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Feasibility analysis of offshore wind power plants with DC collection grid

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ABSTRACT

Offshore wind power plants (OWPPs) tend to be larger in size and distant from shore. It is widely accepted that for long distances HVDC links are preferred over HVAC transmission. Accordingly, one possible approach might be to consider not only a DC transmission system but also for the WPP collection grid. In this paper, a technical and economic comparison analysis of the conventional AC OWPP scheme and four proposed DC OWPPs topologies is addressed. Due to the conceptual novelty of DC technologies for OWPPs, uncertainty on electrical parameters and cost functions is relevant. A sensitivity analysis of the cost and efficiency of the components, OWPP rated power, export cable lengths and some economic data is carried out. For this study, a methodology is proposed and implemented in DIgSILENT Power Factory®. To compare conventional AC offshore collector grid and the various proposed DC configurations, an OWPP based on Horn's Rev wind farm is selected as base case. The analysis of the results shows that, in general terms, DC OWPPs present capital costs comparable with conventional AC OWPPs, as well as lower energy losses, concluding that DC collector grid could be of interest for future OWPP installations.

1. Introduction

Offshore wind power is becoming increasingly relevant due to the existence of higher and steadier wind speeds than onshore and lesser number of installation restrictions allowing the use of larger wind turbines [1]. There is a clear trend towards the development of larger Offshore Wind Power Plants (OWPPs) located far from the shore. This tendency is expected to continue over the coming years, since there are already several projects approved or under development in the North sea [2].

Long distances and large power lead to the use of HVDC technology. Various studies agree that there is a break-even point in the range of 55–70 km where HVDC transmission becomes more cost-effective when compared to HVAC [3,4]. To transmit generated power from the OWPPs to shore using a HVDC link has some major advantages over AC transmission systems including lower cable losses, power system stability enhancement capability and no reactive power compensation requirements [3]. There is currently one OWPP in operation with HVDC link named Bard Offshore 1 which is a 400 MW wind farm connected to the offshore HVDC converter station BorWin Alpha located at a distance of about 125 km from the German shore [5]; but some more are currently under planning and/or construction as those connected to DOLWIN1 cluster [6]. Several research has been carried out considering AC OWPP with HVDC power transmission focussing on different issues such as optimal design of the OWPP layout [7,8], its control and grid integration [9,10].

Adding the aforementioned advantages of DC technologies to its recent development and increased interest, not only for HVDC transmission links but also for Multi-Terminal HVDC [11,12], lead to consider an OWPP concept in which both transmission and collection grid are in DC. Although there are no existing wind power plants with DC collection grid installed or planned, the concept of DC OWPP is being analysed from technical and economic perspectives taking into consideration both parallel [13–16] and series [13,17] configurations. Due to the fact that DC technologies for

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Nomenclature

C_{AC_WPP}	Capital cost of AC WPPs
C_{DC_WPP}	Capital cost of DC WPPs
C_{ACwt}	Cost of full-equipped AC WT
C_{DCwt}	Cost of DC WT without step-up DC/DC converter
C_{ACcab}	Cost of MVAC submarine cables
C_{DCcab}	Cost of MVDC submarine cables
$C_{ca\&inst}$	Cost of cable transport and installation
C_{ACsg}	Cost of AC switchgears
C_{DCsg}	Cost of DC circuit breakers
C_{tr}	Cost of MV/HV transformer
$C_{c\_ACDC\_cg}$	Cost of single AC/DC power converter
C_{platAC}	Cost of offshore substation platform for AC WPPs
C_{platDC}	Cost of offshore substation platform for DC WPPs
C_{plat_DCDC}	Cost of DC/DC converter installed on collector platform
C_{wt_DCDC}	Cost of DC/DC converter installed on the WT
C_{losses}	Cost associated to energy losses
E_{losses}	Energy losses
N_{WT}	Number of WTs
N_{ACcab}	Number of MVAC submarine cables
N_{DCcab}	Number of MVDC submarine cables
N_{ACsg}	Number of AC switchgears
N_{DCsg}	Number of DC circuit breakers
N_{tr}	Number of MV/HV transformer
N_{plat}	Number of offshore platforms installed
N_{plat_DCDC}	Number of DC/DC converters installed on collector platforms
N_{WT_DCDC}	Number of DC/DC converters installed on the WT
$P_g(n)$	Power delivered by the WT
$P_{PCC}(n)$	Net active power transferred to the grid
$p_{wb}(n)$	Probability of occurrence of each state based on Weibull
P_{wt}	WT rated power
T	Time period

collection networks are not standard and still under development, there are some uncertainties to consider and challenges to overcome. Therefore, the development of several critical DC components, such as DC circuit breakers (DC-CB) [18–22] or DC/DC converters [23,24] is crucial. Focussing on DC/DC converters, there are various possible topologies to be used as transformer-less based converters (boost, buck–boost, ćuk, etc.) which are more economical but have some drawbacks as they are non-galvanic isolated and present low elevation ratio, and transformer-based converter which encompasses two power converters connected through an internal medium/high frequency AC transformer. This DC/DC converter type permits to obtain large elevation ratios ensuring galvanic isolation, but at higher cost [23–26].

This paper deals with the technical and economic assessment of four proposed DC offshore collection grids, aiming to determine its cost-effectiveness when compared to conventional AC OWPPs. Because of the uncertainty of DC technology, a sensitivity analysis is carried out taking into consideration various parameters which may affect technical and economic feasibility of DC OWPPs, for example, DC equipment efficiencies, DC component cost, OWPP rated power, export cable length, etc. A methodology is proposed and implemented in DIgSILENT Power Factory®, using the DigSilent programming language (DPL).

2. AC and DC offshore wind power plants configurations analysed

A simplified scheme of an offshore wind power plant transmitting generated power to the main network through a point-to-point HVDC link is shown in Fig. 1; however, a multi-terminal HVDC system may be also considered [27,28]. As it can be seen, the diagram represents both the offshore wind power plant collection grid, which is delimited by the dashed lines, and the transmission link to shore.

This paper focuses on the collection grid (AC or DC) and assumes an HVDC transmission to shore. Hence, the study covers all the equipment required to collect the power generated by the wind turbines and to export it to the offshore transmission HVDC platform, such as submarine cables, protections, wind turbines, collector platforms and DC/DC converters.

A short description of both the AC base case and the four DC offshore wind power plants configurations analysed in this paper is given in the following subsections.

