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Technical challenges in floating offshore wind turbine upscaling: a critical analysis based on the NREL 5 MW and IEA 15 MW Reference Turbines

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Abstract Upscaling is currently seen as one of the most promising techniques to lower the Levelized Cost of Energy of wind farms and is a trend that has been ongoing for many years. Floating wind turbines are still a quite novel technology. In this kind of application, the benefits of upscaling are potentially even greater than those that can be seen in land-based turbines, with a direct impact not only on the turbine cost per installed kW, but also on that of the floater, mooring lines and ancillaries. In this study, a critical analysis on the technical implications of upscaling is carried out, focusing on aero-hydro-servo-elastic design. The study is based on the NREL 5 MW and IEA 15 MW Reference wind turbines in floating configuration; while the two turbines benefit from different design choices and technical maturity, they are well-known, open-access test cases and present several similarities. Both turbines use the same controller, and both are placed on a semi-submersible type floater. The mooring line designs are also conceptually identical, with both turbines being anchored to the seabed through three 120° apart slack catenary lines. The numerical tools used to simulate the wind turbines are also the same: Blade Element Momentum (BEM)-based aerodynamics in combination with second order potential flow derived hydrodynamics. Such approaches are found in the state-of-the-art code OpenFAST®, which is used in the present analysis. The two floating wind turbines are tested in a series of identical sea and inflow conditions (i.e., analogous to the wind farm design process for a given authorized sea region) with varying degrees of severity. Results show how overall performance and rotor loads are only marginally affected by floating installation. When looking at tower loads, however, it is shown how platform motions affect extreme power-production loads significantly. In this regard, the two machines are closely matched and despite the increased stability of the larger floating platform, some ultimate loads tend to increase more on the IEA 15 MW.

Highlights

- Upscaling is key in floating offshore wind for LCOE reduction
- Critical analysis on technical challenges related to upscaling based on two reference turbines
- Turbines simulated in the same metocean conditions
- Although platform RAOs decrease, tower load increases are higher in the larger machines
- Despite technical advancements, this is caused by increase in hub height and weight of RNA

Keywords: floating offshore wind, wind turbine, upscaling

Word count (entire document – excluding references): 10589

List of Acronyms

GenPwr	Generator Power (kW)
GenTq	Generator Torque (kN)
RotSpeed	Rotor Speed (rpm)
GenSpeed	Generator Speed (rpm)
TwrBsMyt	Tower base fore-aft bending moment (kNm)
TwrBsMxt	Tower base side-side bending moment (kNm)
RootMxb1	Blade root in-plane bending moment (kNm) blade #1
RootMyb1	Blade-root out-of-plane bending moment (kNm) blade #1

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RotThrust	Rotor thrust (total) (kN)
RtAeroF _{xh}	Rotor Thrust (aerodynamic) (N)
NcIMUTV _{xs}	RNA assembly velocity in x-direction (m/s)
RootF _{xc1}	Blade 1 root out-of-plane force (kN)
TwrBsF _{xt}	Tower base fore-aft load (kN)
OoPDelf ₁	Blade 1 tip out-of-plane deflection (m)
IPDefl ₁	Blade 1 tip in-plane deflection (m)
TTDspFA	Tower Top fore-aft displacement (respect to tower base) (m)
TTDspSS	Tower Top side-side displacement (respect to tower base) (m)
BEM	Blade Element Momentum theory
COG	Center of Gravity
FOWT	Floating Offshore Wind Turbine
LCOE	Levelized Cost of Energy
RAO	Response Amplitude Operator
HAWT	Horizontal Axis Wind Turbine
DOF	Degree of Freedom
CFD	Computational Fluid Dynamics
NSS	Normal Sea State
SSS	Severe Sea State
NTM	Normal Turbulence Model
ETM	Extreme Turbulence Model
DLC	Design Load Case

1 Introduction

Floating offshore wind is seen as one of the most promising developments for wind energy exploitation, as it would allow to generate power at water depths greater than 60m, where significant capacity can be exploited [1,2]. According to a EU-commission report [2], exploiting offshore energy potential is key to meet renewable energy policy goals. Installing turbines in deep waters, far from shore, has several potential advantages, among which the main ones are the fact that higher distance from shore generally equates to higher wind speeds and higher capacity factors [3]. The latter factor is especially important if put in the context of energy grids with large renewable energy penetration as it can ease wind energy intermittency problems.

According to Bento and Fontes [3], the most frequently perceived barriers towards floating wind is high cost and immature technology. Other industry sources confirm these findings: cost per installed kW of floating wind is significantly higher than that of fixed-bottom wind turbines and even more so of that of onshore wind turbines [4]. When queried on the matter, a panel of experts has predicted median cost decreases of about 40% by 2050 [5]. The panel identified the main cost reduction drivers to be related to improvements in foundation design and manufacturing, transport and installation and economies of scale. On the other hand, for fixed-bottom offshore wind and onshore wind projects, the main cost reduction driver is seen to be the increase in turbine size. Arguably, the latter technologies are more mature than floating wind and have already benefitted extensively from economies of scale, as historical learning rates show [5], and therefore size increase could be a factor in floating wind as well once the technology is more established. Indeed, from a general standpoint, Floating Offshore Wind Turbines (FOWTs) seem particularly suited to benefit from increases in size. In fact, they would not only benefit from higher gross capacity factors as a consequence of larger and higher rotors, but the impact of the floating foundation and installation cost per-kW could be greatly impacted. Moreover, installation of very large machines is also facilitated in offshore conditions, where operators are unconstrained by transport restrictions. Floating offshore wind is anyhow still a novel technology. Therefore, historical data is not yet available. However, when looking at the wind energy industry as a whole, the trend towards larger and larger rotors, especially for offshore applications is apparent. Leading manufacturers are currently developing rotors in the 12-15 MW power range, and the size of installed turbines is constantly increasing [3,6]. This process can be broadly referred to as “upscaling”, and the reason for such increases in size is the reduction of Levelized Cost of Energy (LCOE). While the potential of upscaling in terms of reduction of LCOE is readily arguable, and is even greater in offshore applications, as the larger average turbine size in offshore projects indicates [4], quantifying its impact is difficult. A variety of sources [3,5] indicate learning rates of 15 to 20% for floating offshore projects. Strictly speaking for floating offshore wind, Kikuchi and Ishihara [7] found for example that capital costs per kW can be reduced by up to 57% when upscaling a 2MW FOWT to 10MW using an engineering model. Although indicating which percentage of this cost reduction is attributable to turbine and plan size increases is very difficult, according to Bento and Fontes [3], upscaling is the main factor, while the literature review by Shields et al. [6] points out that upscaling impacts O&M costs as well (with cost reductions up to 23%). However, the possible impact on O&M from a broader perspective is very complex. For example, the use of longer and longer blades, also going over the atmospheric boundary layer in the upper part of their revolution and thus experiencing unprecedented turbulence levels and oncoming flow characteristics [8], could impact the strategies needed for preventive maintenance, which have been shown to be of capital relevance for offshore applications by Ren et al. [9]. Upscaling turbines will have

consequences also on installation. For example, the problems connected to the blade mounting could be enhanced, as shown recently by Jiang et al. [10] in the case of bottom-fixed turbines. Also, it has to be remembered that FOWTs are commonly installed within the harbors [11] and then towed to the installation site. Handling larger machines will require specific upgrades of infrastructures and procedures.

In conclusion, although all the aforementioned aspects will need specific research in the near future, the path towards larger rotors seems to be set, and it is driven by LCOE. New rotor designs are often developed using an upscaling procedure as a baseline upon which improve. For instance, this was the case for the now ubiquitous DTU10MW Reference Wind Turbine (RWT) [12]. The challenges involved with increases in rotor size are also well known [13] and are related to the increase in rotor mass and consequently, loads. Mass increase is reduced thanks to technological advancements, ultimately permitting the increases in size that have been observed. In general, such technological advancements are able to not only outweigh the theoretical mass increases but also allow for rotor design advancements, incorporating modern design trends in an effort to reduce LCOE such as large swept area and low area-specific power. This is noted by Ashuri [14] that records a less-than-square trend of rotor power vs rotor diameter.

On the other hand, in FOWTs, upscaling has been proposed as a viable tool to design support platforms for larger wind turbines. Leimeister et al. [15] discuss the challenges related to upscaling FOWT semi-submersible-type floaters. The authors propose to use the root cube of the turbines nominal power as the scale factor. Ferri et al. [16] proposed an optimization procedure that is able to reduce the peak response amplitude operator (RAO) in pitch up to 50% respect to a traditional scaling based on the square root of the ratio of turbine power. Kikuchi and Ishihara [7] compare two upscaling procedures for FOWT platforms while also proposing a third. The authors conclude that the proposed methods are able to produce a support structure design that is able to resist the overturning thrust forces while upsizing greatly reduces per-kW cost. Interestingly, similarly to what is found when discussing rotor design, all the previously mentioned authors seem to conclude that a rigorous upscaling procedure based on scaling factors is not sufficient and does not produce optimized floater designs. However, the benefits in terms of reduced RAO and cost on larger support structures appear to be clear. From a loading perspective, FOWTs are subject to more complex loading patterns compared to fixed or on-shore wind turbines. In particular, additional gravitational and inertial loading should be expected when installing a turbine of a floating foundation [17]. On a Horizontal Axis Wind Turbine (HAWT), rotor and nacelle mass are located high above sea level. As the turbine pitches and rolls it behaves as an “inverted pendulum”, which causes additional loading on turbine components, especially on the tower [18]. This effect is well known. Jonkman and Matha [19] found that in general both ultimate and fatigue loads on turbine components increase when installed on a spar-type or barge-type floating platform. The effect is also present on semi-submersible type platforms and as noted in [20], a floating turbine may often require additional strengthening.

