcome. As pointed out in [1], more critical comparisons between the emulation techniques and facilities are needed to eliminate uncertainties involved and improve the overall understanding of these complex systems. As each modeling approach, both numerically and physically, presents its own advantages and disadvantages, an important development step is to cross-validate techniques, and by doing so, identify limitations and optimize the combined use between different methods.

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7. ESR 6: Alejandro Jiménez del Toro

Wind energy industry trends towards larger wind turbines, with wind turbine blades (WTBs) above 100 meters long, especially for offshore wind farms. Such blades bring new challenges to design, manufacturing methods and materials that need to be addressed. Carbon fibre (CF) reinforced composites are used in load bearing components, such as the spar caps, to achieve greater stiffness while minimising weight. Compared to traditionally used glass fibre composites, CF composites have lower compression strength, due to the smaller diameter of the fibres, and are significantly more expensive. It is paramount for CF composite to ensure good fibre alignment to maximise their properties, therefore automated manufacturing methods are preferred. Currently, CF spar caps are mainly manufactured by pultrusion of CF reinforced thermoset composites. Greater design flexibility, optimisation and integration could be achieved by means of automated tape placement (ATP) in combination with thermoplastic composites (TCs). TCs have several advantages over thermoset ones, such as ease of automation, storage and recyclability.

Automated tape placement (ATP) is an automated additive manufacturing technology that sequentially places pre-preg CF reinforced tapes following a pre-established path, until the part is laid up (*Figure 1*). It is common to use a laser as the heat source for thermoplastic composite manufacturing, in which case the technology is called laser-assisted ATP (LATP). TCs can be processed in the order of minutes or seconds, and ATP can benefit from their in-situ consolidation capabilities, which consists of the full consolidation of the part by means of pressure exerted by the ATP head. Hence, manufacturing of spar caps for large wind turbine blades of carbon fibre reinforced thermoplastics by means of LATP with in-situ consolidation could be an alternative to thermoset pultrusion.

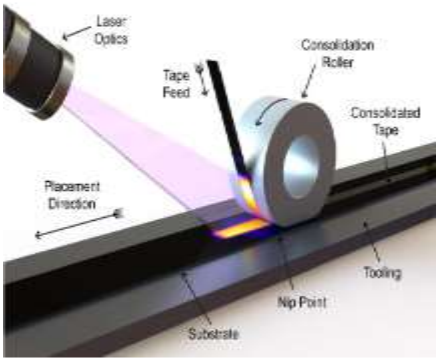

Figure 1. Schematics of a LATP machine[12].

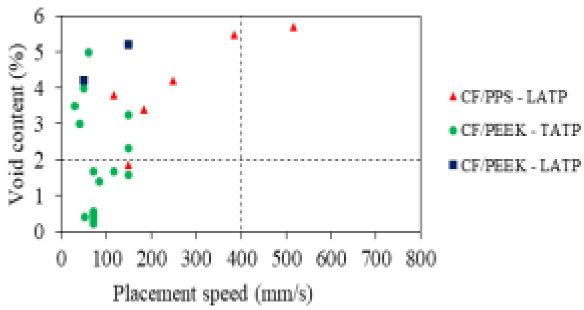

Figure 2. Summary of void content versus placement speed for CF/PEEK and CF/PPS unidirectional composites manufactured by means of LATP and hot gas torch ATP (TATP).

Placement speed and final part quality will determine the usability of this technology. To manufacture spar caps with LATP in a comparable time to current technologies, placement speeds of above 400 mm/s need to be achieved. Using void content as a quality criteria, values lower than approximately 2% should be targeted [18]. As can be seen in *Figure 2*, increasing placement speed negatively affects the final void content [2, 3, 9, 10, 11, 13, 17]. This is a consequence of the shortening of the heating and consolidation process windows, which hinders the development of intimate contact between the tape and substrate. In addition, there is significant scatter in the data at low placement speeds. Hence, both placement speed and void content need to be improved. The development of a high degree of intimate contact, and therefore resin interaction, is necessary to minimise void content and form a resilient bond between tape a substrate. The diffusion of polymer chains through the interface is known as autohesion, and is the mechanism responsible to develop the final bond. Hence, bonding in LATP depends on intimate contact development and autohesion. The later has been considered immediate compared to the development of intimate contact [4].