2.1. Current offshore wind power plant design: AC case

An AC wind farm collection grid can be built in three different possible connection designs: radial, ring and star connected [29]. Theses designs are depicted in Fig. 2. In the radial collection system, the wind turbines included within the same feeder are installed in string configuration as it is shown in Fig. 2(a). It is the most common, economical and simplest collection system but it presents some reliability issues [30]. The ring collection (Fig. 2(b)) system can be understood as an improved version of the radial design in terms of reliability, but it becomes costly. The star collection system attempts to reduce the cable ratings of the cables which connect the wind turbines and the collector point. As it can be seen in Fig. 2(c), such common connection point is usually located in the middle of all wind turbines disposition.

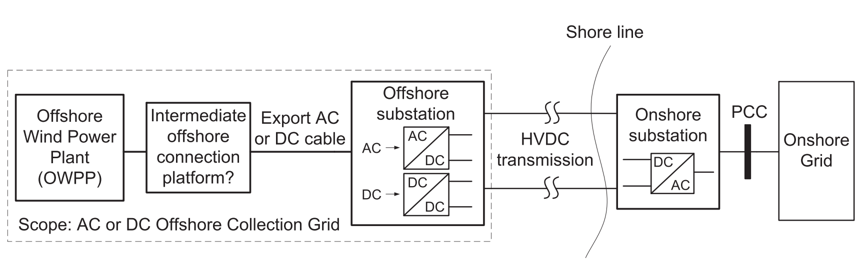


Fig. 1. Schematic representation of offshore wind power plant connection to the main grid. The framed zone remarks the paper focus.

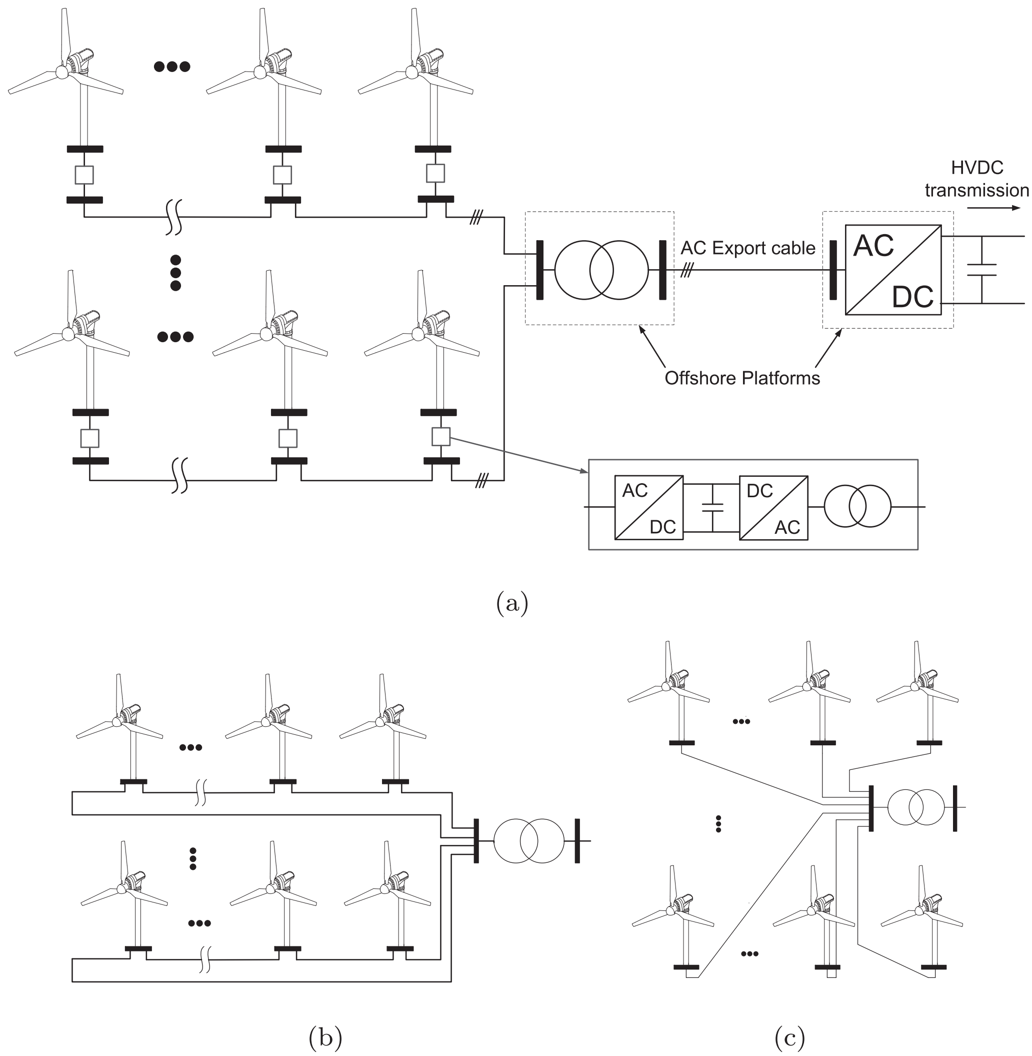


Fig. 2. (a) Radial collection configuration and layout of the AC offshore wind power plant considered (base case). (b) Ring collection configuration. (c) Star collection configuration.

Since radial design is the most common configuration installed thus far, it is adopted as base case.

2.2. DC offshore wind power plant design proposals

As with conventional AC, DC offshore collection grids can be mainly classified into three different designs based on the connection of the wind turbines: parallel, series or hybrid. In the parallel topology, the wind turbine voltage is maintained constant. It is worth remarking that this topology is the most similar to the conventional AC case and the logical first step for DC OWPP. For the series case, the wind turbine current is kept constant while the total voltage of the OWPP grid is the sum of the wind turbine voltages. Finally, the hybrid topology is defined as a mix of both previous topologies. It is designed as a number of wind turbines electrically connected in series with parallel connected feeders. Both series and hybrid topologies present some technical challenges. For example, a higher insulation requirement on the wind turbines because of the total voltage to withstand, and the fact that some electrical components of the wind power plant must be oversized to prevent overvoltages in the wind turbines [31]. Moreover, to handle the circumstance that some turbines are out of operation, the series connected wind turbines should have a bypass designed to short circuit the output of the wind turbines if an internal fault is detected. All these technical issues pose extra uncertainty making it difficult to foresee their short-term feasibility.

