WindFloat-inspired platform designs for different floating turbine sizes

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ABSTRACT: This thesis presents the evaluation of two different floating semi-submersible platform designs to support large offshore wind turbines. Based on the 5MW-platform used in the OC4-project (Offshore Code Comparison Collaboration Continuation), two different models -straight upscale, increasing all dimensions by the same factor, and a design with a draft limited to 20m- were developed to carry 7.5MW and 10MW rated wind turbines. The main focus is set on the analysis and comparison of the platforms' stability, for various load cases representing European offshore conditions in time and frequency domains, based on numerical simulations. In pitch-motion, the most critical of the six degrees of freedom of the platform, larger platforms show a slightly higher response to acting forces. In general, the modified platforms with reduced draft show a better stability in comparison with the straight upscaled platforms. These conclusions are subject to exceptions considering resonant behavior and are discussed for rough sea states. The nacelle acceleration does not exceed the threshold value of 0.2g in any of the analyzed load cases. The infrastructural conditions, mainly harbors, shipyards, dry docks, and natural conditions, such as wind-speeds and distance to shore, seem to allow an implementation of semi-submersible platforms for offshore wind farms. However, strong limitations apply to the biggest platforms. A brief economical evaluation indicates that the economies of scale might justify the deployment of large-scale floating wind turbines.

1 INTRODUCTION

In the last 10 years, the rated capacity of commercial three-bladed upwind turbines has increased threefold. The main driving force behind this development is the minimization of the levelized generation costs. The size of offshore wind turbines will increase as long as technically possible and economically justifiable (Wiser, et al., 2011). The trend is clearly going towards significantly higher power ratings, as Siemens had already installed a 6MW wind turbine onshore in May 2011 (Siemens, 2011). Power ratings of offshore wind turbines will be in the range of 5 to 10MW in the next decade (Smith P. , 2014b).

According to the European Environment Agency, Europe's offshore wind potential could technically meet seven times the energy demand in Europe by 2030 (EEA2009). Favorable wind conditions can often be found far off the coast, where water depths exceed several hundred meters. Floating structures, able to carry wind turbines with power ratings well above 5MW might be an applicable solution to exploit these energy resources.

The resulting Floating Offshore Wind Turbines (FOWT) will have to meet the benchmarks set by bottom-fixed installations. To achieve this, the platforms will need to be stable and cost effective. Furthermore, infrastructural limitations regarding the construction and maintenance efforts have to be considered.

Therefore, the scope of the thesis is to evaluate the platform behavior of two different semisubmersible designs for 7.5MW and 10MW rated wind turbines. These designs are derived from, and compared to a floating 5MW system.

The scaling approaches are briefly presented in this work. The central part of the research efforts consisted in the simulation and comparison of the dynamics of the different designs under a variety of conditions. A brief overview on the infrastructural circumstances of the European North Atlantic and North Sea area is given. Finally the influence of upscaling on the costs is discussed.

2 MODELING STATEGY

2.1 *Reference turbines and platforms*

As most commercial turbines specifications are kept secrets by industrial companies, reference turbines were developed for research activities, allowing easier comparison with a standardized design.

Two reference turbine designs are used in this work. The National Renewable Energy Laboratory (NREL) published detailed specifications of the “NREL offshore 5-MW baseline wind turbine” (NREL 5MW OWT) in 2006. The design is largely influenced by the “REpower 5M wind turbine”, which was the largest and most powerful turbine prototype at that point (Jonkman, Butterfield, Musial, & Scott, 2009).

The Technical University of Denmark (DTU), in cooperation with Vestas, developed the “DTU 10-MW Reference Wind Turbine (DTU 10MW RWT)” (Bak, et al., 2013).

This work also includes the evaluation of a FOWT with a rated power of 7.5MW, as the benchmark for the next generation of offshore wind turbines will be in the range of 6 to 8MW. As no data is publically available for this specific turbine size, the necessary data was obtained from interpolating the available information of the previously mentioned NREL 5MW OWT and DTU 10MW RWT.

As FOWT have been subject to intense research and development efforts only recently, no design is considered to be the standard yet. Different advantages and disadvantages might determine the choice of the floating platform depending on the particular site of deployment (Crozier, 2011). The semi-submersible design is very promising as it combines restoring modes of different other auspicious support structures, such as the ballast stabilized spar buoy, the buoyancy stabilized barge and the mooring stabilized tension leg platform. The main advantage of the semisubmersible platform over the other support structures relies on its shallow draft and good stability behavior. Moreover, a complete construction in the harbor is possible. Consequently, lower costs and risks are associated to offshore operations and larger time periods are available for installation works.

