22nd International Conference on Renewable Energies and Power Quality (ICREPQ'24)
Bilbao (Spain), 26th to 28th June 2024
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.22, September 2024

Analysis of development of floating offshore wind energy in Spain

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Abstract.

Offshore wind energy generation has developed rapidly especially in the last decade. In some countries, despite having good wind conditions for its development, it has not been possible to implement it. This is because its continental shelf is very short, that is, the land under water in shallow seas is not wide enough to install fixed foundations. Consequently, the development of floating platforms is awakening interest in this type of generation, as is the case in Spain.

In this article, a methodology for calculation the generated electrical energy in floating offshore wind farms and the corresponding losses is developed. In this way, all necessary data involved in the methodology have been obtained from the sites destined for offshore wind development. These emplacements have been released by Spanish Government in recently approved Maritime Spatial Plan. The generation potentials in Spanish waters have been evaluated according to most interesting ratios as levelized cost of energy, capacity factor and cost of installed megawatt.

Results show that most of emplacements are interesting enough for the development of OWFs. Deserve to be mentioned three main areas, such as, northwest waters, Canary Island zones and north part of Catalonia.

Key words. Offshore wind, LCoE, floating wind farm, energy cost evaluation

1. Introduction

In September 2023, European Commission (CE) announced the "European Wind Power Package" to support the European wind industry. The "European Wind Power Package" includes two main documents: first, the "European Wind Power Action Plan" [1] and second, "Delivering on the EU offshore renewable energy ambitions" [2]. The latter proposes an offshore renewable installed power of 111 GW and 317 GW by 2030 and 2050 respectively. The first urges to Member States to take immediate actions related to wind power generation such as shorter permitting process, cross border offshore projects, improvement auction design and facilitate access to finance. Finally, the European Council signed the document in December 2023.

On the other hand, the European Parliament and the Council approved new objectives related to renewable energy consumption within European Union, setting out new share of renewable energy in the energy mix of 42,5 % [3].

It is clear that achieving the EU new implemented targets from offshore renewable energy mentioned above, the offshore wind generation will play a key role in the near future. Some countries are developing new objectives [4] in National Energy and Climate Plans (NECPs) updated in 2023. Deserve to be mentioned the new offshore wind markets in Europe, such as Greece, Ireland, Norway, Italy, Spain and Portugal, where offshore wind energy generation is taking shape for the next future. Because of water depth drops sharply near the coastline in these countries, no offshore wind farms (OWFs) with fixed foundations have been built yet.

However, this situation is changing thanks to the last decade´s progress in the field of floating structures for turbines. In fact, up to now 38 floating turbines totalling 237,38 MW are installed worldwide, and governments are requiring the identification of new areas to accommodate floating turbines. Therefore, it is clear that new studies are becoming necessary in deeper waters.

Bearing all these issues in mind, this work is divided into the following sections. Second section, is focused on current situation of offshore wind generation in Spain. Third section shows the description of all different allocations included in Spanish Maritime Spatial Plan (MSP). Fourth chapter analyses and develops an evaluation methodology of OWFs in each of the allocations selected in the third chapter. Finally, some conclusions are stated.

2. Current situation in Spain

Currently there are not OWFs in operation connected to power grid in Spain. There is only one turbine installed in the Canary Islands with a nominal power of 5 MW [5] and a floating 2 MW turbine in the waters of Vizcaya [6]. As explained before, this situation is due to an orographic issue since the seabed is located in waters deep enough to consider the installation of turbines using fixed foundations unfeasible, valid for depths of up to approximately 50 meters. The Spanish continental shelf is very narrow, which means that the potential is very limited due to the impossibility of anchoring the turbines to the seabed.

However, thanks to the development of floating technology this difficulty can be overcame so several promoters have presented various initial documents for the construction of large-scale offshore wind farms in the recent years. Up to now, according to the Ministry for the Ecological Transition and the Demographic Challenge (MITECO) [7], there are 56 offshore wind project proposals in the pipeline for public consultation of their environmental evaluations, with powers ranging between 10 MW to 1200 MW. So far, the total required power to be installed in this process stage is 20027,4 MW.