As it is stated previously, the parallel design is the configuration similar to the radial design for AC cases. To ease the comparison between AC and DC technologies, these wind power plant designs are chosen. For the parallel configuration, four possible DC OWPP schemes are proposed within this paper depending on DC/DC converter requirement and offshore collector platforms existence. Such proposals are briefly described below and shown in Figs. 3–6.

2.2.1. DC OWPP configuration 1 (DC1)

In Fig. 3, the scheme of DC1 configuration is presented. In this case, each wind turbine feeder is directly connected with the HVDC main substation, where a DC/DC converter is included (instead of an AC/DC converter) to step-up the voltage to deliver the power to the onshore network via an HVDC transmission link.

The main benefit of this configuration is the avoidance of using an intermediate collector platform which implies savings in capital costs. Nonetheless, the considerable distance between the OWPP feeders and the main platform leads to the requirement of both larger number and an increased cross-section of inter-array cables in order to avoid large power losses.

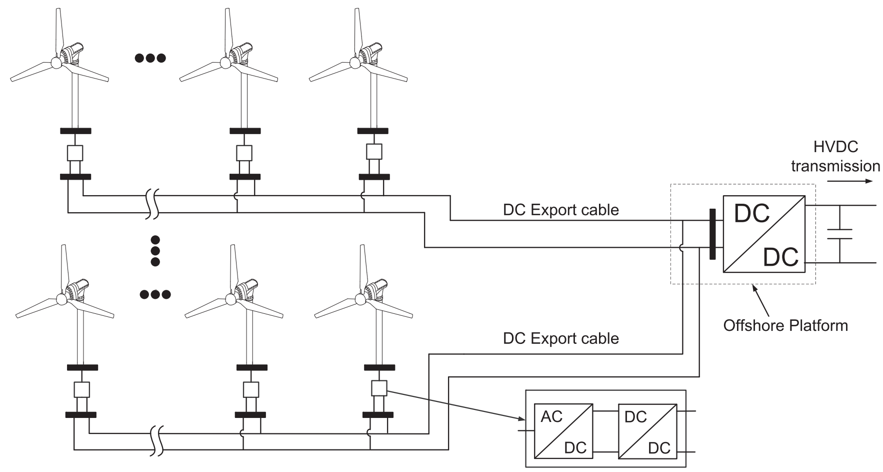


Fig. 3. Simplified representation of the DC OWPP configuration 1 proposal (DC1).

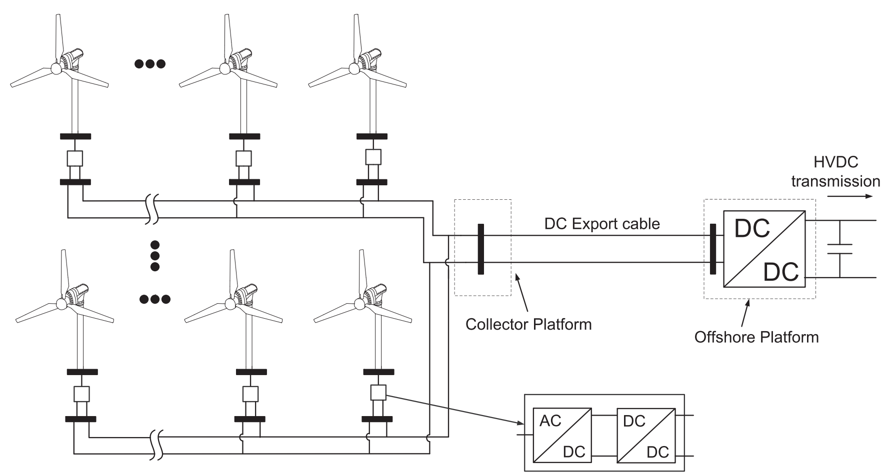


Fig. 4. Scheme of the DC OWPP configuration 2 proposal (DC2).

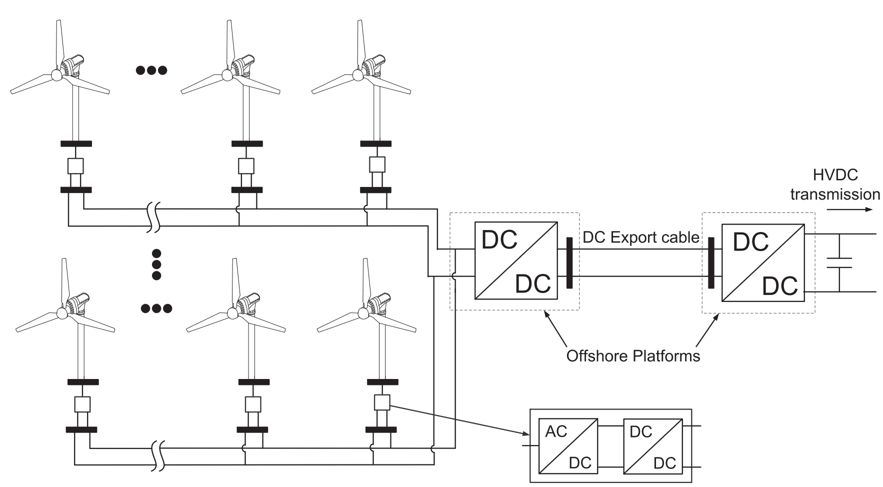


Fig. 5. Representation of the proposal of the DC OWPP configuration 3 (DC3).

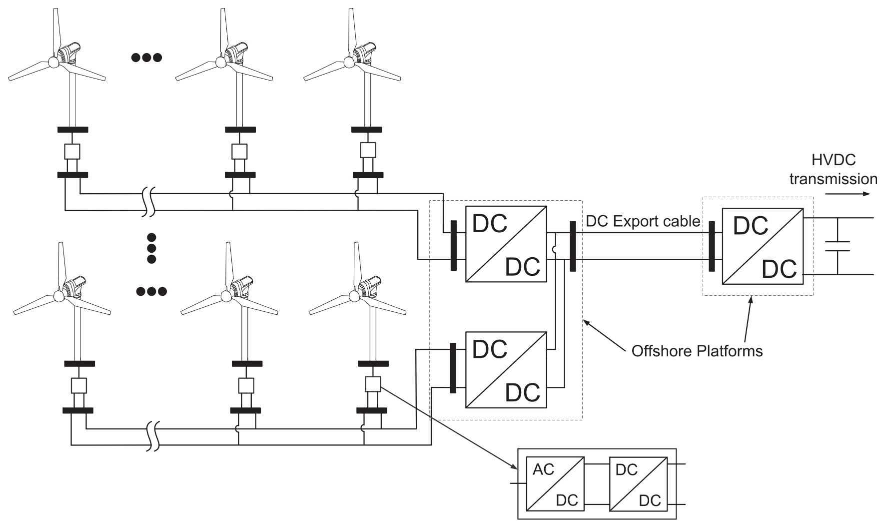


Fig. 6. Proposal scheme of the DC OWPP configuration 4 (DC4).

