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Floaters upscaling for multi-megawatt floating wind turbines

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Abstract. The floating wind industry requires wind turbines with increasing power ratings, which will require bigger platforms. However, few floater concepts are publicly available for numerical simulation of future wind turbines. To overcome this limit, this work proposes a fast and straightforward upscaling methodology to upscale already available floating platforms to greater wind turbine power ratings. The methodology does not aim to optimize the floater design, but it can generate realistic floater data for preliminary numerical simulations. The methodology is applied here to four floaters: a semisubmersible, a barge, a TLP and a spar. The platforms are upscaled for a 15 MW wind turbine and a specific deployment site. The upscaling methodology is adapted for each floater since some differences arise from one platform to the other. Whenever possible a comparison with already existing 15 MW substructures is proposed and commented.

1. Introduction

Floating offshore wind turbines (FOWT) technology is expected to achieve full industrialization in the next years. A noticeable trend that can be observed in floating wind is the move towards larger wind turbines, with power ratings equal to or even higher than 15 MW [1] [2] [3]. In this view, it is crucial to know the characteristics of the floaters needed to support future wind turbines, in order to perform all the numerical analyses that are necessary to validate such concepts. Unfortunately, data about substructures designed in the framework of industrial projects are rarely shared, making it challenging to know the dimensions and masses of floating wind systems that will be deployed soon. To address this issue, this work proposes a quick and straightforward methodology to upscale or modify already existing and publicly available floater concepts for an arbitrary wind turbine size, in a specific deployment site.

The upscaling procedure is based on the comparison of the overturning moments between lower and higher rating wind turbines and it is applied to four floaters: a concrete semisubmersible, a steel barge, a steel TLP and a concrete spar. Platforms are originally available for 5 MW and 10 MW wind turbines and are upscaled to host the IEA 15 MW wind turbine. A publicly available wind turbine model is adopted here for the ease of data availability, even if the upscaling methodology is in principle applicable also to commercial wind turbines, provided that the necessary parameters listed in this work are known. Upscaled floaters are coupled to a mooring system tailored for a specific site of deployment and the whole FOWT is modelled in OpenFAST [4]. The paper is organized as follows: Section 2 reports the upscaling methodology, Section 3 describes the 15 MW wind turbine adopted in this study and the reference concepts used as the basis for upscaling, Section 4 collects and comments on the data of upscaled floaters, Section 5 shows their dynamic behaviour, Section 6 concludes the work.

2. Upscaling methodology

2.1. Geometry upscaling

The upscaling methodology is based on geometry similarity, meaning that the floater is upscaled without changing its shape. This approach is chosen for two main reasons:

1. It is the fastest and easiest way to increase floater dimensions.
2. It allows the application of Froude's scaling laws to many of the floater properties, such as hydrostatic and hydrodynamic characteristics, without the need to recompute them.

At the same time, such a simple upscaling scheme limits the possibility to have an optimization of floater parameters going towards greater dimensions, because the outcome of the upscaling procedure is heavily dependent on the original shape.

Within a framework of geometric similarity, the only degree of freedom allowed for the upscaling is a single length scale λ, that is applied to length dimensions and it is then extended to all the other geometric dimensions of the floater. Table 1 shows how to upscale the main parameters that determine the geometry and the hydrostatic behaviour of the platform.

Table 1 Froude's proportionality laws for geometrical and hydrostatic quantities

Parameter	Dimension	Scale factor
Draft	m	$\sim\lambda$
Position of center of buoyancy	m	$\sim\lambda$
Waterplane area	m^2	$\sim\lambda^2$
Displaced volume	m^3	$\sim\lambda^3$
Waterplane inertia	m^4	$\sim\lambda^4$

The same way of reasoning can be extended also to hydrodynamic properties such as added mass, radiation damping and wave force transfer function. Potential flow hydrodynamic properties can be upscaled by applying Froude's similarity laws, similar to what is done on model downscaling for wave basin tests [5]. Estimating potential flow properties usually requires a panel code and a non-negligible computational burden, but by applying Froude's laws upscaling becomes straightforward and hydrodynamic quantities evolve according to powers of the length scale λ, as reported in Table 2.

