



Key Performance Indicators and Target Values for Multi-Megawatt Offshore Turbines

Chaviaropoulos, Panagiotis K. ; Natarajan, Anand; Jensen, Peter Hjuler

Publication date:
2014

[Link back to DTU Orbit](#)

Citation (APA):

Chaviaropoulos, P. K. (Author), Natarajan, A. (Author), & Jensen, P. H. (Author). (2014). Key Performance Indicators and Target Values for Multi-Megawatt Offshore Turbines. Sound/Visual production (digital), European Wind Energy Association (EWEA).

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.



Key Performance Indicators & Target Values for Multi-MW Offshore Turbines

Takis CHAVIAROPOULOS
CRES

Anand. NATARAJAN
DTU WIND ENERGY

Peter Hjuler JENSEN
DTU WIND ENERGY

Introduction / Motivation



- This work is done in the context of Innwind.EU whose overall objective is the high performance innovative design of beyond state-of-the-art 10-20 MW deep offshore wind turbines.
- The assessment of innovation necessitates the establishment of a framework where different designs can be compared against a reference one on the basis of suitable key performance indicators (KPIs).
- These performance indicators are cost driven and evaluate the
 - Direct effect on Levelised Cost of Electricity (LCOE)
 - Indirect effect on downstream components (loads, weight)

Support by:



EWEA 2014, Barcelona

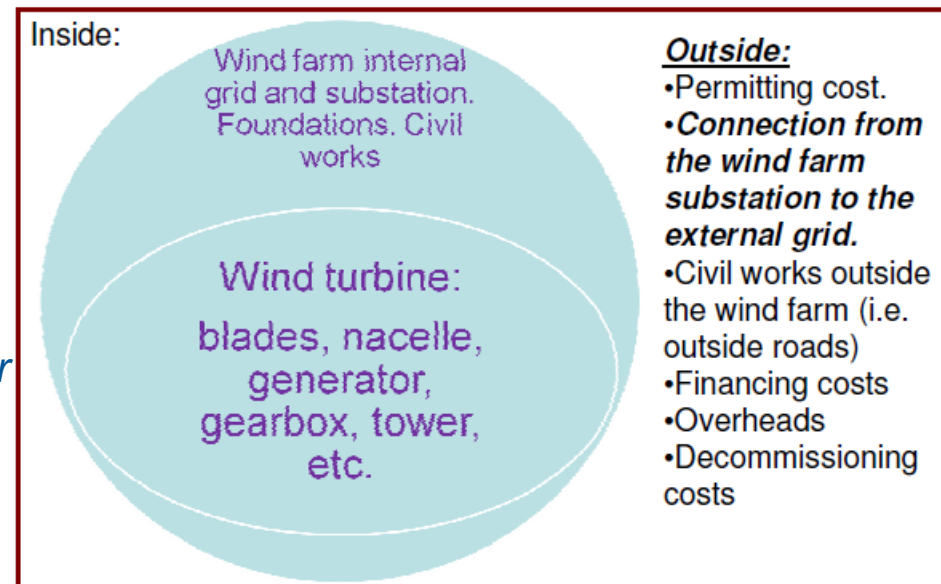
LCOE as a KPI for the European Industrial Initiative



The LCOE represents the sum of all costs over the lifetime of a given wind project, discounted to the present time and levelized based on annual energy production.

$$LCoE = \frac{(C+BOP) * FCR + O\&M}{AEP}$$

- All turbine capital costs (C)
- Balance of plant incl the foundation, electrical cabling, logistics (BOP)
- FCR – fraction of capital costs per year
- Annualized O & M (OPEX)
- Annual energy production, AEP



Support by:



EWEA 2014, Barcelona

LCOE Targets for 2020 (EWII)



- The parameters needed for the LCOE calculation are:

PARAMETERS	ONSHORE	OFFSHORE
Capital investment cost – CAPEX (€/kW)	1 250	3 500
O&M costs including insurance(€/kW/yr)	47	106
Balancing costs (€/MWh)	3	3
Capacity factor (%)	25	40
Project lifetime (years)	20	25
Real discount rate (%)	5,39	5,39
Total plant capacity (MW)	40	300
Size of wind turbines (MW)	2.5	5-7

- The Table below shows the results of EWII-LCOE calculations assuming a linear reduction of the LCOE from 2010 to 2020 that reaches 20 % by 2020.