2.2.2. DC OWPP configuration 2 (DC2)

This configuration design, shown in Fig. 4, considers an offshore grid in which all wind turbine strings are connected to a common offshore collection point. The present scheme differs from DC1 in the connection to the main offshore platform, since such collector grid includes an intermediate offshore platform gathering the inter-array cables from the feeders. Export cables with higher cross-section are used to interconnect the intermediate platform with the main offshore substation, where, as in the previous case, a DC/DC converter is installed.

One of the main advantages of this scheme design is the non-requirement of DC/DC converter in the offshore collector platform. This fact saves both investment costs and energy losses costs related to power converter. Moreover, it enables the installation of a smaller intermediate offshore platform in comparison with a conventional AC offshore platform with step-up transformer. On the other hand, one of the most relevant disadvantages may be the large amount of power dissipated in the export cable depending on the OWPP voltage level.

2.2.3. DC OWPP configuration 3 (DC3)

The scheme diagram of DC OWPP configuration 3 proposal is presented in Fig. 5. Within this configuration, there are two step-up DC/DC converters. The first one located at the end of the whole wind farm is used to increase the voltage to export the power to the main offshore platform. The other DC/DC converter is required to step-up the voltage to deliver the power to the shore.

This scheme has the advantage of reducing the losses in the export cable due to the voltage increase, which is specially worthwhile if the distance between the collector and the main HVDC offshore platform is significant. However, this topology entails some drawbacks as reliability issues because of lack of redundancy; since if the DC/DC converter fails, the generated power of the whole wind power plant cannot be delivered.

2.2.4. DC OWPP configuration 4 (DC4)

Finally, a schematic representation of DC OWPP configuration 4 is shown in Fig. 6. As it can be seen, this proposal includes one single step-up DC/DC per wind turbine feeder. This power converter increases the voltage of the system to deliver the power to the main offshore platform where another step-up DC/DC converter is installed to transmit the generated power to the shore.

Compared to the previous configuration (DC3), the reliability of the system is increased because of the step-up converter redundancy. On the other hand, a disadvantage of this configuration in comparison with the previous one is the larger capital expenditures associated with the higher required number of DC/DC power converters. Moreover, the collector platforms that allocate all the DC/DC converters may be increased in size and cost.

3. Analysis methodology

A general overview of the steps required to analyse the methodology developed to evaluate both capital and energy losses cost of AC and DC OWPP configurations is presented in Fig. 7. It is worth noting that after the application of this methodology the comparison of those OWPP configurations can be performed.

The proposed methodology is composed by four main steps which can be briefly introduced as follows: first, an initialization of the system and process is needed to design the electrical WPP collection grid. In this step, all electrical elements except the cables are selected according to voltage ratings (set by the user). Second, in the cable selection process, the type of inter-array and export cables are selected and the number of parallel lines required is determined. The cable selection is based on minimizing the cross section of the cable used ensuring both not overcoming the maximum admissible loading, and a proper and continuous operation under full load condition. Third, a technical analysis to calculate the energy losses of the WPP through load flow simulations is performed. Finally, a cost analysis is carried out calculating the capital expenditures of each component included in the wind power plant design, as well as the costs associated to energy losses considering both non-generated power and cable losses.

In the following subsections, these two last processes (technical and economic assessment) are explained in more detail.

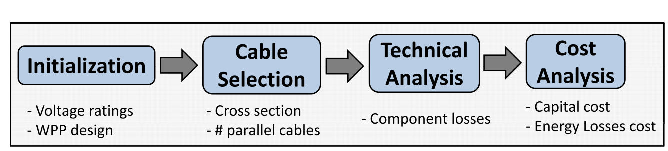


Fig. 7. General flowchart of the methodology proposed for OWPP evaluation.

3.1. Technical analysis

After the initialization of the process and the configuration of the wind power plant, the technical analysis can be carried out. As previously stated, this is mainly based on the calculation of the energy losses produced within the WPP by means of several load flow simulations. Considering this, the steady-state energy losses of each WPP configuration over a period of time T may be computed as

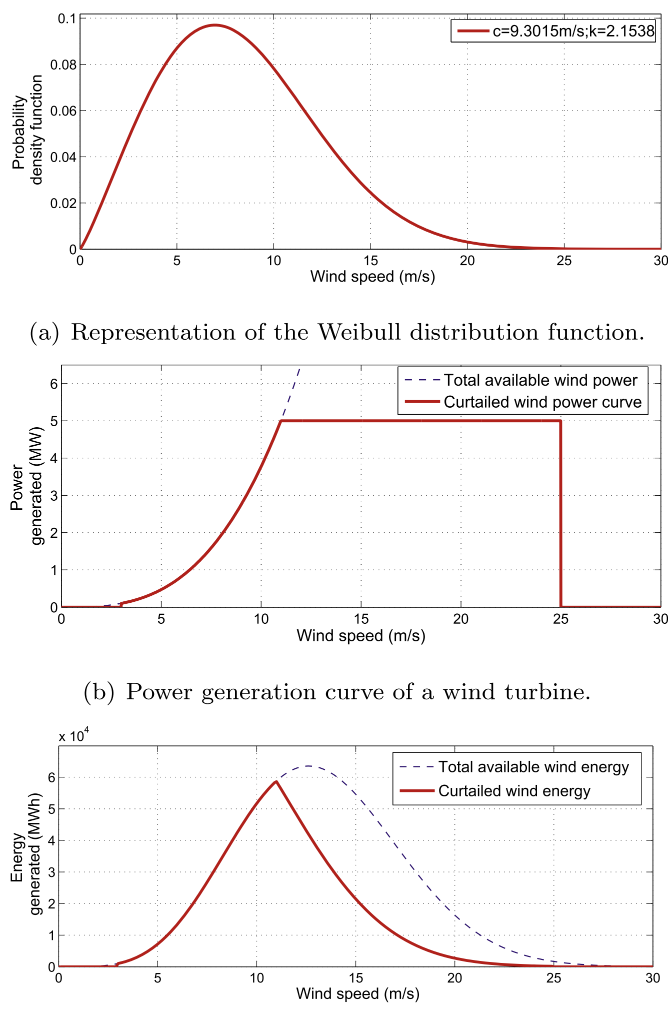
$$E_{losses} = T\sum_{n=1}^{N}(P_g(n) - P_{PCC}(n))\cdot p_{wb}(n) \tag{1}$$

where $P_g(n)$ is the power delivered by the WPP, $P_{PCC}(n)$ is the net active power transferred to the grid at the Point of Common Coupling (PCC), N is the maximum number of generation states, being equivalent to the wind speeds set under consideration, and $p_{wb}(n)$ refers to the probability of occurrence of each state according to the Weibull distribution function used shown in Fig. 8(a).

