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

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Upscaling of floating offshore wind turbine system

In floating offshore wind farm projects, turbine size is getting larger.

Hywind Project

2.5 MW ⇨ 6 MW

Fukushima FORAWARD Project

2 MW・5 MW・7 MW

WindFloat Project

2 MW ⇨ 8.4 MW

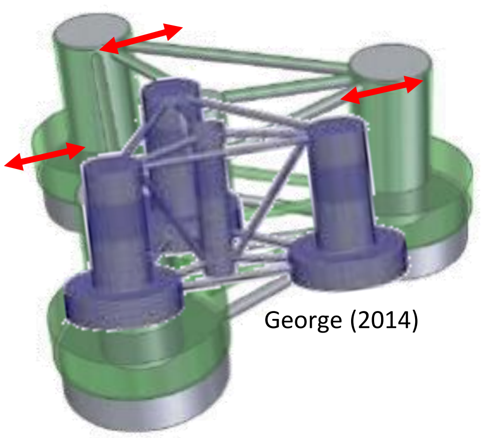
What is upscaling rule of floating offshore windfarm system ?

Previous studies about upscaling

- ✓ Three previous researches upscaled OC4 floater for 5 MW into that for 10 MW turbine.
- ✓ Satinert et al. (2016) used optimization algorithm. (Not comparable to other researches)

■ Proposed upscaling procedure

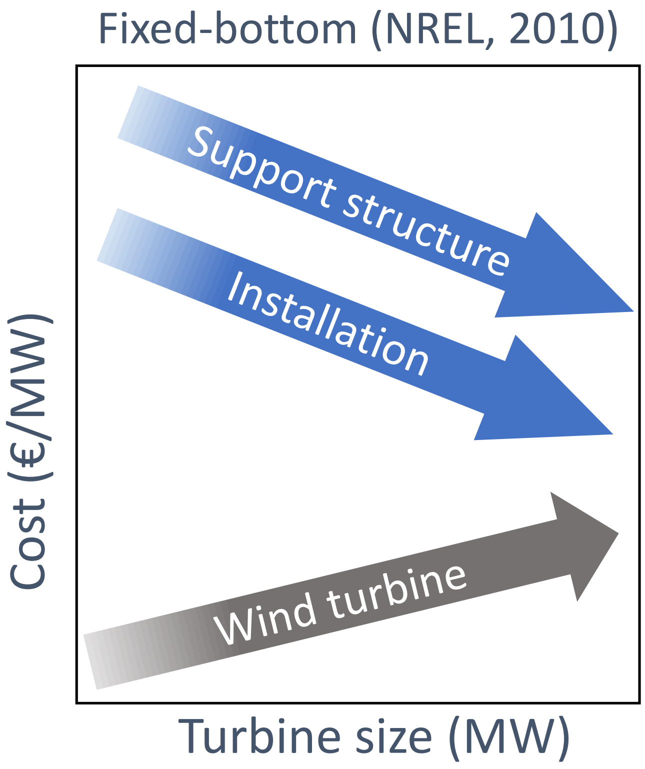
	Main parameter	Leimster et al. (2016) NTNU	George (2014) Lisbon Univ.
Heave	Draft	Scale-up	Dock size
	Freeboard	Scale-up	Scale-up
Pitch	Distance b/w columns	Scale-up	Scale-up
	Diameter of upper column	Static pitch angle $q = F_{55}/C_{55}$	Balance b/w gravity and buoyancy
Surge	Mooring line	Mooring line length	Angle at fairlead