Current models describing the evolution of the degree of intimate contact are based on resin squeeze flow upon compaction [16]. These models assume that intimate contact development occurs from the flattening of asperities on the surface of the tapes, and describe it as a function of asperities geometry, applied pressure and polymer or composite viscosity. Recent work has shown that percolation flow also plays a role in the final degree of intimate contact. Kok [6] was able to reach degrees of intimate contact close to 100% for resin rich surfaces of CF/PEEK. The authors identified that the most significant rate limiting factors for the impregnation of the dry fibres in the tape's surface were the initial fibre volume fraction, the fibre bed permeability, and the resin viscosity. Çelik et al. [1] observed that CF/PEKK tapes with resin poor surfaces had incomplete surface impregnation after compaction. Hence, the authors defined the degree of effective intimate contact, DEIC, as a new magnitude that considers only the intimate contact that leads to further autohesion. The authors identify this phenomenon as a reason for the lack of accuracy on the prediction of the degree of intimate contact of the current squeeze flow-based models.

Composite processability is significantly governed by resin viscosity, which is measures the mobility of the polymer chains above the glass transition and melting temperature. It is typically measured by means of oscillatory or capillary viscometers [14]. However, these techniques cannot achieve characterisation times close to those in LATP. Viscosity depends, among other factors, on the degree of crystallinity [7]. For semi-crystalline polymers, crystals can hinder chain mobility above T_g [5]. Moreover, for PPS with T_m being 320 ºC, temperatures higher than 370 ºC are needed to erase all residual metastable nuclei above melt [15]. In addition, constraints imposed by persistent order above T_m can be experimentally observed for polymers like PEEK [8] or PPS [15] - this is known as "memory effect". Yan et al. [15] studied the memory effect in PPS powder and concluded that the ideal molten state cannot be reached, since order can be found in the melt even above 370 ºC. The aforementioned studies were done using a differential scanning calorimetry (DSC), which heating rates and residence times are incomparable to those seen in LATP. Therefore, it could be expected that the effect of remaining nuclei and memory effect would be greater in LATP conditions than it has been observed in DSC experiments. Thus, viscosity values used in LATP predictive models could be an overestimation and one of the reasons for their lack of accuracy.

To achieve the required placement speeds and void content to manufacture load bearing parts in LATP, a better understanding of the polymer microstructure upon heating and at the end of the heating stage is required. Due to the short heating times and elevated heating rates, melting and melt relaxation kinetics need to be evaluated to assess actual matrix viscosity prior entering the consolidation phase. Given that viscosity cannot be measured in LATP conditions, and that current values obtained from viscometers could not be accounting for melting and melt relaxation kinetics, alternative parameters should be used to describe the processability of the resin in LATP.

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8. ESR 7: Huzaifa Syed

Optimization of dynamic cable configuration

In the past few years, floating offshore wind technology has taken a massive leap towards commercialization around the world across continents from Europe and Asia . In February 2020, there were wind farms consisting of 2180 turbines with a combined capacity of 8113 megawatts in the UK . The United states constructing its first commercial scale offshore wind farm located 15 miles off Cape Cod in Massachusetts , its hoped to be aiming for 800 MW producer and many more across the world. Despite its huge potential, numerous problems remain to be investigated in depth to achieve the required commercial maturity across the sector.

