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Upscaling and levelized cost of energy for offshore wind turbines supported by semi-submersible floating platforms

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Abstract. This study aimed to clarify upscaling and levelized cost of energy for offshore wind turbines supported by semi-submersible floating platform. Firstly, the upscaling rules of turbines, floaters and mooring lines are investigated, and the upscaling procedure is proposed based on the construction constraints and the static balance. Then, floater models are upscaled for 5, 10 MW turbines based on the semi-submersible floater for 2 MW turbine designed in Fukushima FORWARD project. By performing dynamic analyses, it is found that, the kinematic law for floaters is satisfied in the heave direction and relaxed in the surge and pitch direction. The dynamic similarity for mooring lines is satisfied by changing the mooring line quality. Finally, the levelized cost of energy is assessed by using engineering models and experience of demonstration projects. The initial cost is reduced 45 % and 57 % respectively for 5 MW and 10 MW comparing to 2 MW turbine.

1. Introduction

Floating offshore wind turbine (FOWT) systems have been upscaled from the demonstration. In 2017, Hywind Scotland Pilot Offshore Wind Farm has installed 6 MW turbines on spar floating platforms, which were upscaled from the 2.5 MW turbine in the demonstration project [1]. WindFloat project has a plan to install 8.4 MW turbines on semi-submersible floating platforms, which are upscaled from the 2 MW turbine in the demonstration project [2]. However, the upscaling rule of FOWT system is not clearly described. Upscaling procedure with the kinematic and dynamic similarity law is unclear. In Fukushima Floating Offshore Wind Farm Demonstration project (Fukushima FORWARD) [3], 2 MW, 5 MW and 7 MW floating wind turbines have been constructed, but the direct comparison is difficult because the floater types are different.

Three researches were conducted on upscaling semi-submersible floaters. Steinert et al. [4] upscaled Offshore Code Comparison Collaboration Continuation (OC4) floater for 5 MW turbines [5] into those for 7.5 MW and 10 MW turbines using Particle Swarm Optimisation algorithm. The static and dynamic pitch angle, the heave eigen-period, the nacelle acceleration and the tower base stress were considered as constraints in the optimisation problem. The calculated platform steel amount per kW for 10 MW was smaller than that for 7.5 MW, which did not consistent with the other two researches. Lemister et al. [6] upscaled OC4 floater for 5 MW turbines to those for 7.5 MW and 10 MW turbines using the scale-up law and the static balance in the pitch direction. All floater parameters were scaled up by the scale factor of the cube root of the turbine mass ratio. The diameters of upper columns were enlarged to have the same static pitch angle which is defined as the ratio of the overturning moment into the restoring moment of the floater. George [7] also upscaled OC4 floater for 5 MW turbines to those for 7.5 MW and 10 MW turbines using the scale-up law and the static balance, but the draft was designed from the dry dock capacity in order to allow a complete manufacture in the dock. In order to complement insufficient of displacement volume due to the draft restriction, the diameter of upper column was enlarged to satisfy the vertical static balance between the vertical buoyancy and the gravity. The priority of the scale-up law, the static balance and the construction constraints are not clear. The upscaling rule on the catenary mooring lines has not yet been discussed well, but George [7] suggested the diameter of mooring lines can be determined by the maximum force acting on fairleads. The effect of upscaling on floater motions and mooring forces should be clarified by performing dynamic analyses. The satisfactions of the kinematic similarity in floater motions and the dynamic similarity in mooring forces are to be confirmed. The accuracy of dynamic analysis methodology performed in this study was verified by Ishihara and Zhang [8], where the simulated floater motions and mooring forces agreed well with the measurement for semi-submersible floater used in Fukushima FORWARD project.

The effect of upscaling on the cost is important. The reduction of levelized cost of energy is necessary [9] to compete to fixed-bottom types in the deep water. The upscaling turbine is one promising solution for the cost reduction, which is validated for fixed-bottom types [10]. Myhr et al. [11] showed the effect of the different floater type on the cost of energy by using the engineering model, where turbine, floater and mooring line costs were estimated by assessed steel weights. However, the effect of turbine size on the cost is not clear.

In this study, upscaling and levelized cost of energy are investigated for offshore wind turbines supported by semi-submersible floating platforms. Firstly, upscaling rule of turbines, floaters and mooring lines are investigated and the upscaling procedures are proposed in section 2. The semi-submersible floater for 2 MW turbines used in Fukushima FORWARD project is then upscaled to those for 5 MW and 10 MW turbines. The effect of upscaling on floater motions and mooring forces is investigated by dynamic analyses in section 3. Finally, the levelized cost of energy is assessed based on the upscaled FOWT models by using the engineering model and the demonstration project experience in section 4.