In this context, from a technical standpoint, the effect of upscaling on turbine components is unclear. On the one hand, larger turbines, installed on larger supporting platforms, are expected to be less prone to wave-induced motion. On the other hand, however, the increases in mass, rotor swept area, and nacelle height induce significant loads and overturning moments [21] and could pose a serious challenge in terms of load amplification. In this context, this study aims to partially fill this knowledge gap, with particular reference to the implications on the aero-hydro-servo-elastic design of the rotors, which are the main focus of the analyses presented herein. To this end, upscaling is referred to in a broader sense in the present study. By analyzing two very different sized rotors, we attempt to give qualitative indications of the benefits and challenges that arise when increasing the power and size of a FOWT. More specifically, since the metocean conditions in the installation sites are likely the same for floating wind farms, independently from the rotor size, the scope of the paper is to critically analyze how the combination of a possibly lower response to irregular sea states of large structures and the increased loads coming from larger machines affect the overall performance of the system.

In particular, attention is focused on the sea-to-land ratios of global control parameters such as power, torque, rotor speed and on sea-to-land ratios of ultimate loads in both power-production and parked conditions and on the platform motion response of the two floaters, rather than on cost. Sea-to-land ratios are used as a comparison metric to overcome the difficulties in comparing loads on such differently sized structures, and also because they quantify load variations with respect to installing the turbine on-shore, for which relevant industrial experience does exist yet. This is relevant as load amplification due to turbine motion, constitutes one of the most relevant obstacles to be overcome by floating wind technology. The causes for such amplifications will be discussed in detail in the following sections. It is worth pointing out that one of the key points of novelty of the present study is that the two turbines are simulated using the same turbulent wind fields and stochastic sea states, as if they were installed in the same stretch of sea. This is as an opposite to using the same wind conditions referred to each turbine’s hub-height, as typically is the case during design and certification, in an effort to more broadly discuss the effects of the increased turbine’s size.

The NREL 5 MW RWT [22] and the IEA 15 MW [23] are selected as study cases. Over the years, several floater concepts have been tested by academia [24]. While barge-type designs have been found to produce excessive sea-to-land load amplification on the turbine [18,24], other floater types such as spar floaters, tension-leg platforms and semi-submersibles all have their advantages. In particular, semi-submersible floaters are currently gathering the most interest as this kind of design does not require complex seabed mooring line anchoring, has a shallow draft for easy transport to the installation site [25] and guarantees good stability to wind and wave conditions. In this context, both the turbines compared here are mounted on semi-submersible type floaters, with slack catenary mooring lines [26][27].

An important premise for the analysis of the study is, however, that the two considered test cases do not represent strictly a scaled version of each other. They have been designed in different times, benefiting of different levels of refinement.

This is particularly true for the floaters, with the DeepCwind semi-submersible designed for the NREL 5 MW being conceived approximately a decade ago, and is much less refined from a design stand point than the VolturUS-S system used for the 15 MW turbine. On the one hand, this makes the comparison of results affected by the specific features of selected machines, as will be discussed extensively in the paper. On the other hand, it is very difficult to find complete cases strictly comparable, with a certain number of design-based differences always in place. Moreover, the use of two well-known cases, for which complete and open-access models are available, allows the results presented herein to be easily replicable, and used as a starting point for further investigations and improvements. Other testcases will be anyhow introduced in the discussion section to highlight some of the main talking points that surfaced during the detailed comparison of the 5MW and 15MW machines. In particular the two semi-submersible concepts proposed for the DTU 10MW in the Lifes50+ project [28] will be discussed. It was not possible to use the two testcases in the full detailed comparison since they are developed on the basis of different semi-submersible concepts, with one being of concrete construction and the other being a four column, X-shaped platform. Data from the Hywind Scotland commercial project [29] are also used for a comparative analysis.

The study is organized as follows. In Section 2, the numerical methods used are explained. In Section 3, the characteristics of the two FOWT concepts are discussed, while in Section 4 the environmental conditions that were used are explained. Finally, results are shown in Section 5 and discussed in detail together with possible implications in Section 6.

2 Methods

Both the wind turbine numerical models examined are created in OpenFAST v2.4.0 [30], an open-source aero-servo-hydro-elastic non-linear wind turbine simulation tool developed by the National Renewable Energy Laboratory (NREL). It is worth pointing out that, the scientific community is studying higher fidelity methods to simulate very large rotors like those considered herein. However, the selection of an open-source, credited tool like OpenFAST for the present analysis goes in the direction of providing a critical analysis that can be easily replicated and/or extended by the scientific community, further stimulating the research on an important topic like upscaling in FOWTs. In particular, the goal of this study was to define a set of metrics easily replicable by researchers that could enable a sufficiently fair comparison of turbines having different sizes. Moreover, it is worth remembering that the selected simulation tool has been thoroughly validated and has proven to be able to capture the dynamics of FOWTs well [31,32].

While it is out of the scopes of the present study to present all OpenFAST's characteristics in detail, the modelling choices that were adopted for the two turbines will be briefly discussed.

2.1 Aerodynamics

Both turbines are modelled using AeroDyn v15 [33]. The wind turbine's wake is modelled using Blade-Element-Momentum theory (BEM), with corrections for high thrust, tip and root losses and misaligned inflow. The blades are modelled using a set of tabulated lift and drag coefficients. Airfoil properties are calculated for a Reynolds number of 10^7 for the IEA 15 MW using 2D CFD [23]. 360-degree extrapolation is performed using Viterna's method and rotational corrections are applied using the Du-Selig stall delay model [34]. Lift and drag coefficient are derived from measurements at a Reynolds number of $7 \cdot 10^7$ in the case of the NREL 5M RWT [22,35]. 3-D corrections are applied again using the Du-Selig stall delay model. Correction for dynamic stall are used, in the form of the Beddoes-Leishman dynamic stall model, for both turbines in order to model the dynamic effects that arise during normal operation.

Dynamic wake effects are modelled using the approach proposed by Oye [36]. This model is able to account for the fact that changes in blade induction do not apply instantly to the entire wake by applying a filtering procedure to the axial and tangential induced velocities at each blade section. By inducing a time-lag in the wake, time-varying induction changes due to rotor motion or varying inflow conditions can be more realistically modelled.

2.2 Hydrodynamics

The semi-submersible floater is considered as a 6-DOF rigid body. Its interaction with the sea is computed using Hydrodyn, OpenFAST's hydrodynamics module. Both turbines are modelled using potential flow theory. Added mass, linear damping and wave-response coefficients are pre-computed in the frequency domain using an external potential flow solver, such as Wamit [37]. Both turbines are modelled using second-order wave theory, as implemented in Hydrodyn [38], and second order difference frequency forces [39] are considered using a full quadratic transfer function. Additional quadratic damping, due to flow separation on the semi-submersible columns is modelled using Morrison elements in case of the NREL 5 MW and using an additional quadratic damping matrix in case of the IEA 15 MW. In case of the NREL 5 MW only quadratic drag is considered in Morrison's equation, and added mass is neglected as this is already modelled using potential flow. Drag coefficients are estimated based on tabulated values [27]. As for the heave plates, quadratic drag coefficients in the heave direction are derived from matching wave tank tests with numerical results [27]. In case on the IEA 15 MW, additional quadratic damping is determined based on steady-state CFD simulations. Once the simulation has converged pressure is integrated along the submersed part of the floater and drag force is computed [26].

2.3 Structural dynamics

The structural dynamics are solved using a modal-based structural module, ElastoDyn [30], for both turbines. The floating platforms are modelled as 6-DOF rigid bodies, upon which turbines with flexible towers and blades are placed. The structural deformations are calculated as linear superposition of the pre-determined mode shapes, allowing for a very fast solution with limited degrees of freedom to solve for [40]. Blade edgewise and flapwise flexibility, tower fore-aft and side-side flexibility as well as platform DOFs are considered for both turbines.