The power generated by the WPP for each state, $P_g(n)$, is computed by considering the power curves of the wind turbines shown in Fig. 8(b), while the amount of power received at the PCC, $P_{PCC}(n)$, is calculated by means of multiple load flows (one per each generation state) and relies on the components efficiency which are included within the WPP collection grid. The total energy yield by each wind turbine is shown in Fig. 8(c), where the dash blue (in the web version) line represents the total wind energy available and the solid red (in the web version) line is the actual energy generated.

Due to the uncertainty existing over DC technology for WPPs, some parameters such as the efficiency of DC/DC converters or DC protections, are not well defined. Thus, the energy losses previously introduced in equation (1) results of only the cable losses consideration. Thereby, the total steady-state energy losses including the power losses of power electronic elements (AC/DC and DC/DC converters, and DC breakers) are evaluated by means of a sensitivity analysis.

From the technical analysis, the breakdown of the losses is obtained. This breakdown allows to determine the effect of each element into the total power losses, distinguishing among the different existing losses.



(a) Representation of the Weibull distribution function.

(b) Power generation curve of a wind turbine.

(c) Energy yield function of the wind turbine.

Fig. 8. Generated energy distribution calculations.

3.2. Cost analysis

The cost analysis deals with the calculation of the total cost of a wind power plant. Those results provide a basis to enable the comparison between AC and DC WPP configurations and to determine which one is the most cost-effective. To this end, the procedure presented in Fig. 9 is applied. In order to validate the results obtained for the base case during this process, the AC WPP cost model is compared to the wide-accepted cost estimations reported by the European Wind Energy Association (EWEA) [32]. Likewise, a sensitivity analysis is performed for the DC OWPP cases to overcome their uncertainty.

Within the economic methodology analysis, a cost function is included considering both the capital expenditures (CAPEX) and the costs associated to the energy losses during the lifetime of the installation (preventive and corrective maintenance actions are not considered in this study). By using this function the total cost calculation of each OWPP configuration analysed can be performed.

3.2.1. Capital expenditure functions

According to the particular study focus, as previously stated, on the offshore collector network, the capital cost function for both an AC and a DC WPP (C_{AC_WPP} and C_{DC_WPP}, respectively) is formulated as

$$C_{AC\_WPP} = \sum_{N_{wt}} C_{ACwt} + \sum_{N_{ACcab}} (C_{ACcab} + C_{ca\&inst}) + \sum_{N_{ACsg}} C_{ACsg} + \sum_{N_{tr}} C_{tr} + C_{c\_ACDC\_cg} + \sum_{N_{Plat}} C_{platAC} \tag{2}$$

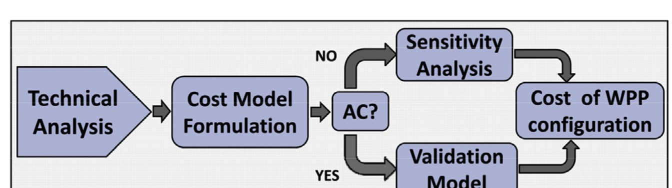


Fig. 9. Methodology used for the economic analysis.

$$C_{DC\_WPP} = \sum_{N_{wt}} C_{DCwt} + \sum_{N_{DCcab}} (C_{DCcab} + C_{ca\&inst}) + \sum_{N_{DCsg}} C_{DCsg} + \sum_{N_{WT\_DCDC}} C_{WT\_DCDC} + \sum_{N_{Plat\_DCDC}} C_{Plat\_DCDC} + \sum_{N_{Plat}} C_{platDC} \quad (3)$$

where N_{wt} is the number of wind turbines within the WPP, N_{ACcab} and N_{DCcab} are the number of MV AC and DC submarine cables, N_{ACsg} and N_{DCsg} are the number of AC and DC switchgears, N_{tr} is the number of MV/HV transformers for the AC WPP, N_{WT_DCDC} and N_{Plat_DCDC} are the number of DC/DC converters in the WT and platforms, respectively, and N_{Plat} represents the number of platforms installed. The calculation of the capital cost of each component is detailed in the following. It is worth noting that all the costs are expressed in k€.

Fully-equipped wind turbines. The cost of a fully-equipped wind turbine for the AC case [33], including the turbine, the back-to-back converter and the LV/MV transformer, can be computed by

$$C_{ACwt} = 1.1 \cdot \underbrace{\left(2.95 \cdot 10^3 \cdot \ln(P_{wt}) - 375.2\right)}_{C_{wt}} \quad (4)$$

where P_{wt} is the rated power (in MW) of the wind turbine and the coefficient 1.1 includes the costs of transport and installation.

In the DC case, the cost of wind turbines is assumed to be similar to the AC case. The difference relies on the not needing to include a back-to-back power converter nor transformer but only a single AC/DC power converter. Thus, the cost of the power converter and transformer is assumed as a certain percentage of the total cost of the wind turbine and can be expressed as [32]

$$C_{DCwt} = \cdot K_{wt} \cdot C_{ACwt} \quad (5)$$

where K_{wt} refers to the sensitivity parameter of the percentage explained above, affecting the capital cost of the DC wind turbine.

AC and DC cables. The cost of MVAC submarine cables within the offshore MV collection grid are calculated through the following cost function [33]

$$C_{ACcab} = \alpha + \beta \exp\left(\frac{\gamma I_n}{10^5}\right) \cdot L \quad (6)$$

where I_n is the cable ampacity (in A), L is the cable length (in km) and the coefficients α, β and γ depend on the nominal voltage level. For example, for cables of 30–36 kV they are defined as 52.08 k€/km, 75.51 k€/km and 234.34 1/A, respectively.