2. Upscaling rule and procedure

2.1. Upscaling rule of turbine

Bladed demo 2 MW [12], NREL 5 MW from the National Renewable Energy Laboratory [13], DTU 10 MW from the Technical University of Denmark [14] are used. The diameters and thickness of the tower bottoms are enlarged for the larger bending moments due to floater motions. The hub heights are set as higher than the rotor diameters.

Table 1 shows the ratio of main parameters of the turbine models. In the geometrical similarity, the scale of weight and power follows $m \sim D^3$ and $P \sim D^2$, respectively, where D is the scaling factor of rotor diameter. The relationship between rotor diameter and turbine power exactly follows the geometrical similarity, which is $1 : \sqrt{5/2} : \sqrt{10/2} = 1 : 1.58 : 2.23$. The ratio of turbine mass including RNA and tower is 1: 2.96: 5.97, which is below D^3 law and follows D^2 law, which come from the turbine technology improvement as mentioned by Sieros et al. [15]. The maximum thrust force and overturning moment are calculated by using FAST [16] for onshore. It is found that the ratio of maximum overturning moment follows almost D^2 law.

Table 1. The ratio of main turbine parameter between each turbine size.

	2 MW	5 MW	10 MW
Rotor diameter	1	1.58	2.23
Power	1	2.50	5.00
Turbine mass (RNA mass + Tower mass)	1	2.96	5.97
Hub height	1	1.22	1.57
Maximum thrust force	1	2.09	4.20
Maximum overturning moment	1	2.52	5.26

2.2. Upscaling rule of floater

The upscaling rule of floater is investigated by surveying the design in Fukushima FORWARD project. Table 2, Table 3 and Figure 1 show the main parameters of the floater geometries. The main difference of Fukushima floater from OC4 is that the deck and pontoon have rectangular cross sections with a hexagon center, which were modelled with equivalent cylinders in this study.

In Fukushima FORWARD designs, the draft d_{draft} was decided by the dry dock capacity or the port depth, the freeboard $d_{freeboard}$ was decided by the maximum wave height and the diameter of main column was decided by the diameter of tower base $D_{tower-bottom}$. In this study, these constraints have the priority for the feasible design.

As design criteria, the static balance is important. For the static balance, the dominant parameters in surge, heave and pitch directions are the angle at fairleads of mooring lines, the balance between the gravity and the buoyancy, and the static pitch angle. The upscaling procedure based on the static balance is discussed in section 2.4 where the diameter of upper column D_{UC}, the distance between the columns d_{CC} and the weight of ballast $M_{ballast}$ are decided. In this study, the static balance in the sway and roll directions are not discussed since this FOWT is symmetric. The static balance in the yaw direction is also neglected since the semi-submersible floating platform provides large restoring forces comparing with the spar type platform, and the damping ratio in the yaw direction is about 8% as shown by Ishihara and Zhang [8].

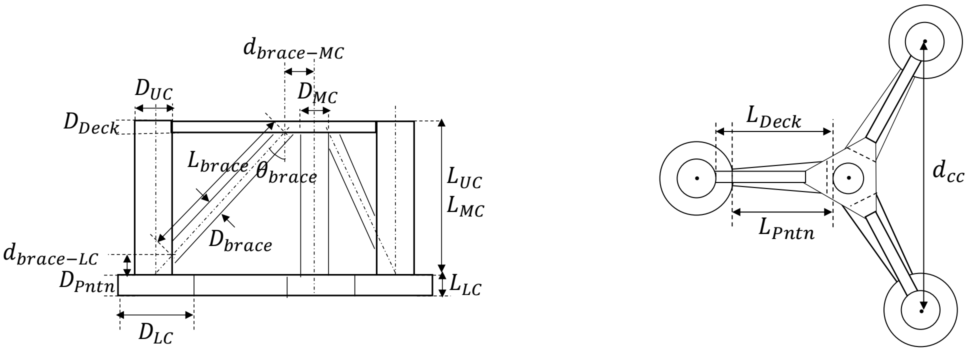
The thickness of element t is set as a constant because they are mainly designed by the static water pressure. The length of lower column, the distance between brace connection points from main column and lower column, the diameter of brace are assumed to be constant. The lengths of brace, upper column, main column, deck and pontoon are geometrically derived from other parameters.

Table 2. Parameters for floater geometry.