Table 2 Froude's proportionality laws for potential flow hydrodynamic quantities

Parameter	Dimension	Scale factor
Added mass matrix	kg - kg m - kg m^2	$\sim\lambda^3 - \sim\lambda^4 - \sim\lambda^5$
Radiation damping matrix	N s m^{-1} - N s rad^{-1} - N s m rad^{-1}	$\sim\lambda^2\sqrt{\lambda}$ - $\sim\lambda^3\sqrt{\lambda}$ - $\sim\lambda^4\sqrt{\lambda}$
Wave force	N – N m	$\sim\lambda^2$ - $\sim\lambda^3$

The wave force is scaled with a square power because only the surface of the floater is increasing, while the incident wave height is not changing from one turbine size to the other. This is different from what is done in a wave basin, where the wave height also evolves with the same length scale λ of the floater, and then the wave force evolves with the third power of λ. A different approach must be instead used for viscous drag properties, due to the well-known dependency of viscous phenomena on Reynolds' similitude and not on Froude's one. The choice made in this work is to use directly the drag coefficients of the original concepts, even if altered geometry and motion conditions imply different Reynolds and Keulegan-Carpenter numbers and a re-evaluation of drag coefficients.

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2.2. Mass upscaling

The mass of the floater derives from the vertical equilibrium of forces, given by the downward action of floater weight W_{FL}, the wind turbine weight W_{WT}, the mooring downward force T_M and the upward buoyancy force $\rho g \nabla$, as in equation (1).

$$W_{WT} + W_{FL} + T_M = \rho g \nabla \tag{1}$$

In the equation above, the wind turbine weight W_{WT} and the buoyancy force $\rho g \nabla$ are known from wind turbine data and the upscaling of geometry, the floater weight W_{FL} is the unknown and the mooring tension is not specified at this stage of the analysis. The strategies to account for the mooring downward force in the absence of a mooring design depend on the type of floater. Specifically, they are different for floaters moored with catenary mooring systems and for TLPs. In the former type of floaters, the mooring downward force is usually a small portion of the floater and wind turbine weight, usually around some percent point; in this case, the mooring tension can be just neglected and a preliminary value of the floater mass is obtained. When the final design of the mooring system is known, the value of mass can be tuned to achieve the desired equilibrium. In the case of a TLP, instead, the iterative process between mooring system design and mass evaluation is more complex, because the mooring tension is a non-negligible entry in the vertical equilibrium of the floater. Floater mass and mooring system must be defined together, following this workflow:

1. Water depth and fairlead position are known, then also the cable stretched length L. Assuming a tentative cable size, the vertical stiffness k of n lines, each one with axial stiffness EA is:

$$k = \frac{EA}{L} n \tag{2}$$

2. The heave natural period T_3 of a TLP should be shorter than the one of first order waves. The guideline found in [6] suggests a heave natural period below 3.5s; in this work, a maximum period of 2.5s is assumed due to the presence of short waves (peak period T_p=3s) on the deployment site. The mass of the floater m is derived by the natural period in heave (eq. (3)), knowing the added mass A_{33} and the hydrostatic stiffness C_{33}:

$$T_3 = 2\pi \sqrt{\frac{(m + A_{33})}{k + C_{33}}} \tag{3}$$

3. The mass of the floater determines the amount of excess buoyancy force of the hull, which in turn is tensioning the cables. As a rule of thumb, the static tension on cables was kept below 30% of the line Minimum Breaking Load (MBL). If this criterion is not met, a new cable size or a different value of mass must be adopted, and a new iteration is started.

The floater center of gravity (CoG) and the inertia moments can be directly upscaled thanks to Froude's similarity laws, respectively with a proportionality of λ and λ^5. Alternatively, they can be recomputed based on the new hull geometry, together with the amount and position of ballast, if they are known in the original floater.

2.3. Choice of the length scale

The length scale is derived by comparing the overturning moment of the lower rating wind turbine M_{T_0} and the one of the IEA 15 MW wind turbine M_T. The overturning moment is here intended as the maximum steady-state thrust force times the hub height of the wind turbine, taken on the mean sea level (MSL). If the floater dimensions and mass are upscaled according to Froude's law, its hydrostatic restoring K_θ is upscaled with the fourth power of the length scale λ:

$$\dim K_\theta = N\, m\, rad^{-1} \sim \lambda^4 \tag{4}$$

Now, the overturning moment also evolves with the fourth power of a length dimension:

$$\dim M_T = N\ m \sim \lambda^4 \tag{5}$$

The ratio between overturning moment and rotational stiffness, in a linear analysis, is the static tilt angle θ of the wind turbine, then a pure number:

$$\theta = \frac{M_T}{K_\theta} \tag{6}$$

The length scale is derived from the overturning moment, as displayed in equation (7):

$$\lambda = \sqrt[4]{\frac{M_T}{M_{T,0}}} \tag{7}$$

and it is used to upscale floater dimensions. The rotational restoring is then increasing at the same rate as the overturning moment of the turbine and ultimately the static pitch angle is preserved from the original to the upscaled floater. The adoption of a length scale derived from the overturning moment guarantees in this way that the upscaled floater is as stable as the original one. The final value of the length scale is given by the assessment of the floater performance, which can be satisfactory at a scale lower than the one derived from overturning moments, or conversely may require a higher scale, as detailed in Section 4.