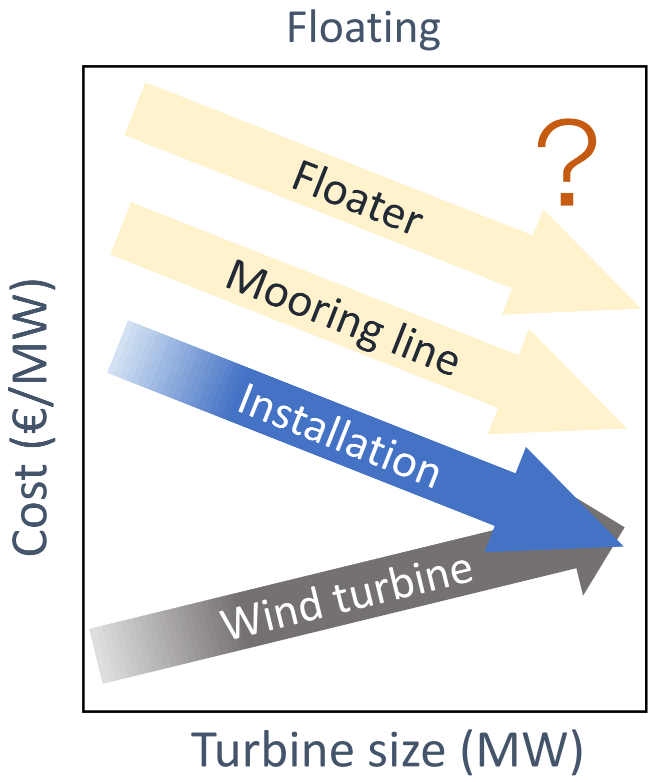


What factor has priority for upscaling ?
The relationship between upscaling rule and floater motion or mooring force need to be clearly described.

Requirement for cost-reduction

Myhr et al. (2016) has investigated the effect of different floater type on cost of energy by using engineering cost model, where the cost is assessed from steel amount of initial design of floater and mooting line.





Upscaling turbine effect of floater and mooring line is quantitatively not clear.

Objectives

1. Upscaling rule of turbine, floater and mooring line are investigated and upscaling procedure is proposed.

2. The semi-submersible floater for 2 MW used in Fukushima FORWARD project is upscaled that for 5 MW and 10 MW. The relationship between upscaling rule and floater motion or mooring force is investigated by dynamic analysis.

3. The levelized cost of energy is assessed by using upscaled floater and mooring line model.

Upscaling rule of turbine

	2 MW Bladed Demo	5 MW NREL	10 MW DTU
Rotor diameter	1	1.58	2.23
Turbine mass (RNA mass + Tower mass)	1	2.5	5
Hub height	1	1.22	1.57
Maximum thrust force	1	2.09	4.20
Maximum falling moment	1	2.52	5.26

※The diameter and thickness at tower bottom were enlarged by referring Fukushima 2MW wind turbine.

■ Rational upscaling ratio

$$\mathrm{P} \sim s^2 \qquad 1^2 : 1.58^2 : 2.23^2 = 1 : 2.5 : 5$$

$$\mathrm{m} \sim s^3 \qquad 1^3 : 1.58^3 : 2.23^3 = 1 : 3.9 : 11.1$$

The ratio of mass followed s^2 law due to technology progress (Sieros et al. 2012)

The ratio of maximum overturning moment followed s^2 law.

■ Construction constrains

Draft	Freeboard	Diameter of main column
Dock size and port depth	Designed maximum wave height	The diameter of turbine tower bottom
		

Ref.) Fukushima FORWARD

■ Design criteria

Surge	Stiffness from mooring line
Heave	Balance between gravity and buoyancy
Pitch	Static pitch angle (The ratio of falling moment to restoring moment)

Construction constrain was prioritized for feasible upscaling.
The design criteria for floater motion was investigated.

Upscaling rule of mooring line

- Design criteria: The allowable stress. (DNV-OS-E301)

Methodology of increasing allowable stress	Cost
Increase diameter of mooring line	↗
Increase number of mooring line	↗
Increase chain quality (strength) of mooring line (R3→ R4→ R5)	→

The design criteria for mooring force was investigated.

- What is the relationship between upscaling and similarity law.