To avoid the problem that would arise due to the enormous demand of floating OWFs and taking into account that the regulations are completely outdated a planned reorganization is necessary. Hence, the Spanish Government has taken some decisions during the last years:

1) The approval in January 2020 of the National Integrated Energy and Climate Plan (PNIEC) 2021-2030 [8], which includes the objectives related to Renewable Energy until 2030. Later in June 2023, the PNIEC was updated and wind technology has an additional objective to install 62 GW and 3 GW of onshore and offshore wind respectively [9].
2) Refuse the admission of new applications in June 2021 in Royal Decree-Law 12/2021 [10]. Currently there is a provisional moratorium included, which indicates the non-admission of new requests for zone reservation for offshore wind generation facilities at least until the approval by the Government of a new regulatory framework that establishes the new requirements. However, applications submitted prior to this Royal Decree-Law continue to be processing in accordance with the provisions of Royal Decree 1028/2007 [11], which establishes the necessary procedure for processing authorization applications of electricity generation facilities in the territorial sea. For offshore pilot projects, all the requirements must fulfilled according to Ministerial Order TED/1204/2022 [12].
3) In September 2021, the Maritime Space Planning (MSP) [13] was published to allow planning for the appropriate use of marine spaces and coexistence with other corresponding activities. Later in February 2023 the final MSP version was slightly renewed and approved by Royal Decree 150/2023 [14], aiming to make an orderly deployment of future OWFs, maintain a development plan that respects the environment, compatibility with other activities (fishing, military, specially protected spaces, uses of the local population...) as well as port infrastructure needed. It identifies 4 Spanish maritime subdivisions and 19 total suitable locations for offshore wind development, as Figure 1 shows. Additionally there are for innovation and testing small-scale prototypes 3 areas, such as the Canary Islands Ocean Platform (PLOCAN) [15], the Biscay Marine Energy Platform (BiMEP) [16] and the R&D&I Platform in Marine Energies of Catalonia (PLEMCAT) [17].
4) In December 2021, the Roadmap for the Development of Offshore Wind and Sea Energy was finally approved, with the objective of achieving 1~3 GW of offshore wind power and 40~60 MW through other offshore generation technologies for the year 2030. A new clear and orderly regulatory framework specific to each generation technology will also be processed [18].
5) In February 2024, a draft of a new Royal Decree [19] was released which regulates the production of electrical energy in installations located at the Spanish sea, was released. In the same way, it establishes new administrative authorizations, economic regimes and the mechanisms/procedures necessary for granting permissions.

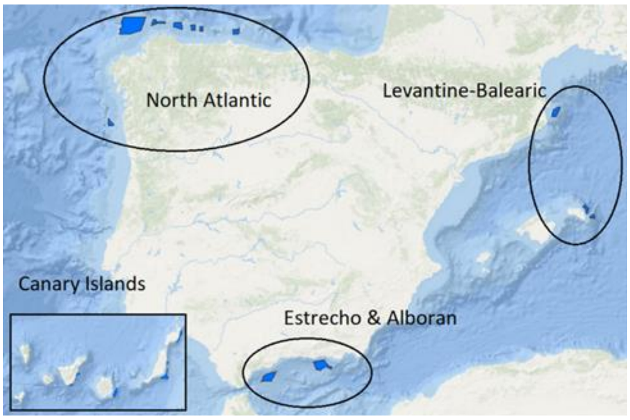

Fig. 1. Spanish maritime subdivisions for OWFs development.

3. Energy balance evaluation study

A. Conditions and Assumptions

All information related to the areas included in Spanish MSP with high potential for the development of OWFs has been collected from [20][21], such as zones´ denomination, average wind speed, water depth, sea area, shortest distance between OWF-maintenance hub and wind power density (WDP). All this information can be observed in Table I.

As distance shows, some of the locations are close to shoreline so transmission system will be as Medium Voltage Alternating Current (MVAC) without Offshore Substation (OSS). In these cases substation is allocated onshore. Otherwise, some locations are far enough from the coast so the High Voltage Alternating Current (HVAC) with OSS is the best choice for an efficient transmission system. Cots related to transmission system are charged to TSO, so the generators are responsible for design, payment and operation of the OWF including OSS. These costs are not included in the calculations for estimations of overall costs. The capacity of each OWF has been chosen based on the available area, the proximity to land and the environmental impact it may have. Floating structure option has been assumed because of great water depths as Table I shows.

