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Influence of offshore wind turbine size in levelised cost of energy

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Abstract.

Offshore wind energy is developing rapidly in recent years. Within the offshore wind energy industry, the main advance that has occurred has been the wind turbine growth. In fact, the offshore turbines have changed from small turbines adapted to the marine environment to turbines that currently range between 16~18 MW. This increase has been done in order to cut down costs and get longer production of wind energy, consequently, reducing the levelized cost of energy.

The current mechanisms for assigning marine sites are based on successive auctions organized by government agencies. In some countries, these auctions are carried out through reverse bidding, that is, they are awarded to the promoters who present the lowest sales price for the energy generated or, in the case of other countries, that price marked in the auction has a partial weight of 60%~80% in the final ranking. Other countries organize a second type of reverse auction to award subsidies, which, being limited, are awarded to the promoters who present the lowest energy sales price.

In this article, a comparative study developed for evaluation of the value of levelized cost of energy, as a result of bigger nameplate capacity of the offshore wind turbines. The results show that the bigger turbine capacity, the lower the levelized cost of energy is obtained.

Key words. Offshore wind, LCoE, wind turbines, energy cost evaluation

1. Introduction

The worldwide installed capacity of offshore wind energy reaches 72,6 GW, being concentrated mainly in two areas such as China and the countries that share the North Sea, according to the data provided by the consulting firm 4COffshore [1]. In fact, both areas concentrate around 90% of the global market. The evolution of this generation technology is clearly ascending, although the exponential growth seems to be related to the objectives that had been set both in the EU by the 2020 deadline and with the elimination of subsidies in China in 2021. According to [1] and taking into account the wind farms currently under construction, the growth is expected to slow down in the coming years.

However, the objectives and forecasts regarding the power that will be installed until 2030 are very discordant. According to the most recent reports relating to this type of generation [2][3], it is estimated that 359 GW and 248 GW will be installed respectively by 2030. The chronological development of offshore wind energy can be seen in Figure 1, taking into account the offshore wind farms (OWFs) completely connected to the grid during the period 2000-2023. Installed power corresponds to the accumulated annual value. Currently the number of turbines installed globally amounts to 13480 units.

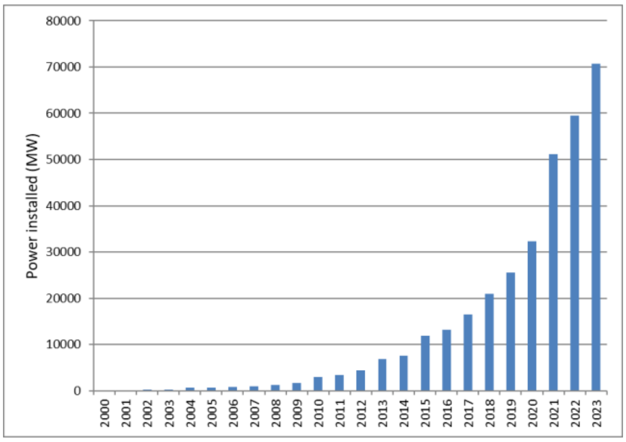

Fig. 1. Offshore wind power installed worldwide. Own elaboration.

However, the pace of implementation of OWFs has been very different. The first turbines were installed in the marine environment in the nineties in countries such as Denmark, Sweden and the Netherlands, although they are prototypes or pilot parks of very low capacity. The definitive takeoff would begin in the year 2000, with the United Kingdom leading its development on a commercial scale. Since then, the great increase in offshore wind energy is due to various factors, which mean that its development is concentrated in the North Sea since it meets ideal conditions. On the one hand, excellent wind conditions and a long continental shelf with excellent bathymetry make the project have a certain viability; in fact, this last factor has been the key to the highly concentrated development in some countries. On the other hand, a previous business of onshore wind farms and a strong marine industry already established in other types of activities, transferred and adapted to marine conditions this type of generation that was already well established on land. The offshore wind power installed by countries can be shown in Table I, as well as the quantity of offshore wind turbines (OWTs). On behalf of the administrations, their contribution laid in reducing taxes on generating companies as well as specifically subsidizing the energy generated. Finally, technological innovations aimed to the marine environment, have played a key role to the correct deployment and maturity that have been achieved up to now.