	Symbol	Explanation
Draft	d_{draft}	Decided from the port depth
Freeboard	$d_{freeboard}$	Decided from the maximum wave height
Diameter of main column	D_{MC}	Decided from the tower bottom diameter
Diameter of upper column	D_{UC}	Variable
Diameter of lower column	D_{LC}	Variable
Distance between the columns	d_{CC}	Variable
Thickness of element	t	Assumed to be constant as Table 4
Diameter of brace	D_{brace}	Assumed to be constant as 2.25 m
Equivalent dimeter of deck	D_{Deck}	Assumed to be constant as 2.25 m
Equivalent diameter of pontoon	D_{Pntn}^{MC} D_{Pntn}^{LC}	The ratio of $D_{Pntn}^{MC}$and $D_{Pntn}^{L,C}$ to L_{pntn} is assumed to be constant
Length of lower column	L_{LC}	Assumed to be constant as 4 m
Distance between brace and main column	$d_{brace-MC}$	Assumed to be constant
Distance between brace and lower column	$d_{brace-LC}$	Assumed to be constant
Angle of brace	θ_{brace}	$atan\left((d_{cc}/\sqrt{3}-d_{brace-mc}-D_{UC}/2)/(L_{UC}-d_{brace-LC}-D_{deck})\right)$
Length of brace	L_{brace}	$(d_{CC}-d_{brace})/cos\,\theta_{brace}$
Length of upper column	L_{UC}	$d_{draft}+d_{freeboard}-L_{LC}$
Length of main column	L_{MC}	$d_{draft}+d_{freeboard}-L_{LC}$
Length of deck	L_{Deck}	$d_{CC}/\sqrt{3}-D_{UC}-D_{MC}$
Length of Pontoon	L_{Pntn}	$d_{CC}/\sqrt{3}-D_{LC}-D_{MC}$

Table 3. Parameters for floater weight.

	Symbol	This study
Density of steel	ρ_{steel}	7874 kg/m^3
Weight of ballast	$M_{ballast}$	Variable



(a) Side view of floater (b) Top view of floater

Figure 1. Floater configuration and parameter

Table 4. Thickness of floater plate

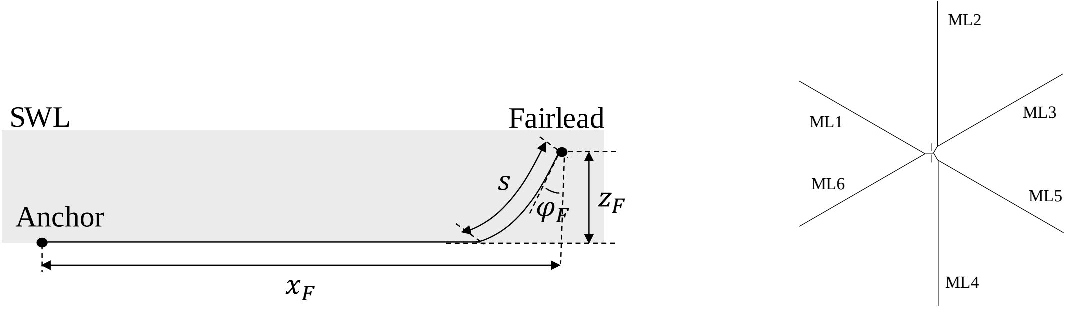
	Unit	Value
Main column, Upper column, Lower column, Cap of upper column and lower column	[mm]	60
Brace, deck, pontoon	[mm]	30

2.3. Upscaling rule of mooring line

The configuration of catenary mooring lines is described in Figure 2. Six mooring lines are attached in symmetric, which is double mooring number of OC4 because the Japan law strictly requires the redundancy in the accidental limit sate. The parameters of Fukushima FORWARD Project are used as shown in Table 4.

The mooring lines shall have enough length to avoid uplifts at anchors for all relevant design conditions in the ultimate limit state. Also, the local peak stresses shall not exceed the allowable stress with a safety factor as suggested by DNV-OS-E301 [17].

In order to increase the allowable stress ratio, three methods are used in Fukushima FORWARD project: increasing diameter of mooring line, increasing the number of mooring line and increasing chain quality like R3, R4 and R5 which represents the strength of steel.



(a) Side view of one mooring line (b) Configuration of mooring line

Figure 2. Side view and configuration of mooring line

Table 5. Parameters for the mooring line geometry.