DC cable costs can be computed by Ref. [34]

$$C_{DCcab} = K_{cab}(A_p + B_p 2 V_{rated} I_{rated}) L \quad (7)$$

where V_{rated} and I_{rated} are the cable ratings (in A and V respectively), the constants A_p and B_p depend on voltage rating and K_{cab} refers to a sensibility parameter on cable cost.

Finally, the cable transport and installation costs are assumed to be equal in both cases

$$C_{ca\&inst} = K_{cinst} 365 L \quad (8)$$

where K_{cinst} is a variable parameter in DC case, but always constant (1) in AC. It is worth noting that this equation provides an average value, and does not reflect particularities of each case study such as seabed composition, water depth, among others.

MV/HV transformers. Referring to [33], the cost of a MV/HV transformer can be expressed as

$$C_{tr} = 42.688 A_t^{0.7513} \quad (9)$$

where A_t is the transformer rated power (in MVA).

AC/DC power converter. A single AC/DC power converter cost function which is installed before the HVDC link receiving the total power of the collection grid, has been determined in Ref. [34] through comparison of real installation cases. This leads to the following equation

$$C_{c\_ACDC\_cg} = 200 P_r \quad (10)$$

where P_r is the rated power of converter (in MW).

DC/DC power converters. According to [34], the DC/DC converter cost can be based on Table 1 which is suggested by the industry.

To consider a wide-spread power ratings, linear interpolation between points is done (C_{c_DCDC}). Since there are different possible DC/DC converters within the collection grid (wind turbine and offshore platforms), they must be treated separately for the cost analysis.

$$\begin{aligned} C_{WT\_DCDC} &= K_{WTcon} C_{c\_DCDC} \\ C_{Plat\_DCDC} &= K_{Platcon} C_{c\_DCDC} \end{aligned} \quad (11)$$

where C_{c_DCDC} is the cost of the DC/DC converter, K_{WTcon} and $K_{Platcon}$ represent the cost variability of the converters themselves.

AC and DC switchgears. The cost model of the AC switchgears can be found in Ref. [33] as

$$C_{ACsg} = 40.543 + 0.76 V_n \quad (12)$$

where V_n is the nominal voltage in kV. For DC case, according to [34], the cost of the DC breakers is twice the AC switchgears cost.

$$C_{DCsg} = K_{CB}(2 C_{ACsg}) \quad (13)$$

where K_{CB} represents a possible uncertainty on the cost hypothesis.

Offshore platform for AC and DC based WPPs. The cost of an offshore substation platform for AC WPPs is computed as [33]

$$C_{pl\_AC} = 2534 + 88.7 N_{wt} P_{wt} \quad (14)$$

where N_{wt} is the number of wind turbines within the OWPP and P_{wt} is the wind turbine rated power.

With regard to the DC OWPPs study, there exist various types of offshore platform that could be considered such as feeder, collector and main platform. Thus, the DC offshore platform cost based on the AC case can be expressed as

$$C_{pl.DC} = K_{Col}(2534 + 88.7 N_{wt} P_{wt}) + K_{Feed}((2534 + 88.7 N_{wt} P_{wt}) 1.1) + K_{Plat}(2534 + 88.7 N_{wt} P_{wt}) \quad (15)$$

where K_{Col}, K_{Feed} and K_{Plat} represent the cost variability depending on the type of platform required. It is worth noting

Table 1
Cost of the DC/DC converters [34].

DC/DC converter type	C_{c_DCDC}
2 MW dc/dc converter to be used with series dc layout	330 k€/MW
High power (150 MW and above) to be used in the large DC layout	220 k€/MW
2 MW dc/dc converter to be used with small and large DC layout	165 k€/MW

that a cost correction factor is included for the feeder platform cost; since, bigger space is needed when larger number of DC/DC converters are installed, in spite of the amount of power remains the same.

Since the references considered are from diverse years, the cost results are updated to 2013 prices through the consumer price index of Spain (≈2 %).

3.2.2. Cost associated with the energy losses

Energy losses costs associated with those produced within the WPP considering both cases, can be computed as

$$C_{losses} = \sum_{t=1}^{T} (K_e t + C_e) E_{losses} \tag{16}$$

where K_e represents the slope of the equation $P_e(n) = K_e t + C_e$, being P_e the energy price for the year t and C_e a fix cost (89.5 €/(MWh·year)). T is the lifetime of the OWPP and E_{losses} are the energy lost during this period calculated in (1).

3.3. Sensitivity analysis

Due to the fact that the novel concept of OWPPs based on DC collection grid are not a reality yet, some uncertainties rise up regarding both electrical efficiency and their manufacturing cost. With the aim to overcome such problem, a sensitivity analysis is carried out. This is done by modifying several parameters providing a wide range of possible admissible solutions. As it can be seen in Tables 2 and 3, three different scenarios (S1, S2 and S3) of sensitivity parameters are considered within the study. Such scenarios are mainly related with the expected status of this technologies as positive, average (base case) and negative. It is worth noting that the S2 parameter values are the base case, and correspond to those values presented into literature [33–36] and industry suggestions. Likewise, S1 and S3 values are selected mainly based on discussion with industry and academia hypothesis, since the technology is not available yet. The main idea is that such values will provide insight on the influence of the component parameter on cost.

Aiming to examine the influence of a single parameter on the overall cost of a particular WPP configuration, several analyses are performed by modifying only one sensitivity parameter while keeping the other in their base value. Alike, in order to determine the maximum cost range admissible for each WPP scheme, a more general study considering all the sensitivity parameters varying together is also carried out.

Table 2
Non-cost parameter values used for sensitivity analyses.

Type of analysis	Sensitivity parameter	S1	S2	S3
Effect of the rated power of wind turbines (MW)	P_{rated}	2.5	5	7.5
Effect of the export cable distance (km) [36]	D_{export}	10	40	70
Effect of the losses of the DC breakers (%) [20]	P_{loss_b}	0.001	0.05	0.25
Effect of the losses of the DC/DC power converters (%)	P_{loss_DCDC}	1	2	3
Effect of different forecasted energy prices (€/MWh) [37]	K_e	−1.1789	2.1105	5.3
Effect of different maximum admissible cable loading (%) [38]	*MaxLoading*	72	80	88

Table 3
Capital cost parameter values used for sensitivity analyses.

