Technical and economic assessment tool for offshore wind generation connection scheme: Application to comparing 33 kV and 66 kV AC collector grids

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Keywords

<< Generation of electrical energy>>, <<Emerging technology>>, <<DC/DC>>, <<Efficiency>>

Abstract

The paper presents a tool for technical and economic assessment of offshore wind power connecting architectures ; they highly influence cost effectiveness of offshore wind generation, particularly when power electronic converter based transmission technologies and long distance transmission cables are employed. Due to its models flexibility and accuracy, the developed tool is powerful for analysis and design of innovative connection alternatives.

Introduction

Onshore wind power infrastructures are already installed at the most promising locations is Europe. In the same time and with the advantage of higher wind resources and reduced intermittency, installed offshore wind power (WP) generation is rapidly increasing, contributing to reach renewable energy rate targets. ENTSO-E considers that it could represent an installed power of 25 GW in 2020 and 83 GW in 2030 [1]. However, offshore wind energy cost still needs to decrease compared to other production sources. Energy cost is measured as the standard LCOE: levelized cost of energy, (see equation (1)). LCOE basically depends on investment cost (of the whole infrastructure including wind turbines) and annually produced energy (itself depending on overall power efficiency). In a comprehensive study, in 2012, The Crown Estate (TCE) evaluated the potential in LCOE reduction for offshore wind [2]. Besides finance and contracting, design and installation processes of wind turbines as well as power collection and transmission infrastructures are considered as potential subjects of innovation. In 2013, Prognos and Fichtner [3] carried out a similar study for German offshore wind power.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + O_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (1)$$

where:
- I_t : investment cost at year t
- O_t : operating cost at year t; it includes at least maintenance
- F_t: fuel cost of year t (zero for wind power)
- E_t: produced energy at year t
- r: discount rate
- N: number of years the system is exploited

Collection and transmission infrastructures, forming together offshore connection grid, collects and transmits power from wind turbines to onshore grid. It takes a substantial part in the LCOE as it implies electrical losses and important investment costs, particularly when the wind farm is located far from shore and so HVDC transmission is employed. As a result, there is a strong need to improve connection grid regarding both investment cost and losses. For instance, the current connection solution (Figure 1) for offshore wind farms far from shore implies, among others, costly platforms for MMCs (Modular Multilevel Converters) [4], [5]. TCE study [2] is holistic and could not assess in detail technological alternatives for power connection. Several studies tackled this problematic, starting with Lundberg's [6] and others [7], [8]. Main limitations of these studies are either that considered technologies are outdated (a HVDC two level voltage source rectifier is typically not competitive in comparison to the MMC) or technical and economic assessment tools are built considering technological alternatives a priori, making the assessment of new alternatives costly in software development. Finally, losses models are sometimes not sufficiently accurate, this is particularly the case for submarine cables.

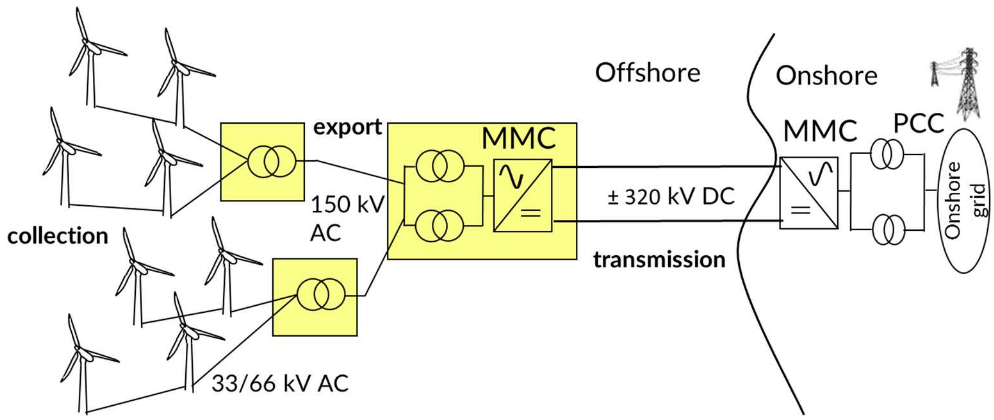


Figure 1: Technological solution for long distance offshore wind farms connection