Table I. - Offshore wind power and turbine installed by countries. Own elaboration.

Country	Power (MW)	Turbines
China	34772	6327
United Kingdom	14790	2765
Germany	8235	1565
The Netherlands	5274	807
Denmark	2635	666
Belgium	2261	399
Vietnam	1681	431
Taiwan	1501	201
France	482	81
Sweden	191	80
Rest of World	789	159
Total	72611	13480

In this way, OWFs have changed from being generation plants with a few turbines without an offshore substation (OSS) near the coast, to large generation centers with several OSSs, many turbines and high-voltage transmissions over long distances. This has constantly raised a series of new challenges faced by the promoters and operators of the electrical system, such as intermittency in generation, the location of new integration points in the grid of large volumes of energy, storage, floating turbines/substations, floating cables and new concepts in the transmission system. Furthermore, this circumstance requires the construction of new substations on land as well as network reinforcements if necessary.

The developers of OWFs and offshore wind turbine manufacturers (OTMs) being conscious about turbine importance in offshore harsh ambience, have focused on the development of OWTs aiming for a new design, which must meet the following characteristics:

- Low price, considering that the cost of OWF energy project, turbines can cover 40~50 % of the total cost of the project.
- Low Operation & Maintenance (O&M) cost, whose total percentage in a project of this type can represent 20~30 % of the final cost. For this, access and repair must be easy by helicopter from the top or from the base by boat. In fact, access from the upper hatch is preferable for faster access to the nacelle, where the generator, converters, transformer and gearbox are located, since maintenance in the marine environment is critical.
- Failure rate and repair times must be as low as possible. To do this, it is necessary to standardize every element that makes up the turbine, but also, doing it in a modular way. For this reason, turbines with brushes and slip rings have been disappearing from the market.
- Low losses, compact and lightweight design.

Bearing all these issues in mind, this work is divided into following sections. Second section is focused on the current OWTs technology and on the present market based models. Third section shows the description of a simple comparative evaluation to calculate the Levelized Cost of Energy (LCoE). In the fourth section a case study is developed to analyse the importance of OWT size and its impact on LCoE ratio. Finally, some conclusions are stated.

2. Offshore wind turbines. Present market and technology.

In addition to the characteristics described above, developers are aware of the importance of turbine capacity. This issue means that fewer turbines are necessary for a specific OWF. Moreover, bigger size of OWT provokes a domino effect. Therefore, among several advantages the cable length of inner-array system is reduced, less OWTs are needed, quantity of foundations reduction causes simpler layout, and naval logistic and O&M activities save important volumes of Capital Expeditures (CAPEX). For this reason during the last years the OWTs have suffer a significant increase of nameplate capacity as can be shown in Table II for OWTs above 10 MW market clearly dominated by oversupplied Chinese industry [4]-[7]

The evolution of wind turbines to the present day has offered two different but similar models that are dominant in the market. On the one hand, it is evident that the Permanent Magnet Synchronous Generator (PMSG) is the most used. The vast majority of turbines commissioned in recent years use this technology, except for small intertidal wind farms installed in Asia. Within this category, it can be divided depending on the number of stages of the gearbox between the rotor and the generator. While some manufacturers prefer Direct Drive (DD) technology, that is, without a gearbox with a single low-speed axis, others have developed turbines with medium-speed (MS) generators with 1 or 2 stage gearbox.

In the first group of manufacturers are Siemens-Gamesa and General Electric, together with Dongfang Electric and Korean manufacturer Unison. In the second group Vestas, Mingyang Smart Energy, Haizhuang and Goldwind prefer to use MS-PMSG. Both types of turbines are offered by Shanghai Electric, but in addition to these models, there are also other high-speed models. Although lately their use has been more limited, Envision and Windey offer a Doubly Feed Induction Generator (DFIG) yet.