The platform concept examined in this work originates from the joint research project of the “DeepCwind Consortium”. This research group aims to develop deep-water offshore wind technology towards a mature state. This platform is depicted in the Figure 1. It was examined in the OC4, the Offshore Code Comparison Collaboration Continuation project, a code-to-code comparison program involving several universities, research institutes and industrial partners, “which analyzed shallow, transitional, and deep water offshore wind turbine concepts” (Musial & Jonkman, 2010).

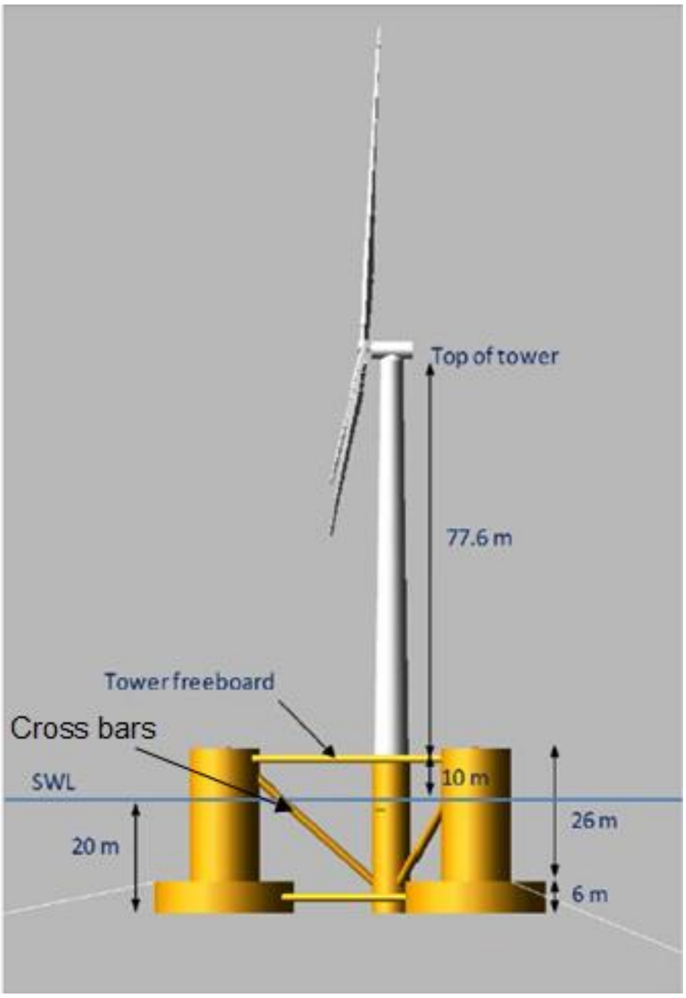

Figure 1 The semi-submersible 5MW-configuration as examined in the OC4 (Robertson A. , et al., 2013b)

2.2 *Platforms Up-Scaling*

The main cost driver of a FOWT is the platform. In the WindFloat project, it accounted for 42% of the total costs (Maciel, 2010). The structural design has a decisive influence on the technical and economic feasibility of the system. The methodology of scaling the platform from supporting a 5MW wind turbine towards 7.5MW and 10MW turbines is thus one of the key aspects in this work. Two methods for adapting the platform’s size to the additional load are examined. In the first approach, the design and proportions of the 5MW DeepCWind-structure are maintained. All its dimensions are linearly increased to accommodate the higher weight and thereby ensure the buoyancy. The factor by which all dimensions are increased is referred to as the scaling factor s (Ásgeirsson, 2013). Accordingly, the scaling factor s is proportional to the cubic root of the increase in mass.

In the second approach, the draft is limited to 20m, equivalent to the 5MW reference design. The relatively shallow draft of the semi-submersible platform marks one of its key advantages, as it allows a complete installation in the dry dock.