Type of analysis	Sensitivity parameter	S1	S2	S3
Effect of the cost of DCDC converters	K_{WTcon} $K_{Platcon}$	0.75	1	1.25
Effect of the cost of the DC breakers	K_{CB}	1	2	3
Effect of the cost of platforms that support converters	K_{Plat} K_{Feed}	0.75	1	1.25
Effect of the cost of platforms without converters	K_{Coll}	0.5	0.75	1
Effect of the cost of the cables	K_{cab}	0.5	1	1.5
Effect of the cost of the cables installation	K_{cinst}	0.5	1	1.5
Effect of the B2B and transformer cost over total WT cost	K_{wt}	0.9	0.925	0.95

4. Case study

In this section, the proposed methodology previously described is applied to a particular case study. From the output of this methodology, the cost-effectiveness of DC OWPP configurations in comparison with the conventional AC solutions can be determined.

In order to facilitate the analysis comparison between the AC base case and the 4 DC OWPPs proposed configurations considered within this paper, all the DC collector grids studied present exactly the same characteristics in terms of number and location of wind turbines as the AC scheme. Each DC OWPP topology analysed is studied as two different cases depending on its collection grid voltage rating (A-±20 kV and B-±50 kV). The voltage rating at the export cable is ±80 kV for DC3 and DC4 configurations.

In with this regard, the general wind farm designs are based on the well-known Horns Rev wind farm which is composed of 80 wind turbines laid out in a regular matrix form of 10 columns and 8 rows. The spacing among wind turbines is 7 rotor diameters (D) in both directions. As it is previously stated, the radial design is adopted connecting all the turbines within a column to one feeder.

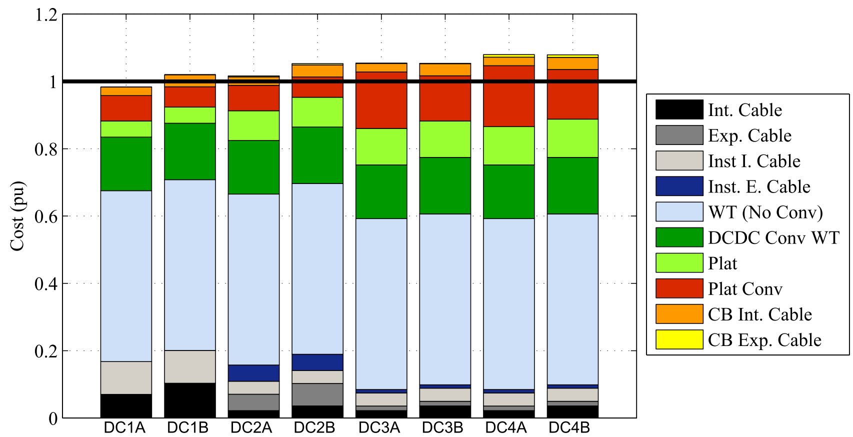
4.1. AC cost function validation

With the aim of validating the AC cost functions used for cost modelling, the values obtained have been compared to the investment cost estimations provided by EWEA for OWPPs [32]. Table 4 presents cost predictions for three different scenarios (minimum, average and maximum) according to offshore technology development forecast.

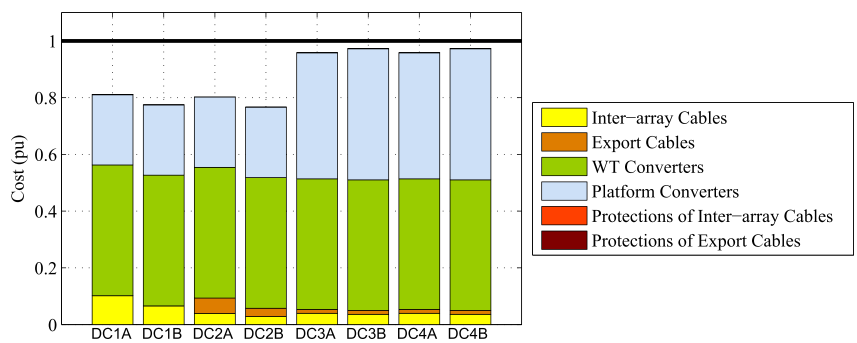
As it can be seen, the obtained cost values lay on these expected ranges; therefore, the AC cost functions can be validated. For the grid connection cost calculation, various electrical components of the OWPPs including cables, platforms, converters, switchgears and transformers, are gathered. It is worth noting that although wind turbine and grid connection costs fits in between the average and maximum cost estimations, the total CAPEX results to be among minimum and average scenarios, since not all the costs considered on CAPEX (SCADA, installation costs, among other) are included.

Table 4
Capital cost comparison for OWPPs (in k€/MW).

	EWEA estimations			AC cost function
	MIN	AVG	MAX	
Wind turbine	570	920	1260	1040
Grid connection	280	500	760	690
Total CAPEX	1780	2080	2370	1900



(a) Capital costs (AC base cost = 758.95 M€)



(b) Costs associated with energy losses (AC base cost = 278.37 M€)

Fig. 10. Breakdown of all the DC OWPP configurations setting all the sensitivity parameters at their base values (S2). The solid black line indicates the cost of the AC base case.