Although the procedure specified in equations (4) to (7) is valid in principles, limitations apply when a real case is handled. The hydrostatic restoring rotational stiffness K_θ of a floating wind turbine:

$$K_\theta = \rho g I_w + \rho g \nabla z_{COB} - M g z_{COG} + K_{moor} \tag{8}$$

depends on the mass of the wind turbine, the position of its center of gravity and the stiffness of the mooring system, as reported in equation (8). (I_w is the waterplane inertia, z_{COB} is the vertical position of the center of buoyancy, M is the mass of the floating system and z_{COG} the position of its center of gravity). The wind turbine mass and its center of gravity change from a lower rating to a higher rating generator, but they do not follow the same scaling of the overturning moment. In the same way, the stiffness contribution of the mooring system does not scale as the other stiffness terms connected solely to floater geometry. Nevertheless, in a semisubmersible and in a barge the restoring is dominated by the waterplane inertia, and the contribution of wind turbine mass and CoG position is scarce; similarly, the mooring restoring in rotational motions is negligible if a catenary mooring system is used. In these floaters, then, the upscaling of K_θ is very close to Froude's upscaled value. Care should be put in floaters that exploit taut or semi-taut moorings or that have a predominant ballast restoring contribution.

2.4. Mooring system design and check of floater performance

Providing a fully assessed and optimized mooring system is out of the scope of this work. Care is put into sizing mooring lines to obtain a proper dynamic behaviour of the platform, both as maximum excursions and natural periods, and a line diameter that is realistic in terms of resistance. A preliminary sizing of cables is performed with analytical calculations, using catenary equations or, in the case of a TLP, modelling lines as linear springs. Guidelines for cable dimensioning, size and resistance of different line components are found in [7] and [8]. Lines are sized to counteract the maximum wind loading on the turbine, found in rated operation. It is set, as compensation for static conditions, not to overcome half of the line MBL and to avoid anchor uplift in catenary moorings. The mooring system stiffness matrix is computed analytically with the equations listed in [9] so that platform natural periods can be quantified.

Concerning the assessment of upscaled platforms, instead, controller stability and platform static pitch are assessed in a step wind test, from cut-in to cut-out, performed in calm water. The RAO of the floater gives then an indication of the placement of natural frequencies and the level of damping found on motion modes (see Section 5). Another check to be carried out is the one on the natural frequency of the tower. In this work, a stiff-stiff tower (see Section 3) has been coupled to the platforms, so that for every floater the first natural frequency of the freely floating tower falls above the rotor 3P excitation range. The mooring system is verified in time-domain dynamic simulations both in operative conditions (maximum thrust) and in the site 50 years of return wind, wave and current. No fatigue limit state or accidental limit state evaluation is performed.

3. Reference wind turbine and original floater concepts

3.1. Reference wind turbine

The floater types analyzed in this work are upscaled to host the IEA 15 MW wind turbine [10], a reference, open-source model that is commonly used for numerical studies on future floating wind turbines. The IEA 15 MW turbine is an upwind, three-bladed wind turbine with a direct-drive generator, featuring a 240 m rotor diameter and a hub height of 150 m. The turbine tower that is adopted in this work is the one used for the floating version of the reference turbine hosted on the VolturnUS semisubmersible [11] and it follows a stiff-stiff design. The wind turbine features the ROSCO reference controller, an open-data industry-standard controller for fixed and floating wind turbines [12]. Adaptation of the control system to the upscaled floating platforms is performed by applying a detuning procedure on control gains [13] in the framework of the ROSCO scheme. Detuning of controller gains is needed to avoid aerodynamic instabilities due to the coupling of the closed-loop power controller with the low-frequency rigid modes of the platforms; it is preferred to the floating feedback strategy for ease of implementation. The optimization of controller performance is out of the scope of this work and controller adaptation is pursued solely to avoid platform instabilities. The main data about the wind turbine reference model are reported in Table 3.