Carbon trust which excels in decarbonization for organizations around the world and is an expert guide to Net Zero, performed a Floating wind joint industry R&D survey which aims to deliver support achieve 70GW by 2040. The report claims and highlights that there is a lack of suitable dynamic cable currently on the market and more than half of the challenges faced in case of the dynamic cables relate to the cable dynamics and fatigue life [1]. As the technology itself is in its infant stage, it is yet to achieve the knowledge and experience in case of the dynamic cables. Most of this knowledge is derived from experience in the oil and gas industry which has been there for several decades. Though dynamic riser cables have been field tested in the past, it is difficult to understand the coupled dynamics in the floating wind environment.

Previous approaches to optimize the cable configuration in terms of fatigue life have performed simulations on various platforms like Orcaflex, DNV DeepC and even MATLAB codes built to replicate the model and dynamic behavior of the dynamic cables.

MARINET performed set of fatigue tests on dynamic cables using the DMac test rig by applying loads exceeding normal operation in order to accelerate components degradation and the development of failures [2].The bending stiffness and structural damping obtained through these set of tests depict that these play a very vital role in the global hydrodynamic role which in turn affects the fatigue life of the cable. It was also noticed that severe bending can cause fretting fatigue in the conductor leading to failure [2]. which is the same in case of Marta et al.(2015) [3], where fretting was identified as one of the crack initiation mechanism. To understand the local behavior within the cable to determine the root cause of the failure, Skeie et al. (2012) [4] studied the stick-slip behavior. There has been difference of opinion among authors on the best performing cable configuration. while Dectot (2017) [5] concludes it to be the lazy wave configuration, Krugel and spaargaren[6] promote steep wave configuration as the best performing. yang et al (2018) [7] using the DNV DeepC software [8] has come up with a peculiar configuration in which the cable hangs freely between two floating devices without contact with the seabed. Throughout the literature there exists large uncertainties due to various model assumptions made. there hasn't been a clear approach to reproducing actual real operational conditions.

Another rarely discussed aspect of the dynamics of the cable is the role of Vortex induced Vibration which has been observed in cylindrical risers in the oil and gas sector. There have been attempts in using vortex-suppressing devices to mitigate the possible fatigue damage and increased drag force. Models of both finite span rigid cylinders and flexibly mounted cylinders free to vibrate in crossflow at different frequencies and amplitude help in the understanding of principal VIV mechanisms. VIV generally occurs when the frequency of vibration of the cable synchronizes with its Strouhal frequency. and this stage is known as the Lock-in condition. Sarpkaya (2004) [9] and Williamson & Govardhan (2004) [10] in their study on VIV of flexible risers have stated that the Lock-in can occur over a range of flow velocities, and the vortex shedding frequency can be driven relatively far from the Strouhal frequency. R. Bourguet [11] in his findings of Vortex-induced vibrations of a long flexible cylinder in shear flow studies using Direct numerical simulation of the flow past a flexible cylinder, concludes that the lock-in condition does not occur continuously as a function of time as a result of synchronization of the wake with a single vibration frequency which also corresponds to the locally predominant frequency of the structural response. It was also observed that multiple vortices splitting events occur as a result of the discontinuity in the Lock-in pattern. it is evident from Dahl et al. (2010) [12] that this is also the case in high Reynolds number. Both physical experiments (Chaplin et al., 2005;Trim et al., 2005;Vandiver et al., 2009;Huera-Huarte et al., 2014;Gao et al., 2015,2016) and numerical simulations (Newman and Karniadakis,1997;Bourguet et al., 2011,2013) have been performed to clearly understand the VIV response. It has been noticed that Physical experimentations become more complicated and expensive when the length to diameter aspect ratio exceeds 10^3 and the process to meet the required actual requirements of engineering practice is difficult to obtain in case of CFD simulations with larger aspect ratio. VIV response of a flexible cylinder has many additional complicated characteristics as compared to that of the rigid cylinders, such as standing wave behavior, travelling wave behavior, multiple response frequencies and time-sharing. (Facchinetti et al., 2004a) [14]. In case of a rigid cylinder the VIV response remains constant along the span (Facchinetti et al., 2004a) [14]. The most common and reliable model used to predict the VIV behavior on a cylinder with large aspect ratios is the wake oscillator method. Future work involves studying the effects of the platform motion on the global configuration of the cable leading to fatigue and determining an efficient cable configuration accordingly. Keeping in mind also the economical aspect of the new cable configuration.