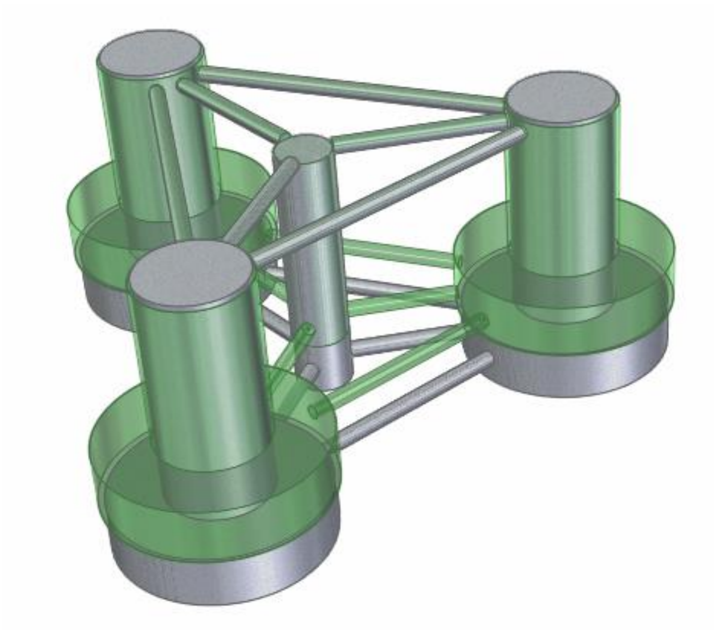

Figure 2 CAD-model of the 10MW S (grey) and the 10MW RD (green) design

The total mass and mass moments of inertia of the platforms were computed using 3-dimensional models of the platform, generated with Solid Edge ST6. The overall volume and total weight (including ballast water) of both 10MW platforms are identical, same for the 7.5MW platforms. In the following, the designs are referred to as “Scaled” (S), for the direct upscale of the 5MW, and the “Reduced Draft” (RD), for the 20m draft limited platforms.

Table 1. Comparison of platforms dimensions, mass and mass moments of inertia

	5 MW	7.5 MW		10 MW	
		S	RD	S	RD
Scaling factor s (-)	-	1.13	-	1.26	-
OC[1] upper diameter (m)	12.0	13.4	14.3	15.1	15.8
OC lower diameter (m)	24.0	27.1	28.5	30.3	31.8
OC height (m)	32.0	36.2	32.0	40.3	32.0
Distance[2] between OC (m)	50.0	56.5	56.5	63.0	63.0
CM position[3] (m)	13.7	15.2	13.7	17.0	13.5
Minimum width (m)	67.3	76.1	77.5	84.9	86.5
Total draft (m)	20.0	22.6	20.0	25.2	20.0
Mass of steel ($*10^6$ kg)	3.85	4.67	4.55	5.80	5.58
Total mass[4] (t)	13.4	19.4	19.4	27.0	27.0
Mass moment of inertia[5]					
in Pitch ($*10^{10}$ kg*m^2)	0.68	1.2	1.3	2.0	2.0
in Roll ($*10^{10}$ kg*m^2)	0.68	1.2	1.3	2.0	2.0
in Yaw ($*10^{10}$ kg*m^2)	1.2	2.2	2.2	3.6	2.8

In summary the main difference between the scaled and the reduced draft design lies in the geometry of the offset columns. The distance between offset columns remains the same. The diameter of the main column of the reduced draft and scaled platforms stays the same in each power level, as it has to fit the tower dimensions of the wind turbine.

The overall weight is kept constant by adjusting the amount of ballast water. Hence, the displaced volume of the whole platform is the same in each power level.

2.3 *Load cases*

The dynamics of each turbine-platform system were simulated in different conditions defined by four load case sets, and using FAST (version 8.03.02). FAST is a computer-aided engineering tool for horizontal axis wind turbines developed by the NREL and distributed online in open-source. It is an aero-servo-hydro-elastic code capable of simulating the response of a FOWT to most environmental loads. The hydrodynamic properties of the platform were determined using WAMIT®.

The first set of load cases attempts to check system floatability and estimate its natural frequencies using free decay tests. No aerodynamic model is considered at this stage.

The second load case set estimates the performances of the systems under idealized offshore conditions, namely with a steady wind speed (constant in time and uniform in space) and regular wave excitation defined by a single frequency sine wave. Three load cases were considered with wind velocities below rated, at rated and above the turbines’ rated wind speed. The regular waves considered have a height of 6m and a period of 10s, as used in the OC4-project to represent the sea conditions in the North Sea (Schmidt & Ahrendt, 2006).

Electrical power production is simulated using a variable speed generator-torque controller with a PI collective blade pitch.