2.4 Control

FOWT control is currently an active research topic. A recurring issue in variable-speed, active-pitch controlled FOWTs is reduced or negative platform pitch damping in above rated conditions [41,42]. In simple terms, when employing a traditional control loop developed for fixed-bottom wind turbines, rotor motion in the surge direction (see Figure 1(b)) may induce fluctuations in thrust and torque, that in turn may cause the controller to react accentuating such oscillations instead of damping them out. Various solutions to this problem are being studied, currently however existing solutions involve de-tuning the controller or incorporating complicated tuning procedures [43]. An additional solution is to include the nacelle velocity to the Proportional-Integral (PI) gain schedule as an additional proportional gain. This solution is proposed in [43] and adopted in the ROSCO controller by NREL [44–46], which is used in both the turbine models. The ROSCO controller is a variable-speed and variable-pitch open-source controller. It's generic tuning procedure for the on-shore version of the NREL 5 MW rotor is proposed in [44] and also discussed in [46]. Using the ROSCO toolbox [47], the PI gains for the pitch and torque controller can be tuned easily, and only require the specification of the control bandwidth (natural frequency) and damping ratio (Table 1). In the present study, the ROSCO toolbox generic tuning algorithm is used for both turbines. The standard control parameters are used for the IEA 15 MW, as summarized in table 1. More details are also provided in [26]. It is interesting to note that although a nacelle velocity feedback loop is used to reduce platform pitching, the controller natural frequency of 0.2 rad/s is below the platform-pitch first natural frequency of about 0.21 rad/s, which is in line with traditional “derating” strategies. As for the NREL 5 MW, the torque controller natural frequency and damping are those suggested in [46], while the pitch controller bandwidth is reduced to 0.2 rad/s, below the 0.23 rad/s pitch natural frequency of the platform, to increase platform stability similarly to what was done in the OC3 and OC4 projects [27,48]. Damping ratio was increased to a value of 1.0 in an attempt to reduce rotor speed overshoots. In both turbines, torque is saturated at its nominal value in above rated conditions, effectively meaning that a constant torque control strategy is adopted. Moreover, TSR-tracking torque control is employed below rated for the IEA 15 MW, while standard rotor-speed proportional torque control is used for the NREL 5 MW. The specifics of each control strategy are discussed in detail in [44,46], however the two strategies are overall very similar and they are the control strategies the turbines were intended to use at the moment they were designed. Finally, the nacelle velocity feedback proportional gain is found using the generic ROSCO tuning procedure for both turbines.

Table 1: natural frequency and damping of torque and pitch P-I controllers

Parameter	NREL 5 MW	IEA 15 MW
Torque controller natural frequency	0.15 rad/s	0.12 rad/s
Torque controller damping	0.7	0.85
Pitch controller natural frequency	0.2 rad/s	0.2 rad/s
Pitch controller damping	1.0	1.0

3 FOWT Models

The IEA 15 MW RWT is a reference wind turbine, recently developed during IEA wind task 37. In the present study, it is mounted on the Volturn US-S steel semi-submersible platform developed by the University of Maine [26].

The NREL 5 MW wind turbine was designed by the National Renewable Energy Laboratory to foster the development of offshore wind. In the present study, it is mounted to the DeepCWind semi-submersible used during the Offshore code Comparison and Collaboration project (OC4) [31], and has become over the years one of the most studied FOWT. Both turbines use a tri-column, semi-submersible type floater. For the 5 MW wind turbine heave stability is provided by heave plates located at the bottom of the main columns that are connected through a series of cross-braces. In the case on the U-Maine floater for the IEA 15 MW, the three main columns are connected to the main column by three radial pontoons of rectangular cross-section, which provide heave-damping to the platform, removing the need for additional heave plates. The two turbine designs (schematically depicted in Figure 1a) are over 15 years apart and therefore incorporate design principles and trends from their respective periods. The main characteristics of the examined turbines are indicated in Table 2. As shown in the table, rated power increases by a factor of 3. Both total turbine mass including the tower and rotor swept area increase by a factor larger than 3, increasing respectively 3.22 and 3.63 times. This is a result of the larger turbine being of more recent design, and thus incorporating modern design trends. Therefore, the IEA 15 MW RWT benefits from a lower areal-specific power and is able to reach rated power output at a lower wind speed respect to the NREL 5 MW. Total turbine mass increases of a factor larger than 3 because of the marked increase in tower weight.

In fact, the RNA weigh increases only 2.83 times with respect to the NREL 5MW, while tower weight increases 3.59 times from 351t to 1260t. The increase in tower weight is caused by the fact that the designers of the IEA 15 MW thought it was necessary to stiffen the tower in order to avoid resonance issues and the 1st fore-aft and side-side natural frequencies were placed above the 3P frequency range, as opposed to being between 1P and 3P [26]. On the other hand, this was not necessary for the NREL 5 MW. As will be discussed later in the study, this design choice has a non-negligible impact on the dynamics of the floating system and will represent a point of discussion regarding appropriate upscaling strategies.

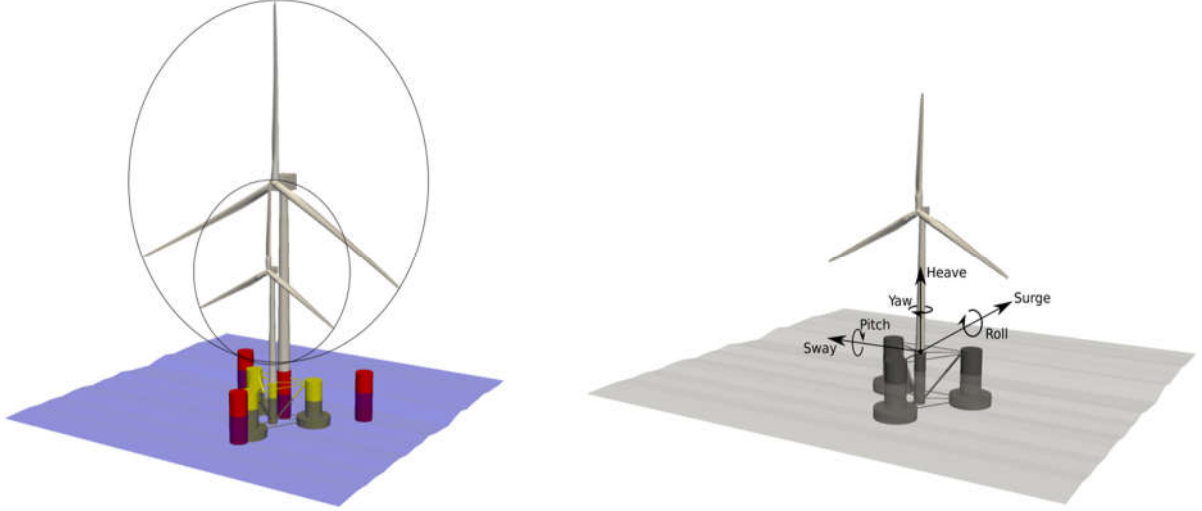


Figure 1: Representation of the two modelled FOWTs (a). Submersed pontoons for the IEA 15 MW are not represented. Floating platform's DOFs illustration (b).

Regarding platform global characteristics, both platforms have the same 20m draft and main column diameter. The distance between the main columns increases of a factor 1.8 while total ballasted mass increase by only 1.3 times, indicating that potentially much less steel is used in the larger turbine, with respect to rotor power.

If we compare this to a simple platform upscaling using the scaling factors $sf1 = \sqrt[3]{3.22} = 1.477$ using the turbine's mass ratio, as proposed in [7], or $sf2 = \sqrt{3} = 1.732$, using the turbine's rated power ratio as proposed in [15], it is apparent how the distance between the main columns increases of a factor greater than the scale factors. Moreover, draft and main column diameter do not vary as they would if a simple upscaling procedure would be applied, as shown in [16]. In more detail, the DeepCWind semi-submersible platform was designed to be representative of the dynamics of a semi-submersible platform as a test-bench article. On the other hand, the VoltturnUS-S semi-sub upon which the IEA 15 MW is installed benefits from the design knowledge gained in the Aqua Ventus New England demonstration project and is far more commercially realistic than the DeepCWind semi-submersible. This reflects the state of the industry when the two floating concepts were developed; in fact floating offshore wind was in its very early years when the DeepCWind semi-sub was developed [3,49]. Arguably, the same is true for the turbines, the IEA 15 MW being a more refined design than the NREL 5 MW. While this is undisputedly true, the differences between the designs can also be seen as a technological difference, and thus worthy of being included herein. Anyhow, it must be remembered that the results of the present study have to be interpreted also under this spotlight. Finally, regarding the mooring system, effective cable diameter and stiffness increase over 4 times, and cable weight increases 6 times. Such relevant cable diameters are necessary to keep the turbine in place but certainly add to the cost of the system.

Table 2: Main characteristics of the examined FOWTs.

	NREL 5 MW	IEA 15 MW	Scale factor
class	I OB	I OB	-
n° blades	3 (upwind)	3 (upwind)	-
rated power	5 MW	15 MW	3
rotor diameter	126 m	240 m	1.9
hub height	90 m	150 m	1.7
swept area	12469 m ²	45239 m ²	3.63
Specific power	400 W/m ²	331 W/m ²	0.83
turbine mass	700 t	2250 t	3.22
RNA mass	349.4 t	991.4 t	2.84
Peak Cp	0.482	0.489	1
Design TSR	12	7.5	0.62
control	ROSCO controller	ROSCO controller	-
platform	Semi-submersible	Semi-submersible	-

ballasted platform mass	13500 t	17850 t	1.3
draft	20 m	20 m	1
freeboard	10 m	15 m	1.5
distance main columns	50 m	90 m	1.8
main column diameter	12 m	12 m	1
mooring system	3-line slack catenary	3-line slack catenary	-
water depth	200 m	200 m	-
cable diameter	0.0766 m	0.333 m	4.31
Cable mass	113.35 kg/m	685 kg/m	6.01
cable stiffness (EA)	7.536 E8 N	3.27 E9 N	4.34

The tower for the IEA 15 MW to use in the onshore variant of the machine was completely redesigned to match frequency requirements. It was originally intended to use the tower designed for installation on the monopile foundation [23], extended to reach ground level as the transition piece from monopile to tower is located at a height of 15m above sea level. This however pushed the tower natural frequencies into the 3P range. Therefore, a reduction in natural frequency was required to place tower frequencies between the 1P and 3P range as originally intended. For simplicity, the monopile tower was used as a starting point and only wall thickness was varied percentage wise along the entire tower. Reducing wall thickness by 35% achieved the goal of placing the natural frequencies where intended by the turbine designers [23]. Tower resistance was verified statically using the maximum loads predicted for the on-shore turbine during operation. In the context of this work this was considered sufficient, and we did not check if fatigue related requirements are met.