Table 3. Main parameters of the IEA 15 MW wind turbine

Parameter	Unit	Value
Turbine class	-	IEC Class 1B
Rating	MW	15
Rotor radius	m	240
Hub height	m	150
Cut-in wind speed	m/s	3
Cut-out wind speed	m/s	25
Rated wind speed	m/s	10.59
RNA mass	t	1017
Tower mass	t	1263

3.2. Original floater concepts

Open-data concepts chosen as the basis for upscaling are designed for 5 MW, 10 MW or already 15 MW wind turbines. In the latter case, the upscaling methodology reduces to an adaptation of the floater to a prescribed hub height and a specific deployment site, in terms of water depth and entity of environmental loads. Four concepts, whose data are reported in Table 4, are here taken as a reference basis:

1. Olav Olsen star floater [14]: a concrete semisubmersible designed during the LIFES50+ project to host the DTU 10 MW wind turbine. The floater has three catenary mooring lines, anchored at a water depth of 130 m.

2. The ITI Energy barge [15]: a steel barge intended to host the 5MW NREL wind turbine [16]. The barge is deployed in 150 m deep water and it has 8 mooring lines connected in pairs at each vertex of the box-shaped hull.
3. MIT/NREL TLP [15]: a steel TLP designed for the same wind turbine of the spar. The mooring system is composed of 8 taut lines connected in pairs at the end of each spoke. The anchors depth is 200 m.
4. WindCrete spar [17]: a concrete spar designed during the COREWIND project, already sized for a 15 MW wind turbine. The spar is deployed in 200 m deep water and it is moored by three catenary mooring lines. Delta connection is realized at fairleads to improve the yaw stiffness of the mooring system.

Table 4. Main parameters of reference floaters

	Olav-Olsen	ITI Barge	MIT TLP	WindCrete
Turbine rating (MW)	10	5	5	15
Material	Concrete	Steel	Steel	Concrete
Draft (m)	22	4	47.89	155
Displaced volume (m^3)	23509	6000	12180	40540
Mass (incl. ballast) (t)	21709	5452	8600	36550
Column distance/Width x length/Diameter (m)	37	40 x 40	18	18.60
CoG of the platform below MSL (m)	15.23	0.28	40.61	113.08

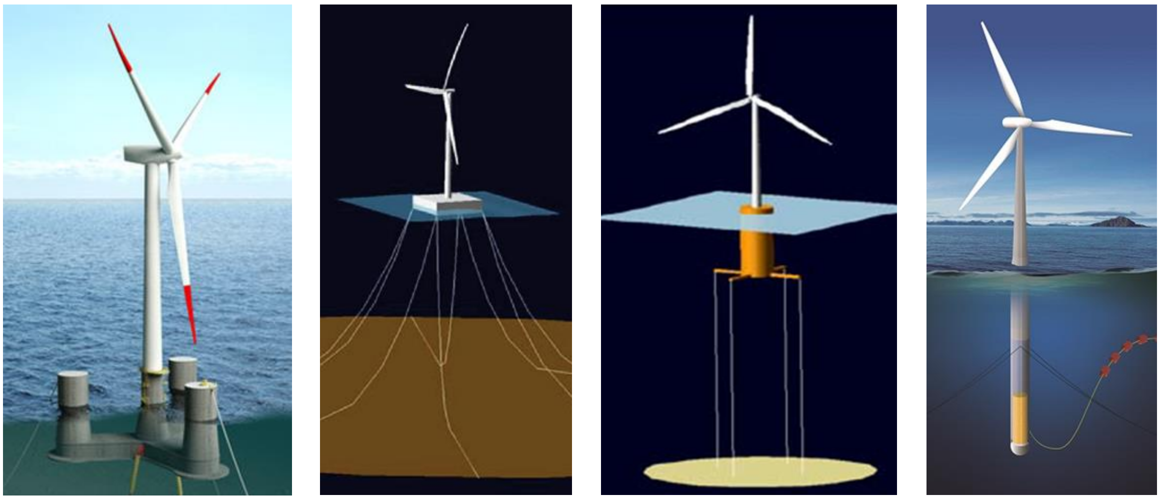


Figure 1. Reference floater concepts. From left to right: semisubmersible, barge, TLP and spar

4. Upscaled floater data

The adaptation or upscaling of floaters according to the methodology reported in Section 2 is now applied to the four reference concepts mentioned in Section 3. All the concepts are adapted to the 15 MW IEA wind turbine, with hub height fixed at 150 m. The water depth is 100 m for the semisubmersible, the barge and the TLP, while it is 380 m for the spar.