	Symbol	Value
Length	$L_{mooring}$	673 m
Diameter	$D_{mooring}$	0.132 m
Stiffness	EA	2.41E+09 N
Mass density in air	$w_{mooring}$	382 kg/m
The angle at fairlead	φ_F	40 degree

2.4. Upscaling procedure

The upscaling procedure is proposed based on upscaling rules. At first, the draft d_{draft}, the freeboard $d_{freeboard}$ and the diameter of main column D_{MC} are decided based on the construction constraints. The floater displacement including the ballast and turbine weights is then scaled up by the square-cube law. The scale parameter s is decided by cube root of the ratio of turbine mass $M_{turbine}$, instead of taking the square root of power ratings considering technology development in consideration as suggested by references [6] and [7].

$$s = \sqrt[\frac{1}{3}]{\frac{M_{turbine}^{upscale}}{M_{turbine}^{original}}} \tag{1}$$

$$\nabla_{floater}^{upscale} = \nabla_{floater}^{original}\, s^3 \tag{2}$$

The displacement of the one offset column ∇_{OC} is obtained by extracting that of the main column. The pontoon and brace displacements were disregarded.

$$\nabla_{OC} = \left(\nabla_{floater} - \nabla_{MC}\right)/3 \tag{3}$$

In this study, the geometry ratio is assumed for the offset columns as

$$D_{LC} = 2D_{UC} \tag{4}$$

$$L_{UC} = d_{draft} - L_{LC} \tag{5}$$

Here, L_{LC} is 4 m. The diameter of upper column D_{UC} is found by solving the following equation.

$$\nabla_{OC} = \left(\frac{\pi D_{UC}^2}{4}\right) \times \left(d_{draft} - 4\right) + \left(\frac{\pi D_{LC}^2}{4}\right) \times 4 \tag{6}$$

Here, the dimeter of upper column becomes 7.6 m, 12 m and 17 m for each turbine size, which is the ratio of $1 : \sqrt{5/2} : \sqrt{10/2} = 1 : 1.58 : 2.23$, since the draft and the length of heave plate are constant. The static balance in heave and pitch directions are satisfied, but the increase of structure occupied density leads larger hydrodynamic forces due to the structure and fluid interaction. Then, the distance between columns d_{CC} are enlarged 5 % respectively from 2 MW to 5 MW and 10 MW.

The diameter of upper column is recalculated from the static pitch angle expressed by the following equation.

$$q = \frac{F_{55}}{C_{55}} = \frac{F_{55,upcaled}}{C_{55,upscaled}} \tag{7}$$

where F_{55} is the maximum overturning moment from the turbine. As shown in Table 1, the ratio of maximum overturning moment is 1: 2.52: 5.26. In order to satisfy the static balance in the pitch direction, the ratio of floater restoring moment in the pitch direction C_{55} should be the same ratio of maximum overturning moment. Floater restoring moment in the pitch direction C_{55} is calculated as shown by Equation (9).

$$C_{55} = \rho_{water}\, g\, \nabla_{floater}(z_B - z_G) + \rho_{water} g I_y \cong \rho_{water} g I_y \tag{8}$$

$$I_y = \frac{3\pi}{64}D_{UC}^4 + \sum_{i=1}^{3}\frac{\pi}{4}D_{UC}^2 x_{UC,i}^2 + \frac{3\pi}{64}D_{brace}^4 + \sum_{i=1}^{3}\frac{\pi}{4}D_{brace}^2 x_{brace,i}^2 + \frac{\pi}{64}D_{MC}^4 \tag{9}$$

where ρ_{water} is the water density, g is the gravity acceleration, z_B is the center of buoyancy, z_G is the center of gravity and I_y is the moment of inertia of the water plane area. x_{UC} and x_{brace} are the distance between the x-z plane and the upper column and brace on the water plane. The first term in the right hand is the restoring moment due to the distance between buoyancy and gravity. The second term in the right hand is the restoring moment due to the water plane area. In semi-submersible floaters, the effect of first term is less than 1 %. In this study, only the second term is considered to decide the distance between the columns d_{CC}. The floater wall thickness is considered as constant as shown in Table 4.

After all parameters are decided, the steel weight of floater $M_{floater,steel}$ is found. Based on the equation of equilibrium, the ballast mass $M_{ballast}$ is calculated as

$$M_{ballast} = \nabla_{floater}\rho_{water} - M_{turbine} - M_{floater,steel} \tag{10}$$

The angle at fairlead is set as constant of 40 degree in order to keep the same stiffness in the surge direction for each turbine size. The mooring length would be decided by evaluating the anchor location where vertical force is zero in extreme environmental condition.

Table 6 shows comparison of the conventional upscaling rule and the proposed one. This study did not use the scale-up law and applied construction constraints and static balance.

