A METHOD TO UPSCALE A FLOATING OFFSHORE WIND TURBINE FROM 5 MW TO 15 MW

A Thesis

by

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ABSTRACT

This thesis presents a method to upscale the NREL 5 MW reference wind turbine and the OC4 reference semisubmersible from 5 MW to 15 MW. The basis for the upscaling method is an assumption for the overturning moment scaling with turbine power rating. Focusing on the semisubmersible, this allows for upscaling by preserving max static pitch angle, or in other words, by scaling pitch restoring stiffness with the same factor as overturning moment. This was accomplished by increasing column radius, or column distance, or both. Increasing column radius increased the heave natural period and metal mass, while increasing column distance raised the center of gravity and metacentric height but slightly decreased the heave natural period, potentially exposing the platform to resonant effects. Comparison was also made to the VolturnUS-S 15 MW platform, whose design was observed to increase the heave natural period while lowering the center of gravity, addressing issues with scaling column distance. Finally, a method for estimating the upscaled platform parameters for different overturning moment assumptions was developed after observing that the upscaled platform had much greater pitch restoring stiffness than the VolturnUS-S platform. The estimation indicated that for the assumed overturning moment scaling, platform metal mass per unit power would always decrease when upscaling.

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All work conducted for the thesis was completed independently by the student.

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NOMENCLATURE

Symbol	Unit	Description
s	[-]	Scale factor
r	[m]	Radius
m	[kg]	Mass
h	[m]	Height
M	[Nm]	Moment
I	[m^4]	Second moment of area
y	[m]	Distance to bending axis
σ	[N/m^2]	Bending stress
k	[Nm/rad]	Pitch stiffness
A	[m^2]	Area
ρ	[kg/m^3]	Density
CGz	[m]	Center of gravity z-position
CBz	[m]	Center of buoyancy z-position
GM	[m]	Metacentric height

1. INTRODUCTION

Background and Motivation

The United States can play a significant role in addressing the challenge of climate change, as the second largest emitter of CO_2 and the largest emitter of CO_2 per capita in 2019 (Joint Research Center, 2020). More than half of all energy consumed by the U.S. electric power sector is sourced from coal and natural gas, with 90% of its coal and 36% of its natural gas production being consumed by the electric power sector (EIA 2019).

To limit the effect of global warming to 2 degrees Celsius by the end of the century, it is estimated that 15-18% of the global electricity supply must come from wind energy by 2050 (IEA 2013). In their 2015 Wind Vision Report, the U.S. Department of Energy projected that under policy conditions as of January 1, 2014, U.S. wind energy could reach 25% by 2050, and set an ambitious but viable goal for 35% by 2050, but noted that the industry is very sensitive to federal policy support, particularly for development of offshore wind, with relatively high Power Purchasing Agreement (PPA) prices in the range of $180/MWh to $240/MWh. Nonetheless, more recent offtake agreements have seen prices as low as $65/MWh in a PPA with Vineyard Wind, driven by state-level policies (Musial et al, 2018), though a levelized estimate of price may be closer to $98/MWh (Beiter et al, 2019).

The National Renewable Energy Laboratory, reviewing global Levelized Cost of Energy (LCOE) projections from recent studies, estimated that the LCOE for fixed-bottom offshore wind turbines will fall from around $120/MWh in 2018 to $50/MWh in 2030, while the LCOE for floating offshore wind turbines will fall from around $175/MWh in 2018 to $70/MWh in 2030, with high potential for cost reductions as floating wind technology is still at an early stage (Musial et al, 2018).

While the 2015 DOE Wind Vision Report expects only about one-fifth of the electrical power supplied by wind to come from offshore sources in their 35% wind scenario, as more than half of the United States' offshore wind resources are at depths of 60m or greater (Musial et al, 2016), reducing the cost of floating wind energy remains a pertinent challenge. As wind turbines break past the 10 MW mark, the scaling of floating substructures to support them may be an important factor in continuing to reduce the cost of offshore wind energy, if not the greatest factor in terms of potential for reducing costs (The Carbon Trust, 2015).

However, floating platform size and weight is heavily dependent on intellectual property, which poses a barrier to collaboration on research and development. The National Renewable Energy Laboratory has published definitions of reference wind turbines rated at 5 MW and 15 MW (Jonkman et al, 2009, Gaertner et al, 2020), and these have been accompanied by reference floating semisubmersibles via the Offshore Code Collaboration Continuation (OC4) and the University of Maine, respectively (Robertson et al, 2014, Allen et al, 2020). Illustrating the impact of intellectual property, these two reference semisubmersibles use similar but different designs that may complicate comparison between semisubmersibles of different scales. Additionally, the National Offshore Wind Research and Development Consortium advises that more research is still needed on the effects of scaling on floating substructures (NOWRDC 2019), and support structures using the NREL 15 MW reference turbine or another set of credible specifications are still being solicited (NOWRDC 2020).

Previous and Ongoing Research

A number of reference wind turbines have been designed and published by various institutions to encourage collaboration on research. These reference turbines may be at or beyond current manufacturing capability, and they form a reference for comparison for various upscaling methods. Limited specifications such as hub height or rotor radius are also rarely available for commercial wind turbines.

WindPACT

In the early 2000s, the NREL funded the WindPact project to investigate the effects of rotor design and upscaling on the cost of energy (COE) in the 750 kW to 5 MW range, with the goal of 30% reductions in COE for competitiveness with fossil fuels. While this goal was not met, with only 13% reductions, the project produced four reference wind turbines rated at 750 kW, 1.5 MW, 3 MW, and 5 MW (Malcolm and Hansen, 2006). The 1.5 MW turbine was noted to be similar to the GE 1.5s wind turbine and the closest representation of commercial technology at the time, with the other turbines being used to illustrate scaling effects. Models for these turbines were initially implemented in FAST_AD and later updated to FAST v7 and v8 in 2018, with the note that the wind industry has since made large innovations that would discourage comparison with modern wind turbines (Rinker and Dykes, 2018).

Recommendations for design of offshore wind turbines (RECOFF)

Also in the early 2000s, the Risoe DTU National Laboratory of Denmark coordinated a project for developing standards in the design of offshore wind turbines. Their recommendations were based on a 5 MW wind turbine. A detailed reference wind turbine design could not be found, but it is mentioned here for its relevance to the NREL 5 MW reference turbine.

Dutch Offshore Wind Energy Converter (DOWEC)

The final project to be mentioned from the early 2000s is the Dutch Offshore Wind Energy Converter project performed by an industry and research institution consortium of Ballast Nedam, Van Oord ACZ, NEG Micon Holland, LM Glasfiber Holland, Delft University of Technology, and the Energy research Centre of the Netherlands. The objective of the project was to develop a 6 MW wind turbine for deployment in wind farms in the North Sea. The design used monopile foundations (Kooijman et al, 2003).