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9. ESR 8: Rahul Chitteth Ramachandran

Topic : Installation and decommissioning of large floating offshore wind farms

Floating offshore wind turbines (FOWT) represent the upcoming frontier of renewable energy systems. A few experimental and pilot-scale floating offshore wind turbine projects have been deployed around the world and array-scale deployments will be a reality soon. Many innovative FOWTs have been designed in the recent years [1]. The installation of these FOWTs presents multiple challenges as they are designed to be deployed in harsher sea conditions. The installation methodologies vary depending on the type of the floater used [2]. For example, the installation of Spar-type platforms requires the use of expensive heavy-lift vessels while semi-submersible platforms can be installed using simpler vessels. Similar challenges arise during the decommissioning operations too. The decommissioning of offshore structures usually follows a reverse-installation approach [3]. In the case of FOWTs, many of them can be towed back to the shore for dismantling. It can be assumed that these operations require extensive hiring of various vessels which contributes towards a significant portion of the Levelized Cost of Energy (LCOE). A study by Castro Santos et. al. [4] showed that 36% of the costs are incurred during the installation, operation & maintenance, and decommissioning phases of a floating wind farm. There is a chance for optimization in these areas by proper planning and introducing new innovations.

As mentioned before, the installation methods differ according to the type of floater used for the FOWT. Generally, the floaters can be classified into Semi-submersibles, Tension Leg Platforms and Spar-type platforms [5]. Semi-submersible platforms are buoyancy-stabilized floaters utilizing the large waterplane area of the hull for stabilizing [6]. They can be fully constructed and assembled onshore. They are towed to the farm location by using simple tugs. The installation of anchors and mooring system is comparatively easier than other platform types, as they employ drag-embedded anchors which are easy to install. For decommissioning the platforms, they can be simply towed to the quay using simple tugs also. This makes the semi-submersibles attractive from a marine-operation point of view [2].

The installation of Spar-type platforms requires the use of heavy-lift vessels, as they must be assembled in sheltered waters due to the high draught of the floaters [7]. Once they are fully assembled in the sheltered waters, they are towed to the farm location and attached to the pre-installed mooring lines. Decommissioning operations would also follow a similar approach, where the platform will be towed to a sheltered location and will be partially dismantled instead of bringing the whole structure to the port/quay. The Hywind Scotland is a wind farm employing Spar-type FOWTs which can produce 30 MW from 6 turbines [8]. The installation operations were carried out after careful planning and extensive metocean assessments [9].

Wind farms consisting of TLPs are still not a reality. A few design concepts and demonstration scale TLPs have been evolving in the recent years and the technology is quickly gaining momentum. Traditional TLPs are constructed using the help of bespoke vessels due to the unstable behaviour of the floater before attaching to the tendons which holds the structure in place. The tendons are subjected to large vertical loads and the mooring system is more complex than others. A few upcoming designs are aimed at addressing this problem. For example, the TLP design introduced by GICON offers easy installation and decommissioning using simple tugs [10]. The GICON TLP is placed on a concrete slab which is connected to the TLP using tendons. The slab can be ballasted and submerged into a suitable depth to provide the required tension and thereby the required draught to the TLP. Other technologies like Tetraspar [11] platform and Ideol platform [12] also offer cheap and easy installation using simple tugs compared to Spar-type platforms.