Table 2. Load case set 2, idealized conditions

Case number	Wind speed U_{steady}(m/s)	Wave height H_{steady}(m)	Wave peak period T_{steady}(s)
2.1	10.0	6.0	10.0
2.2	11.4	6.0	10.0
2.3	13.0	6.0	10.0

The third load case set simulates the dynamics of the system in conditions that could be encountered by the system in operational conditions. This load case set introduces irregular waves and turbulent wind. Electrical production is considered with the same control strategy than in the load case set 2.

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[1] Offset Columns

[2] distance center-to-center

[3] Center of Mass position vertically below sea water level

[4] including water ballast

[5] around center of mass

Table 3. Load case set 3, Operational conditions

Case number	Wind speed U_{mean}(m/s)	Significant wave height H_s(m)	Peak spectral period T_p (s)
3.1	10.0	6.0	10.0
3.2	11.4	6.0	10.0
3.3	18.0	6.0	10.0
3.4	25.0	6.0	10.0
3.5	11.4	8.0	12.0
3.6	11.4	10.0	14.0
3.7	11.4	14.0	16.0

The last load case tends to check the ability to of the structure to survive extreme conditions. In this configuration, turbine blades are feathered, rotor motion is locked and power production is suspended.

Table 4. Load case set 4, Survival conditions

Case number	Wind speed U_{mean}(m/s)	Significant wave height H_s(m)	Peak spectral period T_p (s)
4.0	50.0	15.0	19.0

In all the load cases and for all the turbines and platforms, the structural elements are considered to be rigid (no internal stress nor element deformation are considered). All the simulations were carried for a water depth of 200m, using the same mooring system, a catenary mooring system designed for the 5MW platform used in the OC4 project. The simulation time, considered time sample (simulation time without transient time) and time step are given in Table 5 for each load case set.

Table 5. Simulation time parameters

Load case set	Simulation time (s)	Considered time sample (s)	Time step (ms)
1.x	900.0	900.0	12.5
2.x	1100.0	900.0	12.5
3.x	3600.0	3400.0	12.5
4.x	3600.0	3400.0	12.5

3 PLATFORMS DYNAMICS COMPARISON

3.1 *Free Decay tests and steady state conditions*

As the wall-thickness of up-scaled models is kept constant, the ratio between the platform's deadweight and its volume decreases for larger platform dimensions. Thus, the ballast water had to be adjusted to match the designed draft and CM of every platform configuration. The first FAST simulations serve to validate the trimming and the integrity of the inputs.

To verify if and how the floating structures restore to the equilibrium position, free decay tests are run. They are then used to determine the natural frequencies of each platform for each platform degree of freedom. Natural periods are summarized in Table 6. Results in sway and roll are not shown since they are very similar to surge and pitch, due to platform symmetry.

Table 6. Comparison platforms natural periods T_{nat}

Degree of freedom considered	5 MW	7.5 MW		10 MW	
		S	RD	S	RD
T_{nat} in Surge (s)	113	144	145	212	206
T_{nat} in Heave (s)	18	19	19	20	19
T_{nat} in Pitch (s)	26	28	25	30	28
T_{nat} in Yaw (s)	80	110	108	154	154

In general, and as expected, the up-scaling of the platforms results in larger natural periods due to an increase of platform inertia, relatively to hydrodynamic damping and mooring line stiffness. This is particularly visible in surge and yaw, where the natural periods almost double between 5 and 10 MW. It is interesting to see that scaled and reduced draft designs have a very similar behavior. However, in heave and pitch, the oscillations of the reduced draft designs seem to be more damped than those of the scaled platforms, due to a larger horizontal area. This is positive for platform stability.

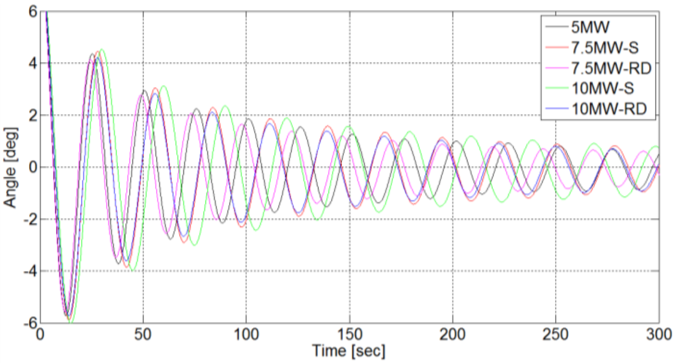

Figure 3. Pitch free decay test

It is also of interest to compare the platform natural frequencies to the power spectral densities (PSD) of the sea states considered in the third load case set. One can see that natural frequencies in heave lie close to the peaks of the Pierson-Moskowitz spectra of the roughest sea states (load cases 3.7 and 4.0). This can potentially cause resonance and will be investigated later in this report.