A tool has been developed to assess innovative connection alternatives (including “all-in DC” solutions, Figure 2) for which power electronic converters are a key technology [9]. Power electronics application must take into account grid system (including cables, mechanical structures etc.) and intrinsic constraints. Optimized sizing of innovative connection alternatives is a must as it limits the risk of biased conclusion on comparison of different alternatives: each should be assessed with optimized cables routing and components power ratings. Therefore the tool development roadmap therefore includes the ability to perform design optimization for connection alternatives.

The structure of the paper is so that in a first part, the assessment tool structure is presented with included models and prospects for optimization extension. The application of the tool to a comparison of inter-array voltage level alternatives (33 kV AC or 66 kV AC) is then presented on a realistic case study.

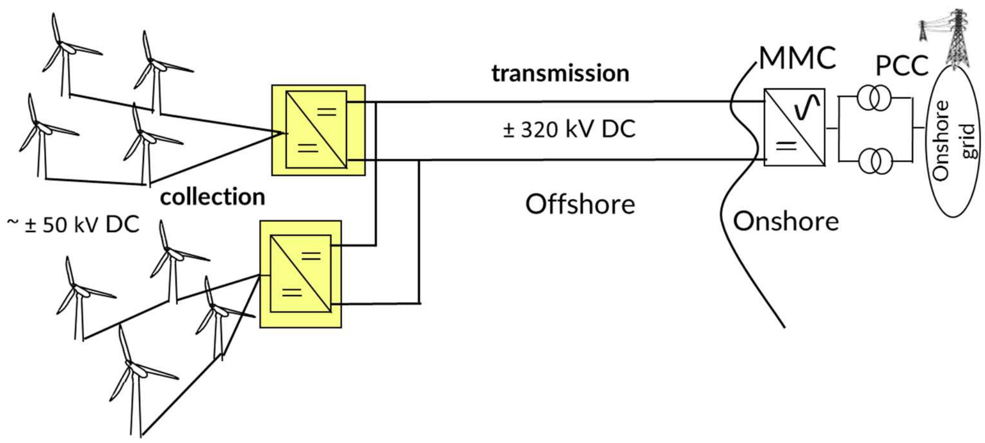


Figure 2: All-in DC generic structure for long distance offshore wind farms connection

I. Assessment tool framework and models

The assessment tool (synoptic scheme Figure 3) was designed to perform both technical and economic quantitative analysis. Flexibility of the tool is a strong requirement as it must be possible to assess different connection alternatives, even if they are considered a posteriori. Another requirement is the accuracy of quantitative performance evaluation (efficiency and costs encompassed in the LCOE) as criteria should be used for decision making.

I.1 Assessment tool framework

The tool is developed in the object oriented language python for which there are numerous scientific libraries and which is highly flexible. To perform an assessment, the tool must consider a case study and a technological connection alternative. A case study comprises the definition of the wind farm total installed power, the wind turbines power rating, the wind resources and the distance to shore if the transmission network is a part of the analyzed system.