Turbine	s^2 law ○
Floater	Kinematic similarity law **?**
Mooring line	Dynamic similarity law **?**

Floater motion or mooring force

Constant	Satisfied
Decrease	Relaxed
Increase	Change quality

The rule for evaluation of the relationship between upscaling rule and FOWT was decided.

Upscaling procedure of floater

Decide the upscaled **displacement volume** from square-cube law

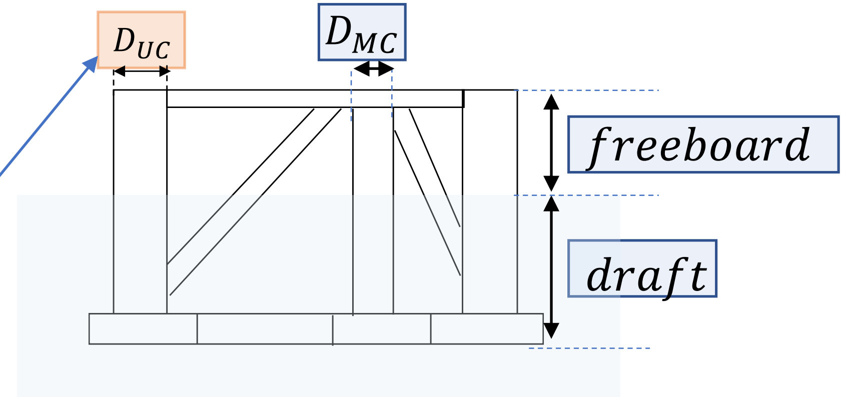
Derive **the diameter of upper column** from equilibrium equation

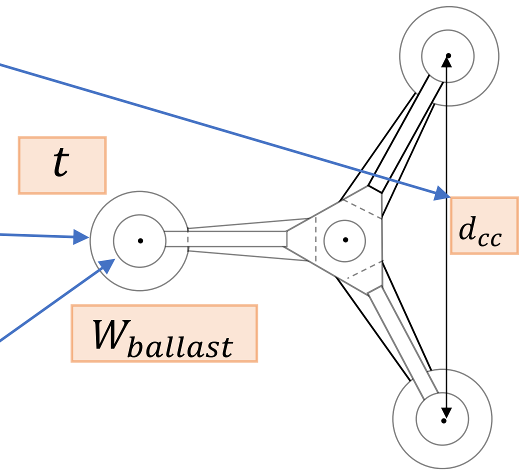
Derive **the distance between columns** from static pitch angle

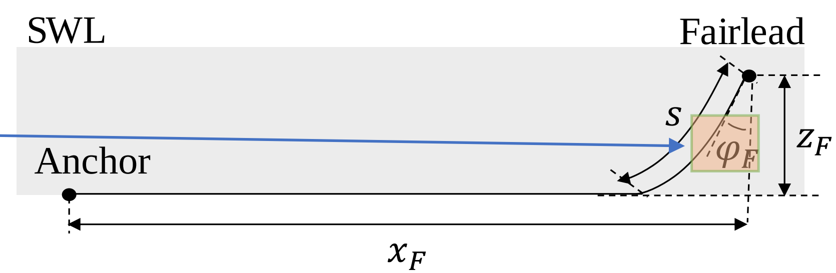
Derive **floater wall thickness** from hydrostatic and hydrodynamic loading