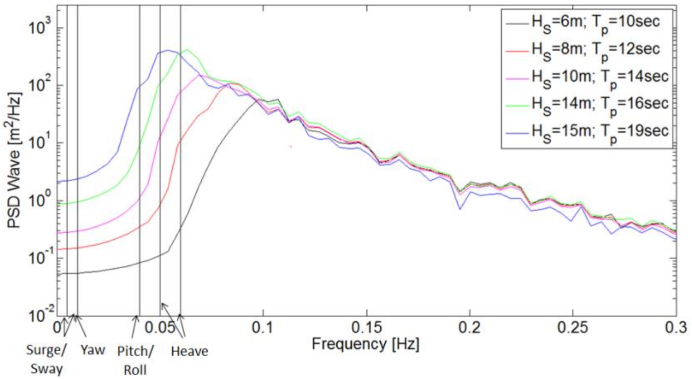

Figure 4. Pierson-Moskowitz spectra of the considered sea states compared to platform natural frequencies

In idealized conditions (steady wind and regular waves), the largest platform pitch occurs at a wind speed of 11.4m/s. This is linked to the control strategy that pitches the blades at wind speeds greater than the rated speed of 11.4m/s. Thus, the greatest thrust forces on the rotors apply at rated wind speed, inducing the largest platform pitch motions. Since platform pitch is critical for the operation of the system, the interpretation of the results in the third load case set will be centered on platform motions at rated wind speed.

Table 7 Thrust force and platform pitch of DTU 10MW Scaled

Case number	Thrust (*10^3 kN)	Mean Pitch angle(°)	Max Pitch angle(°)
2.1	1.2	3.53	4.27
2.2	1.5	3.79	4.61
2.3	1.1	2.73	3.43

3.2 *Operational conditions*

In operational conditions (turbulent wind and irregular waves), the 10 MW platforms seem to experience larger displacements in surge than the 7.5MW platforms, which already experienced bigger displacements than the 5MW turbine. The differences in surge displacement between the reduced draft and scaled design for the same rated power are very limited, showing that the mean displacement in surge is more dependent on the mooring design than on the platform geometry.

Table 8. Comparison of platforms displacements for LC3.2

Degree of freedom considered	5 MW	7.5 MW S	7.5 MW RD	10 MW S	10 MW RD
Surge (maximum in m)	9.2	18.0	17.9	33.3	33.2
Heave (maximum in m)	1.0	0.7	1.1	0.6	0.9
Pitch (maximum in °)	5.2	5.4	4.6	6.5	5.3
Pitch (average value in °)	2.8	3.3	2.4	3.6	3.0

In the same way, big platforms seem to pitch more than the small ones. The reduced draft designs seem to be more stable in terms of pitch than the scaled platforms, with a lower pitch average.

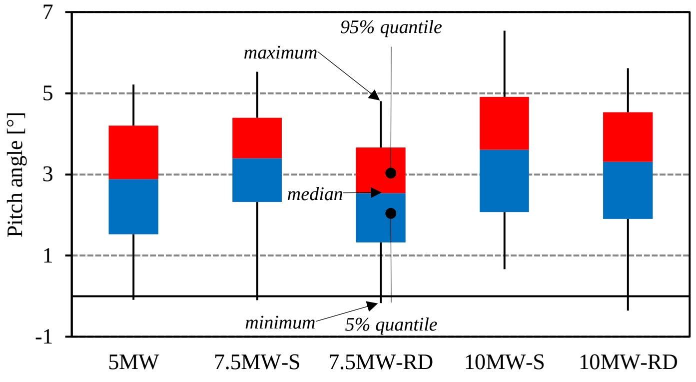

Figure 5. Box plot of pitch motion for load case 3.2

On the contrary, heave motions tend to reduce for larger system sizes. The free decay tests showed a slightly bigger damping in heave direction for the reduced draft than the scaled design, in the same power level. Nevertheless, the reduced draft platforms experience greater heave motions than the scaled ones for the same wind and wave conditions. When looking at natural frequencies of all the platforms, one can see that the heave natural frequencies of the 5MW, 7.5MW-RD and 10MW-RD platforms are closer to the peak frequencies in the wave spectra. The frequency domain analysis of the load case 3.2, depicted in figure 6, shows that these platforms have a significantly larger response in heave than the scaled platforms.