LCEO evolution	ONSHORE		OFFSHORE	
	Abs.	Rel.	Abs.	Rel.
LCOE by 2010 (€/MWh)	71,80	100	106,93	100
LCOE by 2015 (€/MWh) (-10%)	64,43	90	95,57	89
LCOE by 2020 (€/MWh) (-20%)	57,15	80	84,77	79

Support by:

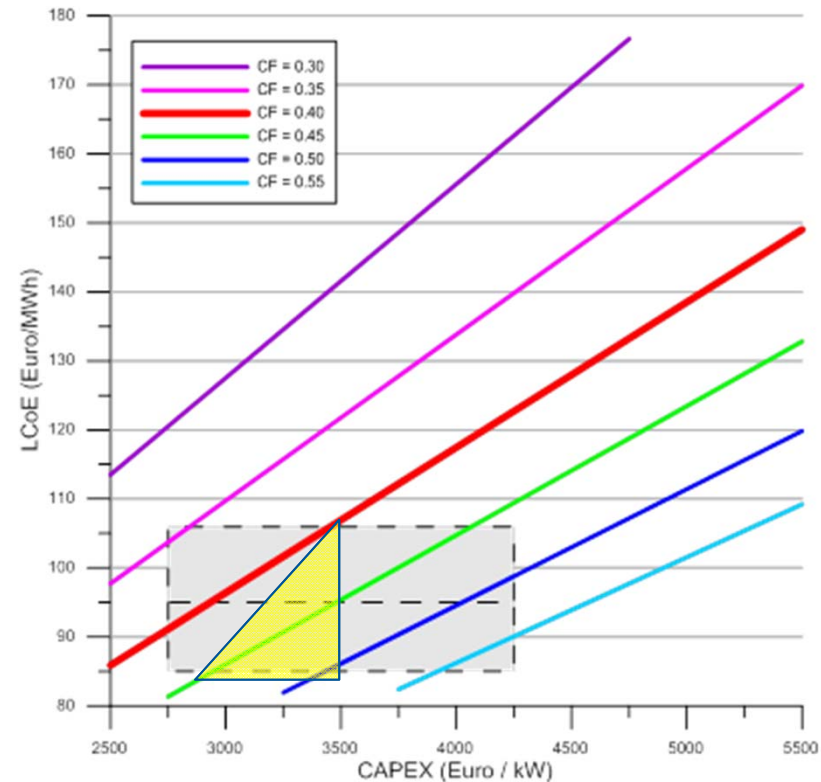


LCOE Sensitivity to CAPEX and CF



- The Figure at right is quite instructive regarding the sensitivity of LCOE to its main drivers CAPEX and CF
- Calculations have been done with fixed OPEX = 106 (€/kW/yr)

NOTE: One percentage unit increase of CF has similar effect to LCOE as a 100 Euro/kW CAPEX reduction



Support by:



CAPEX Split for the Reference Case



	Roland Berger [5]		Ref [6]	Crown Estate- SITE B [7]	
	3MW Turbine	6MW Turbine	6MW Turbine	4 MW Turbine	8 MW Turbine
CAPEX SPLIT (M€ /MW)					
<i>Turbine</i>	1,35	1,55	1,45 - 1,60	1,26	1,55
<i>Foundation</i>	0,96			0,84	0,74
<i>Installation</i>	0,62			0,71	0,36
<i>Electrics</i>	0,58				
<i>Other</i>	0,39			0,65	0,65
SUM	3,51			3,46	3,30

Turbine	Rotor	<i>Rotor lock</i>	0,2357	1,00
		<i>Blades</i>	0,2220	
		<i>Hub</i>	0,0137	
	Nacelle systems	<i>Gearbox</i>	0,1291	0,2979
		<i>Generator</i>	0,0703	
		<i>Rotor brake</i>	0,0132	
		<i>Nacelle cover</i>	0,0135	
		<i>Nacelle structure</i>	0,0280	
		<i>Couplings</i>		
		<i>Shaft</i>	0,0191	
	Electrics & control	<i>Pitch system</i>	0,0266	0,0767
		<i>Variable speed sys</i>	0,0501	
		Tower	0,2630	
	Other		0,1300	
	BoP Only	<i>Foundation system</i>	0,4400	1,00
<i>Offshore transportation & installation</i>		0,3000		
<i>Offshore electrical I&C</i>		0,2600		