Table 6. Comparison of upscaling rule in each research

Parameter	Conventional (NTNU [6])	Conventional (Lisbon [7])	Proposed
Floater mass including ballast	Square-cube law	Square-cube law	Square-cube law
Draft	Scale-up	From the dock size	From the dock size
Freeboard	Scale-up	Scale-up	From the designed wave height
Diameter of main column	From the tower bottom diameter	Scale-up	From the tower bottom diameter
Diameter of upper column	Static balance in pitch	Static balance in heave	Static balance in pitch
Distance between columns	Scale-up	Scale-up	5 % increase

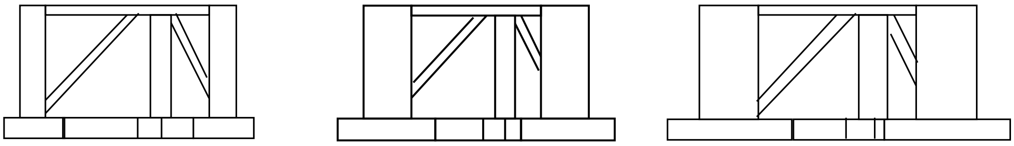
3. The effect of upscaling on floater motion and mooring force

3.1. Static balance

Table 7 shows the upscaled parameter derived by the proposed upscaling rule. Figure 3 illustrates the overview of upscaled floater. The static balances are satisfied in the heave and pitch direction.

Table 7. Upscaled floater parameters for each turbine size.

		Symbol	Unit	2 MW	5 MW	10 MW
Construction constraints	Draft	d_{draft}	[m]	21.3	21.3	21.3
	Freeboard	$d_{freeboar}$	[m]	10.7	10.7	10.7
	Diameter of main column	D_{MC}	[m]	5.0	6.0	6.0
Square-cube	Floater weight with ballast	$M_{floater}$	[kg]	5,528,247	13,820,618	27,871,073
Static balance in the heave	Diameter of upper column	D_{UC}	[m]	8.0	12.0	16.5
	Diameter of lower column	D_{LC}	[m]	16.0	24.0	33.0
Static balance in the pitch	Center of gravity (From bottom)	z_G	[m]	10.7	10.2	14.5
	Center of buoyancy (From bottom)	z_B	[m]	7.13	7.4	7.86
	Moment inertia of water plane area	I_y	[m^4]	56627	142700	297858
	Restoring moment in pitch direction	C_{55}	[kgm^2/s^2]	561,150,237 (1)	1,400,236,576 (2.52)	2,922,670,343 (5.26)
	Distance between columns	d_{CC}	[m]	47.8	50.2	52.7
Static balance in the heave	Floater steel weight	$M_{floater,s}$	[kg]	2,409,276	4,018,045	5,180,545
	The ballast weight	$M_{ballast}$	[kg]	3,118,971	9,802,573	22,690,528



(a) 2 MW (b) 5 MW (c) 10 MW

Figure 3. The constructed floater for each turbine size.

3.2. Dynamic analysis for floater motion and mooring force

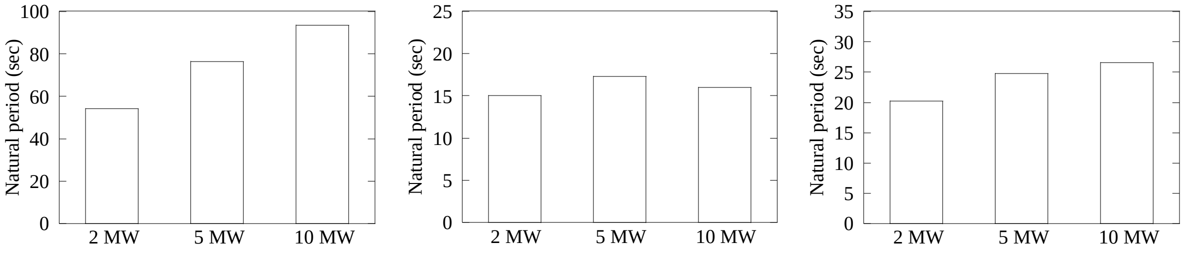
Dynamic analysis is performed to investigate the relationship between upscaling rule and FOWT similarity law. The similarity law is satisfied when the floater motion and mooring force is constant, the similarity law will be relaxed when the floater motion decreases, and the strength will be changed when the mooring force increases. FAST v8.10 [16] is used in this research. Hydrodynamic added mass, hydrodynamic damping and wave-excitation force are obtained by using the potential theory. AQWA [18] is used in this research. The viscous drags are considered in FAST simulation by applying Morison's representation. In this analysis, the drag force coefficients in Table 8 are used, which were obtained by the water tank test in Reference [8].