The evolution of the installed OWTs is observed in Figure 2. The most obvious conclusion that can be noted, is that the two technologies that are clearly taking off are PMSG generators, more specifically Low Speed (LS-PMSG) and Medium Speed (MS-PMSG) generators. Both options began to be installed in OWFs in 2014 with Siemens with DD technology and with Vestas for medium speeds. The rest of the turbines have been relegated and there are no purchase orders in progress. As an exception, small intertidal projects or those very close to the coast in Asian countries can be highlighted, where DFIG and SCIG turbines are still the most used alternative and the wind characteristics are more similar to land-based sites.

Table II. – Information related to OWTs above 10 MW available on the market or announced

Manufacturer	Model	Power (MW)	Rotor Diameter (m)	Specific Power (W/m^2)	Generator Type
Siemens-Gamesa	SG-10-193	10	193	341,81	LS-PMSG
	SG-11-200	11	200	350,14	
	SG-14-222	14	222/236	361,68/320,04	
Vestas	V164-10	10	164	473,39	MS-PMSG
	V236-15	15	236	342,90	
General Electric	Haliade X	12/13/14,7/15,5	220	315,68~407,75	LS-PMSG
Dongfang Electric	DF186-10000	10	186	368,03	LS-PMSG
	DF211-13000	13	211/245	371,78/275,75	
	DF260-18000	18	260	339,02	LS/MS-PMSG
Goldwind	GW 252/16000	12/13,6/14,3/16	252	240,59~320,79	MS-PMSG
Haizhuang	HZ210-10000	10	210/220/236	288,71~228,60	MS-PMSG
	HZ260-18000	12,5/18	260	235,43/339,02	
MingYang	MySE-11-230	11	230	264,75	MS-PMSG
	MySE-10-242	10/12	242	217,40/260,89	
	MySE-14-260	14/16	260	263,68/301,35	
	MySE-18-292	18/20	292	268,79/298,65	
	MySE-22-310	22	310	291,48	
Shanghai Electric	W11000/208	11	208	323,72	LS-PMSG
	W16000/252	16	252	320,79	MS-PMSG
	W14000/263	14/18	263	257,70/331,33	
Envision	EN10-220	10/10,5	220	263,06/276,22	DFIG
	EN12-252	12	252	240,59	
	EN14-252	14	252/270	280,69/244,51	MS-PMSG
	EN18.8-286	18,8	286	292,64	
Windey	WD225-10	10	225	251,50	DFIG
	WD245-13	13~15	245	275,75~318,17	
	WD260-16	16~18	260	282,52/339,02	MS-PMSG
CRRC Zhuzhou	8.0MWD225	8~12	225	201,20~301,80	MS-PMSG
	14MWDXXX	14~16	-	-	
	16MWD260	16~20	260	301,35~376,69	-
Unison	U210-10	10	210	288,71	LS-PMSG
Sany Energy	SE13.XX	13/16	-	-	DFIG

Thus, of the 13480 turbines installed in offshore locations worldwide, 4889 turbines are SCIG (36,26%), 1211 turbines are DFIG (8,98%) and the remaining 7380 turbines are PMSG (54,74%) of which LS-PMSG models represent 29,25%, MS-PMSG 19,89% and HS-PMSG 5,60%.

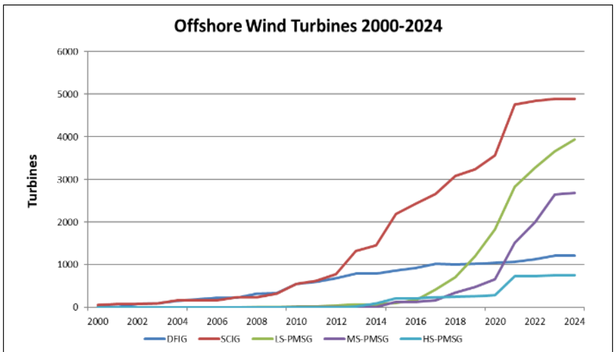

Fig. 2. Turbines disclosed by type chronologically. Own elaboration.