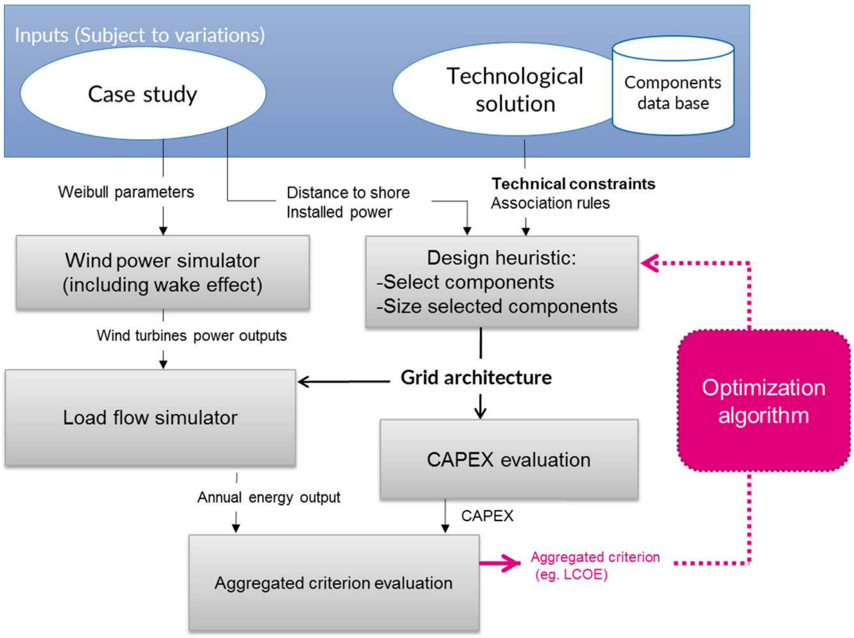


Figure 3: Synoptic of an assessment tool dedicated to offshore wind connection grid studies

The "Design heuristic" block in the synoptic scheme represents the method for the building of the connection system from a component data base defined by choice of a technological alternative. It constructs the architecture of the grid by defining its topology (connections between components) and by performing sizing of each component on the basis of its power rating. The result is a grid system represented by a graph whose edges and vertices are components (using NetworkX Python library).

The obtained architecture is analyzed by a CAPEX (CAPital EXpenditure) evaluation method. In parallel, a wind power simulator determines the power produced by each turbine depending on the wind velocity distribution. The grid architecture and the power to be collected and transmitted are taken as inputs for the load flow simulator.

The "load flow simulator" encompasses load flow methods (for both AC and DC) and is able to compute the losses and to check if the electrical static constraints (typically permanent overvoltage or overcurrent) are respected.

The "Load flow simulator" has electrical variables (voltages, currents) and energetic variables (active branches and reactive power inputs/outputs) as results. Probabilistic expected values of any of these numerous variables can be computed by using a Weibull distribution function, which models wind resources (see probability density function f_{WB} in equation (2), where k and λ are respectively shape and scale parameters of Weibull law). Probabilistic expected values are calculated on the basis of equation (3), where Y is a quantity depending on wind velocity, whose expected value $E(Y)$ is computed. Y can typically be produced power. v_{min} and v_{max} are respectively cut in and cut out speeds of wind turbines. Annual produced energy of the wind farm E_{annual} is the major macro energetic quantity. It is computed as the multiplication of one year duration T with expected produced power at the PCC (Point of Common Coupling) (see equation (4) where P_{pcc} is power at PCC). Finally, LCOE criterion is computed from CAPEX and annual produced energy criteria.

$$f_{WB}(v) = \frac{k}{\lambda}\left(\frac{v}{\lambda}\right)^{k-1} e^{-\left(\frac{v}{\lambda}\right)^k} \quad (2)$$

Though not yet implemented, one milestone of the midterm development roadmap is to include an optimization loop (e.g. based on a metaheuristic algorithm) to the tool so to comply with the requirement of unbiased conclusions for alternatives comparison, particularly for component sizing. Currently, used heuristic minimizes CAPEX whilst respecting rating constraints (e.g. for selection of a cable, the one with the smallest core cross section ensuring that maximal operating current is lower than ampacity is retained).