NREL 5 MW

In the latter half of the 2000s, the NREL developed a 5 MW reference turbine to support the development of offshore wind technology. The turbine was developed based on available information on commercial wind turbines, particularly the REPower 5M wind turbine, and supplemented by the results of the WindPACT, RECOFF, and DOWEC projects where more detailed specifications were unavailable (Jonkman et al, 2009). It has been referenced extensively in research pertaining to offshore wind turbines and forms part of the basis of this investigation as well.

DTU 10 MW

The Light Rotor project was a collaboration between DTU Wind Energy and Vestas to design a 10 MW reference rotor. A 10 MW reference wind turbine was also designed, taking inspiration from the NREL 5 MW turbine, to enable investigation of the performance of the rotor, and it was also subsequently used in the INNWIND.EU project for testing simulation models (Bak et al, 2013). In addition, the design was updated in 2019 as part of IEA Wind Task 37 on Systems Engineering in Wind Energy to take into account feedback received by users of the reference wind turbine as well as to reflect more current technology.

LEANWIND 8 MW

The focus of the LEANWIND project was research on improving the efficiency and reducing the cost of offshore wind installations. To facilitate this research and to fill the gap between the NREL 5 MW reference turbine and DTU 10 MW reference turbine, an 8 MW reference wind turbine was developed based on the Vestas V164 8 MW wind turbine and validated by DNV-GL (Desmond et al, 2016). The project began in 2013 and ended in 2017.

INNWIND.EU

In a similar timeframe of 2013 to 2017, the INNWIND.EU project developed innovations in wind turbine design to reduce the LCOE of the 10-20 MW range, pursuing the goal of a 20 MW turbine set by the UpWind project's investigations on upscaling in 2011. 10 MW and 20 MW reference wind turbines were designed to showcase these innovations, though it is noted that the manufacturing processes necessary for producing such turbines are not yet fully developed (Jensen et al, 2017). This project also established the linear scaling laws for wind turbines that are later compiled in a book chapter by Jamieson (2018), and found them to be unfavorable for cost (Sieros, 2012).

NREL 15 MW

Finally, the NREL, collaborating with the DTU and various other individuals in industry and the research community, has recently published the definition of a 15 MW reference wind turbine as part of IEA Wind TCP Task 37. This reference wind turbine bridges the gap between 10 MW and 20 MW while exploring just ahead of current industry technology (Gaertner et al, 2020). This reference wind turbine sets the upper bound of this investigation, the upscaling of wind turbines and semisubmersibles to 15 MW.

Additionally, as previously mentioned, a few reference floating substructures have also been published to encourage collaboration in research and development of floating offshore wind turbines.

Offshore Code Comparison and DeepCWind

The Offshore Code Comparison Collaboration (OC3) project was established under IEA Wind Task 23 and developed three fixed-bottom and one floating spar-based models for use in validating simulation and modeling tools for offshore wind turbines (Jonkman and Musial, 2010). The DeepCWind project similarly generated test data for validating floating offshore wind turbine modeling tools with model tests of a spar, a tension-leg platform, and a semisubmersible. The DeepCWind semisubmersible was subsequently used in the Offshore Code Comparison Collaboration Continuation (OC4) project with the NREL 5 MW reference wind turbine for further work in the validation of modeling tools and comparison to the model test data generated by DeepCWind (Robertson et al, 2014).

The DeepCWind project also resulted in the production of the VolturnUS 1:8 floating wind turbine, a 1:8th scale test prototype of a 6 MW floating wind turbine deployed off the coast of Maine in 2013 and the first grid-connected offshore wind turbine in the U.S. (Dagher et al, 2017). The VolturnUS is also the precursor to the VolturnUS-S, the reference semisubmersible designed for the NREL 15 MW reference wind turbine (Allen et al, 2020).

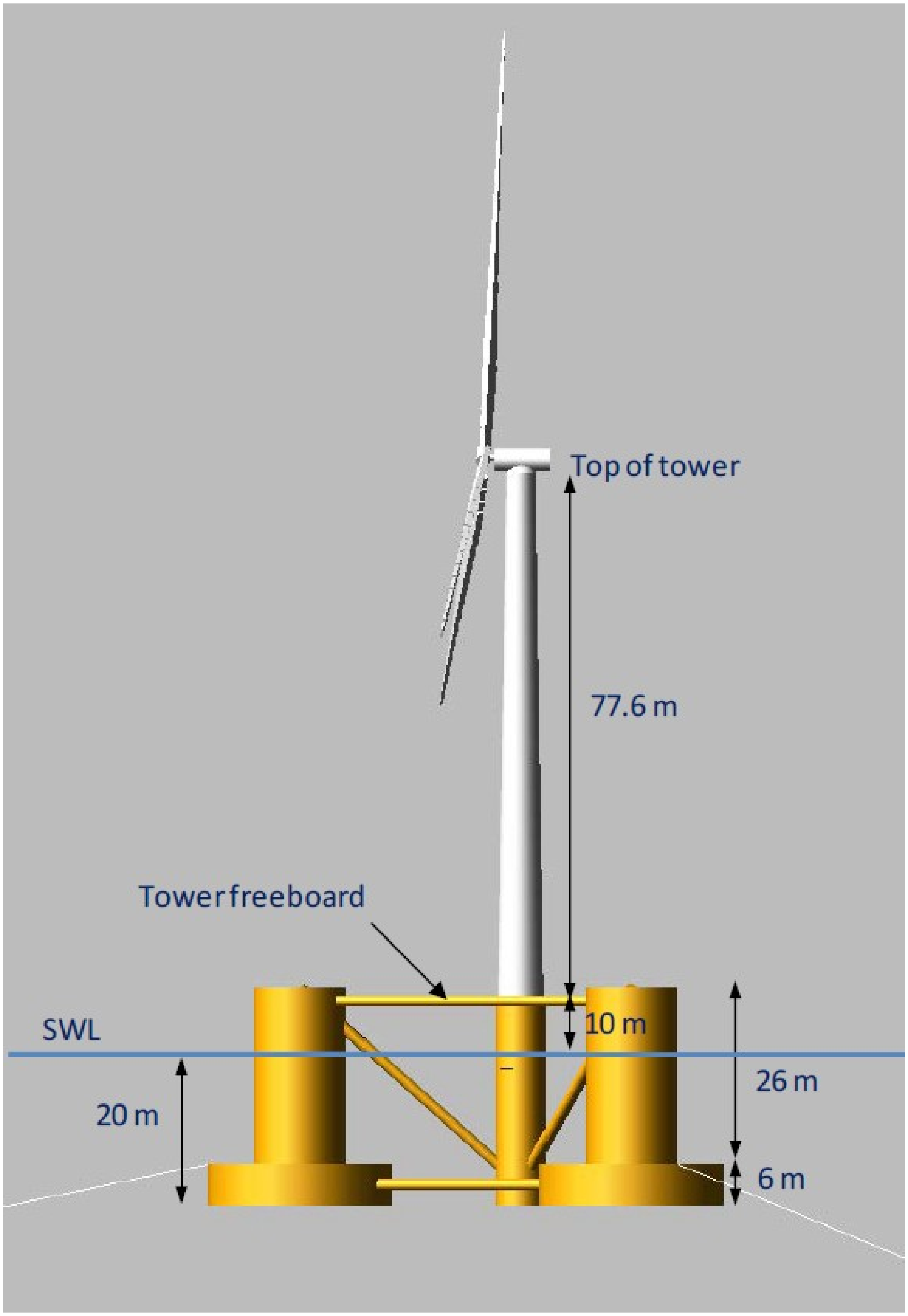

Figure 1-1 OC4 DeepCWind Semisubmersible for NREL 5 MW Wind Turbine (Reprinted from Robertson et al, 2014)