Table 8. Drag coefficients used in this study.

Elements	C_d	Elements	C_d
Upper column	0.61	Pontoon	0.63
Main column	0.56	Brace	0.63
Lower column	0.68		

Figure 4 shows the simulated natural periods in the surge, heave and pitch direction. The natural period is derived from Equation (11) where M_{ii} is mass of FOWT, A_{ii} is added mass, K_{ii} is mooring line stiffness and C_{ii} is hydrostatic stiffness in *i* direction. The predicted natural periods in the heave direction shows almost the same among different turbine sizes. In the surge and pitch directions, the natural periods become larger with the turbine size since the effect of added mass increases significantly.

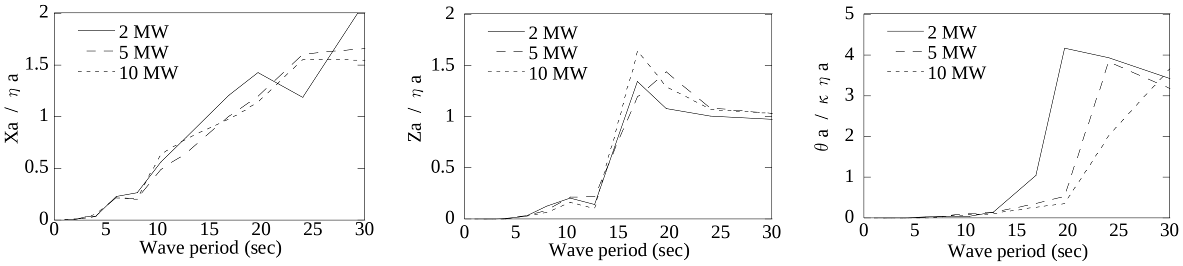
$$\mathrm{T} = 2\pi\sqrt{\frac{M_{ii} + A_{ii}}{K_{ii} + C_{ii}}} \tag{11}$$



(a) Surge (b) Heave (c) Pitch

Figure 4. Simulated natural periods for each turbine size.

Figure 5 reveals the response amplitude operator (RAO) in the range of dominant wave periods. In the surge direction, the natural periods shift longer, and so the floater motion is same in the dominant wave period region. In the heave direction, RAO among three turbine sizes matches well corresponding to the natural periods. In the pitch direction, the natural periods shift longer which indicates the floater motion in the pitch direction decreases with larger turbine size.



(a) Surge (b) Heave (c) Pitch

Figure 5. Response Amplitude Operator for each turbine size.

DLC6.1 case is calculated for the extreme condition in conformance with IEC61400-3 standards [19] requirement. In this study, the environmental condition at Fukushima offshore site is applied [20]. Extreme wind speed of 50 m/s for the 50-year-recurrence period, turbulence intensity of 0.11, wind share of 0.11, wind direction of 0-degree, Kaimal spectrum is applied for the wind conditions. Significant wave height of 11.7 m and the peak wave period of 14.76 sec, the wave spectrum of Pierson-Moskowitz is applied for the wave conditions. The current speed is set as 1.44 m/s.

The maximum floater motions are shown in Table 9. The floater motion in the surge direction increases with larger turbine size due to the current effect, but it is allowable displacement. Those in the heave direction are almost same for each turbine size, while those in the pitch direction decrease with larger turbine size. It is clarified that the kinematic similarity law in the heave direction is satisfied and those in the surge and pitch directions are relaxed.

The maximum, average and standard deviation of mooring force are shown in Table 9. The maximum mooring force of 5 MW and 10 MW become 1.07 and 1.67 times respectively to that of 2 MW. In order to keep the same stress ratio, the quality of mooring line is upgraded from R3 to R5 for 10 MW turbine. Here yield strength of R3 is 410 N/mm^2 and that of R5 is 760 N/mm^2. The ratio of R5 to R3 is 1.85. The dynamic similarity law of mooring line is satisfied by changing the quality of steel.