$$E[Y] = \int_{v_{min}}^{v_{max}} Y(v).f_{WB}(v)dv \tag{3}$$

$$E_{annual} = T.\int_{v_{min}}^{v_{max}} P_{PCC}(v).f_{WB}(v).dv \tag{4}$$

I.2 Components and load-flow models

Wind power simulator uses wind turbine models based on industrial wind velocity/power curves. The "Load flow simulator" uses pylon library (Transcription of Matpower in Python language) for AC load flows and a new DC backward forward developed algorithm for DC load flows. Wind turbines are modelled as PQ buses in load flow models (Q being inexistent in DC case). Impedances parameters used in both AC and DC load flow methods are based on component models. Cables models are based on IEC 60287 standard [10]. For AC cables, the use of cable core impedance is not sufficient since it neglects losses in screen and armors due to circulating currents while they are quite important for AC submarine cables (e.g. around 15 % for 33 kV). Developed cable models also take into account the loading dependence [11][12] which results to conductor temperature variations. Transformers are modelled with a pi description scheme by using per unit parameters. Power electronic components such as HVDC converters (AC/DC or DC/DC) are modelled by means of efficiency curves determined offline; it makes the simulation much faster and compatible with an optimization process.

Even though power losses are paramount, investment costs models and especially associated input data cannot be neglected because they strongly influence the LCOE. Wind turbines supply and installation investment costs are based on analytical models derived from Prognos and Fichtner data [3]. Cables, transformers, switchgears and HVDC converters investment costs are calculated with analytical models also derived from public data, coming from [5] for HV and from [13] for MV. Mechanical offshore structures (such as platforms) investment costs data are also taken from [5]. For AC platforms, internal additional knowledge is used to build models of jacket and topside weights depending on apparent power of offshore substation transformers, on water depth and on number of J-tubes. Platform cost model then depends on jacket and topside weights.

II. 33 kV AC and 66 kV AC voltage levels comparison.

Inter-array grid collects power from wind turbines of a wind farm and is connected with an offshore AC substation. Up to now, it was based on an AC 33 kV voltage system. However, wind farms and turbines power ratings are continuously increasing [14], making the use of higher collection voltage level (66 kV) interesting [13], [15]. It is proposed to apply the assessment tool to the comparative study of 33 kV and 66 kV voltage systems for inter-array grids.

For this purpose, the studied system consists of wind turbines including their mechanical structures, inter-array cables and AC substations (These last ones are the interfaces between a collection grid and export grid). An AC substation comprises one or several transformers in parallel, MV and HV switchgears and bus bars. Mechanical platforms are parts of the studied system: they are made of foundation, carrying part (jacket), and topside part. J-tubes are important elements associated to platforms; their function is to serve as sheaths for cables from sea bed to topsides. As their number depends on number of feeders their contribution to platform costs are impacted by inter-array grid voltage level. Power outputs of the studied system are measured at secondary sides of export transformers. A schematic of the studied system is represented in Figure 4.

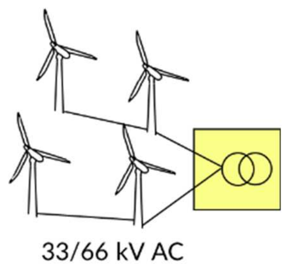
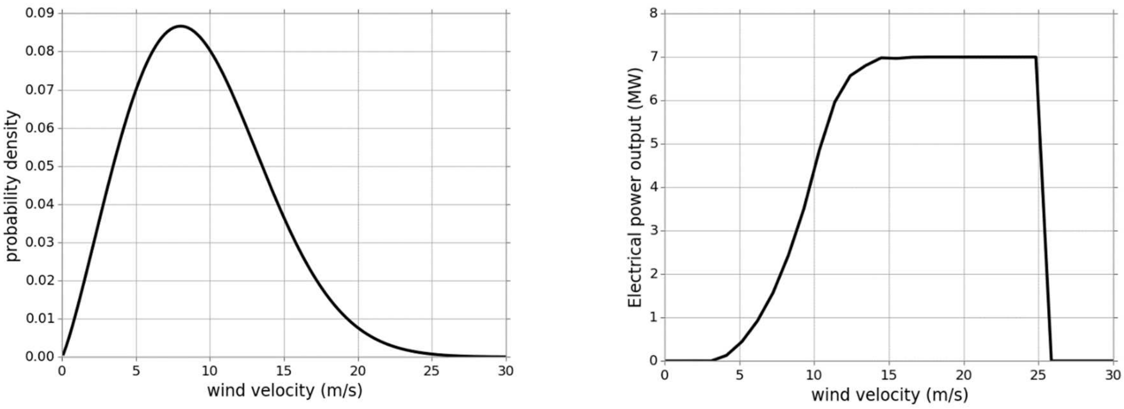