Table 5 collects the length scales resulting from the analysis of overturning moments on the reference floater concepts. It is to be noted that the 15 MW wind turbine used in the WindCrete project is modelled with a reduced hub height and generates a greater thrust force. Thrust force reduction found in the reference wind turbine of this work is due to the peak-shaving procedure implemented in the ROSCO controller [12] and is generally used in floating installations. The peak-shaving routine is adopted to decrease the stability requirements of the floaters and ultimately obtain a more economical design. Its main drawback is the reduction of generated power in the near-rated region, and consequently of the wind turbine energy yield [18]. The peak-shaving routine adopted in the reference turbine of this work is the one used on the publicly available model of the VolturnUS semisubmersible [11], version 1.1 [19].

Table 5 Aerodynamic thrust force, hub height and overturning moment for the reference 5, 10 and 15 MW wind turbines. The 15 MW wind turbine in bold is the reference model for this work, while the one denoted with (*) is the one used for the WindCrete floater

Turbine size (MW)	Thrust force (kN)	Hub height (m)	Overturning moment (kNm)	Scale (-)
15	**1785**	**150**	**267750**	**1**
5	819	90	73710	1.38
10	1635	119	194565	1.08
15*	2419	135	326565	0.95

4.1. Semisubmersible

The length scale used for upscaling is 1.15. The scale is a bit higher than the one evaluated by the overturning moment comparison with the DTU 10 MW wind turbine, to compensate for the deviations of the system mass and CoG position from the Froude's upscaled values, as explained in Section 2.3. An overview of the upscaled model is provided in Table 6. A comparison is proposed between the actual floater data for the 15 MW size and the values coming from a pure Froude's upscaling of the original floater parameters.

Table 6 Main parameters of the upscaled semisubmersible. The column "15 MW size" reports the final upscaled floater data, while the column "Froude's scaling λ=1.15" shows the pure Froude's upscaled values

Parameter	Unit	10 MW size	15 MW size	Froude's scaling λ=1.15
Draft	m	22	25.3	25.3
Column distance	m	37	42.55	42.55
Outer column radius	m	15.8	18.18	18.18
Pontoon breadth	m	16	18.4	18.4
Water displacement	m^3	23509	35754	35754
Floater mass	t	21709	32686	33016
CoG of the entire system on MSL	m	-6.84	-7.18	-7.87
Ballast restoring (entire system)	Nm/rad	-1.7576E+09	-3.317E+09	-3.0740E+09
Static tilt at rated	deg	4.8	4.7	4.8

The deviations from Froude's upscaled values of mass and CoG position are worsening the stability of the floater. The ballast restoring contribution, negative in the original floater, becomes more negative than Froude's upscaled value. Then, a slightly increased length scale (1.15) than the one shown in Table 5 (1.08) is needed to achieve a static tilt of 4.7° at near rated conditions, practically equal to the one of the original floater. Semisubmersible parameters are compared with the ones of the Activefloat model [17], another concrete semisubmersible designed during the COREWIND project that hosts a 15 MW wind turbine with a hub height of 135 m.

Table 7 Comparison between the upscaled semisubmersible and the Activefloat

Parameter	Unit	Upscaled semisubmersible	Activefloat
Draft	m	25.3	26.5
Column distance	m	42.55	34
Pontoons breadth	m	18.4	17
Outer column radius	m	18.18	17
Floater mass	t	32686	34387
CoG of the entire system on MSL	m	-7.18	-10.90

The greater difference between the shapes of the two semisubmersibles is in the column distance, which in the Activefloat is less even than the reference 10 MW semisubmersible. The lower CoG of the system in the Activefloat is improving the ballast contribution to stability, probably allowing for a lower footprint. Overall, looking at other data, the design of the upscaled semisubmersible is satisfactory and can be deemed to be realistic. The static pitch curve in increasing wind speed is shown in Figure 3.

4.2. Barge

The barge floater is upscaled with a length scale equal to 1.35, yielding the floater parameters that are reported in Table 8 and compared with the original concept.

Table 8 Main parameters of the upscaled barge. The column "15 MW size" reports the final upscaled floater data, while the "Exact scaling λ=1.35" shows the pure Froude's upscaled values

Parameter	Unit	5 MW size	15 MW size	Froude's scaling λ=1.35
Draft	m	4	5.4	5.4
Width x length	m	40 x 40	54 x 54	54 x 54
Water displacement	m^3	6000	14762	14762
Floater mass (incl. ballast)	t	5452	11087	13347
CoG of the entire system on MSL	m	8.04	22.17	10.85

The static tilt angle is 2.86° in the 5 MW size and 2.66° in the upscaled size (Figure 3). Similar to what happens in the semisubmersible the ballast restoring is upscaling unfavourably due to the turbine mass and position of the CoG. The upscaled floater is lighter than the Froude's upscaled one, while the position of the CoG is practically double the Froude's scaled value, with a detrimental effect on stability. However, in this type of floater the contribution of ballast restoring is negligible with respect to the waterplane one and practically no effect is visible in the upscaled floater. Unfortunately, to the authors' knowledge, no 15 MW barge floater models publicly available in literature have been found, then a comparison with other concepts is not possible. What can be suggested here is to reduce the scaling dimension to achieve a smaller floater due to the very large waterplane area and limited static tilt angle.