Derive **ballast weight** from equilibrium equation

Set **angle at the fairlead as constant** for all turbine

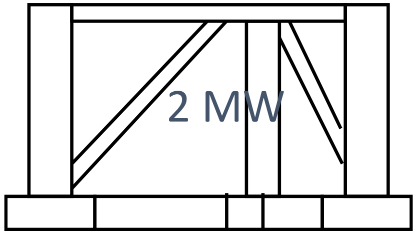


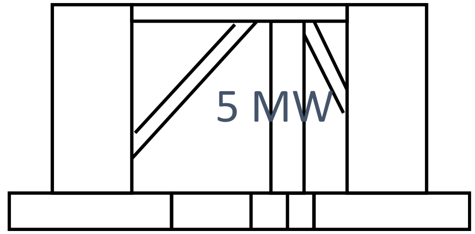


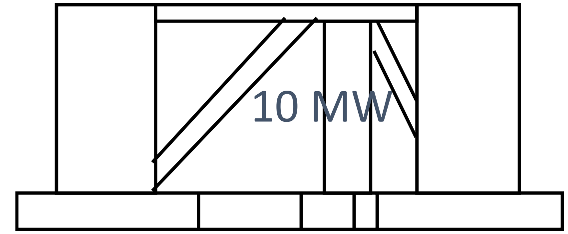


The upscaling procedure of floater and mooring line was proposed.

Static balance of upscaled floater





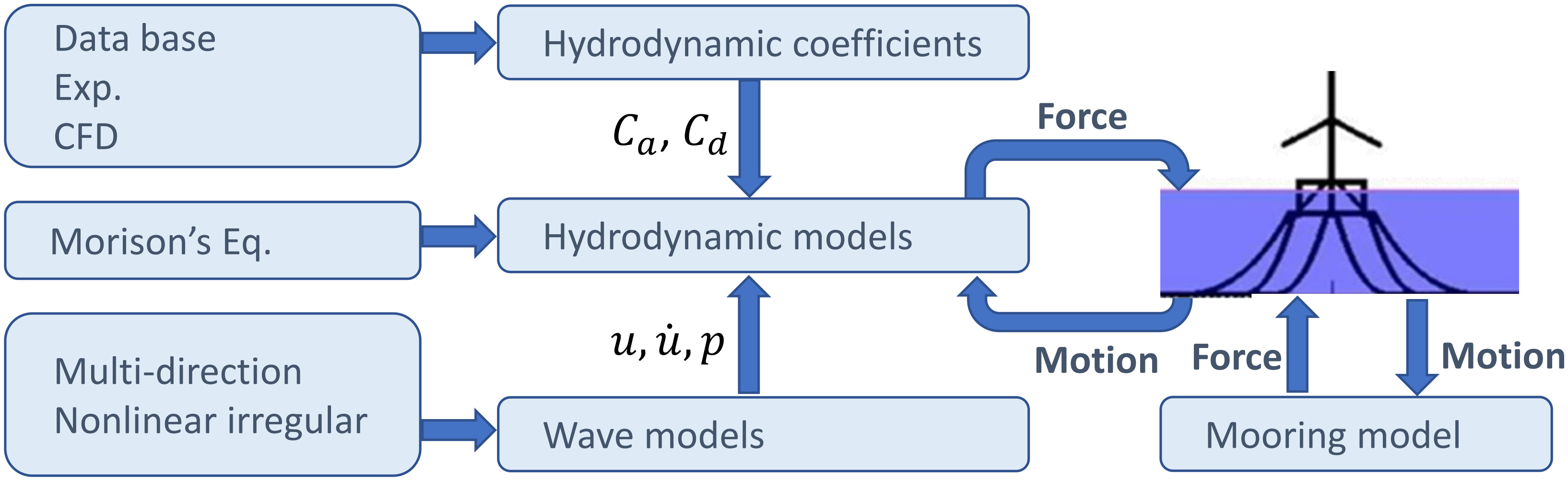


		Unit	2 MW	5 MW	10 MW
Constrains	Draft	[m]	21.3	21.3	21.3
	Freeboard	[m]	10.7	10.7	10.7
	Diameter of main column	[m]	5	6	6
Static balance in heave	Diameter of upper column	[m]	8	12	16
	The ballast weight	[kg]	3,118,971	9,802,573	22,690,528
Static balance in pitch	Moment of inertia of water plane area	$[m^4]$	58542	147526	307932
	Restoring moment in pitch direction	$[kg \cdot m^2/s^2]$	588,431,626 (1)	1,482,847,699 (2.52)	3,095,150,356 (5.26)
	Distance between columns	[m]	47.3	50.2	54.3
Static balance in surge	The angle at fairlead	[deg]	40	40	40