Figure 4: Schematic of one cluster system including wind turbines, inter-array cables and AC platform

II.1 Study case presentation

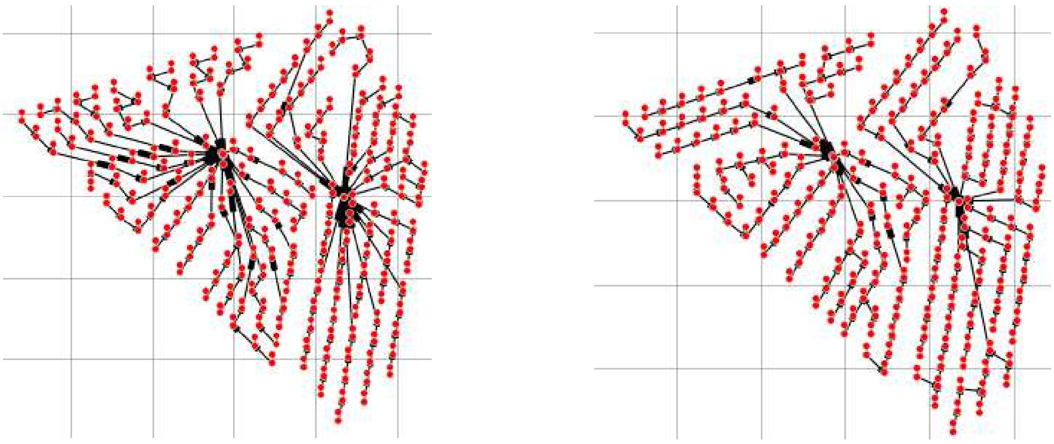
LCOE of studied system depends not only on electrical part but on many other factors such as wind resources, wind turbine performances (fluids mechanic and electrical overall efficiency) and wind turbines locations. As a result, it is paramount not to base results on unrealistic conditions. The study is therefore applied to a real study case, being Borssele wind farm which counts two clusters of one hundred wind turbines each. As wind turbine individual power rating is 7 MW, total peak installed power is 1400 MW. Data are taken from [13] for wind farm layout and from [16] for wind resources ($k = 2.2$ and $\lambda = 10.57$ m/s, corresponding to Weibull distribution function represented in Figure 5 (a)). The 7 MW wind turbine power curve characteristic is taken from TCE study [2] and is shown Figure 5 (b).



(a) Weibull density probability function **(b)** wind turbine power curve

Figure 5: Study case dependence to wind velocity definition

By using these data, the design heuristic defines the grid architecture as mentioned in section I. The obtained graphs (see Figure 6 where there are two clusters in both 33 kV and 66 kV cases) are then analyzed by assessment blocks to compute indexes (annual yield energy at the export transformers output side, investment cost and obtained LCOE).



(a) 33 kV **(b)** 66 kV

Figure 6: Obtained network architectures by considering 33 kV (cluster 1) and 66 kV (cluster 2) voltage levels)