Figure 1-2 VolturnUS-S Semisubmersible for NREL 15 MW Reference Wind Turbine

(Reprinted from Allen et al, 2020)

WindFloat

WindFloat is a semisubmersible for floating offshore wind turbines 5 MW or larger designed by Principle Power (Roddier et al, 2009). A 2 MW prototype was successfully tested from 2011 to 2016, and one of three 8 MW turbines deployed off the coast of Portugal began delivering power in 2020 (Principle Power, 2020). A generic design has been published for a 5 MW wind turbine at OMAE 2011, although the design was not able to be accessed by the investigator.

Figure 1-3 WindFloat Design (Reprinted from Roddier et al, 2009)

Upscaling Research

Research into the upscaling of wind turbines has been approached in a variety of ways. Jamieson (2018) detailed the ‘Square-Cube’ law of linear scaling and an analysis of commercial data on scaling trends of commercial wind turbines. Nonlinear and optimization-based methods have also been developed. Capponi et al. (2011) developed a nonlinear method for upscaling of wind turbine blades based on keeping stresses constant while upscaling to 20 MW, finding that accounting for self-weight would require a heavier blade. Ashuri (2012) developed a multidisciplinary optimization method for taking into account structural, aerodynamic, control, and cost considerations simultaneously. In their work, they highlight the mass increase of the blade, which also increases the mass of the nacelle and tower to support these loads, as an important consideration for future design solutions, and find that upscaling appears to be always disadvantageous for cost without technological innovation. Notably, they examined exclusively fiberglass blades, as opposed to carbon fiber.

Research has also been conducted into the effects and implications of upscaling wind turbines. The UpWind project investigated the limits of upscaling, concluding that a 20 MW wind turbine would be feasible (UpWind 2011). Riziotis et al. (2012) considered the implications of the linear upscaling of a 5 MW reference wind turbine to 20 MW. They find that the control system will have a slower response but aerodynamic simulations reveal decreased thrust and fore-aft bending loading and less coherent wind.

Kikuchi & Ishihara (2019) found that the maximum overturning moment roughly follows a square law while scaling from 2 MW to the NREL 5 MW and DTU 10 MW reference turbines and used the overturning moment scaling as the basis for upscaling a semisubmersible based on that of the 2 MW turbine in the Fukushima FORWARD project. They found that the max overturning moment scaled at only slightly higher than the scale factor squared. This finding is supported in the description of the LEANWIND 8 MW reference wind turbine (Desmond et al, 2016), which estimates the max top thrust for the NREL 5 MW and 10 MW turbines to be 1600 kN and 3200 kN, respectively.

Other research involving the upscaling of semisubmersibles for floating wind turbines includes that of Leimeister et al. (2016), which applies the linear square-cube scaling of the wind turbine to the semisubmersible to upscale the OC4 semisubmersible from an NREL 5 MW turbine to a Fraunhofer 7.5 MW turbine. George (2014) follows similar methodology but retains a constant draft to facilitate hypothetical construction in European dry docks. They upscaled an OC4 semisubmersible from an NREL 5 MW turbine to a DTU 10 MW turbine and a 7.5 MW turbine generated by linearly interpolating between the two reference turbines and found that the constant draft version had improved stability.

2. DESIGN OF UPSCALED WIND TURBINES

Reference Wind Turbines

The reference wind turbine to be upscaled in this investigation is the NREL 5 MW reference wind turbine. It is worth noting that the tower height differs between its standalone technical report and the technical report of the OC4 semisubmersible system. As the OC4 semisubmersible has a freeboard of 10 meters, the tower has been shortened by 10 meters to maintain hub height, and thus the tower mass also differs. The DTU 10 MW, IEA 10 MW, and NREL 15 MW reference wind turbines will also be used to compare with the upscaled wind turbine.

Table 2-1 Specifications of reference wind turbines

	NREL 5 MW	DTU 10 MW	IEA 10 MW	NREL 15 MW
Rotor Radius m	63.0	89.2	99.0	120
Hub Height m	87.6	119	119	150
Tip Speed m/s	80	90	90	95
Generator Type	Gearbox	Gearbox	Direct Drive	Direct Drive
Blade Mass t	17.74	41	47.7	65.25
Nacelle Mass t	240	446	543	632
Tower Mass t	250	605	628	860
Total Mass t	600	1279	1395	1877

The semisubmersible to be upscaled is the Offshore Code Comparison Collaboration Continuation (OC4) semisubmersible. The upscaled semisubmersible will then be compared to the VolturnUS-S semisubmersible for the NREL 15 MW reference wind turbine.

Linear Upscaling of Wind Turbines

When considering the upscaling of wind turbines, one of the places to start is scaling by geometric similarity. This is explained in detail by Jamieson (2007) When scaling all dimensions by the same factor, it is possible to keep the flow geometry over the blades similar by keeping the tip speed constant. As the power generated by a wind turbine is related to the swept area of its rotor, this allows for a straightforward upscaling of the wind turbine using a factor that scales with the square root of the power rating, or with the rotor radius. The mass will scale to the third power of this factor, as will aerodynamic moments, resulting in stresses that are independent of scale. Moments due to weight, however, will scale to the fourth power of the scale factor.

This is not without caveats; the Reynolds number will increase, although the difference may be negligible for larger wind turbines whose Reynolds number is already in the millions. More significantly, the relative length scales of turbulence due to the earth's boundary layer, which is dependent on topography or sea state, may vary with turbine size and can increase both loads upon and power generated by the wind turbine beyond what is expected with geometric similarity.

Furthermore, empirical trends do not always follow linear trends. In particular, the fore-aft aerodynamic moment at the tower base of the wind turbine may have scaling closer to the square of the rotor radius than the cube.

Empirical data collected by Jamieson (2007, reprinted by Turaj, 2012) shows the fore-aft moment scaling with a power of 2.33, although Turaj (2012) notes that this data has considerable scatter. It should also be noted that this data reflects older, smaller wind turbines than are being considered here, with the NREL 5 MW wind turbine having a rotor diameter of 126m. More recently, Kikuchi and Ishihara (2019) found that the ratio of maximum overturning moments between a 2 MW turbine and the NREL 5 MW and DTU 10 MW reference turbines is very close to the ratio of their power ratings, or scaling to the power of 2.