3. Process for calculation of the levelised cost of energy.

A. Conditions and Assumptions

The LCoE has been chosen as the objective function. The LCoE value can be defined as a function representing the correlation between overall costs of the project and Annual Energy Delivered (AED) to the grid over the whole lifetime. The most common expression is the following:

$$\mathrm{LCoE}(€/\mathrm{MWh}) = \frac{\sum_{t=1}^{n+1} \frac{\mathrm{Overall\ Costs}_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{\mathrm{AED}_t}{(1+r)^t}} \qquad (1)$$

Where: AED stands for Annual Energy Delivered to the power grid, *t* is the time in years and *r* the discount rate.

According to abovementioned equation there are several ways to reduce the value of the LCoE: on the one hand, reducing investment costs as well as O&M expenses, and, on the other hand, maximizing the energy injected into the network, maximizing production and reducing energy losses. However, both concepts are oppositely related in such a way that it is about reaching a cost-production balance that makes the design of an OWF optimal for a minimum LCoE value.

In order for all the turbines to have the same generation profile, the turbine curves have been designed with the same specific power (SP) of 350 W/m2. With different SP the influence of power would not be clear, since the diameter of the rotor influences the generation.

B. Generation model

For estimating energy annual production (AEP) wind rose probability data *f(v*$_i$*)* along with power curve obtained from [8][9] *P(v*$_i$*)* are needed. In this way, the gross AEP is calculated as follows:

$$\mathrm{AEP\ (MWh)} = \int_0^{v_{max.}} P(v_i)f(v_i)8760\ dv \qquad (2)$$

$$P_{out}(MW) = \frac{1}{2}\rho v_i^3 C_p \eta_{eff} \qquad (3)$$

Where: η_{eff} is the efficiency of the turbine electrical equipment, C_p is the power coefficient and ρ is the air density. Taking into account the parameters from [9] the power curves from the turbines can be assessed:

$$C_p = 0{,}22\left(120\frac{1}{\lambda_i} - 5\right)e^{-\frac{12{,}5}{\lambda_i}} \qquad (4)$$

The statistical distribution of the wind is represented by Weibull distribution:

$$f(v_i; k, c) = \frac{k}{c}\left(\frac{v_i}{c}\right)^{k-1} e^{-\left(\frac{v_i}{c}\right)^k} \qquad (5)$$

The Weibull distribution consists of two parameters, first, the scale factor *C* in (m/s) and, second, the dimensionless shape factor *k*.

C. Losses model

The energy injected to the grid AED can be expressed:

$$\mathrm{AED\ (MWh) = AEP - AEL} \qquad (6)$$

Where: AEL stands for Annual Energy Losses
These losses can be:

- Air losses: Air losses model comprises both wake and blockage effects totalling about 12 % of the generated energy [10].

- Electrical losses: they are mainly in cables of inner-array system, which collects and transmits to OSS all energy generated by turbines. Inner array grid power losses are calculated in accordance with the international standard IEC 60287 [11]. The optimization of the array feeders for lowest LCoE value has been obtained from [12]. All cable losses have been calculated with a general adopted expression:

$$P_{losses}(W/m) = 3I^2R_{AC,T}(1 + \lambda_1 + \lambda_2) + W_d \qquad (7)$$

- Unavailability losses: The unavailability of any cable array of the OWF can be calculated as follows:

$$\mathrm{Un.\ (MWh)} = \int_0^{v_{max.}} P(v_i)f(v_i)F_{i,j}\ dv \qquad (8)$$

Where: P(vi) is the power that cable supports, f(vi) is the probability during fail time and $F_{i,j}$ the time where cable *i* in string *j* fails. The time that cable fails is:

$$F_{i,j}(\mathrm{hours/year}) = d_{cable,i,j}.\lambda_{array}.\mathrm{MTTR}_{array} \qquad (9)$$

Where: $d_{cable,i,j}$ is the distance of the cable *i* in string *j*, λ_{array} is the failure rate of the cable and MTTR is the time needed to repair the damage cable.