II.2 Capital expenditures analysis

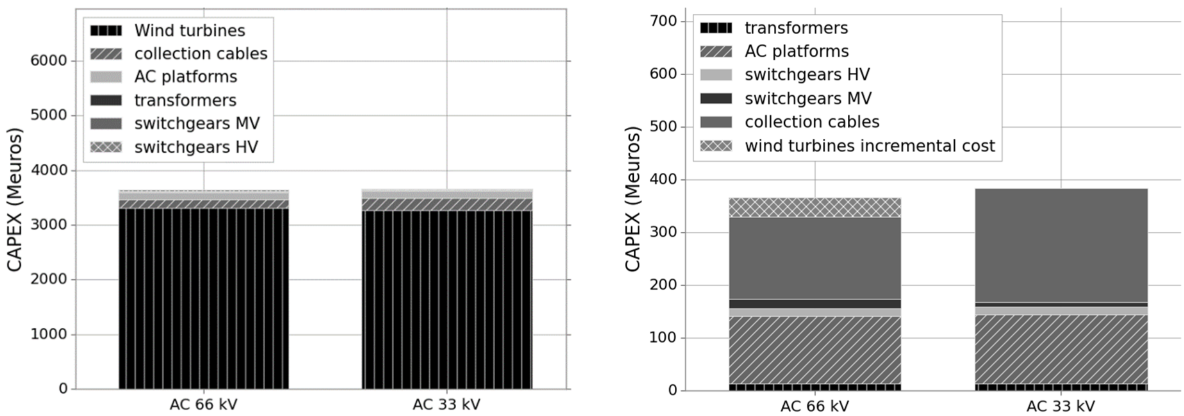
CAPEX of the studied system is drastically dominated by wind turbines total CAPEX (including tower and foundation, supply and installation costs) (see Figure 7 (a)). Indeed wind turbines total CAPEX represents close to 90 % of total CAPEX for the studied system. As a result, a limited share of total CAPEX is impacted by change of inter-array cables voltage level from 33 kV to 66 kV. This impacted CAPEX is represented in Figure 7 (b).

Components unitary supply costs are basically higher for 66 kV than for 33 kV (around +15% for cables supply, +350% for MV switchgears and +100% for LV/MV wind turbines transformers) but total investment costs at system level depend on discriminating factors: the inter-array cables total length and the number of feeders per offshore substation.

In the studied case, there are 430 km of inter-array cables for 33 kV and 310 km for 66 kV. There are 20 and 10 feeders (and as many J tubes and MV switchgears bays) per AC substation for 33 kV, respectively 66 kV inter-array voltage levels. Investment cost variation direction depends on following items:

- AC platform total CAPEX decreases by around 2% from 33 kV to 66 kV due to the lower number of J-tubes.
- Total CAPEX for MV switchgears of offshore substations is almost twice as high in 66 kV compared to 33 kV. This is because unitary cost increase is not compensated by decrease of number of units.
- Total CAPEX for inter-array cables (supply and installation costs) decreases by around 30%: this is because supply costs per unit length of cables increases but is compensated by decrease of total cabling length.
- The total incremental cost of wind turbines due to encapsulated LV/MV transformers and MW switchgears costs increase for 66 kV compared to 33 kV. In share of total CAPEX, this total incremental cost is the most important cost increase (of the same magnitude order as the savings in the inter-array cabling system). However, as stated in [13], involved technologies could become less expensive as their maturity increases.

Finally, as a result of above mentioned elements, Figure 7 (b) shows a moderate decrease in CAPEX of studied system in 66 kV compared to 33 kV: -0.47% on the basis of total CAPEX given in Figure 7 (a)), representing 17 M€.



(a) Full system **(b)** without common wind turbine CAPEX share

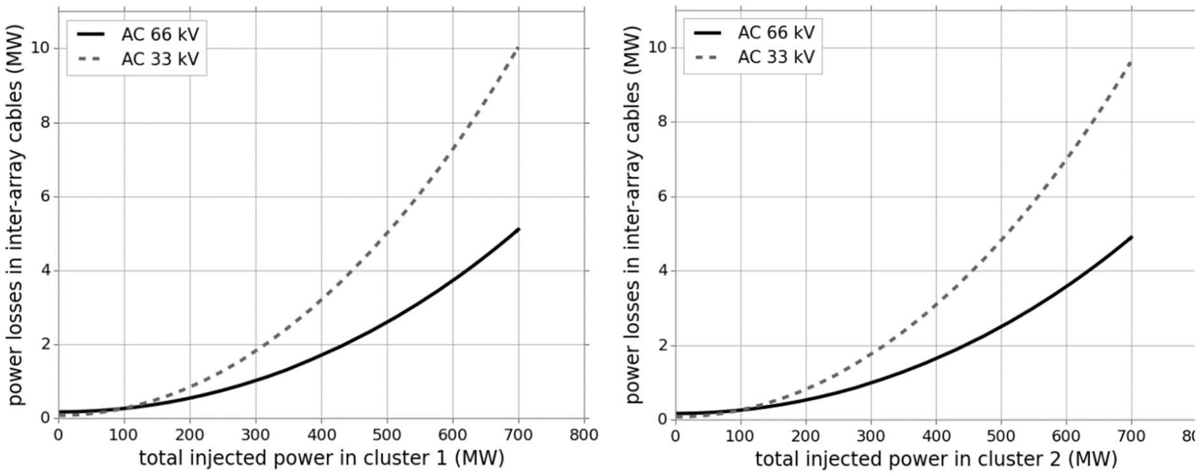
Figure 7: CAPEX breakdown for 33kV and 66kV inter-array cables voltage levels