4 Environmental Conditions

Onshore wind turbines are typically designed using environmental conditions determined based on a set of pre-defined wind turbine classes. Offshore wind turbines, let alone floating offshore turbines, are much more recent and international design standards are not as clear cut. In particular, while a standard wind turbine class can be defined for the wind conditions, the wave conditions must be derived for the specific installation site. In this study, average metocean data, broadly representative of the sea states of the west coast of the United States has been used [50]. The data was derived from averaging measurements gathered using buoys off of the west United States coastline.

In particular, following the spirit of the study, the two wind turbines are here simulated using the same environmental conditions, as if they were installed in the same, generic, site. Simulations are performed in accordance to DNVGL-ST-0437 design standards [51]. A limited, but significant for Rotor-Nacelle Assembly (RNA) and tower loading, subset of Design Load Cases (DLCs) was used in this study. In particular, power-production conditions are simulated through DLCs 1.1-1.2, using a Normal Sea State (NSS) and Normal Turbulence Model (NTM) for the wind inflow. The significant wave height is determined as the expected wave height value at the installation site, conditioned on the mean wind speed and is consistent with the one used in [23]. Six six-hundred second simulations are used in these load cases. While the simulation time to use to correctly estimate fatigue loading is currently debated [52], the nature of this study is comparative and the employed simulation time is considered sufficient. NSS sea conditions and extreme turbulent wind (ETM) are used in DLC 1.3. In DLC 1.6 the turbines are simulated using NTM wind and a Severe Sea State (SSS). For this sea condition, the significant wave height is determined as the 50-year return extreme wave height conditioned on mean wind speed. The wave height is computed by finding the environmental contour with a 50-year return period using virocon [53]. The Inverse First Order Reliability Method (IFORM) is used within virocon, as suggested in the IEC 61400-3 standard [54]. The data used to generate the 50-year environmental contours is based on the 0-degree wind-wave misaligned significant wave heights found in the accompanying excel sheet of [50]. In DLC 1.4, an extreme coherent gust with direction change is simulated in combination with a NSS wave condition. DLC 6.1 is computed using an extreme sea state and extreme wind speed model with a combine wind-wave return period of 50 years, while a 1-year return period is used in DLC 6.3. The significant wave height, return period and mean wind speed are consistent with the ones used for these DLCs in [23]. These latter DLCs were computed but not included in the final study. Given the academic and comparative nature of this study, wind and waves are considered to be aligned for all DLCs, and no wave spreading functions are used. This is consistent with what was done by other authors in [18,23,26]. Moreover, no DLCs with the presence of faults were simulated, as the comparison is aimed at normal operating conditions. The wave period distribution is modelled using the Jonswap spectrum [55]. Finally, in order to have a more comprehensive view of the phenomena involved, the turbines are simulated in calm sea and in onshore conditions. The detailed environmental conditions that were used are found in Appendix A. The fact that the same met-ocean conditions are used for turbines with different hub-heights means that the two machines will be subject to the same wave environment, while mean hub-height wind speeds will be higher for the machine with a higher hub height.

5 Results

The results section is organized as follows: The differences in platform motions are discussed first, as together with inertia forces they are the ultimate cause of the loading increases in offshore conditions. Next the effects of platform motions are discussed; extreme loads are considered first, focusing on tower loads in particular. Finally, fatigue loading is briefly tackled.

5.1 Platform Motion

Qualitative and quantitative considerations regarding platform dynamics can be derived from RAOs. RAOs correlate the response of a certain load or degree of freedom of the system to the incoming wave frequency. In the present study RAOs were calculated using the procedure described in [56]. A banded white noise spectrum from 0 to 1.5 Hz was used to excite the platform. The response is shown in Figure 2 considering wave excitation only and wind and wave excitation. A 12 m/s and an 18 m/s constant wind field with a shear factor of 0.12 and no turbulence was used in the latter simulations, to evaluate the effect that aerodynamic forces and control may have on platform RAOs. The similarities between the floating platforms is apparent from looking at Figure 2. RAOs are qualitatively similar in Heave, Pitch and Surge. When no wind excitation is present the natural frequencies of the platforms in the respective DOFs can be clearly made out, with the larger floater showing lower natural frequencies, as expected. The presence of the 12 m/s wind field in combination with the ROSCO nacelle-velocity feedback controller is able to significantly damp out the peaks in response at the FOWT's natural frequencies, as is especially clear when looking at platform surge (Figure 2c). Focusing on surge, both the RAO decreases for both turbines when wind is present, a trend that was generally noted also in [25] when observing the response of a spar-type platform. Although decreases are small, it must be noted that they are larger for the IEA 15 MW, which shows lower surge RAO in general. Platform pitch, on the other hand, shows mixed behavior: RAOs slightly decrease for both turbines (but especially the NREL 5 MW) in the 0.1-0.2 Hz range, while they increase between 0.05 and 0.1 Hz. As discussed for the surge RAO, the RAO peaks at the floaters natural frequencies are significantly reduced. Finally, blade pitch RAO is shown in Figure 2d. This metric is significant in this case since no variations in the wind field are present and we can therefore expect the controller to be reacting to the motions induced by the waves alone. The trends are very similar for both turbines both at 12 and 18 m/s mean wind speed, indicating that the ROSCO controller is quantitatively behaving in the same manner when employed on the two machines. Finally, it must be noted that RAOs are nearly identical, with the exception of blade pitch RAO, for both machines at 12 and 18 m/s mean wind speed.

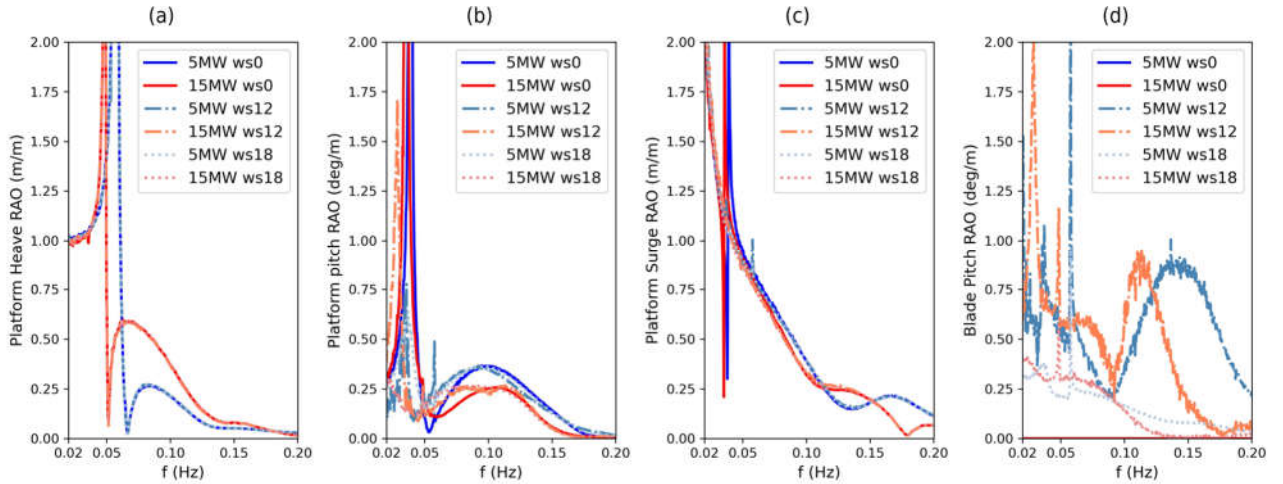


Figure 2: Response Amplitude Operators: platform heave (a), pitch (b), surge (c) and blade pitch (d).

To further understand the loading trends and dynamics of the two offshore systems it is useful to focus on normal power production conditions (DLC 1.1) and normal power production in extreme seas (DLC 1.6). This allows us to highlight the effect of increased wave loading in similar wind conditions. As previously discussed, one of the main concerns when speaking of floating offshore wind is increased tower base loading due to inertial and gravitational forces caused by platform motions.