4.3. TLP

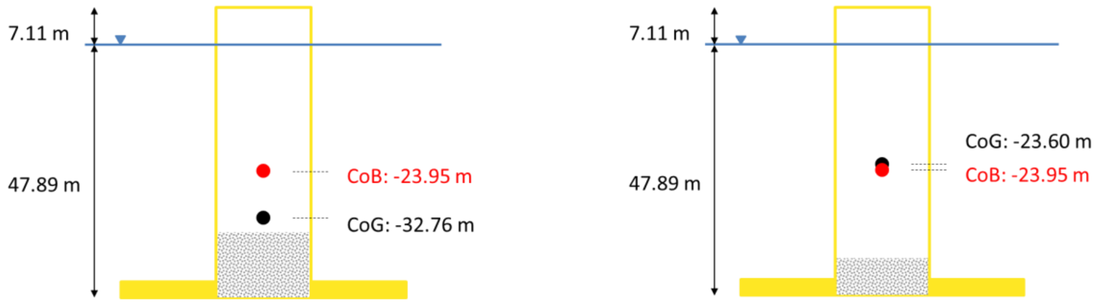
No upscaling of hull geometrical dimensions is pursued in the TLP. The main reasons for this are the dimensions of the 5 MW design and the stability mechanism of the TLP. Regarding the original design, the 5 MW platform has already a high draft, which if upscaled furtherly would result in a quite unrealistic design for a TLP. The other reason is that the rotational restoring of such a platform is given in its greatest part by the mooring system, or cable size and fairlead footprint, and then the adaptation of the platform to the 15 MW size is done mainly acting on these parameters of the system. Then, keeping fixed the hull dimensions, two main changes have been made to the floater. Firstly, the hull is de-ballasted to generate sufficient excess buoyancy even carrying the heavier 15 MW wind turbine; then, the spoke length is increased to achieve a greater fairlead footprint (Table 9).

Table 9 Geometry and mass parameters of the upscaled TLP

Parameter	Unit	5 MW size	15 MW size
Hull mass	t	384	384
Ballast mass	t	8216	5116
Ballast CoG on MSL	m	-41.57	-43.95
Floater mass (incl. ballast)	t	8600	5500
CoG of the entire system on MSL	m	-32.76	-23.60
Fairlead radius	m	27	40
Cable material	-	Steel	Polyester

Cable axial stiffness	N	1.50E+09	6.63E+08

A sketch of the new hull arrangement is given in Figure 2. The center of gravity and the inertia moments of the 15 MW floater are determined according to the new position and amount of the ballast.



a) b)

Figure 2 Arrangement of ballast and center of gravity position in the original and upscaled TLPs

The resulting platform is lighter than the 5 MW version. Due to de-ballasting the floater is no longer stable without the mooring system, contrary to what happens in its original size. The relative position between the center of gravity and the center of buoyancy (Figure 2) is generating a destabilizing moment, which is not counteracted by a sufficiently high waterplane restoring. In this case, the floater needs temporary buoyancy modules to be towed out to the installation site. Overall, the maximum tilt angle in the upscaled floater is 0.18° (Figure 3), which is similar to the one found in the original concept, equal to 0.2°.