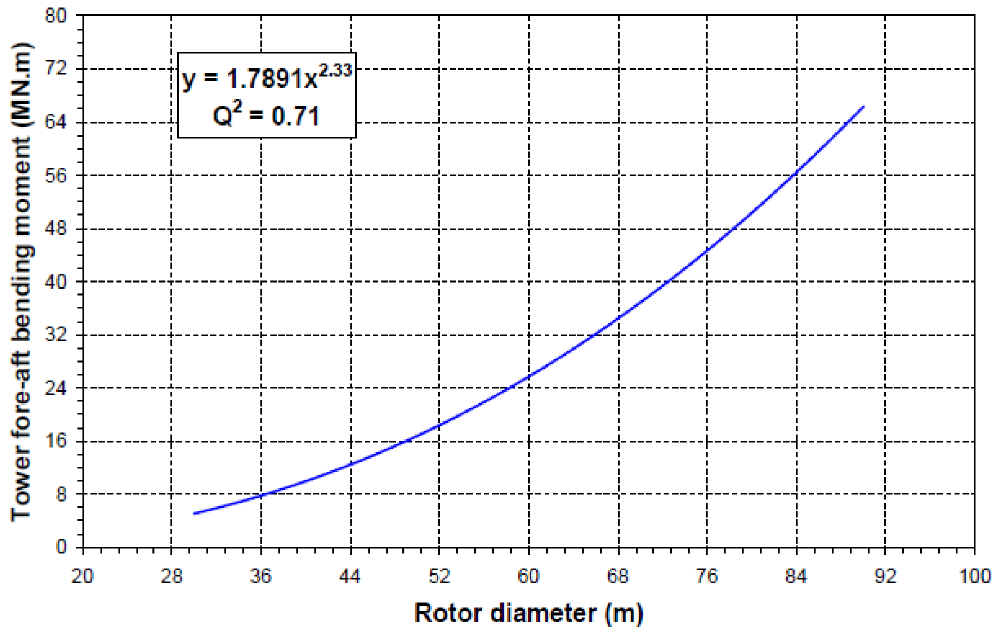

Figure 2-1 Tower fore-aft bending moment scaling with Rotor diameter (Reprinted from Turaj, 2012, reprint from Jamieson, 2007)

While linear upscaling is generally a good fit for technologies at the same level of development and optimization, the reference wind turbines of interest in this case all reflect different levels of development. To showcase this, the blades of the NREL 5 MW reference wind turbine will be upscaled linearly. Increasing the mass of the wind turbine blades results in a corresponding increase in the mass of the nacelle and tower to support additional loads. Using the scale factor (s), rotor radius will scale with s, while the blade mass will scale with s cubed.

$$s_{10} = \sqrt{\frac{10\,MW}{5\,MW}} = 1.414$$

$$r_{rotor,10} = r_{rotor,5} * s_{10} = 63.0\,m * 1.414 = 89.1\,m$$

$$m_{blade,10} = m_{blade,5} * s_{10}^3 = 17740\,kg * 1.414^3 = 50170\,kg$$

Table 2-2 Comparison of linearly upscaled blades with reference wind turbine blades

	NREL 5 MW	DTU 10 MW	IEA 10 MW	Scaled 10 MW	NREL 15 MW	Scaled 15 MW
Blade Mass t	17.74	41	47.7	42.19	65.25	70.04

Comparing the linearly upscaled and reference wind turbine blades reveals both areas of good agreement and discrepancies. While linear upscaling may be acceptable from 5 MW to 10 MW, the size and mass of the blades differ significantly between the 15 MW reference turbine and the corresponding upscaled turbine, with the reference turbine blades being about 10% longer but weighing almost 30% less than those of the upscaled turbine. Detailed information about the structural makeup of the NREL 5 MW reference wind turbine blades is difficult to use for comparison, as the LM Glasfiber product webpage referenced no longer exists, though web searches about the blade in question indicate that it used both glass fiber and carbon fiber. The NREL 15 MW reference wind turbine blades similarly use glass fiber and carbon fiber, though the DTU and IEA 10 MW blades use only glass fibers.

However, some comparison can still be made regarding their geometry. The maximum chord length of the NREL 5 MW reference wind turbine blades is 4.652 meters at approximately 1/4 span. Upscaled to 15 MW, this would be approximately 8 meters. However, the NREL 15 MW reference wind turbine blades have a maximum span of only 5.77 meters, approximately 30% shorter. This is likely in part due to the higher tip-speed of the larger reference turbines, which results in a more slender blade. Higher tip-speeds produce more noise, limiting their maximum speed for onshore turbines, but the larger wind turbines being considered for offshore installation can ignore this restriction. A more slender blade is also typically more flexible, which may raise issues with blade clearance from the tower, but this is addressed with the use of carbon fiber for increased stiffness.

The design of new reference wind turbines in part assumes that wind turbine technology will continue to progress along roughly the same path as existing trends, with the definition of the NREL 15 MW reference wind turbine directly citing the GE Haliade-X 12 MW turbine as inspiration (Gaertner et al, 2020). The design of the DTU 10 MW reference wind turbine similarly reduced their nacelle and hub mass from an upscaled version of the NREL 5 MW reference wind turbine by scaling a Vestas V-164 8 MW wind turbine to give a more "realistic" result (Bak et al, 2013), although this was modified with a lighter hub and a heavier nacelle in 2019 (Bortolotti et al, 2019).

Following these trends, the wind turbine upscaling method will include a modification to the linear upscaling process under the assumption that aerodynamic moments on the tower in the fore-aft direction will scale with a factor close to the square of the rotor radius, 2.3. This will no longer preserve flow geometry over the blades and thus require a new wind turbine blade design, but it provides an estimate that is needed for subsequent upscaling of the floating platform.

Turbine Upscaling Procedure

1. Blades

The wind turbine blade mass will be estimated by scaling with the scale factor to the power of 2.5. This is greater than the 2.3 scaling of the tower in consideration of the self-weight bending moment scaling of the blades.

$$m_{blade,10}=m_{blade,5}*s_{10}^{2.5}=17.74\,t*1.414^{2.5}=42.19\,t$$

2. Nacelle

The Nacelle mass will similarly be assumed to scale by a power of 2.3.

$$m_{nacelle,10}=m_{nacelle,5}*s_{10}^{2.3}=240\,t*1.414^{2.3}=383\,t$$

3. Tower

The hub height will be scaled by keeping the difference between rotor radius and hub height constant, thus keeping the distance between the rotor and the still water level constant.

$$h_{hub} - r_{rotor} = 87.6\,m - 63\,m = 14.6\,m$$

$$h_{hub,10} = 24.6\,m + r_{rotor,10} = 24.6\,m + 89.1\,m = 113.7\,m$$

As the floating platform has 10m freeboard before the start of the turbine tower, 10m is subtracted to find the length of the tower.

$$h_{tower,10} = h_{hub,10} - 10 = 113.7\,m - 10\,m = 103.7\,m$$

Assuming that the aerodynamic moment in the fore-aft direction will scale with s to the power of 2.3, the tower radius and thickness scaling will be calculated such that bending stress is equal to or less than the original tower.