The static balance was satisfied

Dynamic analysis of FOWT system

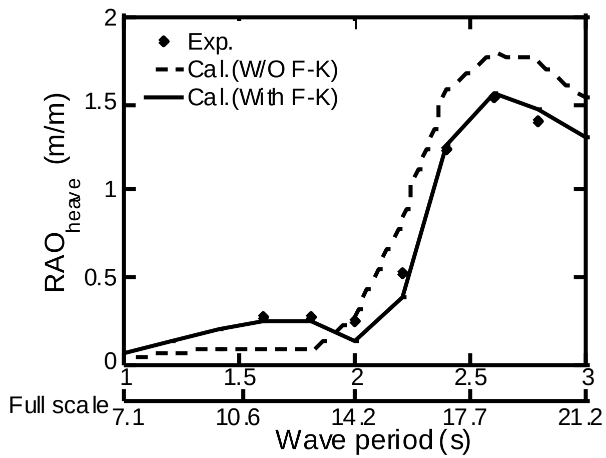
Zhang and Ishihara (2019) Renewable Energy



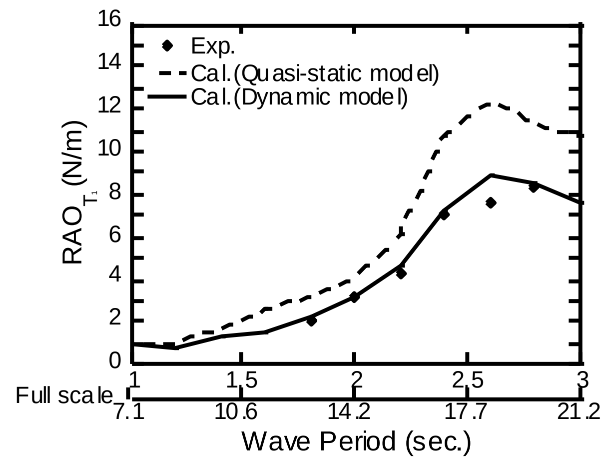
Series of water tank tests

	Towing test
	Forced oscillation test
	Dynamic response test

Predicted floater motion

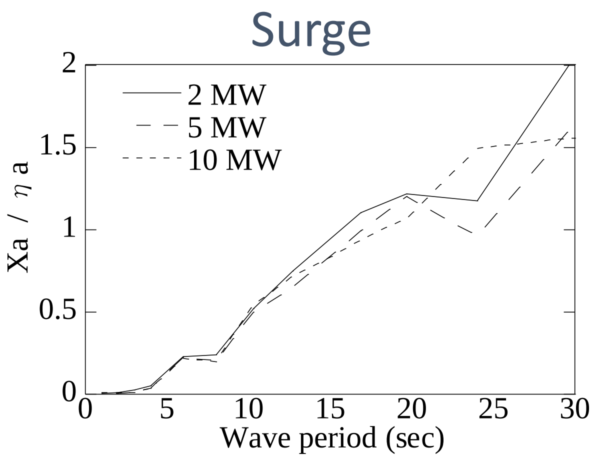


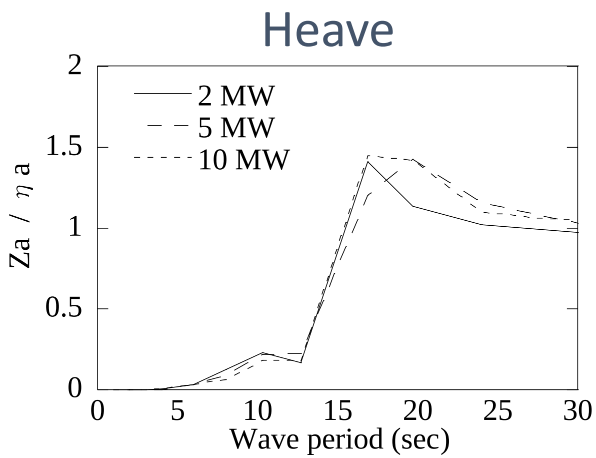
Predicted mooring force

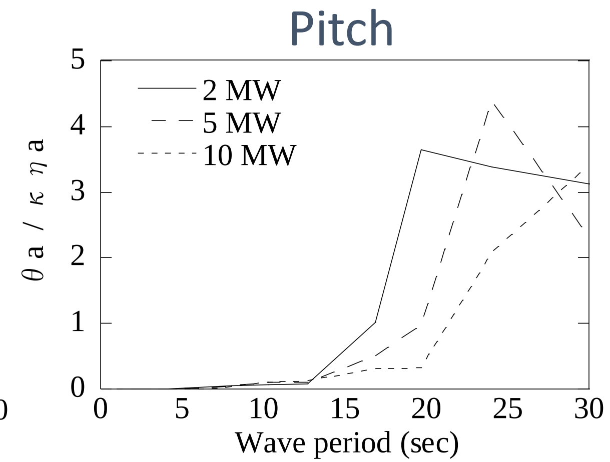