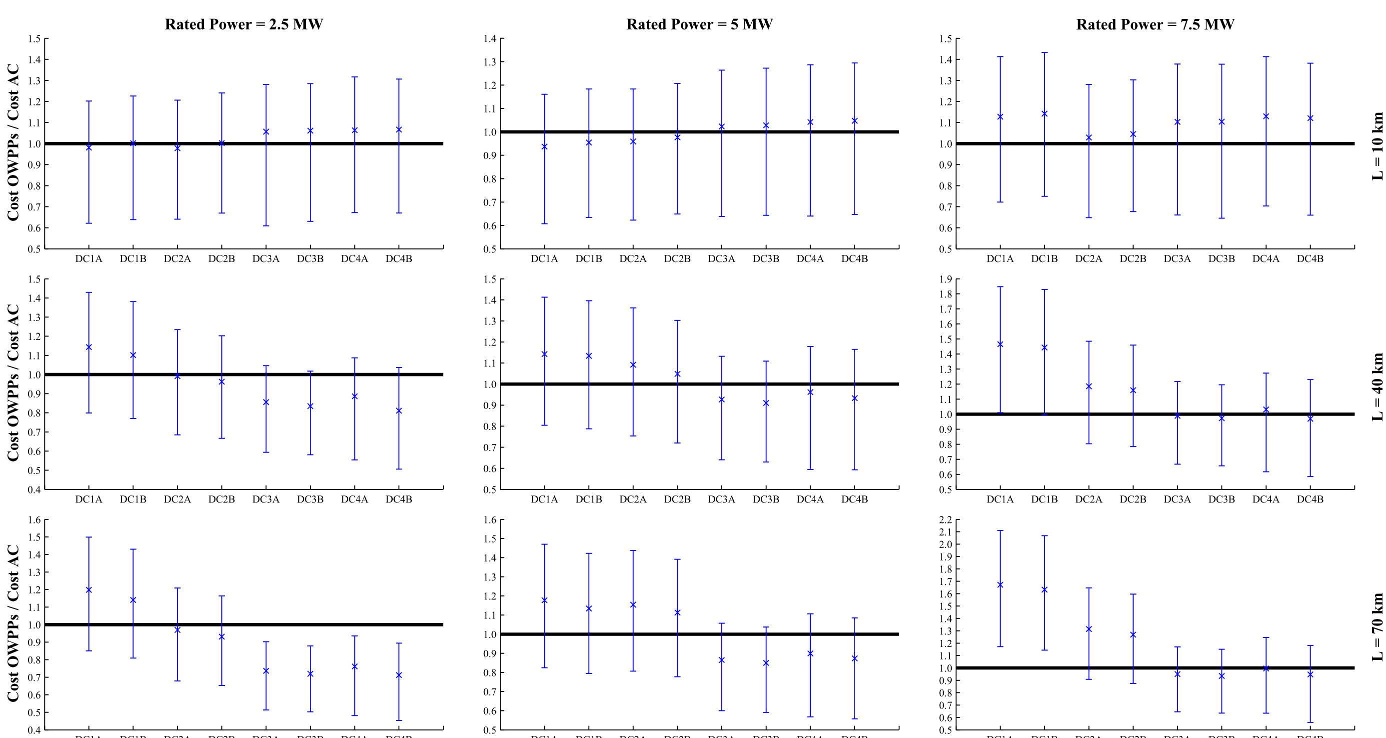


Fig. 11. Total relative WPP costs (including both capital investments and costs associated with losses) for all the cases analysed. The black lines show the AC base case considering a certain export cable length (10, 40 or 70 km) and a particular wind turbine rated power (2.5, 5 or 7.5 MW). The blue line represents the cost sensitivity of DC WPPs. The × symbol indicates the DC base values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Summarized description of the analysed DC OWPP configurations.

DC1x	DC2x	DC3x	DC4x
No collector platform	No DC/DC on collector platform	One DC/DC conv. per WF on collector platform	One DC/DC conv. per feeder on collector platform

where x represents both A and B cases which are based on ±20 kV and ±50 kV, respectively.

4.2. Comparative analysis

After applying the methodology introduced above and considering the sensitivity parameters in Tables 2 and 3, the results shown in Figs. 10 and 11 are obtained. For the sake of clarity, Table 5 shows a brief description of all DC OWPP configurations analysed within the study.

Fig. 10 shows the breakdown of both capital and energy losses costs of all the presented DC OWPP configurations considering a particular case study (wind turbines of 5 MW each and an export cable of 10 km long). The solid line represents the AC cost (base case), while the bars indicate the relative cost of DC OWPP schemes over AC case.

In general terms, it can be seen from Fig. 10(a) that capital cost for DC WPPs configurations are slightly higher than AC case. On the other hand, Fig. 10(b) shows a reduction on the energy losses for the DC cases, as expected. Concerning investment costs, it should be noted that the most critical expenditures refer to wind turbine and DC/DC converters costs installed on wind turbines and platforms, representing 47–50 % and 23–31 % of the total capital cost, respectively. With regard to the energy losses costs, it is clear that the crucial components for DC OWPPs are the DC/DC converter losses (considering both wind turbine and platform converters), being about 92–94 % of the total losses within the wind power plant.

Finally, Fig. 11 presents total relative OWPP costs for all the cases considered for evaluation over its respective AC base case. Table 6 shows all the AC base values obtained for different wind turbine power ratings (2.5, 5 and 7.5 MW) and export cable lengths (10, 40 and 70 km) considering base parameters for the sensitivity analysis (S2). It should be mentioned that the distances between wind turbines (7 D) has been adapted for each particular case according to the specific rotor diameter corresponding to each turbine power rating.

In Fig. 11, all possible combinations of sensitivity parameters are taken into consideration. The edges of the blue lines indicates the minimum and the maximum cost for DC OWPPs representing the most optimistic and pessimistic scenarios for these technologies, respectively. In this figure, it can be seen that at short export cable length (10 km), generally DC1 and DC2 are of interest, since no extra investment must be done for the DC/DC converter. However, it does not occur in DC1 for the case of 7.5 MW where the large number of cables required, due to OWPP power rating, for exporting the power to the main offshore platform (no collector platform installed) leads to larger power losses and significant increase of the investment cost. On the other hand, for long export cables (70 km), DC3 and DC4 appear to be economical due to reduced energy losses and lower number of cables needed. Finally, it can be stated that assuming the optimistic case DC OWPPs are usually cheaper than AC, but in the pessimistic case it is always the worst option.

Table 6
Total cost of AC base cases depending on the wind turbine rating and the export cable length (in M€).

	2.5 MW	5 MW	7.5 MW
10 km	538	1037	1402
40 km	685	1192	1567
70 km	840	1354	1735

5. Conclusion

This paper has presented different DC OWPPs topologies. Also, a methodology to evaluate and compare through a technical and economic assessment the proposed DC OWPPs has been introduced, determining its potential cost-effectiveness when compared to conventional AC OWPPs with HVDC link transmission. Since DC technology for DC OWPPs is not well-established yet, a sensitivity analysis has been done to consider various scenarios. In general terms, the results show that DC configurations involve higher capital expenditures and lower cost of energy losses, as expected.

From this study, the feasibility of DC configurations among current AC systems has been demonstrated. It has been shown that DC OWPPs may be of more interest for cases with longer distances. Likewise, it is not clear (and is extremely sensitive to the DC/DC converter cost) whether the use of DC technologies for larger wind power plants would imply a cost reduction; this is because of the size of DC/DC power converters required.

It is worth remarking that the cost of DC OWPPs are mainly affected by the cost of wind turbines, DC/DC converters and platforms, as well as the energy losses cost of such DC/DC converters. Therefore, both cost reduction and efficiency improvement of the electrical components of the DC OWPP (specially DC/DC converters) are required to make this option still more attractive.

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