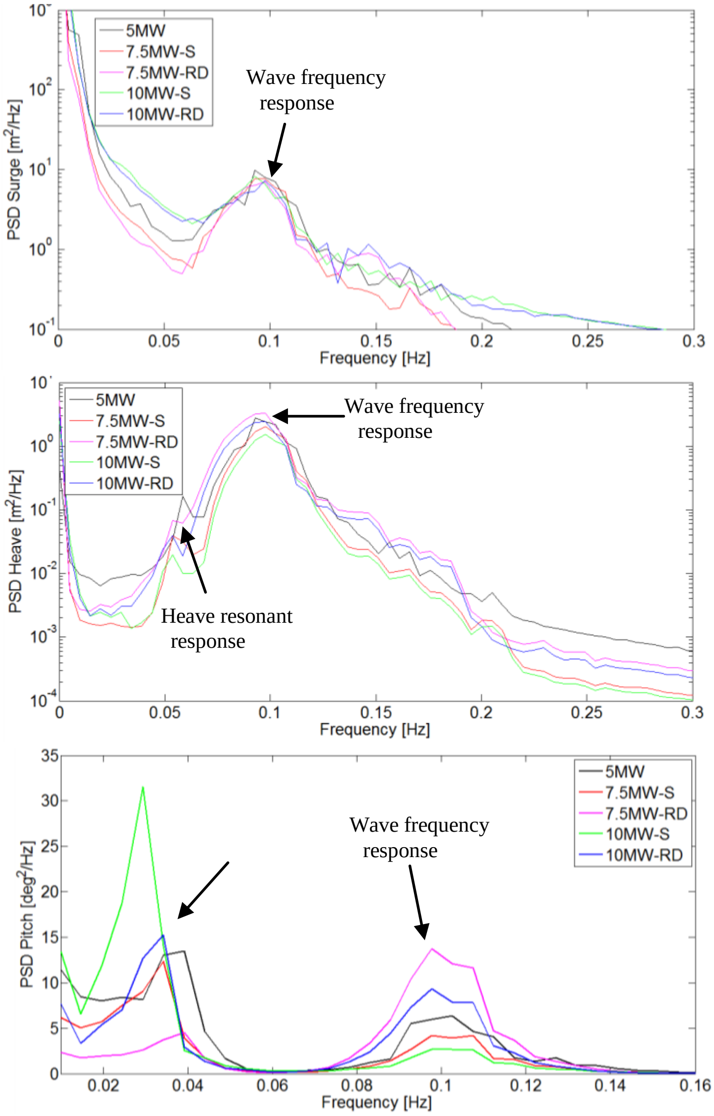

Figure 6. Power spectral density distributions of platform motions for load case 3.2

In addition to high wind speeds and large pitch angles, an excessive acceleration measured at the nacelle can also lead to a safety shutdown of the system. A nacelle acceleration of 0.2*g (or 1.96m/s^2) is generally taken as a cut-out value (Suzuki, et al., 2010). The absolute values of acceleration along the x-axis, corresponding to the wind and waves direction, are compared in Table 9. Maximal nacelle accelerations increase with increasing wave size for all systems. The reduced draft designs experience higher accelerations than the scaled platforms, possibly due to higher wave frequencies responses. Wind speed seems to have less influence on nacelle accelerations than wave height and period.

Table 9. Comparison of nacelle accelerations (in m/s^2)

Degree of freedom considered	5 MW	7.5 MW		10 MW	
		S	RD	S	RD
3.2	1.10	0.96	1.38	0.85	1.25
3.5	1.13	0.97	1.38	0.86	1.26
3.6	1.19	1.02	1.46	0.93	1.24
3.7	1.32	1.19	1.66	1.08	1.44

3.3 *Survivability*

To simulate an extreme sea state condition, a simulation is run with irregular waves of 15m significant wave height and a spectral peak period of 19s. The mean velocity of the turbulent wind is set to 50m/s. This would correspond to the conditions of a 100-year storm event in the North Atlantic (Karimirad, Gao, & Moan, 2009).

The average pitch angles of all platforms are lower than for the operational conditions and relatively equivalent for all the platforms, due to feathered blades. The waves thus have a higher relative influence on the pitch angle of the FOWTs than the wind.