Floater motion and mooring force prediction was validated by water tank test

Floater motion in DLC6.1



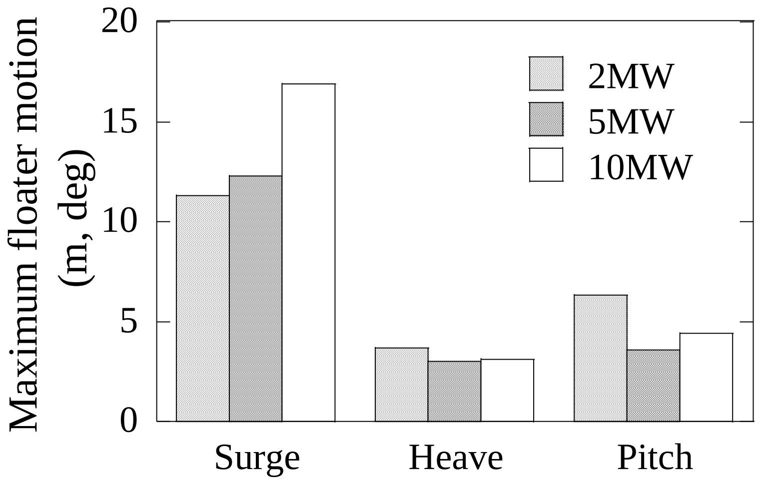




Kinematic law is relaxed in surge and pitch direction

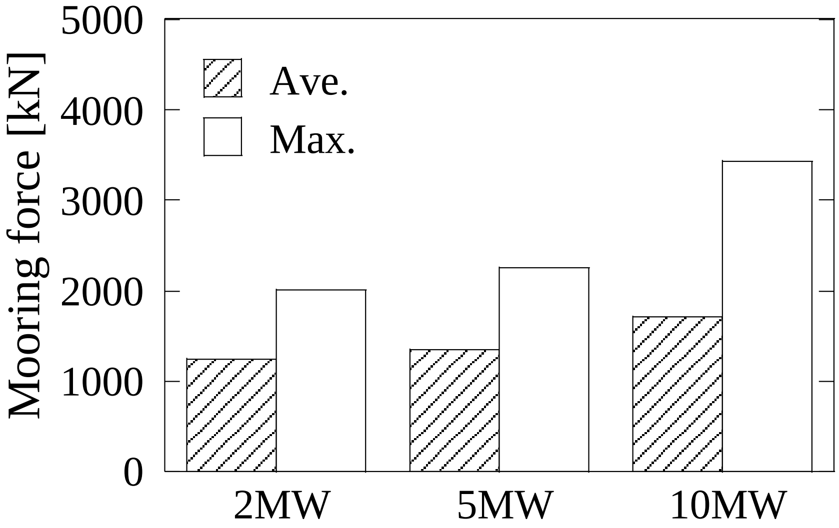
DLC6.1 Environmental condition

Wind	$U_{50} = 50\ \mathrm{m/s}$	$I = 0.11$
Wave	$H_s = 11.7\ \mathrm{m}$	$T_p = 14.76\ \mathrm{sec}$
Current	$U_c = 1.44\ \mathrm{m/s}$	

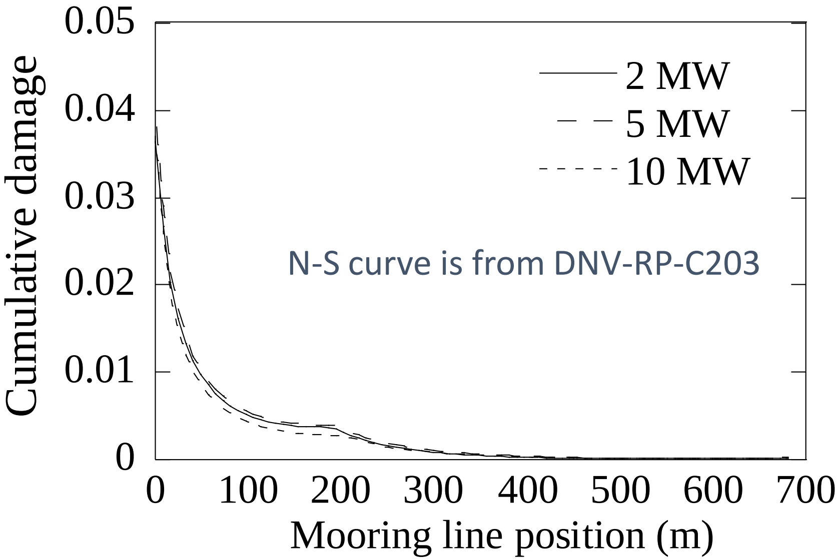