The main challenge when it comes to marine operations is the prediction of weather windows as well as accessing the installed wind turbines [13]. During the planning phase, the metocean conditions of the farm location must be analysed and long-term predictions are to be done to facilitate easy installation, operation & maintenance and decommissioning activities. Significant wave height plays and important role in all these phases as the workability of the vessels are dependent on this. Marine operations become difficult and often impossible as the significant wave heights reach 1.5 m [14]. It is also important to ensure safe transfer of crew to and from the platforms during installation, operation & maintenance and decommissioning. During the decommissioning phase the electrical system, mooring lines and anchors must be carefully removed, and the site must be returned to the pre-installation conditions.

Installation costs consists of costs incurred for the installation of wind turbine, floating platform, electrical system, mooring and anchoring system and the start-up cost [15]. The installation costs of the floating offshore wind platform depend on the port and shipyard costs, transportation/towing costs and site installation costs. The installation costs mainly depend on the location of the farm. The distance from the nearest port and bathymetry are important factors to be considered. The number of anchors used in wind farm also influences the installation costs. It has been observed that the wind turbines grow in size as they enter deeper waters [16], which has a direct influence on dismantling costs. Many innovative technologies can be adopted from the matured oil & gas and fixed offshore wind industries to optimize these marine operations and bring down costs.

In a large wind farm the mooring lines and the anchors can be shared which would reduce their numbers and thereby reduce the costs associated with them. studied various configurations of shared mooring systems and found that mooring system cost reductions up to 60 % and total systems costs reductions up to 8% was possible [17]. The anchors used in a shared configuration should be able to handle large multi-directional loads. The system reliability is found to be reduced in a multi-line system compared to a conventional single-line system. Geo-technical investigation costs are also comparatively lower for the installation of a large floating wind farm in a shared mooring system configuration [18].

As mentioned before, the significant wave height restriction applies to all marine operations. It is important to raise the significant wave height limits for vessels for widening the weather windows. Walk-to-work vessels equipped with motion compensated gangways have been used in the oil & gas and fixed offshore wind industries for many years. Walk-to-work vessels can theoretically provide access in sea conditions with a significant wave height of up to 5 m [19]. Such vessels can be used in the installation, operation & maintenance and decommissioning phases for exploiting wider weather windows and safe access and egress of the crew.

The mating of the Spar-type substructure and the wind turbine is a complex process due to the relative motion of the bodies. Jiang et. al. [20] proposed a floating dry-dock specifically designed to shield the wind turbine assembly from the rough seas during installation. A catamaran installation vessel equipped with pile grippers was proposed by Jiang et. al. [21] to help the installation of Spar-type platforms. An improved design using wires instead of pile grippers was proposed by Vågnes et. al. [22]. These vessels which can carry up to four wind turbines will help avoid the use of expensive heavy lift vessels during the installation of a Spar-type FOWT. Many of these technologies have been validated theoretically but experiments are still pending. Further research is required to address the various challenges on the path to the practical realization of these technologies.

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10. ESR 9: Omer Khalid

Topic: Application of robotics for floating wind operations and maintenance (O&M)

The deployment of floating offshore wind turbines is gaining traction with the opportunities to exploit stronger winds and larger farm sizes, while also reducing potential conflicts such as societal acceptance and visual impact [1]. However, maintaining floating offshore wind farms (FOWFs) to allow them to perform at their optimal level for over 25 years of service can account for 29.5% of the total lifecycle cost [2]. It has been estimated that the operations and maintenance (O&M) of onshore wind turbines account for about 25-30% of the total lifecycle cost of wind turbines, and in the case of offshore turbines, the costs are even higher, in the range of 30-35% [2,3].