1. Bending stress

$$\sigma_{bending} = \frac{My}{I}$$

$$y \propto r_{tower}$$

$$I \propto r_{tower}^4$$

$$M_{10} = M_5 * s_{10}^{2.3}$$

2. Set bending stress equal

$$\sigma_{bending,10} = \sigma_{bending,5}$$

$$\frac{M_{10}}{r_{tower,10}^3} = \frac{M_5}{r_{tower,5}^3}$$

3. Solve for the tower radius scale factor

$$\frac{r_{tower,10}^3}{r_{tower,5}^3} = \frac{M_{10}}{M_5} = \frac{M_5 * s_{10}^{2.3}}{M_5} = s_{10}^{2.3}$$

$$r_{tower,10} = r_{tower,5} * s_{10}^{\frac{2.3}{3}}$$

Thus the tower radius and thickness must be scaled by a factor of s to the power of 2.3 divided by 3, or roughly 0.76. Checking the tower height, we see that the tower height also scales by a factor of s to the power of 0.84 for an upscaled 10 MW turbine and 0.85 for an upscaled 15 MW turbine.

$$\frac{h_{tower,10}}{h_{tower,5}} = s_{10}^{p}$$

$$p = \frac{\log \frac{h_{tower,10}}{h_{tower,5}}}{\log s_{10}} = \frac{\log \frac{103.7\,m}{77.6\,m}}{\log 1.414} = 0.84$$

This means that this method has the added benefit of remaining close to geometric similarity for the upscaling of the tower. The tower mass thus also scales close to a factor of s to the power of 2.4.

$$m_{tower,10} = m_{tower,5} * s_{10}^{0.75+\frac{2*2.3}{3}} = m_{tower,5} * s_{10}^{2.37} = 250\,t * 1.414^{2.37} = 568\,t$$

Comparison of Upscaled and Reference Wind Turbines

Table 2-3 Comparison of upscaled and reference wind turbines

	NREL 5 MW	DTU 10 MW	IEA 10 MW	Scaled 10 MW	NREL 15 MW	Scaled 15 MW
Rotor Radius m	63.0	89.2	99.0	89.1	120	109.1
Hub Height m	87.6	119	119	114	150	134
Generator Type	Gearbox	Gearbox	Direct Drive	Gearbox	Direct Drive	Gearbox
Tower Base Diameter m	6.5	8.3	9.0	8.5	10	9.9
Tower Base Thickness mm	27	38	38	35.2	45.5	41.1

Table 2-3 continued

Tower Top Diameter m	3.9	5.5	5.5	5.0	6.5	5.9
Tower Top Thickness mm	19	20	20	24.8	24	29
Blade Mass t	17.74	41	47.7	42.19	65.25	70.04
Nacelle Mass t	240	446	543	533	632	849
Tower Mass t	250	605	628	568	860	924
Total Mass t	600	1279	1396	1362	1877	2208

<u>Blades</u>

For the purposes of estimating the mass of a wind turbine blade with an optimized structure, assuming that the mass scales with the scale factor to the power of 2.5 results in better agreement with reference wind turbines. Sandia National Labs (Griffith and Richards, 2014) has produced a number of 100 meter blade designs of decreasing mass to as low as under 50 tons, and noted that industry trends showed scaling between 2 and 2.5.

<u>Tower</u>

The tower mass of the scaled 10 MW turbine is lower than that of the DTU 10 MW reference turbine, while the tower mass of the scaled 15 MW turbine is higher than that of the NREL 15 MW reference turbine. Tower base diameter has excellent agreement, and tower base thickness and tower top diameter have agreement within 10%, while the tower top thickness is larger for the upscaled turbines. It should also be noted that while the NREL 5 MW reference turbine has linearly tapering tower wall thickness, the DTU 10 MW and NREL 15 MW reference turbines' towers have instead sections of constant thickness, decreasing stepwise to the top.

<u>Nacelle</u>

Nacelle mass shows that even with the less than linear scaling assumption, the scaled mass continues to be too large compared to that of the reference turbines. While comparing the mass of a gearbox and direct drive generators may be difficult, comparisons might still be made within generators of the same type to shed light on this trend of lightweight nacelles.

With linear upscaling, an increase in rotor size is accompanied by assumptions of constant tip speed and constant generator speed. This means that the gearbox ratio will also scale with the scale factor. Assuming that the gearbox mass must also scale with the torque, which scales cubically, this results in a higher than cubed scaling of the gearbox, albeit less than cubed scaling of the generator. Comparing the NREL 5 MW reference wind turbine with the DTU 10 MW reference wind turbine, the former uses a high speed generator, while the latter uses a medium speed generator, permitting a lower gearbox ratio. As the exact masses of the gearboxes and generators were not specified, it is difficult to make more precise claims as to how mass scaling is affected.

In the IEA 10 MW reference wind turbine, the gearbox generator of the DTU 10 MW reference turbine is replaced with a direct drive generator with an estimated mass of 357.3 tons, while that of the NREL 15 MW reference wind turbine is 371.6 tons. With linear scaling, one would expect the generator mass to scale with torque, i.e. cubically, but in this case there is hardly any scaling at all. The generators were designed with GeneratorSE, a sizing tool for wind turbine generators, and its replacement DrivetrainSE, respectively, and both feature external rotor radial flux topology machines with permanent magnets. The main difference between their designs appears to lie in their thermal design constraints. The IEA 10 MW reference wind turbine limits their specific current loading to 60 kA/m to limit temperatures (a typo lists 60 kA/mm^2 in the text despite being listed at 60 kA/m in the specifications table), while the NREL 15 MW reference wind turbine limits their specific current loading to 100 kA/m and assumes that a thermal management system will be in place to limit temperatures. This assumed thermal management system is directly cited as allowing an increase of power output without a corresponding increase in size, and represents a possible area of technological improvement from one generation of reference turbine to the next. It is also possible that there is a minimum optimal size for direct drive turbines, which tend to be larger. This is reflected in the IEA 10 MW reference wind turbine having a heavier nacelle than the DTU 10 MW reference turbine it is a modification of.

3. DESIGN OF UPSCALED SEMISUBMERSIBLES

Reference Semisubmersibles

The reference semisubmersibles to be upscaled in this investigation is the OC4 semisubmersible for the NREL 5 MW reference wind turbine. The VolturnUS-S semisubmersible for the NREL 15 MW reference wind turbine will be used for comparison.

Table 3-1 Reference semisubmersibles

	NREL 5 MW + OC4	NREL 15 MW + VolturnUS-S
Distance between Centers of Outer Columns m	50.0	89.63
Outer Column Radius m	6.0	6.25
RNA Mass t	350	990
RNA CG_z m	87.6	150
Tower Mass t	250	1260
Tower CG_z m	43.4	56.5
Metal Mass t	3850	3900
Ballast Mass t	9620	13800
Platform Mass t	13500	17800
Platform CG_z m	-13.46	-14.94
Platform CB_z m	-13.15	-13.63
Total Mass t	13400	20000
Total CG_z m	-10.22	-2.31
Pitch Restoring Stiffness Nm/rad	1.05e9	2.65e9

Note that the tower mass has changed for the case of the 15 MW floating wind turbine. Citing a need for increased stiffness, the tower was redesigned by the University of Maine as an isotropic steel tube using WISDEM. In fact, its tower mass now is very close to the tower mass that would be expected from linear scaling of the NREL 5 MW reference wind turbine. The rotor-nacelle assembly, however, is even lighter than before.