Mooring force in DLC6.1 and in DLC1.2

Mooring force in DLC6.1



Fatigue analysis of mooring line in DLC1.2



The maximum mooring force increased according to surge motion increase.

The cumulative damage due to fatigue were not affected by the turbine sizes.

Dynamic similarity is satisfied by changing the quality (strength) of mooring line

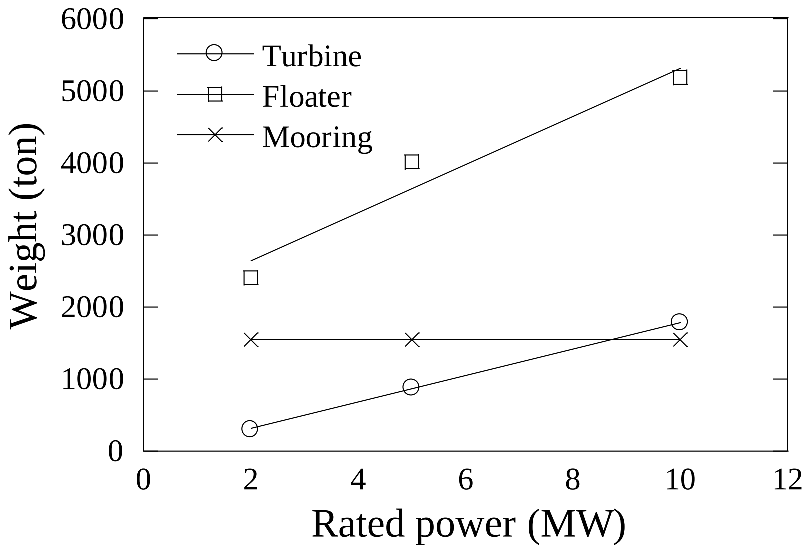
$$LCOE = \frac{ICC \times FCR + O\&M}{AEP}$$