II.3 Inter-array power losses analysis

Power losses in inter-array cables logically decrease in 66 kV in comparison to 33 kV. Figure 8 shows evolution of power losses depending on the power produced in cluster 1 and in cluster 2.

Table 1 shows mean annual quantities corresponding to these losses calculated by using equation (3). It should be highlighted that mean annual power losses are the same as annual energy losses in percentage. These losses are in the order of 1% of the annual produced energy, which is of the same magnitude order as losses in a MMC HVDC converter. They cannot be neglected and are almost two times higher in 33 kV compared to 66 kV.

Another index to observe the discriminating impact of power losses in inter-array cables is the produced power after export transformers located on offshore AC platforms: The corresponding annual yield energy measured after export transformers is 5785 GW and 5817 GWh for 33 kV respectively 66 kV. It corresponds to an increase in annual energy of 0.55% (see Table 2).



(a) cluster 1 **(b)** cluster 2

Figure 8: Losses in inter-array cables depending on power produced by wind turbines.

Table 1: indexes on inter-array cables power losses

Cluster	Wind turbines Mean annual produced power (MW)	Wind turbines gross load factor	Voltage level (kV)	Mean annual inter-array power losses (MW)	Losses percentage of mean annual produced power
Cluster 1	335	47.8 %	33	3.77	1.13 %
			66	1.98	0.59 %
Cluster 2	335	47.8 %	33	3.62	1.08 %
			66	1.90	0.57 %

II.4 Synthesis

LCOE is calculated with a 20 years life span and a 9% discount rate. LCOE OPEX costs (maintenance, insurance and transmission charges), derived from values per installed peak power given in The Crown Estate study [2], are used in 33 kV and 66 kV cases. As system CAPEX decreases and annual yield energy increases when changing inter-array cables from 33 kV to 66 kV, LCOE decreases, as summed up in Table 2.

Table 2: technical and economic macro indexes

Inter-array voltage (kV)	Total annual yield energy (GWh)	System CAPEX (M€)	LCOE (€/MWh)
33	5785	3655	133.2
66	5817	3638	132.1

Up to a certain point, multiplying feeders can allow collecting the produced power with higher and higher power ratings but it turns to become costly in inter-array cabling. This makes it interesting to consider 66 kV voltage level rather than 33 kV because cabling costs savings compensate cost increases of items (such as MV switchgears and LV/MV transformers in wind turbines). One could argue that multiplying the number of platforms could allow carrying on with 33 kV but the cost of platforms would likely become prohibitive.

LCOE criterion has the advantage to avoid introducing bias as parameterized criteria with the cost of energy. Moreover, LCOE criterion allows to be aware of the importance in the influence of a studied factor at the system level, presently inter-array voltage level. This criterion finally has the advantage to give an information on relative importance of efficiency and investment cost.