As main factors and ratios that generators are interested in, the Levelized Cost of Energy (LCoE) is the most important one, together with capacity factor (CF) and annual energy delivered (AED) to the grid. The general expressions in the case of an offshore wind farm, are stated as:

Table I. – Information related to the high potential areas for the development of OWFs according to MSP

Zone	Area (km^2)	Power (MW)	Distance (km)	Depth (m)	Average wind speed (m/s)	*K*	*c* (m/s)	WPD (W/m^2)
NOR 1	116	525	28	100-150	8,62	1,92	9,71	783
NOR 2	1784	1200	61	200-300	10,01	2,05	11,29	1142
NOR 3	109	525	63	180-200	9,76	2,02	11,01	1077
NOR 4	74	525	44	150-200	9,51	2,00	10,73	1005
NOR 5	233	600	27	120-200	8,59	1,87	9,67	792
NOR 6	104	525	46	100-150	8,45	1,84	9,51	769
NOR 7	80	525	63	150-200	8,32	1,75	9,34	779
NOR 8	151	525	45	130-150	7,32	1,54	8,13	627
ESAL 1	535	600	49	600-800	7,42	1,65	8,29	594
ESAL 2	687	600	35	600-800	7,98	1,43	8,80	915
LEBA 1	247	720	27	120-300	10,80	1,66	12,08	1823
LEBA 2	147	525	13	150-170	7,48	1,61	8,34	628
LEBA 3	76	300	18	140-170	7,41	1,62	8,27	608
CAN GC 1	164	525	10	100-500	10,37	2,48	11,69	1080
CAN FV 1	192	525	11	100-1000	8,89	2,55	10,01	666
CAN FV 2	16	300	8	500-1000	8,32	2,67	9,36	529
CAN TEN 1	21	300	4	100-500	8,94	1,80	10,05	936
CAN TEN 2	71	300	5	500-1000	10,29	2,11	11,62	1210
CAN LANZ 1	97	525	5	500-1000	9,35	2,56	10,53	775

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

$$\mathrm{CF}(\%) = \frac{\mathrm{AED}}{P_{\mathrm{OWF}} 8760\mathrm{h}} \quad (2)$$

B. Generation model

For estimating energy annual production (AEP) wind rose probability data $f(v_i)$ along with power curve obtained from [22][23] $P(v_i)$ are needed. In this way, the gross AEP is calculated as follows:

$$\mathrm{AEP}\ (\mathrm{MWh}) = \int_0^{v_{max.}} P(v_i) f(v_i) 8760\, dv \quad (3)$$

The offshore wind turbine (OWT) model chosen for this study is de generic 15 MW output power and 236 m of rotor diameter. For the estimation of the OWT power curve, a general formulation is taken into consideration:

$$P_{out}(\mathrm{MW}) = P_{mech} \cdot \eta_{eff} \quad (4)$$

$$P_{mech}(\mathrm{MW}) = C_p P_{wind} \quad (5)$$

$$P_{wind}(\mathrm{W/m^2}) = \frac{1}{2} \rho v_i^3 \quad (6)$$

$$C_p(\lambda, \beta) = c_1 \left(c_2 \frac{1}{\lambda_i} - c_3 \beta - c_4 \lambda_i \beta - c_5 \beta^x - c_6 \right) e^{-\frac{c_7}{\lambda_i}} + c_8 \lambda \quad (7)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + c_9 \beta} - \frac{c_{10}}{\beta^3 + 1} \quad (8)$$

$$\lambda = \frac{\omega R}{v} \quad (9)$$

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

$$f(v_i; k, c) = \frac{k}{c} \left(\frac{v_i}{c} \right)^{k-1} e^{-\left(\frac{v_i}{c}\right)^k} \quad (10)$$

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

Inevitably the AEP will be reduced due to different losses. These losses can be divided into:

- Air losses: Air losses model comprises both wake and blockage effects. Wake effect could be defined as the consequence in terms of a curtailment of wind intensity and increase of wind turbulence downstream wind turbine. This effect spreads through the rest of emplacement

becoming a negative impact on the rest of wind turbines positioned behind in different wind directions, thus less energy is available and less energy is produced.
The second phenomenon related to wind losses, is the blockage effect. This is a predisposition of the wind to slow down as it approaches to a wind turbine, for this reason this concept shows that freestream and unwake turbines cannot be neglected from wind losses [24]. According to several authors these losses are very difficult to estimate but they are assumed as 10 % and 2 % of energy losses.