Due to different natural frequencies, the general behavior of the platforms is the opposite in this load case than reported in the previous one. Here, reduced draft platforms seem to be more stable than scaled platforms in terms of heave, but significantly less stable in terms of pitch.

Table 7. Comparison of platforms displacements for LC4.0

Degree of freedom considered	5 MW	7.5 MW		10 MW	
		S	RD	S	RD
Surge (maximum in m)	13.1	13.1	15.5	14.1	17.1
Heave (maximum in m)	6.0	6.2	4.8	6.3	5.1
Pitch (maximum in °)	4.8	3.4	5.7	2.7	4.5
Pitch (average value in °)	0.4	0.4	0.3	0.4	0.3

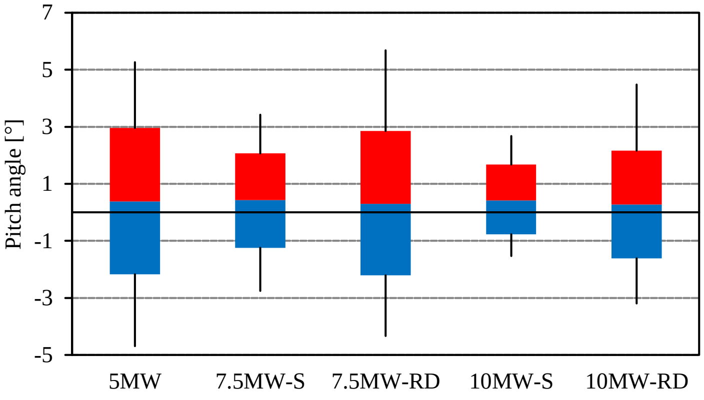

Figure 7. Box plot of pitch motion for load case 4.0

4 FEASABILITY

4.1 *Infrastructural context*

From a technical and economic point of view, one of the main advantages of semisubmersible structures over the other FOWT-platform designs, is the possibility to complete its construction in a harbor. After the construction, the FOWT is towed to the desired position, where the pre-laid mooring is connected to the platform. If a dry dock is used for the construction, as it was in the WindFloat project, only a limited number of shipyards come into consideration for larger platform dimensions. This might lead to longer transport distances and thereby increased costs for the transportation and installation.

The increased dimensions of the platforms presented in this work drastically reduce the number of European dry docks suitable for assembly. The minimum platform width, is the most critical dimension. The 10MW platforms for example, would have a minimum width of almost 90m, making assembly impossible in most of European dry docks. The problem of platform draft might also be critical, but could be mitigated to some extent. In the WindFloat project for example, ballast water was eliminated and additional floaters were installed in order to reduce the platform draft and make it fit Lisnave dry docks in Setúbal.

Table 8. Overview of the largest European dry docks

Company	Location	Length (m)	Width (m)	Draft (m)
Able UK ltd	Billingham, UK	376	120	12.1
Navantia	Cadiz, S	525	100	9.0
Harland& Wolff Heavy	Belfast, IR	556	93	8.4
Maersk *(closed in2012)*	Odense, DK	415	90	11.0
STX Europe	St. Nazaire, F	450	90	-
Keppel Verolme	Rotterdam, NL	405	90	11.0
ThyssenKrupp	Kiel, G	426	88	8.7
Port Autonome	Marseille, F	465	85	9.2
STX Europe	Rauma, FL	260	85	-

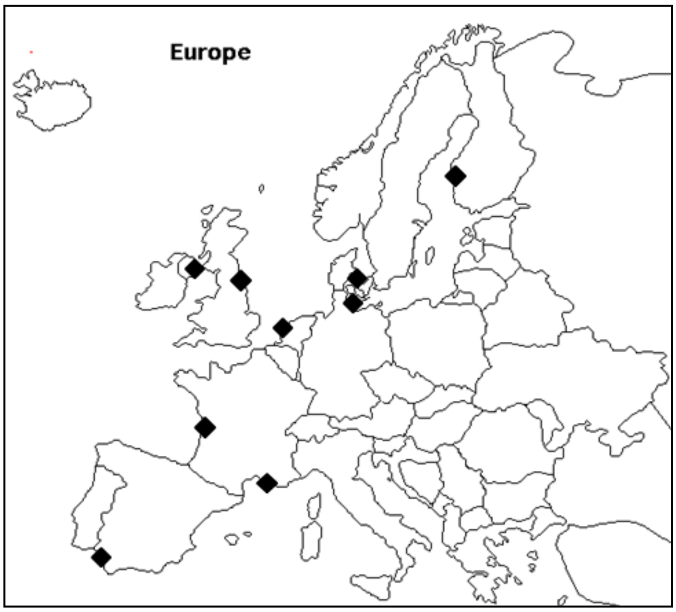

Figure 8 Map of Europe´s largest dry docks (based on Enchanted Learning, 2002)