LCOE CALCULATOR	ONSHORE WIND	OFFSHORE WIND	
	EWII	EWII	
Total Plant Capacity (MW)	P	40,00	300,00
Size of Wind Turbines (MW)	Pt	2,50	5,00
Turbines Cost (€/kW)	Ct	900	1.500
BoP Cost (€/kW)	Cb	350	2.000
Capital Investment Cost (€/kW)	C	1.250	3.500
O&M Costs (€/kW/y)	O&M	47	106
O&M Costs [incl. fixed annual costs, (€/MWh)]	O&M	21,46	30,25
Balancing Costs (€/MWh)	BC	3,00	3,00
Project Lifetime (y)	N	20	25
Capacity Factor (%)	Cf	0,25	0,40
Nominal Discount Rate (%)	dn	0,07	0,07
Inflation Rate (%)	i	0,02	0,02
Real Discount Rate (%)	d	0,0539	0,0539
Capital Recovery Factor (%)	CRF	0,083	0,074
Summation of Discounted Future Expend	SFE	12,058	13,557
Present Value of Total O&M (€)	SO&M	25.838.573	473.853.240
Annual Energy Production (MWh/y)	E	87.600	1.051.200
Levelized Investment (€/y)	LI	4.146.514	77.452.842
Annual Discounted O&M (€/y)	DO&M	2.142.800	34.953.600
Annual O&M / Capital Investment (%)	O&M(%)	0,038	0,030
	LI/E	47,33	73,68
	DO&M/E	24,46	33,25
LCOE (€/MWh)		71,80	106,93
Contribution of CAPEX (Turbines) (€/MWh)		34,08	31,58
Contribution of CAPEX (BoP) (€/MWh)		13,25	42,10
Contribution of OPEX (€/MWh)		24,46	33,25
Contribution of CAPEX (Turbines) (%)		0,47	0,30
Contribution of CAPEX (BoP) (%)		0,18	0,39
Contribution of OPEX (%)		0,34	0,31
		1,00	1,00

Support by:



Split of Turbine & BoP CAPEX to its subcategories (5 MW HAWT)

LCOE Calculator

Calculating LCOE for Up-scaled Designs



- To demonstrate the concepts we shall work with two up-scaling strategies, first with “classical up-scaling” and second with “innovation-based up-scaling”, which implies the adoption of new technologies with a strong potential for cutting the costs (and weight) down but also for increasing the offshore wind farm capacity factor.
- The goal at this stage is not to identify these innovative technologies but to set targets on their desirable performance.
- We shall investigate up-scaling effects on Capacity Factor and Turbine and BoP CAPEX.
- OPEX investigations are not part of Innwind.EU. Increasing the turbine size reduces the OPEX per installed MW. Evidently, the OPEX part which is simply proportional to the number of turbines in the farm is getting down when larger turbines are used. We shall assume that a 10% reduction for the standard practices and a 20% reduction with innovative practices is feasible, following the turbine size increase from 5 to 10 MW.

Support by:

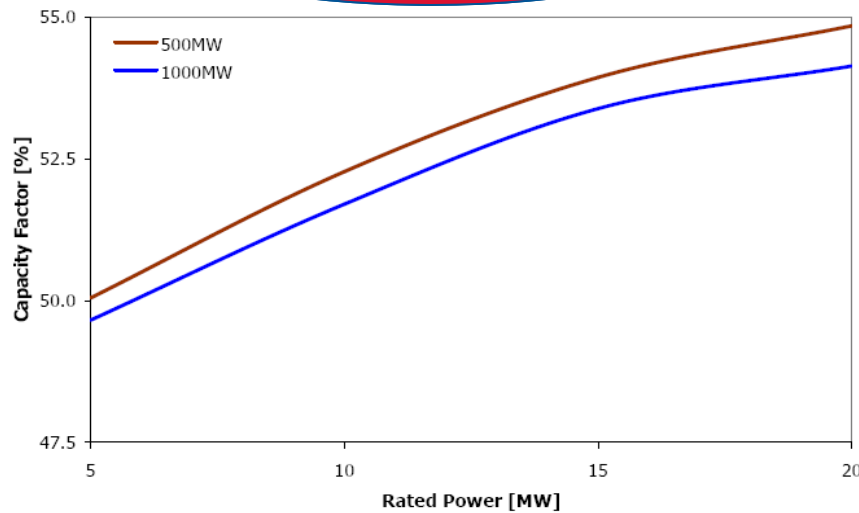


EWEA 2014, Barcelona

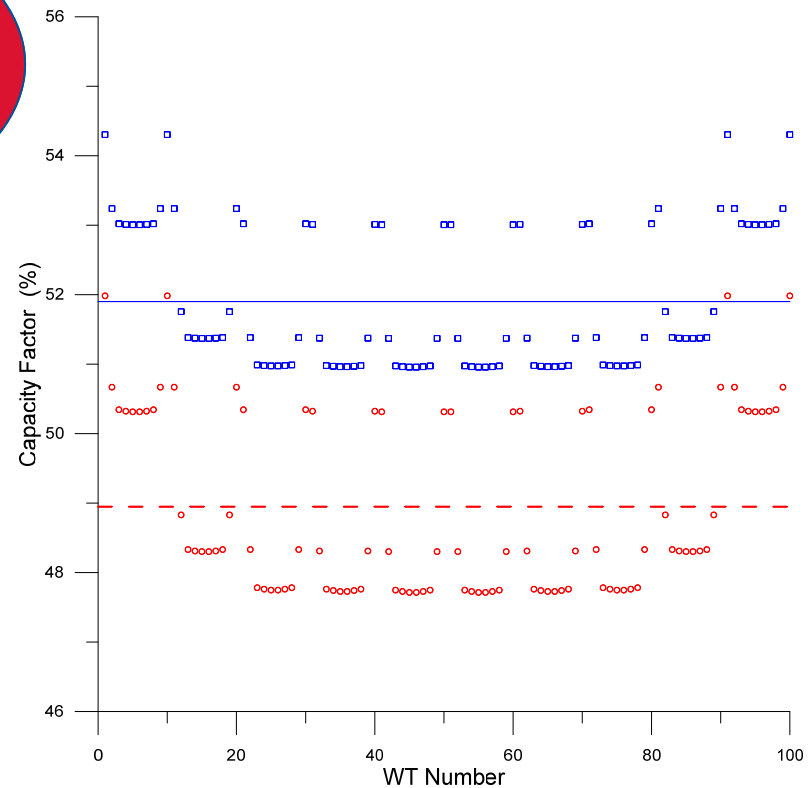
Up-scaling and Wind Farm Capacity Factor



Add 3 percentage units for a standard design and 7 units for an innovative design when the turbine size is increased from 5 to 10 MW.



Classical Up-scaling
Effect of turbine size on the aerodynamic capacity factor of large offshore wind farms