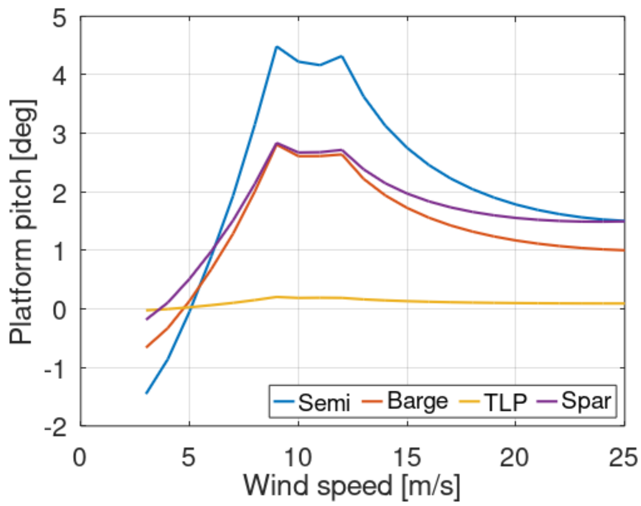


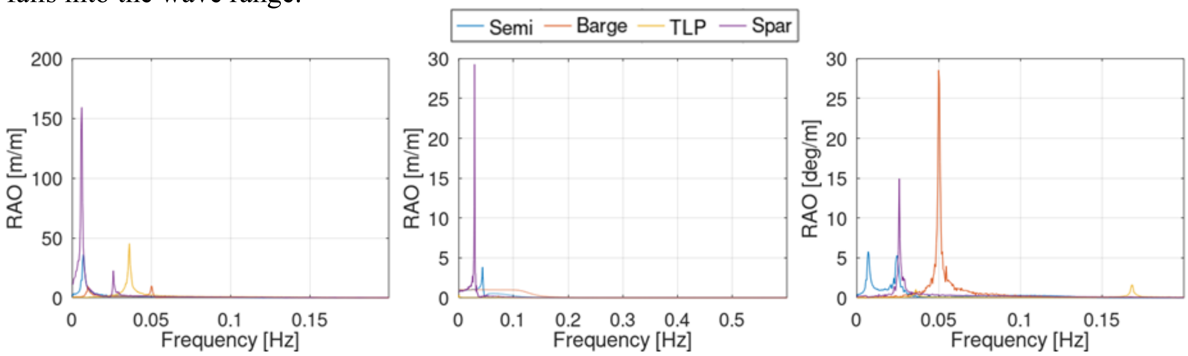
Figure 3 Steady-state platform pitch in increasing wind speed and calm water.

4.4. Spar

In the case of the spar, no changes to hull dimensions are performed, given that the overturning moment scale is even less than one (Table 5) due to the adoption of the peak-shaving in the reference wind turbine. Adaptations to the new hub height of 150 m and the site of deployment require only a small change in the floater mass to achieve equilibrium at the prescribed draft. The platform mass, including ballast, is 37171 t, with respect to an original value of 36550 t. Floater mass is changing due to the adoption of a new mooring system and a different wind turbine tower (eq. (1)), which in the WindCrete spar is made of concrete. Similar to the TLP case, the density and location of ballast are known, and a computation of floater inertia properties is possible. Concerning the mooring system, instead, the presence of the delta connection at fairleads is reproduced here with a linear yaw stiffness, which is tuned to obtain the same yaw natural period of the original concept, equal to 12s. As pointed out in [17], the yaw natural period should be sufficiently small with respect to the roll one to avoid aerodynamic roll-yaw instability [20]; given the slight deviation in mass and inertia the roll period of the adapted spar is practically equal to the one of the WindCrete, hence the original yaw natural period value is deemed suitable.

5. Inspection of floater dynamics

The RAOs of the upscaled floaters are found in Figure 4, while Table 10 shows the natural frequencies of rigid modes. Semisubmersible and spar are characterized by rigid modes well below the first order wave spectrum. The spar has a prominent response in heave due to the small radiation damping in this degree of freedom. The barge floater has a wide waterplane area that causes an intense pitch response. At the same time, it has a heave response that remains unitary in the first order wave range. The wave response of the TLP is limited with respect to the one of the other platforms especially in heave and roll/pitch; the placement of the natural frequency in this last rigid mode is not favourable because it falls into the wave range.



a) b) c)

Figure 4 RAO of the upscaled floaters in the surge (a), heave (b) and pitch (c) degrees of freedom

Table 10 Natural frequencies of rigid platforms modes

Floater	Surge/Sway (Hz)	Heave (Hz)	Roll/Pitch (Hz)	Yaw (Hz)
Semisubmersible	0.0072	0.0435	0.0234	0.0080
Barge	0.0099	0.1169	0.0504	0.0175
TLP	0.0359	0.5465	0.1687	0.1636
Spar	0.0057	0.0290	0.0259	0.0833