The O&M activities for FOWFs involve inspecting and maintaining components of the wind turbines and their subsystems to prevent and address faults. O&M activities on the turbine blades are typically performed by rope-access technicians, often working in extreme conditions and during restricted weather windows. The duration of turbine downtime, and hence the lost energy production can be considerable, while the use of crew transfer vessels (CTVs) and service operation vessels (SOVs) also makes up a significant proportion of wind farm O&M costs [4]. Hence, the O&M of FOWFs poses significant technological and financial challenges pertaining to asset downtime, operational expenditure (OPEX) incurred, and fault diagnosis. Recent advances in the development of offshore robotics have opened up new opportunities for deploying semi/fully autonomous systems for the O&M of offshore wind farms [5,6]. Incorporating robotic systems offshore can not only improve the assets' reliability but could also reduce costs and mitigate the health and safety (H&S) risks associated with deploying human operators to offshore sites with harsh weather conditions. Robotic systems offer various opportunities, ranging from efficiently executing the otherwise repetitive tasks to obtaining continuous and high-resolution data. Furthermore, the potential financial advantages and safety related benefits for the personnel onboard at offshore installations necessitate the need to minimise manual human intervention. In recent years, unmanned aerial vehicles (UAVs) and remotely operated vehicles (ROVs) are being utilized to access the machines and sites that are difficult or dangerous for humans to operate in. Prototype systems have been developed and tested for fault detection in oil and gas pipelines [7,8], subsea survey and repairs [9], and more recently for wind turbine inspections [10]. In general, four different types of robots can be utilized for O&M of FOWFs.

1. Climbing robots: Typically, rope-access technicians are utilized to conduct the turbine blade O&M such as cleaning blades, and inspecting structural defects in windy, high and harsh environments. It is envisaged that a climbing robotic mechanism could replace some of these O&M tasks, improving efficiency in the process while also addressing the H&S aspects. In literature, different types of climbing robots are discussed based upon their design specification [6]. For inspection, climbing robots can be considered that can move vertically or around the tower and blades of a wind turbine. The robot's access to the entire circumference of the tower and to the surface of the blade is imperative as it would determine the range of the O&M tasks that could be conducted.

2. UAVs: UAVs have gained a lot of interest for conducting inspection and other remote sensing applications ranging from surveillance, and infrastructure inspection to data acquisition, and aerial mapping [11]. For instance, UAVs can be utilized to monitor the condition of the solar panels [12]. Another use of UAVs in power systems that has been studied is automatic meter reading [13] along with the inspection of damage to the transmission lines [14]. In the case of FOWFs, different commercial offerings are available where UAVs fitted with data acquisition technology are used to scan the surface of the turbine tower and blades. Advancements in UAV technology have led to increased automation of the task, reducing the workload of the pilot to manually manoeuvre the UAV. The data is then recorded and wirelessly transmitted back to the onshore control station. Post-processing is done to acquire imaging details, acoustic emissions, and sensor measurements. Main benefits of using UAVs to inspect FOWF assets include: 1) A more frequent and spatially large

access to the wind farm in a shorter interval of time; 2) Possibility to mount a variety of imaging and acoustic sensors onto the UAV for feature-rich data acquisition; 3) The H&S aspects regarding the manned access to FOWFs are improved.

3. ROVs: Recent advancements in subsea survey and inspection technology have allowed more detailed studies of the oceans and underwater structures [15]. However, owing to the increased offshore developments with varied scientific requirements, deep sea research remains expensive in terms of logistics and personnel requirements. Subsea technology is routinely used by the offshore oil and gas, and renewable energy industries for inspection, monitoring, and maintenance of assets in areas that are otherwise inaccessible to marine scientists. In recent years, ROVs are increasingly being used at windfarms for conducting such activities along with de-risking offshore operations. The industry is developing new technologies in order to minimize O&M costs and manpower requirements while also improving safety and reliability. For the case of FOWF, two primary applications for ROVs pertaining to O&M are cited [16]: 1) export/array cable surveys and repairs, and 2) scour and structural scans.