Table 9. The maximum floater motion and mooring force in DLC6.1

		Unit	2 MW	5 MW	10 MW
Maximum floater Motion	Surge	[m]	11.8	12.3	17.0
	Heave	[m]	3.6	3.0	3.5
	Pitch	[deg]	6.5	3.9	4.5
Mooring force	Max.	[kN]	2095	2251	3506
	Ave.	[kN]	1264	1351	1659
	Std.	[kN]	204	194	286

The effect of turbine size on fatigue of mooring line is assessed. The occurrence frequency of wind, significant wave height and wave period for each wind speed bin are set as same as Fukushima offshore site. About the current speed, the annual average of monthly maximum of 1.0 m/s is applied without fluctuation. The NS curve described in DNV-RP-C203 [21] fatigue design of offshore steel structure is applied, and the stress concentration factor is analysed by FEM. Figure 6 shows the simulated cumulative damage along mooring line position. The fatigue damage become almost constant for three turbine sizes, which indicates the fatigue of mooring does not become problem due to the upscaling.

Table 10 summarizes the relationship between the upscaling rule and the similarity law. Due to upscaling, the static balance is satisfied in surge, heave and pitch directions. Kinematic similarity law is satisfied in heave direction and those in the surge and pitch directions are relaxed. Dynamic similarity law is satisfied by changing the quality of mooring line.

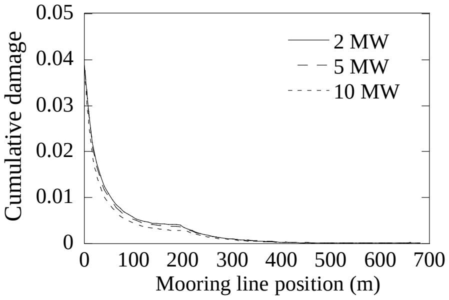


Figure 6. Cumulative damage of mooring line for each turbine size.

Table 10. Relationship between upscaling rule and similarity law.

Similarity law		Proposed	Parameter
Static balance	Floater motion in surge	Satisfied	Horizontal position
	Floater motion in heave	Satisfied	Draft position
	Floater motion in pitch	Satisfied	Static pitch angle
Kinematic similarity law	Floater motion in surge	Relaxed	Natural period
	Floater motion in heave	Satisfied	Natural period
	Floater motion in pitch	Relaxed	Natural period
Dynamic similarity law	Mooring Force	Satisfied by changing quality of mooring line	Stress ratio

4. Cost of energy with turbine size

4.1. Material cost

The material cost is assessed by using the constructed model. Figure 4 shows the weight of turbine, floater and mooring line model with turbine size, which are fitted by the linear equations as shown in Equations (12) - (14). The line of wind turbine almost crosses the origin, which means the weight per MW become constant. On the other hand, the segment of floater line become larger because there are always structure against the wave, which means the weight per MW decrease with power rate.

$$M_{turbine} = 187P_r - 81 \tag{12}$$

$$M_{floater} = 335P_r + 1972 \tag{13}$$

$$M_{mooring} = 1543 \tag{14}$$

From the demonstration project experience in Reference [22], the steel cost per ton is evaluated for the turbine, floater and mooring lines. The unit is Euro and 100 Yen is converted to 0.77 Euro. The steel cost per ton for turbine is 6654 €/ton, that for floater is 1586 €/ton and that for mooring is 2094 €/ton. The cost of mooring line steel for different grade is assessed from the relationship between the price and steel yield strength derived by public document. The cost become 1.14 times to get 1.7-time strength steel.

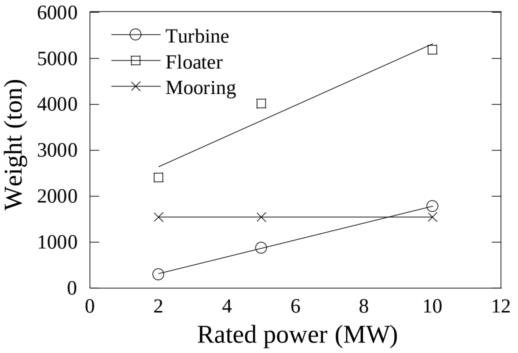


Figure 7. Weight with rated power

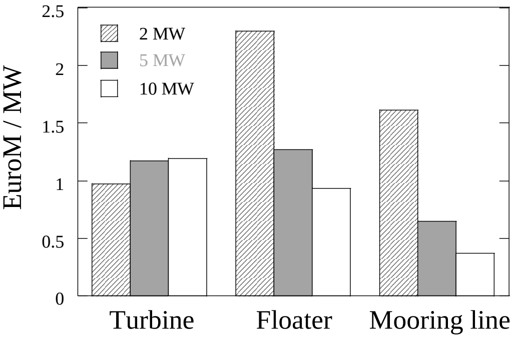


Figure 8. Material cost per rated power

Table 11 shows the comparison of main parameters and weights between the previous and proposed studies. The scale parameter of square-cube law is decided as cube root of the ratio of turbine mass. The weight of floater and ballast followed s^2 law. In this study, the weight of floater and ballast are scaled with exponents below s^2 law and become the lightest as a result of deciding the distance between columns from static balance in the pitch direction.