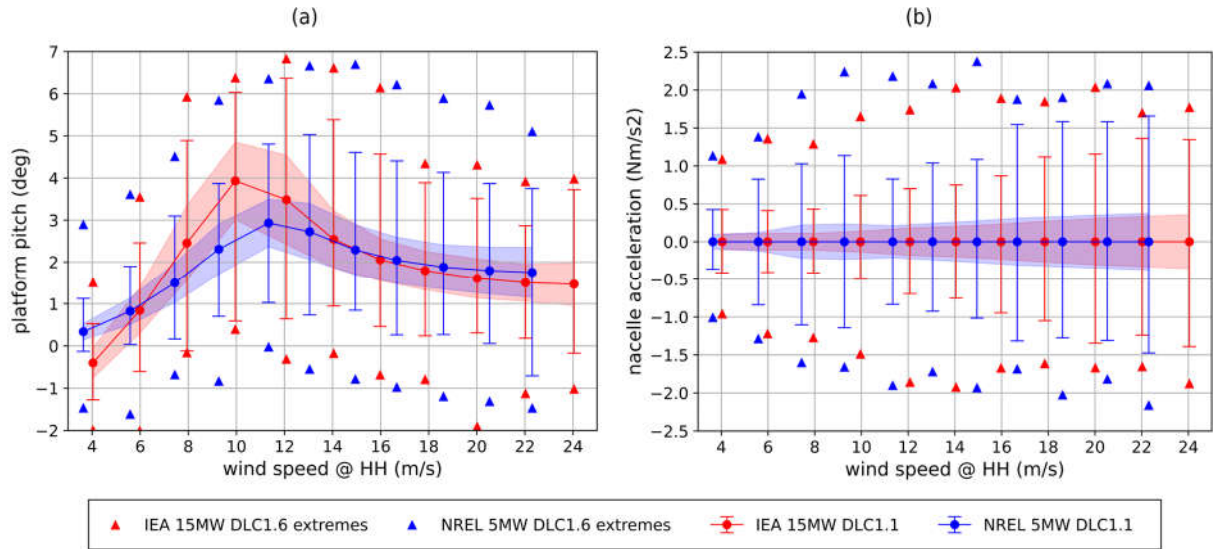


Figure 3: (a) Platform pitch mean, standard deviation (shaded), maxima and minima per wind speed recorded in DLC 1.1. Triangles are referred to DLC 1.6 maxima. (b) Nacelle acceleration in the wind direction in DLC 1.1 (lines and shades) and in DLC 1.6 (triangles).

The mean platform pitch recorded during DLC 1.1 as a function of hub-height wind speed is shown in Figure 3. The differences in hub-height wind speed are apparent and in general the NREL 5 MW RWT operates at a lower wind speed. At 4 and 6 m/s average wind speed platform pitch is lower for the IEA 15 MW. In the latter turbine the center of mass of the rotor-nacelle assembly is located upwind of the tower center axis, while it is located downwind for the NREL 5 MW due to a different drivetrain and rotor design [22,23]. This design feature on the larger turbine acts to partially counter the overturning moment caused by rotor aerodynamic thrust and is beneficial in reducing platform pitch angles. Nevertheless, maximum pitch angle is higher for the IEA 15 MW between 8 and 12 m/s. Both turbines reach their peak pitch angles around rated wind speed, where rotor thrust is at its maximum. The larger values recorded on the 15 MW turbine are due to a combination of factors: the large swept area of the larger rotor leads to large thrust forces, especially below rated power, and the high hub height causes the aerodynamically-caused platform overturning moment to be high.

At higher wind speeds – of 16 m/s and above – platform pitch extremes are lower for the 15 MW turbine. In severe seas (DLC 1.6), the maximum pitch recorded during operation is markedly different, being around 4° for the IEA 15 MW at 20m/s and nearly 6° for the NREL 5 MW. In this range of wind speeds, wave loading prevails over wind loading, as thrust forces are low due to blade pitch feathering, while significant wave height is at its highest. This result is in line with pitch response RAOs, that show higher response in the wave frequency range, namely from 0.8 Hz to 1.2 Hz given the peak spectral periods in question at high wind speeds (Appendix A) on the NREL 5 MW RWT.

Platform pitch peak standard deviation is recorded at 14 m/s nominal hub-height mean wind speed for the NREL 5 MW and 10 m/s for the IEA 15 MW, and is around 45% higher for the larger turbine. On the other hand, at higher wind speeds reductions in standard deviation of around 20% are observed for the IEA 15 MW respect to the NREL 5 MW.

Nacelle acceleration is often used to gauge inertia forces due to platform motion. Although the two turbines behave globally similarly, the NREL 5 MW shows smaller RNA accelerations across all wind speeds, both in terms of absolute maxima and minima in DLC 1.1 and 1.6 and standard deviations.

5.2 Extreme loads

A general overview of the main turbine loads and performance metrics is shown in Figure 4 as a ratio of the onshore recorded values over all of the simulated DLCs. Maximum recorded values during power-production conditions are shown.

The onshore to offshore ratios of general control sensors are shown in Figure 4a. In general, these metrics are mostly unaffected by installation on floating foundations. Rotor thrust is the only sensor that shows notable increases (around 10% for the IEA 15 MW), which are caused by the inertial and gravitational effects of rotor mass that are included in this load sensor. Notably, the peak of this sensor occurs in DLC 1.6, where wave loading is at its highest. On the other hand, aerodynamic thrust ($Rt_{AeroFxh}$) peaks in DLC 1.3 for the 5MW turbine as this sensor does not account for inertial and gravitational loads. Tower loads of both turbines (Figure 4b) on the other hand are significantly affected by floating installation. Except for yaw bearing bending moments, which are mostly affected by aerodynamic imbalances in the rotor, all the monitored sensors increase.

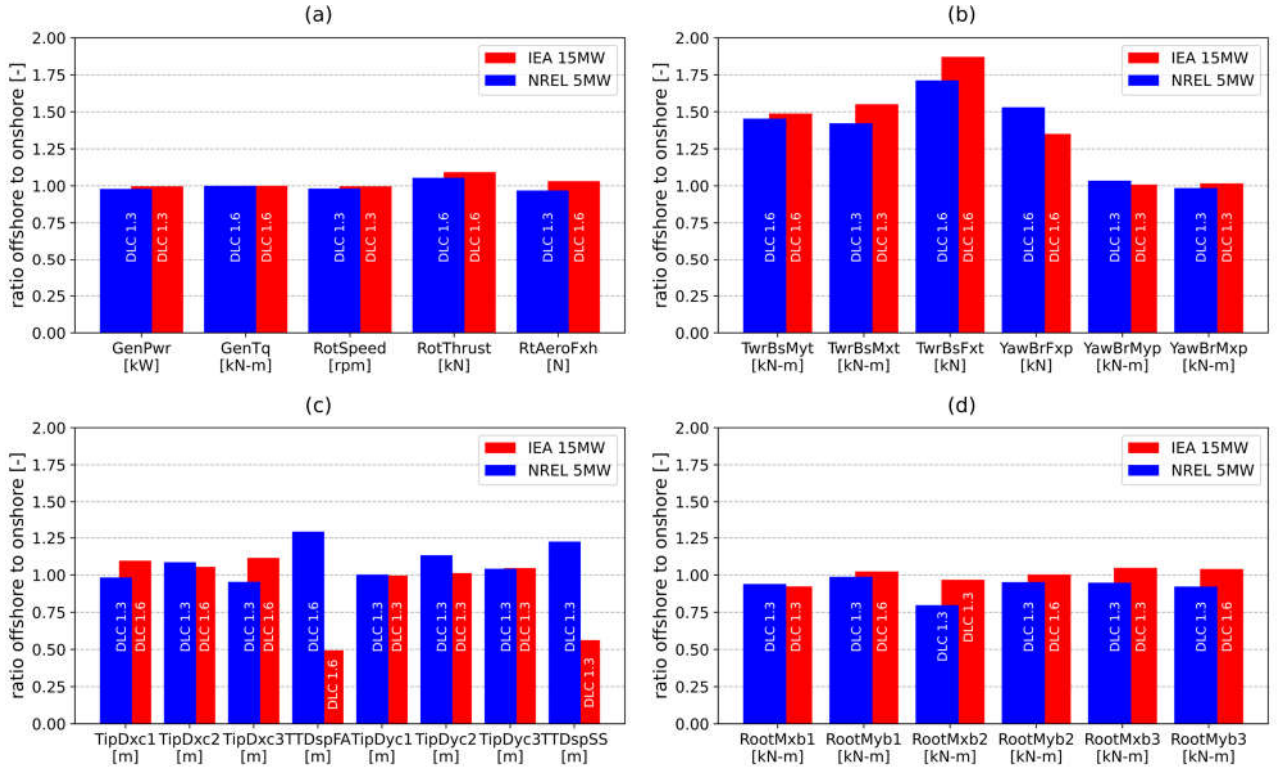


Figure 4: ratio of floating offshore to onshore loads and global performance maxima recorded in DLCs 1.1, 1.3, and 1.6. (a) generator power, torque, rotor speed, rotor thrust, nacelle fore-aft velocity. (b) tower base in-plane and out-of-plane bending moments, tower base fore-aft force, yaw bearing fore-aft and side-side bending moment and yaw bearing fore-aft force. (c) blade 1, 2 and 3 out-of-plane tip displacement and tower top fore-aft displacement, blade 1, 2 and 3 in-plane tip displacement and tower top side-side displacement. (d) blade 1, 2 and 3 out-of-plane and in-plane root bending moments.