Past Upscaling Methods

Once the wind turbine has been upscaled, the floating semisubmersible will follow. Previous works in upscaling of the semisubmersible each follow slightly different rules.

Leimeister et al. (2016) closely followed the linear upscaling of the wind turbine, scaling the dimensions of the platform with the same scale factor that would be applied to the turbine, calculated from the square root of the power rating. Buoyancy was balanced with ballast, and static pitch displacement was found to be greater than the original semisubmersible, although this may be the result of using different turbines at different power ratings rather than upscaling. Note that the middle column of the semisubmersible needed a slightly larger scale factor to accommodate the larger turbine.

George et al. (2014) followed a similar method, but scaling the platform based on the cube root of the mass ratio between the turbines. Additionally, they consider the further modification of keeping the draft constant to facilitate construction in European dry docks, though the platform as a whole is still scaled in height. It is worth noting that the widest dry dock in the United States is only one meter wider (76m) (Newport News Shipbuilding, 2020) than the smallest dry dock considered by George (75m). The OC4 semisubmersible itself is 67 meters wide.

Kikuchi and Ishihara (2019) similarly base their upscaling factor on the cube root of mass ratio between the turbines. However, they do not use it to upscale with geometric similarity. They apply this scale factor to find the displacement of the upscaled semisubmersible, and from this the scaling of the radius of the columns in the semisubmersible is calculated. To find the scaling of the distance between columns, FAST is used find the scale factor of the maximum overturning moment and applied to the hydrostatic restoring moment in pitch. Neglecting the center of gravity and buoyancy terms and considering only the restoring moment due to waterplane area, and then considering only the parallel axis theorem term which is proportional to the distance between columns squared, they calculate the distance between columns, increasing approximately 5% between power ratings of 2 MW, 5 MW, and 10 MW. Note that the freeboard and draft have not been scaled whatsoever.

Semisubmersible Upscaling Procedure

The scaling methods in this investigation takes inspiration from all of the above, holding draft and freeboard constant and scaling the horizontal dimensions to preserve static balance in pitch. The first method will scale the radius of the platform columns and the distance between them equally, while the second method will scale only the distance between the columns. The mooring system will be neglected, as a catenary mooring system that should not affect the hydrostatic stiffness significantly. The steps to calculate both upscaling methods are as follows, with example calculations for the first method:

1. The total restoring stiffness in pitch of the OC4 Semisubmersible is calculated to be 1.05E9 Nm/rad. This value will be scaled to the power of 2.3 to find the total restoring stiffness that would preserve the static pitch angle for an overturning moment that is also scaled to the power of 2.3.

$$k_{pitch,10} = k_{pitch,5} * s_{10}^{2.3} = 1.05e9 * 1.414^{2.3} = 2.34e9\ Nm/rad$$

2. For the first method, the floating platform column radius and distances from each other will be scaled linearly with an estimated scale factor for the semisubmersible (s_s), different from that of the turbine (s). For the second method, column radius will be held constant, and only the distances will be scaled. In both methods, the radii of the supporting pontoons and braces as well as the wall thicknesses (t) of all components are

held constant. Additionally, the center column is widened to match the width of the turbine tower if necessary.

$$s_{s,10}=1.248$$

$$d_{columns,10}=d_{columns,5}*s_{s,10}=50*1.248=62.4\,m$$

$$r_{columns,10}=r_{columns,5}*s_{s,10}=6*1.248=7.49\,m$$

3. Displacement, displaced volume and buoyancy will be calculated, and ballast will then be added until the total weight of the floating system equals the buoyant force.

$$m_{displaced\,water}=\frac{V_{submerged}}{\rho_{water}}$$

$$m_{semisubmersible}=\rho_{steel}*\sum A_{surface,i}*t_i$$

$$m_{ballast}=m_{displaced\,water}-\left(m_{turbine}+m_{semisubmersible}\right)$$

4. Restoring stiffness due to waterplane area is then calculated, with the braces' waterplane area being approximated as circles, and summed with the calculated center of gravity (CG_z) and center of buoyancy (CB_z) terms, which were found to be significant in this case.

$$I_{waterplane}=\frac{\pi}{4}r^4+\pi r^2 d_x^2$$

$$k_{pitch}=\rho_{water}\,g\,I_{waterplane,total}+\rho_{water}\,g\,V_{submerged}\left(CB_z\right)-m_{total}\,g\left(CG_z\right)$$

5. The platform scale factor is adjusted in this way until the total restoring stiffness in pitch reaches the target value. Note that the restoring stiffness in pitch given in the definitions of the NREL 5 MW and 15 MW reference turbines include only the sum of the waterplane area and center of buoyancy terms when referring to hydrostatic stiffness.

$$k_{pitch,10}=3.54\text{e}9-2.90\text{e}9+1.70\text{e}9=2.34\text{e}9\,Nm/rad$$

6. The added mass and added mass moment of inertia are approximated using Det Norske Veritas' Recommended Practice for Environmental Conditions and Loads (2010), with coefficients and reference volumes listed in their Appendix D for each submerged element. This was validated using the definitions of the OC4 semisubmersible and VolturnUS-S semisubmersible, and the work of Masciola (2015) in evaluating the OC4 semisubmersible's intact stability.

Table 3-2 Comparison of calculated natural period with reference

	OC4 (Calculated)	OC4 (Reference)	VolturnUS-S (Calculated)	VolturnUS-S (Reference)
Heave Natural Period s	16.5	17.20	19.1	20.4
Pitch Natural Period s	26.4	27.08	-	-

In reality, the added mass coefficient would vary with the motion frequency and amplitude, but using analytical coefficients for infinite period was sufficient to approximate the natural frequencies, though it is consistent in underestimating the pitch natural period slightly.

Upscaling Trends

Table 3-3 Upscaled floating offshore wind turbines

	5 MW OC4	10 MW 1	15 MW 1	10 MW 2	15 MW 2
Turbine S	1.00	1.41	1.73	1.41	1.73
Platform S	1.00	1.24	1.42	1.57	2.07
Outer Column Distance m	50	62.05	71	78.7	103.7
Outer Column Radius m	6	7.45	8.52	6.00	6.00
RNA Mass t	350	790	1280	790	1280
RNA CGz m	87.6	113.7	133.7	113.7	133.7
Tower Mass t	250	570	920	570	920
Tower CGz m	43.4	54.6	63.3	54.6	63.3
Turbine Mass t	600	1360	2200	1360	2200

Table 3-3 continued

Turbine CGz	69.2	88.9	104.3	88.9	104.3
Metal Mass t	3880	5250	6370	4140	4360
Ballast Mass t	9510	15070	19870	9290	8930
Platform Mass t	13400	20320	26240	13430	13290
Platform CGz m	-13.64	-13.79	-13.91	-13.56	-13.55
Platform CBz m	-13.17	-13.16	-13.15	-13.13	-13.09
Total Mass t	14270	21950	28720	15060	15770
Total CGz m	-10.28	-7.49	-4.89	-4.40	2.83
GM m	7.52	10.37	12.75	15.43	24.05
Heave Natural Period s	16.5	17.3	17.9	16.3	16.2
Pitch Natural Period s	26.4	27.4	28.3	24.2	23.6
Heave Restoring Stiffness N/m	3.82E+06	5.91E+06	7.74E+06	4.08E+06	4.32E+06
Pitch Restoring Stiffness Nm/rad	1.05E+09	2.23E+09	3.59E+09	2.28E+09	3.72E+09

In Table 3-3, the first column on the left is the OC4 reference design. The next two columns are upscaling to 10 MW and 15 MW increasing both the distance between columns and the column radius. The final two columns are upscaling to 10 MW and 15 MW increasing only the distance between columns.