4. ASVs: Autonomous surface vehicles (ASVs) have been the focus of significant research in recent years. While the use of CTVs and SOVs bring flexibility in terms of payload and personnel capacity, their dependence on weather windows and higher leasing costs makes their use for longer duration of time less than optimal. There is a need to reduce costs in this regard. With the anticipated construction of wind farms farther from the coast, a considerable reduction in O&M vessel costs could be possible by eliminating the need for large inspection vessels [17,18]. The use of ASVs in offshore wind energy operations is still nascent. The use of ASVs have benefits in terms of conducting marine O&M for extended duration of time, and without the need for crew deployment. ASVs typically utilize catamaran hulls for higher stability and have a modular design, whereby different types of payload can be mounted based on the specific mission requirements. It is important to consider the varying degrees of autonomy for the ASVs, and their effects on the O&M activities and task allocation. A classification of autonomy levels is provided by the Lloyd's Register where the tasks are divided into decision making, action taking, exceptions handling [19].

While there exist different robotic systems for O&M, there is a need to improve the technology readiness level (TRL) of some of these systems. Furthermore, different design and market challenges exist such lack of testing and validation of existing prototype systems, and the relatively high cost of commercial offerings. There is also a need to do cost-benefit analysis of the robotic systems and their effect on the different key performance indicators such as levelled cost of energy and the wind farm availability. The goal of this project is to address some of these challenges from a techno-economic lens and produce outputs that can give insight in to the viability of incorporating robotics in floating wind energy domain.

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11. ESR 10: Omar Ibrahim

Topic: Development and optimisation of Blue Economy activities coupled with FOWT farms

In a decarbonised world, the share of Renewable Energy Supply (RES) must increase to displace fossil fuel systems. In recent years, energy production, transportation, storage and usage have undergone a profound change [1]. By 2050, in the most ambitious scenario, electricity is expected to be the main energy carrier with over 50% (direct) share of total final energy use, up from 21% today [2]. A bridge is needed to transform green electricity to other final energy use vectors which are available for transport and heat.

According to the International Energy Agency (IEA), to achieve Net-Zero emissions (NZE) by 2050 hydrogen as a clean energy carrier and as a precursor to hydrogen-based fuels (also known as electro-fuels) will have a leading role [3]. In this scenario, global hydrogen use would expand from less than 90 Mt in 2020 to more than 200 Mt in 2030 and the proportion of low- carbon hydrogen would rise from 10% in 2020 to 70% in 2030 [3]. Green, or renewable hydrogen is produced from a renewable energy source through water electrolysis process. It is anticipated that 30% of electricity use will be dedicated to green hydrogen production and its derivatives (termed electrofuels) such as e-ammonia and e-methanol [3]. These electrofuels are expected to play a pivotal role in sectors where direct electrification is challenging especially in hard to abate sectors, such as steel, chemicals, fertilisers, and long-haul transport, shipping and aviation [1,4].

Electricity input for water electrolysers accounts for much of the production cost for green hydrogen and falling renewable power costs are expected to narrow the gap [1]. Producing green hydrogen through electrolysis is a commercially mature technology; however, the focus has primarily been as seasonal storage and a curtailment solution rather than a means of producing affordable hydrogen [5]. Green hydrogen cost is highly dependent on the type and cost of renewable energy supply used, electrolysis technology, the plant scale, as well as the energy vector used in transportation. According to the European Commission's July 2020 hydrogen strategy green hydrogen may cost in future scenarios between 2.5 €/kg and 5.5 €/kg[1] [6]. Using low-cost renewable electricity (of the order of 17 €/MWh), with rapid up-scaling of the industry occurs in the next decade; the cost of green hydrogen may according to IRENA continue to fall below 1.31 €/kg[2] [2]. Achieving those figures relies on a large rollout coupled with climate and energy policies that are yet to materialise. According to IRENA (2021) [2] around 12% of the total global final energy use will be accounted for by hydrogen and its derivatives by 2050. To achieve this, close to 5,000 GW of hydrogen electrolysis capacity will be required, up from just 0.3 GW today.