6. Conclusions

This work reports an upscaling and adaptation procedure of open-data substructures for floating wind turbines. Original concepts are upscaled to a power rating of 15 MW for a specific deployment site. The upscaling procedure is based on geometry similarity and Froude's upscaling, with a length scale derived from the comparison of overturning moment between the original and 15 MW wind turbine. Overall, the application of the overturning moment scale proves to be successful in delivering upscaled floaters with stability characteristics that are in line with the original concepts; small corrections to the length scale are needed due to the deviations of the wind turbine mass and center of gravity position with respect to the Froude's scaled values. In the case of the semisubmersible, the comparison with a similarly shaped 15 MW concrete concept reveals consistent values of mass and draft, but at the same time points out a relevant mismatch in the footprint values, which nevertheless is already found in the original concept. The barge has a very low tilt angle among hull-stabilized floaters, and there is room for an optimization of the length scale to deliver a smaller floater. In the TLP, instead, the negligible ballast and waterplane restoring, with respect to the mooring one, makes it less useful to upscale hull dimensions, and just an adaptation of cable size and footprint is performed; this way of proceeding, however, comes at the expenses of float-out stability. For these two last platforms, unfortunately, no 15 MW concept is publicly available, then a comparison with other data is not possible. In the spar case, finally, the small adaptations to the new wind turbine configuration do not require a replacement of the yaw natural period, which is a critical parameter in this kind of floater.

References

[1] General Electric, https://www.ge.com/renewableenergy/wind-energy/offshore-wind/haliade-x-offshore-turbine (accessed 8 December 2023).
[2] Vestas, https://www.vestas.com/en/products/offshore/V236-15MW (accessed 8 December 2023).
[3] MingYang Smart Energy, http://www.myse.com.cn/en/jtxw/info.aspx?itemid=825 (accessed 8 December 2023).
[4] Jonkman JM, Buhl ML. *FAST User's Guide*, www.nrel.gov (2005).
[5] Chakrabarti S. Physical Model Testing of Floating Offshore Structures. In: *Dynamic positioning conference*. 1998.
[6] Bachynski EE, Moan T. Design considerations for tension leg platform wind turbines. *Marine Structures* 2012; 29: 89–114.
[7] Barltrop NDP. *Floating Structures: A Guide for Design and Analysis*. Centre for Marine and Petroleum Technology, 1998.
[8] Chakrabarti S. *Handbook of offshore engineering*. 2005.
[9] Al-Solihat MK, Nahon M. Stiffness of slack and taut moorings. *Ships and Offshore Structures* 2016; 11: 890–904.
[10] Gaertner E, Rinker J, Sethuraman L, et al. *Definition of the IEA Wind 15-Megawatt Offshore Reference Wind Turbine Technical Report*, www.nrel.gov/publications. (2020).
[11] Allen C, Viselli A, Dagher Andrew Goupee H, et al. *Definition of the UMaine VolturnUS-S Reference Platform Developed for the IEA Wind 15-Megawatt Offshore Reference Wind Turbine Technical Report*, www.nrel.gov/publications. (2020).
[12] Abbas NJ, Zalkind DS, Pao L, et al. A Reference Open-Source Controller for Fixed and Floating Offshore Wind Turbines. DOI: 10.5194/wes-2021-19.
[13] Larsen TJ, Hanson TD. A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine. *J Phys Conf Ser* 2007; 75: 012073.
[14] Pegalajar-Jurado A, Bredmose H, Borg M, et al. State-of-the-art model for the LIFES50+ OO-Star Wind Floater Semi 10MW floating wind turbine. In: *Journal of Physics: Conference Series*. Institute of Physics Publishing, 2018. Epub ahead of print 6 November 2018. DOI: 10.1088/1742-6596/1104/1/012024.
[15] Jonkman JM, Matha D. Dynamics of offshore floating wind turbines—analysis of three concepts. *Wind Energy* 2011; 14: 557–569.
[16] Jonkman J, Butterfield S, Musial W, et al. *Definition of a 5-MW Reference Wind Turbine for Offshore System Development*, http://www.osti.gov/bridge (2009).
[17] Mahfouz MY, Molins C, Trubat P, et al. Response of the International Energy Agency (IEA) Wind 15 MW WindCrete and Activefloat floating wind turbines to wind and second-order waves. *Wind Energy Science* 2021; 6: 867–873.
[18] Smilden E, Sørum SH, Bachynski EE, et al. Post-installation adaptation of offshore wind turbine controls. *Wind Energy* 2020; 23: 967–985.
[19] https://github.com/IEAWindTask37/IEA-15-240-RWT.
[20] Haslum H, Marley M, Navalkar ST, et al. Aerodynamic Roll-Yaw Instabilities of Floating Offshore Wind Turbines. In: *Volume 9: Ocean Renewable Energy*. American Society of Mechanical Engineers, 2020. Epub ahead of print 3 August 2020. DOI: 10.1115/OMAE2020-18273.