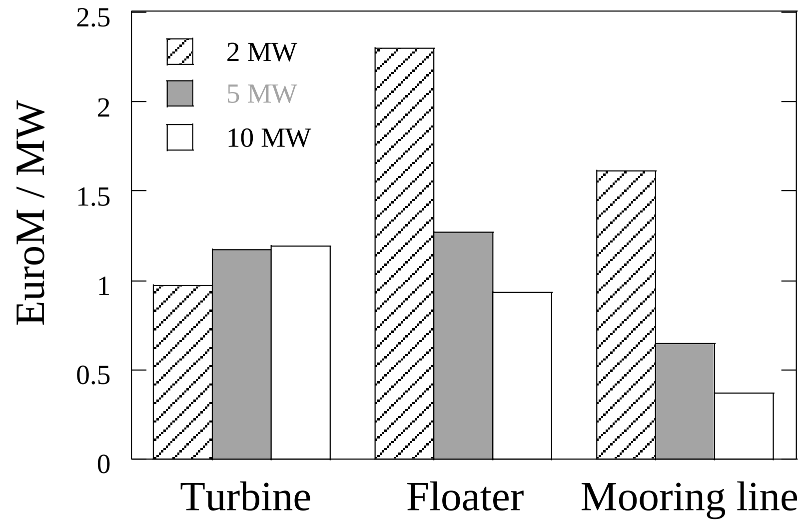
Item		Methodology
Initial Capital Cost	Material	$Steel\ Weight \times Cost\ per\ ton$
	Installation	$Vessel\ cost \times Installation\ day \div Weather\ downtime$ $Installation\ cost\ per\ turbine$
Fixed Charge Rate		$3\ \%\ interest$
Operation & Maintenance cost		$Wind\ and\ wave\ time\ series, Work\ limit\ condition,$ $Vessel\ cost, Turbine\ failure\ rate$
Annual		$Capacity\ factor\ of\ 40\ \%\ and\ Availability\ of\ 90\ \%$

Orange box: Assessed from constructed model

Purple box: Assessed from demonstration project’s experience

Estimation of material cost





The floater and mooring cost per MW decreased with turbine sizes.

		NTNU		Lisbon		Proposed	
		5 MW	10 MW	5 MW	10 MW	5 MW	10 MW
Draft	[m]	20.0	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
Distance b/w columns	[m]	50	58.62	50.0	63.0	50.2	54.3
Floater steel 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)
Mooring line length	[m]	835	1045	835	835	673 × 2	673 × 2

Estimation of installation and O&M cost

Installation cost

Turbine installation

0.92 €M/turbine

Floater towing

0.92 €M/turbine

Mooring installation

3.69 €M/turbine

Operation and maintenance cost

- ECN O&M Calculator was used
- Simulated wind and wave time series
- The work limit condition was 2 m significant wave height
- Turbine reliability was set from ReliaWind

Access vessel

Summary of estimated LCOE

	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]	0.22	0.14	0.11
LCOE	[c/kWh]	32	19	15

The initial cost was reduced 45 % and 57 % respectively for 5 MW and 10 MW comparing to 2 MW turbine.

※ Here estimated Installation and O&M cost has uncertainty because the assumption was very simple.

Conclusions

1. The upscaling rule of floating offshore wind turbine system was investigated from demonstration project experience and the procedure of upscaling was proposed.

2. For floater, static balance was satisfied, but kinematic law was relaxed in surge and pitch direction. For mooring line, dynamic similarity was satisfied.

3. By using engineering models and experience of demonstration projects, the initial cost was assessed for 2, 5, 10 MW turbines. The initial cost was reduced 45 % and 57 % respectively for 5 MW and 10 MW comparing to 2 MW turbine.

Acknowledgments

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