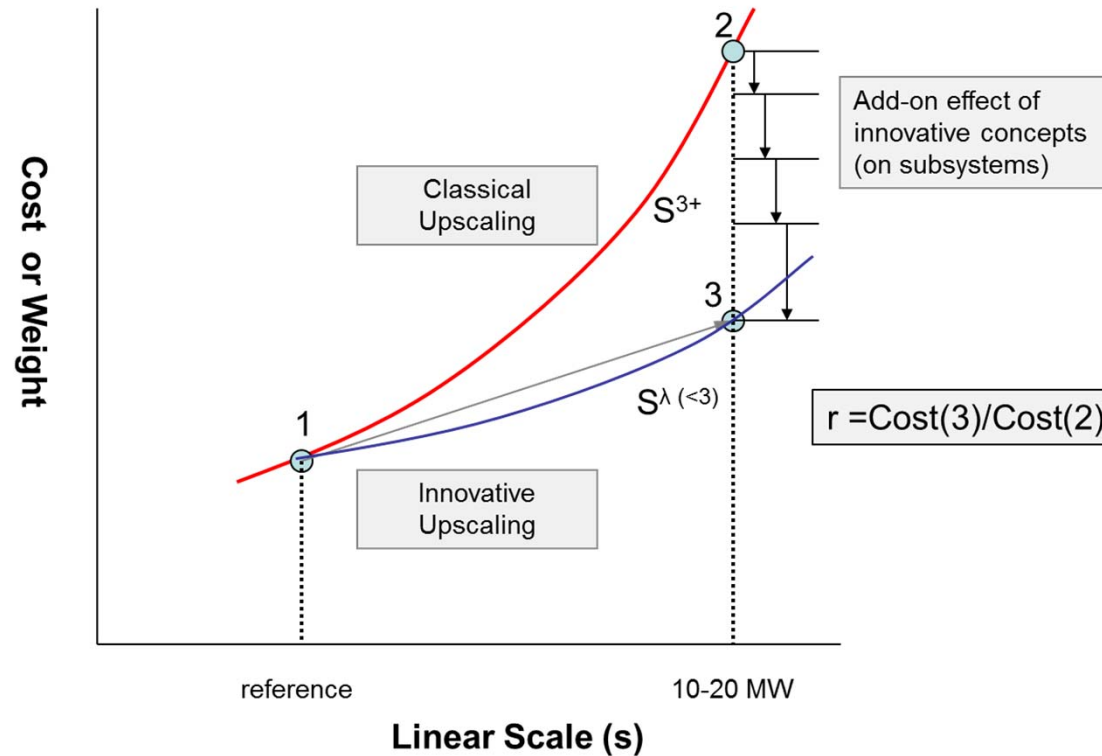


Capacity factor and wake losses in a 10X10 offshore wind farm with 5 MW turbines at 8D spacing. Red dots refer to “standard” and blue squares to “low-induction” turbines.

Support by:



CAPEX - Scaling Exponent and Cost Reduction



$$(\lambda_{clas} - \lambda_c) \ln[s] = -\ln[r]$$

Support by:



Up-scaling and CAPEX



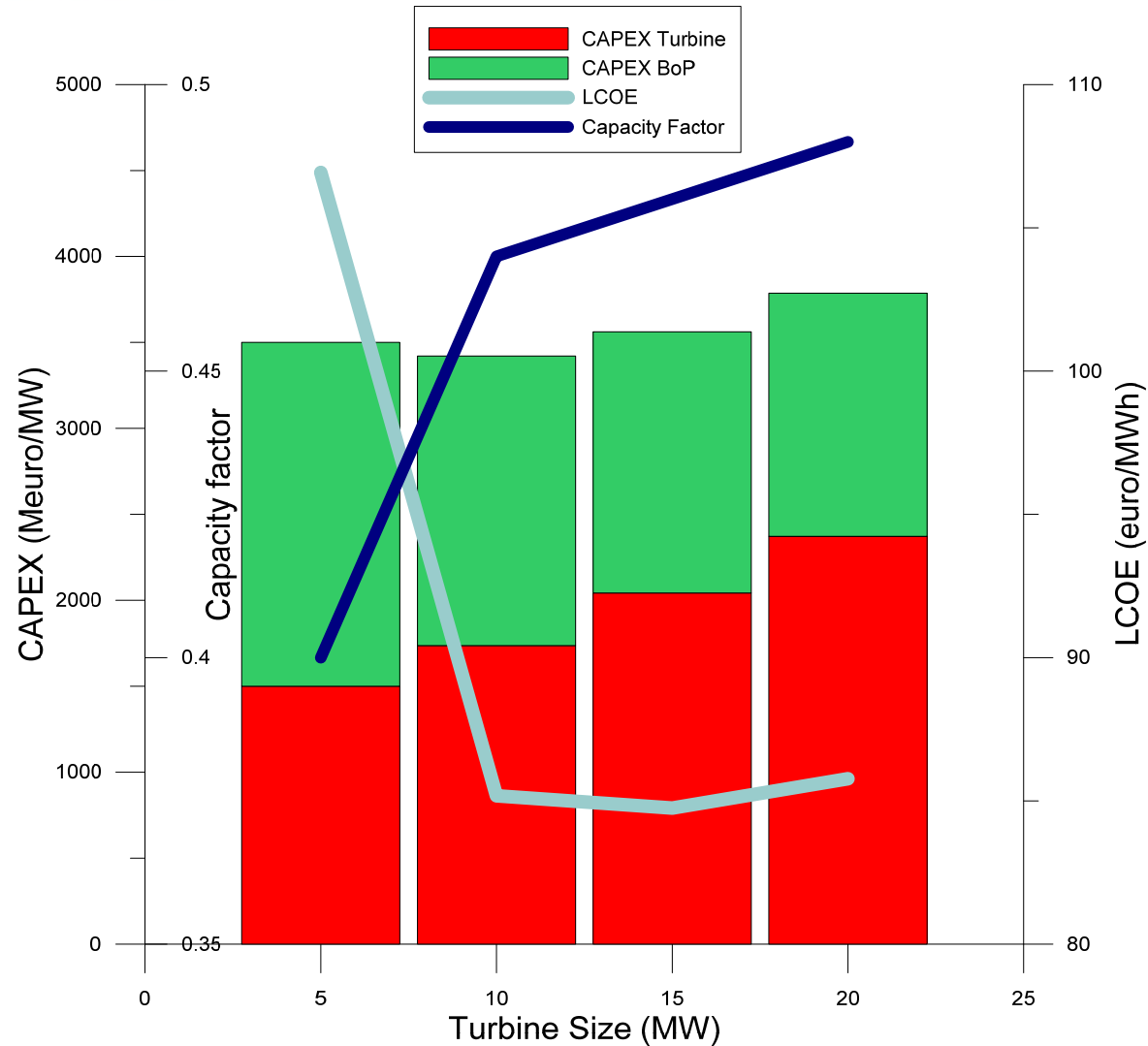
- In classical up-scaling we assume that the scaling exponent for CAPEX is $\lambda_c=3$ for the turbine and its main subcomponents and $\lambda_c=2$ for the BoP part. Namely, the Turbine CAPEX scales-up with s^3 where s is the linear scale factor.
- Our assumption for the BoP scaling exponent needs further discussion. UPWIND project showed that for a fixed water depth, the electrical infrastructure and connection scales-up with the power of the turbine ($\lambda_c=2$) and similar assumptions are made for the other BoP cost categories (offshore foundation system, transportation, installation etc. For a given water-depth and a bottom-mounted design it is logical to assume that the offshore foundation system (monopile, jacket) weight is scaling-up in two dimensions and not in three (as constrained by the fixed water-depth), thus $\lambda_w=2$.
- Going to our “innovation-based up-scaling” figures we shall assume λ_w values lower than 3 and 2 for the turbine and BoP parts respectively. For the turbine part every such λ drop is directly related to technological improvements while for the offshore substructure part the fact that the hub height is not up-scaling linearly but adjusts to a fixed blade-mean sea level clearance leads to λ_w values closer to 1.7 than 2.

Support by:



EWEA 2014, Barcelona

LCEO for Innovation-based Up scaling

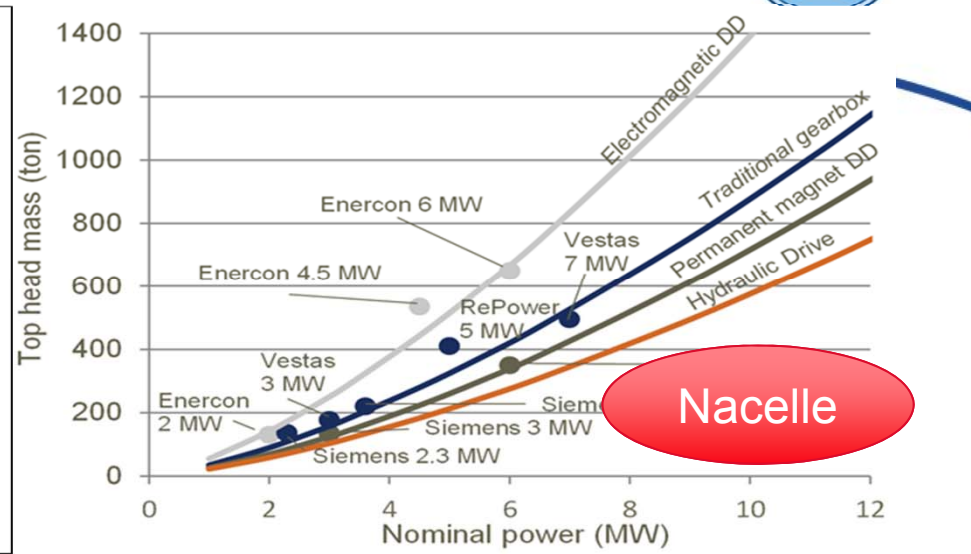
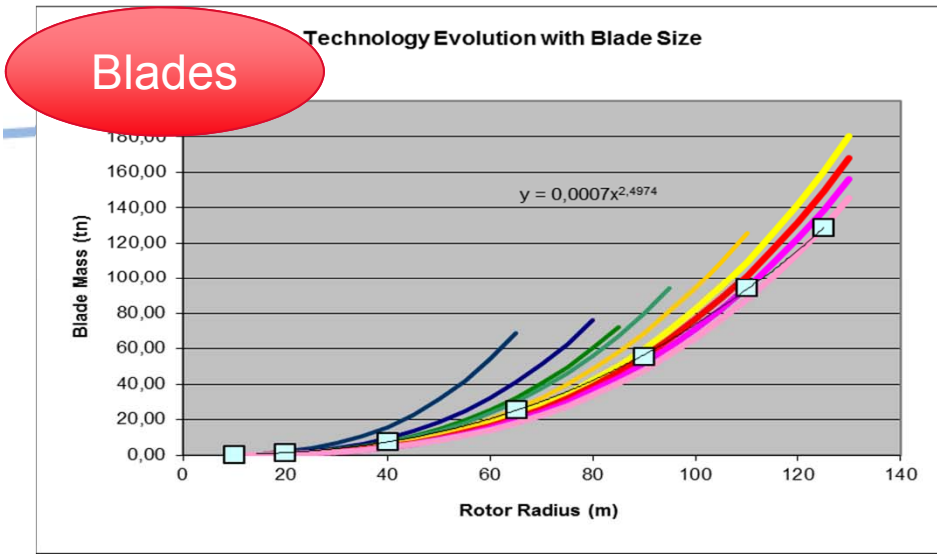


Support by:



EWEA 2014, Barcelona

Setting LCOE Targets at Sub-components Level



Tower optimization assuming a fixed blade-mean sea level clearance (h_{clear}), where the up-scaled tower is expressed as $H(s) = s \cdot \frac{D_1}{2} + h_{clear}$ instead of $H(s) = s \cdot H_1$) results in a scaling exponent $\lambda_w \cong 2,7$ instead of 3+

For the offshore foundation system assuming a given water-depth and a tubular structure the resulting scaling exponent of the optimized mass is $\lambda \cong 1,7$

Overall

Innovative 10MW		
s =		1,41
Subcomponent	λ	r
rotor blade	2,30	0,78
nacelle-system	2,60	0,87
tower	2,50	0,84
offshore foundation system	1,50	0,59