The observed increase in tower base side-side bending moment ($TwrBsMxt$) is due to platform roll oscillations caused by nacelle yaw misalignment. In the context of this paper however, it is more interesting to focus on fore-aft loads ($TwrBsMyt$, $TwrBsFxt$, $YawBrFxt$) that are the most influenced by wind and wave loading as wind and waves are aligned with the x-direction. It's interesting that tower top load increases more for the smaller turbine, opposite to tower base loads that increase the most for the larger turbine. This can be caused by a combination of factors, firstly the larger turbine has a stronger and heavier tower than its onshore counterpart, this component being significantly heavier than the smaller turbine's one. As discussed previously, this increases mass forces acting on the tower base. On the other hand, the increase in RNA weight is more limited, limiting the onshore-to-offshore tower top load increases. Moreover, although this is not reflected in offshore-to-onshore ratios, the RNA is located much higher above sea level on the larger turbine, and therefore inertia and mass forces have a much greater lever arm to act upon, affecting tower base bending moment more markedly. Tower and blade maximum deflections are shown in Figure 4c. Tower top displacements increase around 25% for the NREL 5 MW – as would be expected given the loading increase (Figure 4b) – and decrease significantly for the IEA 15 MW. This is due to the towers employed on the two turbines in this study. In particular the NREL 5 MW tower on the OC4 semi-submersible is the same as defined for the OC3 phase III spar-buoy test-case [48] and is similar in stiffness and weight distribution to the on-shore version, placing the 1st fore-aft and side-side natural frequencies between the 1P and 3P excitation band. On the other hand, the tower on the IEA 15 MW was significantly stiffened to address frequency considerations, as discussed previously in section 3, thus leading to lower displacements. Blade displacements on the other hand show some variation, $\pm 10\%$ respect to onshore. The cause of such variations - that are not large enough to be concerning from a tower clearance perspective - are hard to pinpoint exactly as many factors are at play. However, given that blade root bending show less variation: $\pm 5\%$ respect to onshore with the exception of in plane bending moment of blade 2 on the NREL 5 MW (Figure 4d), the variations in blade deflections are likely due to the controller reacting to different inputs and pitching the blades differently, thus effectively influencing the in-plane and out-of-plane blade stiffnesses.

As discussed previously, tower loads are the most affected by platform motions, and are therefore the focus of this next paragraph. The discussion is focused on tower base fore-aft bending moment, but the same considerations are true for tower base fore-aft force.

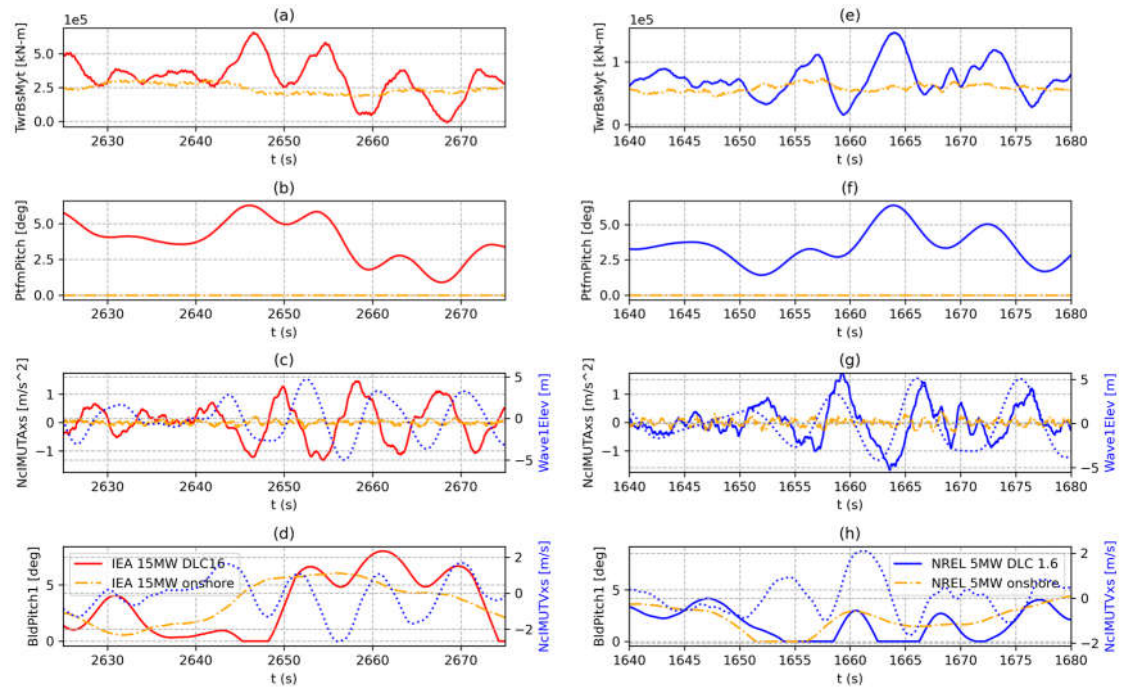


Figure 5: Left (from top to bottom): tower base bending moment (a), platform pitch (b), nacelle acceleration (c) and blade pitch (d) for IEA 15 MW in a 10 m/s average wind speed simulation. Bottom plots also show wave elevation (c) and nacelle acceleration (d) in dashed blue lines on second y-axis. **Right (from top to bottom):** tower base bending moment (e), platform pitch (f), nacelle acceleration (g) and blade pitch (h) for the NREL 5 MW in a 14 m/s average wind speed simulation. Bottom plots also show wave elevation (g) and nacelle acceleration (h) in dashed blue lines on second y-axis.

Figure 5 shows tower base load, platform pitch nacelle acceleration and blade pitch for the IEA 15 MW and NREL 5 MW for the simulations where the maximum fore-aft bending moment is recorded for the two turbines: 10 m/s for the IEA 15 MW and 14 m/s for the NREL 5 MW. The mechanism that causes the extreme load is the same for the two turbines. Both machines are operating near rated wind speed, where mean thrust force peaks and so does mean platform pitch angle. As shown in Figure 5d and 5h the blade pitch controller behaves markedly differently in onshore and offshore conditions. In fact, much higher blade pitch actuation can be noted in floating conditions as the controller attempts to regulate power and nacelle fore-aft motion. In both turbines the peak fore-aft tower load is recorded when the blade pitch controller reduces blade pitch to 0° , attempting to increase nacelle velocity. Ultimately, the load oscillations are caused by the extreme sea state, with the insurgence of a wave train of approximately 5 meters amplitude in both cases (Figures 5c and 5g). Finally, we can also note that the peak bending moment is caused both by a maximum in platform pitch and a minimum in RNA acceleration (Figures 5c and 5g), indicating that both mass and inertia forces are contributing.

5.3 Fatigue loads

An estimate of fatigue loading is given in Figure 6. In this context, we consider zero mean Damage Equivalent Loads (DELs) as a metric as this metric is able to give an effective comparison of damage-weighted load excursions that the turbines experience during operation. While excluding mean loading level may lead to some inaccuracies, the scope of this study is comparative. The procedure used to calculate DELs is the same as adopted in [57], and is also explained in [58]. It is also necessary to note that using the simulated wind fields, the NREL 5 MW is affected by tower resonance at 6 m/s wind speed. This is caused by the fact that the 3P frequency is close to the critical tower frequencies at low rotor rpm. This is a known issue for this turbine and is mitigated by the fact that the wind speed is low and so is mean load. In this context, however, the floating turbine experiences lower loads than the onshore counterpart, as platform hydrodynamics introduce a significant source of damping. Therefore, to keep our comparison as general as possible, the 6 m/s wind speed bin was excluded from calculated metrics.

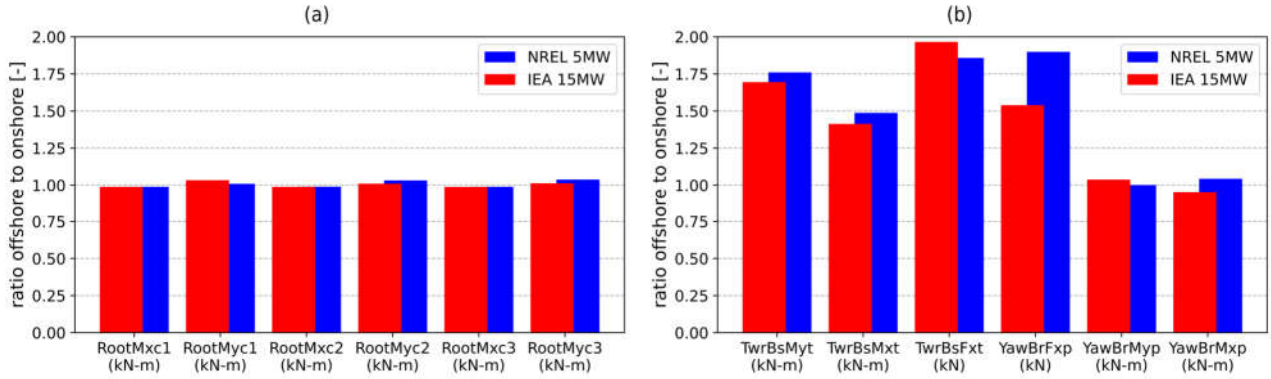


Figure 6: Zero-mean lifetime damage equivalent loads offshore to onshore ratio for main blade (left) and tower (right) load sensors. Only DLC 1.2 is used for fatigue loads. $1 \cdot 10^6$ equivalent number of cycles. 6 m/s wind speed bin is not included in lifetime DELs.

Overall the same trends discussed for extreme loads can be seen. Blade bending moments are unaffected by floating installation while tower fatigue loads increase significantly, with the exception of yaw bearing bending moments. It is interesting to note which combinations of wind and waves cause the most fatigue damage on the two turbines. Figure 7 shows the offshore to onshore ratio of the fore-aft tower base loads for the two turbines.