For inter-array cables MTTR_{array} and λ_{array} values are surveyed and collected in [13].

Finally, all energy losses can be summarized as follows:

$$\mathrm{AEP\ (MWh) = AED + AEL} \qquad (10)$$

$$\mathrm{AEL\ (MWh)} = E_{loss}^{wind} + E_{loss}^{elec} + E_{loss}^{unav} \qquad (11)$$

$$E_{loss}^{wind}\ (MWh) = E_{wake}^{wind} + E_{block}^{wind} \qquad (12)$$

$$E_{loss}^{elec}(MWh) = E_{array}^{elec} \qquad (13)$$

$$E_{loss}^{unav}(MWh) = E_{owt}^{unav} + E_{array}^{unav} \qquad (14)$$

D. Cost and investment model

All prices and costs assumed in this paper are subject to important variability according to the assessments of different authors, so any element could present a wide range of prices. In fact, each OWF has unique distinctive features such as the size, water depth, transmission system length, O&M strategy, etc… Moreover, nowadays´ uncertain economic situation is pushing the price volatility of raw material, increasing logistic costs, surge fuel prices, extreme variable exchange rates, conditioned contracting plans, the rise in inflation rate and delays in the supply chain. All prices from references have been updated to today´s value.

The price of the OWTs has been set out at 1,2 M€/MW for 10 MW model according to [14] and, as the OWT nameplate power of OWT grows, an increase of 2,5% per megawatt has been estimated:

$$\mathrm{Cost_{turbine}(M€)} = 1{,}2 \cdot P_n \cdot 1{,}025^{(P_n - 10)} \qquad (15)$$

As OWTs must be raised over the sea water level, foundations are specifically designed according to the depth of the water, waves, seabed and the turbine itself. Their corresponding costs have been assumed from [15]:

$$Cost_{foundation}(k€) = 320P_n\left(1 + 0.02(Dp - 8)\right)\left[0.8.10^{-6}\left(h\cdot\left(\frac{D}{2}\right)^2 - 10^5\right)\right] \quad (16)$$

Where: Dp represents the depth water (m), h stands for hub height (m) and D is the rotor diameter (m). For the OWF inter-array cable system cost estimation, the following expression has been used [15] in case of 33 kV XLPE insulation cables depending on cross section area:

$$\mathrm{Cost}_{\mathrm{cable,ac}}(\mathrm{k€/km}) = 0.4818\cdot \mathrm{S}_{\mathrm{cond.}} + 99.153 \quad (17)$$

Increasing the voltage level to 66 kV has an extra cost impact of +12% according to [16].

Finally, all the installation works related to offshore marine logistic are assessed from [14] [17] and O&M works from [18] valued at 454,3 k€/turbine/year, composed of workboats with support from helicopters strategy. In case of Development Expenditure (DEVEX) and Decommissioned Expenditure (DECEX) values, they have been extracted from [14].

4. Case study and design principles

The case study of the applied evaluation comprises the following characteristics collected in Table III:

Table III.-Main data for OWF and Inner-Array system

Offshore Wind Farm		Inner-Array System	
Power (MW)	1200	Voltage (kV)	66
Distance (km)	50	P.F.	0,95
Air density	1,22	Frequency (Hz)	50
Air (°C)	25	Cable	Copper
Area (km²)	250	Burial (m)	1,5
K	2,2	Downwind rotor	10D
c (m/s)	9,53	Crosswind rotor	6D
Depth (m)	35	Seabed (°C)	15

The evaluation of the LCoE has been made for 1200 MW OWF assuming some degree of overplanting for correct optimization of inner-array system. The OWTs selected for this study are in the range of 10~18 MW according to the released information by offshore wind industry for the next couple of years expectations.