Platform Mass

The metal mass of the platform increases primarily with column radius scaling. This is to be expected, as the columns contribute most of the metal mass of the platform. The ballast mass also increases with column radius scaling as a result of the increase in displaced volume.

In both upscaling methods, the center of gravity rises because the turbine mass scales more quickly than does the platform mass, and it rises more quickly in the case of scaling only column distance, for which the platform mass does not increase significantly.

Stability and Heave Natural Period

The higher center of gravity that is observed in column-distance-only scaling is also accompanied by a higher GM. This is because the BM is calculated by the moment of waterplane area divided by displaced volume. The moment of waterplane area scales primarily with column distance squared due to the parallel axis theorem, while the displaced volume increases negligibly with column distance.

The heave natural period increases with radius scaling. This is because the added mass contributed by the columns scales roughly with their radius cubed because their reference volume is a hemisphere, while the hydrostatic stiffness scales with radius squared, or their waterplane area. The heave natural period appears to decrease slightly when column distance is scaled because the central column radius cannot be less than the turbine tower radius, which may increase the resonant response of the structure during storm conditions with high enough wave periods.

Comparison with VolturnUS-S

For the purposes of comparison to the VolturnUS-S design, the OC4 semisubmersible was also upscaled by matching the column radius and distance of that of the VolturnUS-S, as the pitch restoring stiffness estimated for the VolturnUS-S design is significantly lower than the estimate used for upscaling to 15 MW.

The main design differences between the two platforms are that the OC4 semisubmersible uses large lower columns that store ballast alongside many pontoons and braces between each column, while the VolturnUS-S semisubmersible uses large rectangular pontoons that store ballast and a single strut to connect each of the outer columns to the main column.

Table 3-4 Comparison of upscaled OC4 with VolturnUS-S

	VolturnUS-S	Upscaled OC4 Comparison
Outer Column Distance m	89.6	89.6
Outer Column Radius m	6.25	6.25
Metal Mass t	4010	4450
Ballast Mass t	13840	9780
Platform Mass t	17840	14240
Platform CGz m	-14.94	-13.69
Platform CBz m	-13.63	-13.08
Total Mass t	20090	16720
Total CGz m	-2.32	1.77
GM m	15.6	15.73
Heave Natural Period s	20.4	16.3
Pitch Natural Period s	27.8	26.4
Heave Restoring Stiffness N/m	4.49E+06	4.59E+06
Pitch Restoring Stiffness Nm/rad	2.65E+09	2.58E+09

Platform Mass

The VolturnUS-S design uses less metal mass than the upscaled OC4 comparison. The majority of this mass can be accounted for in the absent pontoons and braces between columns in the VolturnUS-S design, which total approximately 410 tonnes in the upscaled OC4 semisubmersible. The total platform mass of the VolturnUS-S is also approximately 3500 tonnes higher due to the increased displacement of the large rectangular pontoons. At 12.5 meters by 7 meters and roughly 40 meters long, they displace approximately 10500 cubic meters, while the large lower columns and pontoons of the upscaled OC4 semisubmersible displace approximately 7500 cubic meters of water. This increased displacement results in an increased ballast mass to balance the force in heave, which in turn lowers the center of gravity of the platform.

Stability and Heave Natural Period

The GM of the two platforms is approximately the same. While the center of gravity of the VolturnUS-S design is lower, the metacentric height is also lower due to the increased volume of displacement. However, the VolturnUS-S design also has a higher heave natural period than the upscaled OC4 comparison, raising it away from wave periods in storm conditions. This is due to the increased mass as well as the large rectangular pontoons acting as heave plates to increase the heave added mass, which serves as a design solution to the decreasing heave natural period when scaling column distance. The added mass of the OC4 comparison is calculated to be approximately 14000 tonnes, while the added mass of the VolturnUS-S design is calculated to be approximately 22000 tonnes.

Scaling Parameters with Pitch Restoring Stiffness

As the pitch restoring stiffness of the VolturnUS-S semisubmersible is lower than the prediction used for upscaling the OC4 semisubmersible to 15 MW, it may be beneficial to analyze how platform parameters scale with respect to pitch restoring stiffness.

To do so, parameters such as platform metal mass are first estimated as a function of column distance and radius scaling. Using metal mass as an example, its scaling can be approximated to scale with the following polynomial function:

$$m_{metal} = a\,m_{metal}\,s_R^2 + b\,m_{metal}\,s_R + c\,m_{metal}\,s_D$$

The coefficients a, b, and c represent the proportion of metal mass accounted for by the column caps, the column walls, and the pontoons and braces, respectively, while s_R and s_D represent the scale factors for radius and distance between columns. For the OC4 semisubmersible, the coefficients a = 0.38, b = 0.55, and c = 0.07 can be estimated from the platform geometry. When scaling only the distance between columns, $s_R = 1$, while $s_D = s_s$, the platform scale factor. When scaling both radius and distance, $s_R = s_D = s_s$. The polynomial function is then approximated as a power function with the platform scale factor raised to an unknown power. This power can be calculated by substituting in an upper bound for the platform scaling, such as assuming that the platform will not increase more than 3 times in column radius or distance, and equating the polynomial to the power function.

$$m_{metal}\,s_s^P = 0.38\,m_{metal}\,s_R^2 + 0.55\,m_{metal}\,s_R + 0.07\,m_{metal}\,s_D$$

$$P = \frac{\log\left(0.38\,s_R^2 + 0.55\,s_R + 0.07\,s_D\right)}{\log s_s}$$

$$P = \frac{\log\left(0.38 * 3^2 + 0.62 * 3\right)}{\log 3} = 1.5146$$

This power function has a maximum error of 3.8% difference from the polynomial. The value of P will differ for each upscaling method.