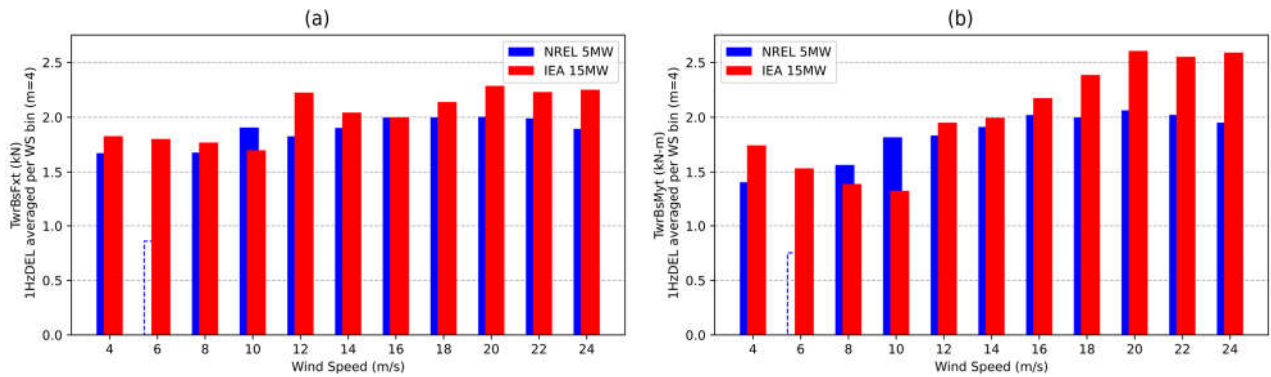


Figure 7: onshore to offshore ratio of 1 Hz, wind speed bin averaged 1 Hz DELs. Tower base fore-aft force (left) and Tower base fore-aft bending moment (right). Simulations are binned based on reference, 150m height, mean wind speed.

It is interesting to note how 1 Hz DELs increase significantly, especially for the IEA 15 MW at higher wind speeds, where wave loading is at its highest. The relatively high increases in tower base fore-aft force DEL at 8 and 10 m/s for the NREL 5 MW can be attributed to the high excursions in nacelle acceleration recorded at these wind speeds.

6 Discussion

As expected by analyzing the broader literature, increasing the size of a semi-submersible FOWT leads to decreased RAOs. This, in turn, lead to decreases in pitch, and, to a smaller extent, surge oscillations caused by wave loading, especially in severe seas. While decreasing overall platform motions for a given sea state is undoubtedly beneficial for reducing the inertial and gravity forces acting on the turbine tower, looking at platform motions in themselves cannot give a full picture. In fact, as it is also acknowledged in the broader literature, as turbine and platform size increase, so do hub height, RNA weight and aerodynamic forces amongst others. All these factors tend to increase overturning moments and reduce the benefits gained by employing a larger semi-submersible platform.

During operation, the two turbines again behave as expected. In particular, the decreased floater response to severe seas is confirmed when looking at platform pitch angles: lower standard deviations and extreme values are recorded, especially in severe seas, for the larger turbine.

When discussing turbine loads, however, the picture is somewhat reversed. In particular, offshore to onshore load ratios are examined as they allow one to quickly grasp how severe additional loading deriving from installation in offshore conditions is. Moreover, by analyzing this metric, one is able to isolate the load increases due to floating installation from load increases due to the upscaled machines themselves [13], which we assume have already been tackled in the design of the machines themselves.

Regarding extreme loading, results are again somewhat expected and in-line with the broader literature, which indicates that tower loading is concerning and should be considered carefully, while blade loading is only minorly affected by offshore installation [18,59]. In this regard, the two analyzed turbines are fairly evenly matched, although slightly higher increases are noted for the larger turbine. The mechanism that causes the extreme loads is the same for the two machines, indicating that the two designs are indeed comparable. Loading peak is caused by the combination of unfavorable wind

and wave loading. Indeed, the turbines are operating near rated, where thrust is maximum and are both subject to a severe wave train. It's interesting to note how platform pitch angles in the two cases are comparable, while nacelle acceleration is larger in magnitude for the smaller turbine. Comparatively speaking, this means that gravitational forces play a larger role compared to inertial forces on the larger machine. Furthermore, the peak in platform pitch is reached when mean pitch is also near its highest. In this perspective, reducing the platform's static pitch angle without increasing pitch RAO would be beneficial. Possible ways of achieving this goal could be increasing the hydrodynamic stiffness without increasing RAOs, employing concrete ballasting as opposed to water ballast in order to lower the platform Center of Gravity (COG) and increase stability or by employing dynamic ballasting systems to reduce mean platform angles. As is often the case, a combination of the three proposed methods could also be employed and be, in practice, the most viable solution.

These results also need to be put into context. The larger machine, being of more recent design, incorporates some smart design features. For instance, the COG of the RNA is placed upwind of the tower, which helps reduce mean pitch angles. Moreover, while the lower areal-specific power implies rotor forces to be comparatively larger than on the smaller turbine, the lower rated wind speed and higher hub height help to offset the peak of aerodynamic loading and the peak in wave loading. This also reduces the overall contribution of wave loading with respect to aero loads. In fact, the ocean waves considered in this study are generated by the interaction of the sea-surface with the wind at the sea-surface level. On the other hand, wind turbines exploit the wind resource high up above the sea water level and because of the presence of the atmospheric boundary layer, for a given wind speed, significant wave height will be higher on a machine with a lower hub height. It is important to note that this study accounts for all of the mentioned effects and nonetheless load increases are larger on the larger rotor. On the other hand, the design of the larger platform may be limited by current technological hurdles, such as harbor size, that may be unable to accommodate large substructures. This could be a reason for which a deeper draft was not employed, that could help decrease static platform pitch angles.

Even if the larger turbine incorporates these smart design features increases in fatigue loads are, again, comparable. Looking at 1 Hz DELs it appears that higher damage is occurring in the IEA 15 MW at high wind speeds. From analyzing power spectral densities of the tower base loads (Appendix B) it is apparent how the main damage source is wave loading as the prevalent response is in the wave frequency band. Therefore, although platform RAOs decrease, the load amplification caused by inertial and gravitational forces increases.

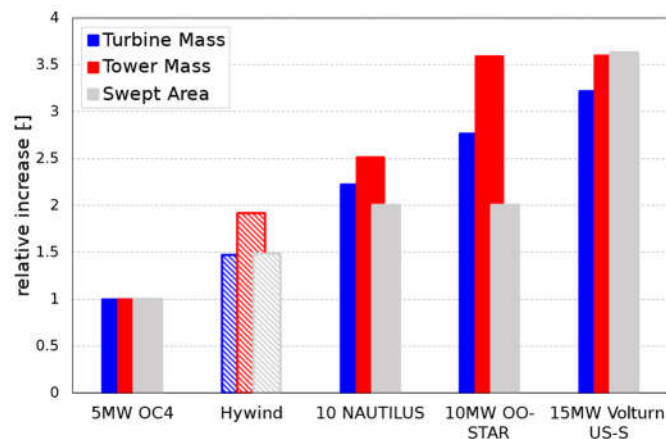


Figure 8: Relative increases in tower and total turbine mass for research floating HAWTs (solid line bars) and a commercial project (dashed line bars). Relative turbine swept area in gray bar.

Given the importance of inertial and gravitational loading of a FOWT foundation, Figure 8 helps give a grasp of the general trends that are observable in this context. The increase of swept area is related to the increase in aerodynamic forces, while increases in mass are related to inertial and gravitational forces. While the exact balance of aerodynamic and inertial/gravitational forces depends on the dynamics and design of the specific system, looking at the overall characteristics of these systems allows one to grasp the relative influence of the forcings acting on the semi-submersible floating systems. With respect to our baseline, the NREL 5MW on DeepCWind semi-sub, turbine weight increases more than swept area does for both the 10MW semi-sub concepts proposed in [28]. Looking at the 6MW turbines employed in the Hywind Scotland commercial project [29], in this case the overall turbine mass increase is comparable to the swept area increase. For the IEA 15MW, overall turbine mass increase is lower than the swept area increase, which is comparable to tower mass increase. In the context of the current study, this indicates that weight increase is relevant for the other presented testcase as well, and therefore so are the inertial and gravitational loading effects discussed throughout this work. Additional R&D technical innovation is therefore needed to reduce the weight of both the nacelle assembly and the blades. In this regard, while major improvements have been made recently thanks to the advancements in aeroelastic blade tailoring, very large FOWT applications will pose specific new challenges to be overcome. Larger rotors will extend beyond the top of the atmospheric surface layer and experience unprecedented inflow characteristics [8], thus needing modifications both in design and control. Downwind wind turbine rotors have also been proposed as a potential future

turbine development [60]. While this configuration has benefits and drawbacks with respect to the standard upwind configuration, placing the rotor downwind allows for more flexible, lighter blades [60]. Moreover, according to [60], downwind wind turbine rotors seem to reduce some ultimate loads and may lead to additional benefits in floating applications.