- 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 [25], keeping on mind conditions of the standard. The optimization of the array feeders for 15 MW turbine has been calculated for 5 OWTs per feeder with 2x800 mm^2 & 3x240 mm^2 copper cable cross sections as [26] shows for lowest LCoE value.
All cable losses have been calculated using the general adopted expression:

$$P_{losses}(W/m) = 3I^2R_{AC,T}(1+\lambda_1+\lambda_2)+W_d \qquad (11)$$

- Unavailability losses: The unavailability of any cable array (F_{array}) of the OWF can be calculated as follows:

$$F_{array\ i,j}(hours/year) = d_{cable\ i,j}.\lambda_{array}.MTTR_{array} \quad (12)$$

Where, *i* is the string number, *j* is the cable/turbine number per string and $MTTR_{array}$ is the average time needed to repair a damaged array cable (hours). Assuming that the failure rate and the MTTR are the same for all the cables and taking into account that the distance is cumulative because the cables are in series connection, the expression for accumulated unavailability AF_{array} in each cable *n* of a specific string *i* can be written as:

$$AF_{array\ i,n}(hours/year) = \lambda_{array}.MTTR_{array}.\sum_{j=1}^{n} d_{cable\ i,n} \quad (13)$$

For inter-array cables $MTTR_{array}$ and λ_{array} values are surveyed and collected in [27].

D. Costs model

Different costs related with Balance of Plant (BoP) for floating elements has been obtained from [28] while the turbines costs are assumed from [29]. In [30] the naval logistic costs for installation are estimated, whereas Operation & Maintenance (O&M) strategy costs are considered from [31].

Table II. – Results of all the high potential areas for the development of OWFs according to MSP

Zone	AEP (GWh)	Energy losses (GWh)	AED (GWh)	Capacity factor (%)	LCoE (€/MWh)	M€/MW	OSS	Transmission system
NOR 1	2125,67	340,73	1784,94	38,78	111,01	4,79	1	HVAC
NOR 2	5834,15	934,59	4899,55	46,57	162,66	8,39	2	HVAC
NOR 3	2479,01	397,33	2081,68	45,23	118,68	6,14	1	HVAC
NOR 4	2407,54	385,86	2021,68	43,92	110,01	5,46	1	HVAC
NOR 5	2402,35	384,84	2017,51	38,35	111,80	4,78	1	HVAC
NOR 6	2052,08	329,07	1723,01	37,43	116,27	4,90	1	HVAC
NOR 7	1985,26	318,53	1666,73	36,21	121,44	5,00	1	HVAC
NOR 8	1630,27	262,13	1368,14	29,72	162,65	5,46	1	HVAC
ESAL 1	1924,54	308,74	1615,80	30,72	299,31	10,60	1	HVAC
ESAL 2	2020,02	324,51	1695,51	32,23	284,10	10,52	1	HVAC
LEBA 1	2788,08	447,39	2340,69	35,60	131,51	5,23	1	HVAC
LEBA 2	1694,10	272,21	1421,89	30,89	148,92	5,10	0	MVAC
LEBA 3	1436,38	231,21	1205,17	45,82	103,28	5,27	0	MVAC
CAN GC 1	2812,23	450,34	2361,89	51,32	80,05	4,52	0	MVAC
CAN FV 1	2354,13	376,40	1977,73	42,97	106,47	5,07	0	MVAC
CAN FV 2	1837,01	293,78	1543,23	58,68	138,06	9,21	0	MVAC
CAN TEN 1	1863,84	299,27	1564,57	59,49	68,73	4,48	0	MVAC
CAN TEN 2	2269,64	363,98	1905,66	72,46	111,70	9,19	0	MVAC
CAN LANZ 1	2521,89	403,4	2118,49	46,03	173,24	9,05	0	MVAC

4. Results and conclusions

In Table II all the results of the study of different zones destined to development of OWFs in Spain can be seen. From this Table II some conclusions can be extracted.

There are three main zones specially interesting in the case of Spain. First, the northwest part with high levels of wind intensity makes the LCoE ratio quite acceptable around 75 €/MWh of energy, called NOR2, NOR3 and NOR4. Second, the north part of Catalonia called ESAL1, with very high ratio of energy generated. Third, the most interesting area corresponds to Canary Islands, where 6 different zones could be deployed for OWFs. These areas are highly recommended because offshore wind resources are extremely high near the coast including high quality of wind and constant wind direction. Moreover, additional advantages could be found for these sites, for example, an OSS is not needed, operation & maintenance costs are low and distances to maintenance hub are short.

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