The ballast mass can be similarly approximated as scaling with the platform scaling to the power of B by relating it to the displacement scaling with column radius squared and metal mass scaling with P, neglecting the mass of the turbine and mooring system:

$$m_{total}\,s_R^2 = 0.67\,m_{total}\,s_s^B + 0.27\,m_{total}\,s_s^P + 0.06\,m_{total}$$

$$B = \frac{\log\left(\frac{s_R^2 - 0.27\,s_s^P}{0.67}\right)}{\log s_s}$$

$$B = \frac{\log\left(\frac{3^2 - 0.27 * 3^P}{0.67}\right)}{\log 3} = 2.2003$$

Finally, the pitch restoring stiffness scaling can also be approximated as a function of platform scaling. This includes calculation of the center of gravity, which depends on the mass scaling of the turbine. Due to the upscaling method assuming that overturning moment scales with the turbine scale factor, the mass scaling of the turbine can be related to the scaling of the overturning moment, resulting in an equation that must be solved numerically. In this case, mass scaled to approximately the same power as overturning moment, and hub height scaled to about a third of that power.

$$s_s^M = \left[I_{Aw} s_R{}^2 s_D{}^2 + V_{disp} s_R{}^2 \left[z_{CB} - \frac{\left(m_{turbine}\, z_{turbine}\, s_s{}^{4M/3} + \left(m_{metal}\, s_s{}^P + m_{ballast}\, s_s{}^B \right) z_{platform} + m_{mooring}\, z_{mooring} \right)}{m_{turbine}\, s_s{}^M + m_{metal}\, s_s{}^P + m_{ballast}\, s_s{}^B + m_{mooring}} \right] \right] / k_{pitch}$$

$$M = 3.5713$$

Once the pitch restoring stiffness scaling has been approximated as a power function, it can be related to the metal mass scaling by dividing the metal mass scaling exponent P with the pitch restoring stiffness scaling exponent M.

$$\frac{P}{M} = \frac{1.5146}{3.5713} = 0.4241$$

This value is within 5% of the value that is obtained by plotting the actual upscaled metal mass vs pitch restoring stiffness and fitting with a power regression, 0.4036. Recalling the initial assumption that overturning moment and thus pitch restoring stiffness would scale with the turbine scale factor to the power of 2.3, we can multiply by 2.3 to obtain the platform metal mass scaling with the turbine scale factor.

$$0.4241 * 2.3 = 0.9754$$

Repeating this process for the case of scaling only column distance, and making an estimate for the additional case of scaling only column radius yields the following:

Table 3-5 Metal mass scaling with pitch restoring stiffness and turbine scale factor

	Scaling Column Distance and Radius	Scaling Column Distance Only	Scaling Column Radius Only
OC4 Metal Mass Scaling Exponent with Pitch Restoring Stiffness	0.4241	0.0653	0.7835
OC4 Metal Mass Scaling Exponent with Turbine Scale Factor	0.98	0.15	1.80

As the power rating of the turbine is defined as scaling with the scale factor squared, this suggests that, for the assumption of overturning moment scaling with the turbine scale factor to the power of 2.3, upscaling is always favorable for reducing the amount of metal mass used per unit power produced.

4. CONCLUSIONS

A method for upscaling a floating offshore wind turbine with a semisubmersible substructure has been presented, with two variations that highlight the different effects of scaling semisubmersible column radius and column distance. This upscaling was done in the range of 5 MW to 15 MW, as those were the two power ratings that had reference floating wind turbine designs available for upscaling and comparison, and because the scaling of the floating substructure represents an important area of potential cost savings as new wind turbines are being developed and reaching the 15 MW mark.

Turbine Upscaling

Turbine upscaling required the assumption that technological innovation would continue on roughly the same path when upscaling from 5 MW. This because the design and loading of wind turbine blades have an impact on the design and loading of the rest of the structure, yet the constraints for optimizing their geometry are altered when moving from onshore to offshore, as higher tip speeds can be employed without noise concerns. Following commercial data, assuming a blade and nacelle mass scaling to the power of 2.5 and 2.3, respectively, and an overturning moment scaling to the power of 2.3 to derive the tower mass, resulted in good agreement between the upscaled wind turbines and reference wind turbines, with a discrepancy in the nacelle mass at 15 MW due to aggressive assumptions of technological improvement on the part of the 15 MW reference design.

Platform Upscaling

Platform upscaling was based on an assumption for the scaling of the overturning moment load that the semisubmersible would experience. By matching the overturning moment scaling with an equivalent pitch restoring stiffness scaling, the upscaled column radius and distance could be calculated. By keeping a constant draft, the submerged volume and ballast mass could then be calculated as well. The first method, which upscaled both column radius and distance equally, showed increased platform metal mass and increased heave natural period. While both methods showed a higher center of gravity and GM, the second method, which upscaled only the distance between columns, saw the center of gravity and GM rise much more quickly. This was accompanied by a slight decrease in heave natural period, which may raise its resonant response to storm condition waves with a period of 10-15 seconds.

VolturnUS-S Comparison

A comparison to the VolturnUS-S design was made by upscaling the OC4 reference design such that the column radius and distance matched that of the VolturnUS-S. This comparison showed that the VolturnUS-S' large rectangular pontoons saved a bit of metal mass while increasing the submerged volume and thus ballast mass, lowering the center of gravity compared to the upscaled design. In addition, large rectangular pontoons also increased the added mass of the system, resulting in a higher heave natural period that brings it away from wave energy periods. However, the GM was approximately the same between the two designs.

Estimating Upscaled Parameters from Pitch Restoring Stiffness

It was noted during the comparison to the VolturnUS-S design that the pitch restoring stiffness of the reference was significantly lower than the target pitch restoring stiffness assumed. Therefore, a method to estimate the scaling of platform parameters with respect to pitch restoring stiffness was presented. This method showed good agreement with the upscaled platform data, and revealed that, for the assumption that overturning moment would scale to the power of 2.3, upscaling would always reduce the metal mass required per power rating. As the pitch restoring stiffness for the 15 MW reference design is quite a bit lower than this assumption, it suggests that upscaling floating wind turbines can significantly reduce the amount of metal used in semisubmersible substructures for the same amount of power. However, the 15 MW reference design assumes a certain amount of technological innovation. Future commercial designs may target a different amount of pitch restoring stiffness, in which case this estimation method based on pitch restoring stiffness may be useful.

Potential Areas of Further Investigation

- More detailed investigation of blade scaling and optimization. The blade scaling had to be simplified for this analysis, as its optimization is fairly complex.
- Inclusion of the mooring system. The mooring system was assumed to not contribute significantly to the hydrostatics used for the upscaling method.
- Structural analysis of the upscaled platforms. The wall thicknesses of all members were held constant when upscaling. While this is a reasonable assumption for hydrostatic pressure, it may stop being reasonable for structural reasons if the column distances scale to high enough values.
- Application of the upscaling methods to different designs. As the VolturnUS and VolturnUS-S designs incorporate large rectangular pontoons, and the former uses a concrete hull, their upscaling trends may differ somewhat from those of the OC4 semisubmersible.
- Dynamic simulations of the upscaled floating wind turbines. One of the next steps in the design of any floating platform would be simulations to confirm that its dynamic responses are within reasonable margins.
- Cost analysis. As one of the background motivations for this investigation is reducing the cost of floating wind energy, analyzing how the cost scales would be a natural follow-up.

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