This study confirms that minimizing the turbine's motion is a key aspect to enable larger and larger designs. Indeed, limiting the increase in mass of the floating systems as component size increases is also a quite intuitive and effective way of limiting the offshore-to-onshore load increases. In this regard, the control system, an aspect that we have only marginally brushed upon in the present work, can play an important role. In fact, by lowering maximum rotor speed (perhaps at the expense of efficiency reductions at rated wind speed), the tower natural frequencies could be lowered allowing for lighter towers. Moreover, being able to more tightly control the rotor speed, and thus allowing for the use of the same controller natural frequencies of on-shore turbines for instance, could eliminate the need for the tower stiffening for the IEA 15 MW discussed in Section 3, greatly reducing load amplification as a consequence. Finally, frequency-avoidance control schemes could also be used to further decrease interference between excitation and resonance frequencies. All these potential solutions require further investigation to prove their effectiveness in a floating environment. Also, it must be noted that the observations discussed in the present study are only valid for semi-submersible type mounted wind turbines. More complex floating substructures such as suspended counterweight concepts [61] could show different dynamic behavior, and may facilitate the upscaling process. In this view, this study should be seen as a preliminary investigation into how FOWT dynamics may affect turbine upscaling and hopes to lead the way to further studies exploring other floater and turbine concepts.

7 Conclusions

In this study, two well-known reference turbines, the NREL 5 MW RWT and the IEA 15 MW RWT, are simulated in the same met-ocean conditions in order to try assessing the different response in terms of performance and loading of machines of different scale to them. Both turbines are installed on semi-submersible floating platforms anchored to the seabed with three catenary mooring lines and use the same controller. The turbines are simulated according to international guidelines as if they were installed in the same sea leg. The turbines are compared through offshore to onshore amplification factors. While significant differences are undisputable between the design of the turbines and floaters, which all benefit from a different level of technical maturity, thus not representing a pure upscaling between each other, the procedure allowed us to discuss some technical challenges in the increase in size of a floating offshore wind turbine, while accounting for technological advancements and current technical limitations.

Results have shown how, although platform RAOs decrease, tower loads are influenced by wave loading to a greater extent in the larger machine. This is due to the increase in weight of the RNA, despite the fact that due to technological advancements RNA weight has increased far less than what would be expected from looking at turbines of a decade ago [13]. Tower weight also contributes to increasing gravitational loading, especially in the IEA 15 MW, where the tower's design required stiffening to support the additional loads. In summary:

- Loading increase is driven mainly by inertial and gravitational forces. Influence on blade loads is limited as these components are light relative to their aerodynamic loading.
- Extreme tower loads are recorded when wave and wind loading is at its highest.
- Reduction in mean platform pitch is beneficial to load reduction. Possible solutions to this end could be to increase platform pitch and roll hydrostatic stiffness or to employ variable ballasted semi-submersible columns.
- Optimization and tuning of control strategies is seen as a key enabler to reduce turbine weight. In particular, reducing rotor speed excursions will enable to more easily place tower natural frequencies between 1P and 3P, and frequency avoidance control strategies can avoid interference between tower natural frequencies and the excitation frequencies.
- A combination of all the above is seen as crucial to enable even larger semi-submersible base floating wind turbine designs in the future
- The different dynamics of other floating substructures may lead to different conclusions regarding potential upscaling and need further investigation.

In conclusion, although increasing the size of a floating wind turbine allows for the use of larger and more stable foundations, the increase in platform stability should be seen as a necessity more than a benefit. As a matter of fact, this study has shown that although RAOs decrease, tower base loads increase as a consequence of increases in component mass and hub height.

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Appendix A –Environmental conditions

DLC	Wind Speed [m/s]	Sea Condition	Significant Wave Height [m]	Peak Period [s]	Shape Factor [-]	Wave Heading [°]	Sea Currents Condition	N° Seeds
1.1	4	NSS	1.1	8.52	1	0	None	6
1.2	6		1.18	8.31	1	0		6
	8		1.32	8.01	1	0		6
	10		1.54	7.65	1	0		6
	12		1.84	7.44	1	0		6
	14		2.19	7.46	1	0		6
	16		2.6	7.64	1.35	0		6
	18		3.06	8.05	1.59	0		6
	20		3.62	8.52	1.82	0		6
	22		4.03	8.99	1.82	0		6
	24		4.52	9.45	1.89	0		6
1.3	4	NSS	1.1	8.52	1	0	None	6
	6		1.18	8.31	1	0		6
	8		1.32	8.01	1	0		6
	10		1.54	7.65	1	0		6
	12		1.84	7.44	1	0		6
	14		2.19	7.46	1	0		6
	16		2.6	7.64	1.35	0		6
	18		3.06	8.05	1.59	0		6
	20		3.62	8.52	1.82	0		6
	22		4.03	8.99	1.82	0		6
	24		4.52	9.45	1.89	0		6
1.4	8	NSS	1.32	8.01	1	0	None	2
	10		1.54	7.65	1	0		2
	12		1.84	7.44	1	0		2
1.6	4	SSS	4.41	11.08	1	0	None	6
	6		4.94	10.80	1.175893	0		6
	8		5.46	10.41	1.86996	0		6
	10		5.94	9.95	2.875399	0		6
	12		6.35	9.67	3.797814	0		6
	14		6.67	9.70	4.185094	0		6
	16		6.90	9.93	4.061018	0		6
	18		7.03	10.47	3.356353	0		6
	20		7.07	11.08	2.607138	0		6
	22		7.02	11.69	1.969604	0		6
	24		6.92	12.29	1.460034	0		6
6.1	47.5	ESS	11.31	18.50	1.00	0	None	6
6.3	38.0	ESS	9.69	16.65	1.00	0	None	6

Appendix B – Tower base bending moment SD at high wind speeds

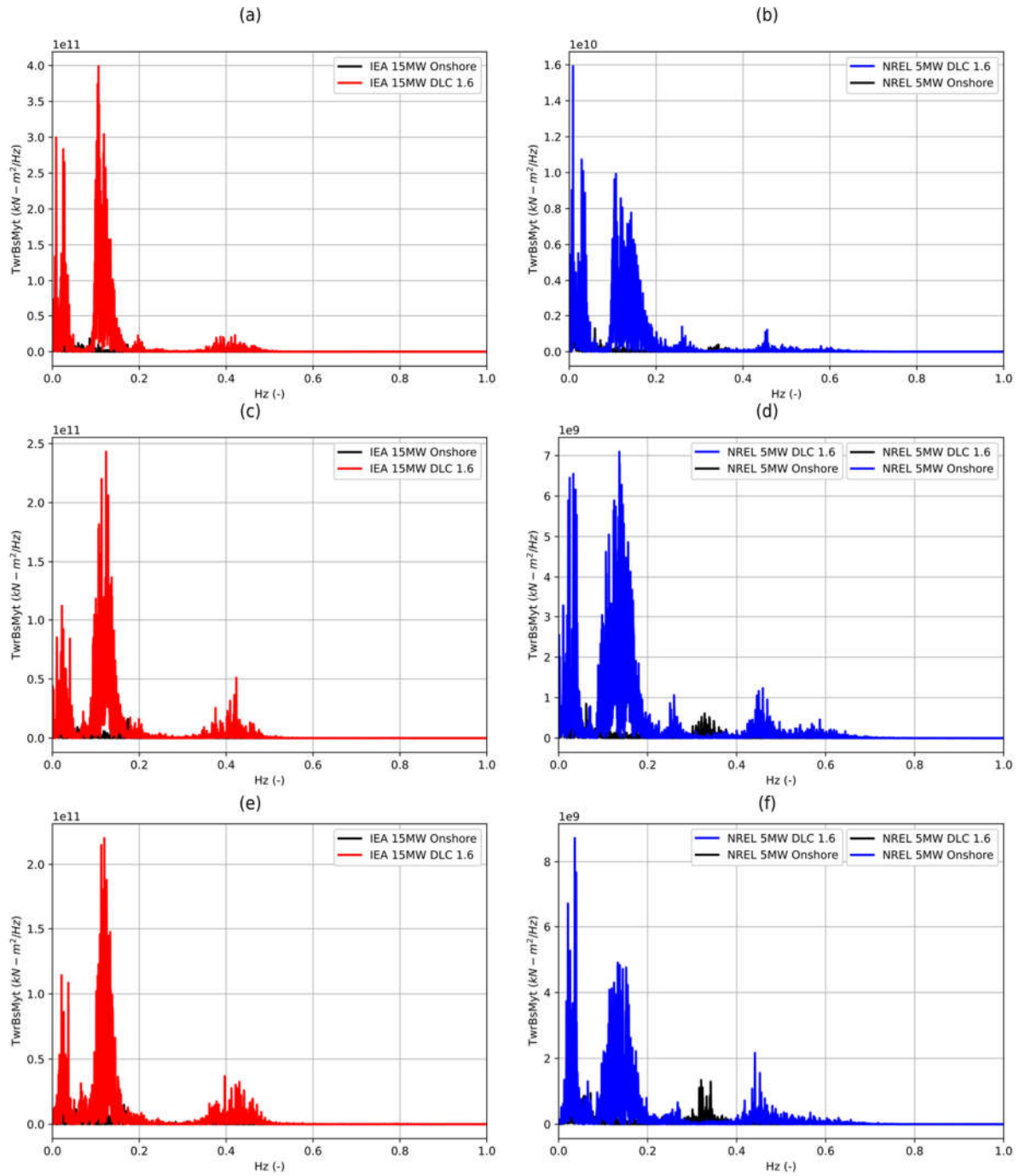


Figure 1B: Power Spectra Density of tower bending moment at 16 m/s mean wind speed for IEA 15MW (a) and NREL 5MW (b), 10 m/s mean wind speed for IEA 15MW (c) and NREL 5MW (d), 24 m/s mean wind speed for IEA 15MW (e) and NREL 5MW (f)