4.2 *Impact on costs*

The main motivation for larger offshore turbines is to generate economies of scale. The wind industry is experiencing an ongoing decrease in the levelized cost of energy for larger turbine sizes in the installation of fixed bottom structures. This motivates turbine manufacturers to further increase turbine dimensions and rated power.

Scaling up floating platform dimensions towards 7.5MW and 10MW systems would have a financial impact through several cost drivers. Some costs are fixed and would not significantly increase for larger platforms, inducing a lower €/MW ratio. These are, among others; environmental surveys, wind, current and wave assessments, analysis of the geological condition of the sea bed, cabling and offshore grid connection, management and project leadership.

According to the first table of this report, the mass of steel needed for a 10MW platform is only 1,5 times bigger than for a 5MW platform. This shows that the upscaling could induce economies of scale through variable costs, such as the cost of steel. Some variable costs, such as annual operational expenditures (OPEX) or cost of working hours for construction and decommissioning, could also participate in this cost reduction, even though it is difficult to estimate at this stage.

However, some marginal costs are likely to rise relatively to the overall system expenditures for increasing platform sizes: transportation costs, dry dock fees or mooring installation are some relevant examples of potential critical costs.

Finally, a large uncertainty exists on the exact costs of 10MW turbines, as no serial production of equipment, such as bearings, exists at the relevant sizes.

4.3 *Further work*

Since the completion of the modeling tasks reported in this work, some significant improvements have been developed on FAST8. These new features include a finer hydrodynamic model of the OC4 platform using Morison equation and second order wave hydrodynamics. Using these new features could refine the work reported here, especially on the platform degrees of freedom that were not extensively covered by the methodology, e.g. sway, roll and yaw.

Further conclusions could also be drawn carrying out structural and fatigue analysis as well as a parametric mooring design study.

New methods of offshore platform assembly could also be investigated, inspired by recent technical developments in the oil and gas industry.

5 CONCLUSION

This work reports the study of the response to aerodynamic and hydrodynamic loads of floating offshore wind turbines, with rated powers of 5MW, 7.5MW and 10MW for two different floating semi-submersible platform designs. Furthermore the infrastructural conditions of European dry dock sites were examined and a brief cost analysis was performed.

The main focus was set on the analysis and comparison of the platforms' stability for various load cases. The data was analyzed both time and frequency domains. The free decay tests indicate a slightly less damped response of the 10MW-systems compared with smaller sizes. The natural frequencies in pitch, roll, and heave-motion lie close to the peak-frequencies of the wave spectra for extreme waves. This leads to increased amplitudes in the motion along these degrees of freedom due to resonant response. In pitch-motion, the most critical of the six degrees of freedom of the platform, larger platforms show a higher response to acting forces. The platforms with reduced draft show a better stability in pitch in comparison to the straight upscale for operational conditions.

However the platforms with a reduced draft showed a higher resonant response to wave frequencies, which causes bigger pitch angles of these platforms in extreme wave conditions. Further investigations are needed regarding this aspect.

Another critical factor when evaluating the stability of a floating wind turbine is the nacelle acceleration. The tests showed that the threshold value of 0.2g was not exceeded in any of the analyzed load cases.

The examination of the European shipyards and dry docks showed that facilities with sufficient dimensions for a construction of the 10MW-systems are available but would restrict coverage of many potential floating wind farm areas. 7.5-MW platforms are significantly less impacted by those limitations.

The influence of the upscaling on various cost drivers was examined. The costs per MW for steel, labor and preliminary site assessments are expected to decrease. However the cost of dry docks, transportation and mooring installation is suspected to increase critically.

Thus the development of larger semisubmersible platforms seemed beneficial on an economic and technical point of view, and potential further work was identified.

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7 AKNOWLEDGEMENTS

This thesis is based on work conducted within the KIC InnoEnergy Master School, in the MSc program SELECT. This program is supported financially by the KIC InnoEnergy. The main author also received financial support from KIC InnoEnergy, which is gratefully acknowledged.