Support Structure



Scaling Exponents and Cost Targets for 10 MW



REF TURBINE (EWEA 5 MW)						UPSCALED TURBINE								
Capacity (MW)		5,00				Turbine Upscaling Exponent		2,42		Capacity (MW)		10		
Turbine Cost (M€/MW)		1,500				Upscaling exponents				Turbine Cost (M€/MW)		1,742		
						Subcomponent costs (M€)								
Turbine Only	Rotor	Rotor lock	0,0000	0,2357	1,00	0,000	2,50	Turbine Only	Rotor	Rotor lock	0,2276	0,2276	1,00	0,000
		Blades	0,2220			1,665	2,30			Blades	0,2121			3,695
		Hub	0,0137			0,103	2,80			Hub	0,0156			0,271
	Nacelle systems	Gearbox	Generator	0,0703		0,968	2,60	Nacelle systems	Gearbox	Generator	0,1368	0,3014	2,384	
			Rotor brake	0,0132		0,099	2,50			Rotor brake	0,0135		0,235	
			Nacelle cover	0,0135		0,101	2,50			Nacelle cover	0,0138		0,241	
			Nacelle structure	0,0280		0,210	2,50			Nacelle structure	0,0287		0,499	
			Couplings	0,0000		0,000	2,50			Couplings	0,0000		0,000	
			Shaft	0,0191		0,143	2,70			Shaft	0,0210		0,365	
			Yaw system	0,0125		0,094	2,70			Yaw system	0,0137		0,239	
			Bearings	0,0122		0,092	2,70			Bearings	0,0134		0,233	
	Electrics & control	Pitch system	Variable speed system	0,0266	0,0767	0,200	2,30	Electrics & control	Pitch system	Variable speed system	0,0254	0,0685	0,443	
				0,0501		0,376	2,00				0,0431		0,752	
	Tower		0,2630	0,2630		1,973	2,50	Tower		0,2693	0,2693		4,691	
	Other		0,1300	0,1300		0,975	2,50	Other		0,1331	0,1331		2,319	
							7,525							
	BoP Cost (M€/MW)		2,000				BoP Upscaling Exponent		1,50		BoP Cost (M€/MW)		1,684	
						Subcategory costs (M€)								
BoP Only	Foundation system		0,4400	1,00	4,400	1,50	BoP Only	Foundation system		0,4394	1,00	7,400		
	Offshore transportation and installation		0,3000		3,000	1,00		Offshore transportation and installation		0,2519		4,243		
	Offshore electrical I&C		0,2600		2,600	2,00		Offshore electrical I&C		0,3087		5,200		
						10,000								
						17,422								
						16,843								

Support by:



EWEA 2014, Barcelona

Downstream Influence



			Rotor Mass		Nacelle Mass		Tower Mass		OF Mass	
	λ_{from}	λ_{to}	λ_{from}	λ_{to}	λ_{from}	λ_{to}	λ_{from}	λ_{to}	λ_{from}	λ_{to}
Rotational Speed	-1,00	-0,80	?	?	3,00	2,80				
Tower-Top Mass	3,00	2,30					2,70	2,65	1,70	1,66
Max Design Thrust	2,00	1,60	?	?	?	?	2,70	2,46	1,70	1,53

- For bottom-mounted designs a drastic reduction of the nacelle mass does not have an equally important effect on tower and foundation masses. Thus, for bottom-mounted offshore designs, the reduction of the tower-head mass if not followed by an associated cost reduction (rotor or drive train) or an increase of the turbine capacity factor is not a target by itself and it can by no means pursued at the cost of drive train efficiency.
- This statement is not valid for floating designs where the tower-head mass might be an important driver of the cost of the floater.
- Contrary to tower-head mass, the sensitivity of the overall support structure mass to the maximum (design) thrust is significant.

Support by:



Conclusions



- A 20% LCOE drop from present values until 2020 seems quite feasible for deep offshore wind farms. Large (10 MW+), offshore-dedicated, wind turbines designs will be needed for that.
- For fixed water depth, the optimum sizing of the turbine derives by balancing the extra turbine cost with the lower BoP cost per MW as the turbine size increases. This is a common conclusion in all offshore cost studies. It looks that as the water depth increases larger turbines will be the optimum bottom-fixed solution. Nevertheless, this optimum size is still very much dependent on how successful we'll be in implementing new lower cost technologies in turbine and offshore substructure designs.
- Significant LCOE reduction can be expected by improving the wind farm capacity factor. This can be done by using larger turbines with low induction (low-thrust) rotors for better aerodynamic performance and by improving the efficiency of the drive train, power electronics and array cables.
- For bottom-mounted offshore designs, the reduction of the tower-head mass if not followed by an associated cost reduction or an increase of the turbine capacity factor is not a target by itself. This statement is not valid for floating designs where the tower-head mass might be an important driver of the cost of the floater.
- Contrary to tower-head mass, the sensitivity of the overall support structure mass to the maximum (design) thrust is significant.

Support by:



EWEA 2014, Barcelona