The viability of offshore wind to provide this significant resource of energy is investigated in this work. The technical potential of offshore wind can be divided into shallow water (< 60 m), and deep water (60-2,000 m) [7] with the resource in deeper waters offering opportunities associated with resource and potentially less objections from coastal communities. Given the anticipated growth in demand for green energy and the fact that according to Eurek et al., (2017) 80% of the global offshore wind resource is located in waters deeper than 60 m (sites where only floating technologies are viable) [8] it is likely that large scale floating wind will be coupled with hydrogen production over the coming decades. Offshore wind projects dedicated to green hydrogen production of could offer significant cost advantages over projects using electricity directly from the grid. It is partly because of the potential for cost reductions if transmission is reduced or eliminated [7].

1IEA 2019 Hydrogen report [18], and based on electricity prices between 35-87 €//MWh
2 Values converted from USD to EUR using the average conversion factor by the European Central Bank for 2020 [19]

To achieve this major increase in green hydrogen production, the renewable electricity used should offer both, a promising deployment capacity, as well as a competitive cost as represented by the LCoE. According to Offshore Renewable Energy (ORE) Catapult, floating offshore wind (FOW) would achieve considerable cost reduction to the extent that it can be subsidy-free in the UK in early 2030s [9]. It is estimated that this technology will grow significantly in the coming decades, reaching up to 30 GW by 2030 and covering around 5–15% of the global offshore wind installations by 2050 (almost 1,000 GW). The HyWind Scotland floating wind farm recorded a very high average capacity factor (CF) of 57% in 2020 [10]; such high CFs associated with FOW is a key synergy for coupling with hydrogen production. The LCoE values of several FOW platforms are estimated to range between 106.3 €/MWh and 287.8 €/MWh depending on the platform [11]. Hywind Scotland, a 30 MW floating farm installed off the coast of Peterhead in 2017, achieved a LCoE of 211.43 €/MWh [12]. This appears unfavourable in comparison to the cost of current bottom-fixed offshore wind farms at 64.60 €/MWh in the UK for example [13]. However, their advantage of giving access to wide unused wind resources makes them a competitive candidate for this required scale of electrolysers; this is especially so for future projections and accelerates the path to reach decarbonization goals.

A crucial step of any energy system is transporting the energy. Energy transmission is not only electric power lines, there are other energy vectors for transporting energy [14]. The focus of this work is bulk energy transmission of the hydrogen dedicated FOW farm output, with the option of having hydrogen as an energy transmission vector next to the conventional power lines transmission. For instance, hydrogen is looked at being produced both onshore and offshore. An analysis by Jepma et al. [15] stated that on average pipeline transport requires much less CAPEX than transporting electricity, but also that energy losses in hydrogen transport are significantly less than those associated with electric cables. This must be seen as a very different concept to the ongoing discussions of blending hydrogen with natural gas in existing pipelines for decarbonization purposes of various sectors [16].

This work examines possible coupling typologies, addressing the suitable FOW platform used in each typology, as well as proposing some optimum system key design factors and components. The novelty in this work comes in investigating direct coupling of off-grid FOW and green hydrogen through hydrogen pipelines or/and electric transmission cables. It is worth noting that offshore applications of electrolysers can be further de-risked if the challenges regarding their operation in an isolated and harsh environment are addressed. Over recent years, there has been increasing interest in coupling offshore wind with hydrogen production. In the meantime, the Dolphyn project by ERM [17] is considered the only ongoing project in the pipeline that proposes coupling FOW with green hydrogen production. The project concerns the production of hydrogen at scale from offshore floating wind in deep water locations.

In conclusion, there would be no one best coupling typology in the absolute, several criteria come in the decision matrix. The flow of deciding should typically start with the goal at the first place; whether to achieve the highest hydrogen production? or the most energy efficient hydrogen production? or the most cost-efficient LCoH? Then the second level of the decision flow would involve; the scale, the location, technologies selection, expansion plans, and if a specific floating platform needs to be implemented.

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