Conclusion

The challenges to meet regarding offshore wind power cost reduction require to improve the connection system (including collection and transmission). This must take into account electrical passive and active components (basically power electronic converters, mainly dedicated to HVDC conversion) as much as the influence of their weights and volumes on mechanical structures costs. To follow this innovation requirement, a tool dedicated to the assessment of offshore wind connection alternatives was developed and presented in this paper. The tool has been designed to be compatible with the analysis and optimization of HVDC multi terminal grids. Moreover, the accuracy of costs and losses models is an important requirement. It is met by using advanced modelling, as for AC and DC cables models (based on IEC 60287) with the temperature influence. In the paper, the assessment tool is applied to do a comparative study on voltage collection grid level (33 kV AC or 66 kV AC).

Further studies could be done to assess the opportunity to employ 66 kV voltage level as both inter-array system and direct connection to shore for short distances. The prospects for tool extension include the possibility to optimize the design of the offshore wind connection systems for a given technological connection alternative. It is currently based on heuristics. Reliability studies should also be done to quantify forced energy unavailability (as expected value or including uncertainties information into account) due to components outage. The assessment and optimization tool should not only be used for proven (and costly) technologies (such as MMC based HVDC transmission) but also for highly innovative alternatives such as of “all-in DC” solutions, implying DC/DC converters whose design specification is a complex holistic problem.

References

[1] ENTSO-E, “Offshore Grid Development in the North Seas ENTSO-E views,” 2011.

[2] B. Associates, “Offshore wind cost reduction pathways Technology work stream,” prepared for The Crown Estate, 2012.

[3] A. Gerken, P. Heinrich, M. Richter, F. Peter, L. Krampe, and J. Hobohm, “Cost Reduction Potentials of Offshore Wind Power in Germany,” Prognos and Fichtner for the german offshore wind energy fundation and partners, 2013.

[4] W. G. B4.55, “HVDC connection of offshore wind power plants,” Cigré, 2015.

[5] N. Grid, “Appendix E: Technology,” in *Electricity Ten Years Statement*, 2015.

[6] S. Lundberg, “Evaluation of wind farm layouts,” *Epe journal*, vol. 16, no. 1, p. 14, 2006.

[7] T. Ackermann, N. B. Negra, J. Todorovic, and L. Lazaridis, “Evaluation of Electrical Transmission Concepts for Large Offshore Windfarms,” in *Copenhagen Offshore Wind Conference and Exhibition, Copenhagen*, 2005.

[8] P. Bauer, S. De Haan, C. Meyl, and J. Pierik, “Evaluation of electrical systems for offshore windfarms,” in *Industry Applications Conference, 2000. Conference Record of the 2000 IEEE*, 2000, vol. 3, pp. 1416–1423.

[9] S. P. Engel, M. Stieneker, N. Soltau, S. Rabiee, H. Stagge, and R. W. De Doncker, “Comparison of the modular multilevel dc converter and the dual-active bridge converter for power conversion in HVDC and MVDC grids,” *Power Electronics, IEEE Transactions on*, vol. 30, no. 1, pp. 124–137, 2015.

[10] *Electric cables – Calculation of the current rating*. IEC 60287.

[11] H. Brakelmann, “Loss determination for long three-phase high-voltage submarine cables,” *European transactions on electrical power*, vol. 13, no. 3, pp. 193–197, 2003.

[12] X. Yuan, H. Fleischer, G. Sande, and L. Solheim, “Integration of IEC 60287 in Power System Load Flow for Variable Frequency and Long Cable Applications,” 2013.

[13] D. G. Energy, “Tennet, NL Offshore Wind Farm Transmission Systems - 66 kV systems for offshore wind farms,” prepared for TenneT, 2015.

[14] N. Ederer, “The right size matters: Investigating the offshore wind turbine market equilibrium,” *Energy*, vol. 68, pp. 910–921, 2014.

[15] P. Egrot, P. Monjean, and G. Tremouille, “Key parameters for the optimization of a Wind Farm: Impact on the offshore substation,” *CIGRE 2014*, 2014.

[16] B. H. Bulder, E. T. G. Bot, E. Wiggelinkhuizen, and F. D. J. Nieuwenhout, “Quick scan wind farm efficiencies of the Borssele location,” *Energy research Centre of the Netherlands*, 2014.