Table 11. Comparison between conventional and proposed floater.

		Conventional (NTNU [6] OC4)		Conventional (Lisbon [7] OC4)		Proposed (Fukushima)	
		5 MW	10 MW	5 MW	10 MW	5 MW	10 MW
Scale parameter		1	1.26	1	1.26	1	1.26
Draft	[m]	20	24.9	20.0	20.0	21.3	21.3
Upper column	[m]	9.9	14.3	12.0	15.8	12.0	16.0
Lower column	[m]	24	30.34	24.0	31.8	24.0	32.0
Distance between columns	[m]	50	58.62	50.0	63.0	50.2	54.3
Turbine weight	[kg]	600,000 (1)	1,203,000 (2.01)	600,000 (1)	1,195,000 (1.99)	881,540 (1)	1,777,740 (2.02)
Floater weight	[kg]	3,567,000 (1)	7,598,000 (2.13)	3,850,000 (1)	5,580,000 (1.45)	4,018,045 (1)	5,180,545 (1.29)
Ballast weight	[kg]	8,354,000 (1)	18,768,000 (2.25)	9,550,000 (1)	21,420,000 (2.24)	9,802,573 (1)	22,690,528 (2.31)
Mooring length*	[m]	835.5 (1)	1045.3 (1.25)	835 (1)	835 (1)	673×2 (1)	673×2 (1)

* Please notify that the number of mooring lines is three in OC4 model and six in Fukushima model.

4.2. Levelized cost of energy

The effect of the turbine size on the levelized cost of energy is assessed for 100 MW capacity wind farm. The installation cost is assessed with a simple assumption in this study. The cost per turbine is determined by using the demonstration project experience as follows. The installation steps are categorized into turbine assembly, floater towing and mooring installation. 0.92, 0.92, 3.69 €M per turbine are assumed respectively for each step. 0.6 k€/kW is assumed for the cable installation. With these simple assumptions, the installation cost decreases with the turbine size since the number of turbines become less. Operation and maintenance costs are also simply assumed as 0.1 €k/kW/year as reference [23] showed for commercial phase. 1 £ is converted to 1.11 €. Table 12 summarizes the assessed initial capital cost and O&M cost in this study. 20-year-operation period, the interest rate of 3 %, capacity factor of 40 %, the availability of 90 % are assumed. The result is summarized in Table 12.

Table 12. The cost evaluation for each wind turbine size

	Unit	2 MW×50	5 MW×20	10 MW×10
Design	[€k /kW]	0.1	0.1	0.1
Wind turbine	[€k /kW]	1.0	1.2	1.2
Floater	[€k /kW]	2.3	1.3	1.0
Mooring line	[€k /kW]	1.6	0.6	0.4
Installation cost	[€k /kW]	2.8	1.1	0.5
Cable	[€k /kW]	0.6	0.6	0.6
Initial Capital cost	[€k /kW]	8.4	4.9	3.8
Annual O & M cost	[€k /kW/year]	0.1	0.1	0.1
LCOE	[c/kWh]	21.1	13.6	11.3

5. Conclusions

In this study, the upscale rule is proposed based on the construction constrains and similarity laws, and the levelized cost of energy for the floater is assessed by using engineering models. The following conclusions are obtained. Please note that the proposed upscaling law is one way of thinking and not the absolute solution.

1) The design criteria are investigated from demonstration project experience and the upscaling procedure is proposed based on the construction constraints and static balances.
2) For the floater motion, the static balance in surge, heave and pitch direction is satisfied, while the kinematic law is satisfied in the heave direction and relaxed in the surge and pitch directions. For the mooring line, the dynamic similarity is satisfied by changing the quality of the mooring line.
3) The initial cost is assessed for 2, 5, 10 MW turbines by using engineering models and the experience of demonstration projects. The initial cost is reduced 45 % and 57 % respectively for 5 MW and 10 MW turbines comparing to 2 MW turbine.

In summary, the goal of the upscaling is to provide the same kinematic and dynamic characteristics for the upscaled floaters because the motion of platform is constrained by the offshore wind turbine designed for the bottom mounted foundations. Static balance and dynamic similarity law are recommended for the upscaling procedure. The construction constraints are also considered. Note that the proposed upscaling laws in this study can be used as an example and not are absolute laws.

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