Table IV. – Assumptions for optimization of design of OWF and overall costs according to different model of OWTs

Turbine Model	Turbines	Strings	String Design Optimized	Overall Costs (M€)			
				Turbines	Cables	Installation	O&M
WTG190-10 MW	120	15	3x800 mm² & 5x300 mm²	1440,00	110,12	197,75	20,90
WTG200-11 MW	112	16	2x800 mm² & 5x300 mm²	1404,48	108,86	184,60	19,50
WTG209-12 MW	102	17	2x800 mm² & 4x300 mm²	1360,48	107,37	171,45	17,76
WTG217-13 MW	96	16	2x800 mm² & 4x300 mm²	1352,47	105,92	158,30	16,72
WTG225-14 MW	90	18	2x630 mm² & 3x240 mm²	1331,34	95,65	151,65	15,67
WFG233-15 MW	80	16	2x630 mm² & 3x300 mm²	1236,24	93,40	132,00	13,93
WTG241-16 MW	75	15	2x800 mm² & 3x240 mm²	1205,33	90,77	125,35	13,06
WTG248-17 MW	72	18	2x630 mm² & 2x240 mm²	1198,70	91,07	118,85	12,54
WTG255-18 MW	68	17	2x630 mm² & 2x185 mm²	1168,74	86,52	112,20	11,84

Table V. – Results of OWF according to different model of OWTs

Turbine Model	Power (MW)	AEP (GWh)	Overall Losses (GWh)				AED (GWh)	LCoE (€/MWh)
			Array	Wake	Unav. turb.	Unav. cable		
WTG190-10 MW	1200	5156,49	51,96	618,77	257,82	24,75	4203,19	62,05
WTG200-11 MW	1232	5309,63	54,69	637,15	265,48	25,48	4326,83	60,73
WTG209-12 MW	1224	5277,96	45,26	633,35	263,89	25,33	4310,13	58,82
WTG217-13 MW	1248	5359,24	52,46	643,10	267,96	25,72	4370,00	55,12
WTG225-14 MW	1260	5424,05	47,70	650,88	271,20	26,03	4428,24	53,19
WFG233-15 MW	1200	5145,05	48,67	617,40	257,25	24,69	4197,04	52,05
WTG241-16 MW	1200	5153,32	50,71	618,39	257,66	24,73	4201,83	50,65
WTG248-17 MW	1224	5233,15	40,48	627,97	261,65	25,11	4277,94	49,35
WTG255-18 MW	1224	5204,00	47,30	624,48	260,20	24,97	4247,05	48,49

5. Results and conclusions

According to the results shown in Table IV and Table V, the decrease in LCoE depending on the OWT bigger size shows an evident trend. This reduction is due to two main reasons. Firstly, the power itself that causes the domino effect, because of less turbines are needed and a unit of MW is cheaper. Thus, the turbine costs cover bigger ratio of the OWF project finally the ratio LCoE goes down, at approximately 2 € per additional MW of turbine power.

Less unit number of turbines provokes less number of inner-array cables, a reduction of foundations, as well as, an important reduction of installation costs including turbines, foundations and cables. From the point of view of O&M the reduction of costs shows the same tendency.

Secondly, taking into account the perspective of losses there is not a clear dominant tendency. The wake effect losses and the failure ratio of turbines are not dependent of the nameplate power of the turbines, so there is not a clear saving of energy.

The losses related to the cables are practically constant. In any case, they are slightly smaller when the turbine power is bigger. This is because of bigger electrical currents and as equation 7 shows the bigger is the current, the bigger is the power loss. Moreover, a failure of inner-array cable could provoke greater loss of energy if the turbine is more powerful depending the position of the damaged cable in the string.

As a main conclusion, deserve to be mention that the main reason of the LCoE decrease is the cost savings of whole project if a bigger turbine is selected. As an average LCoE ratio reduction, it is between 1,74~6,29% range as Table V shows, taking into account step by step results for 1 MW bigger turbine.

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